Modeling and Simulation for Qualification of Additive Manufacturing

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GIF AMME Workshop on Advanced Manufacturing
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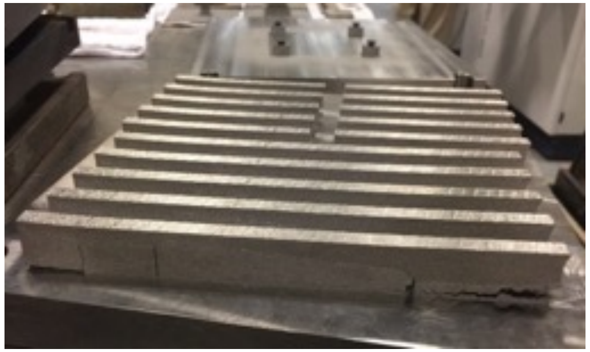
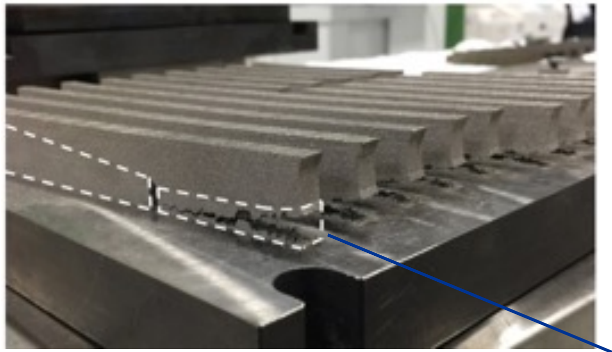
ANSYS ADDITIVE MANUFACTURING RESEARCH LABORATORY

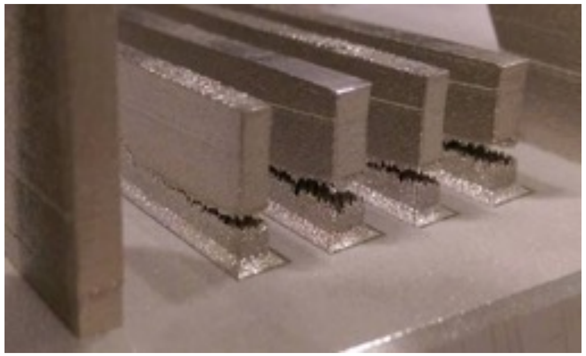
Ansys Additive Manufacturing Research Lab (AMRL)

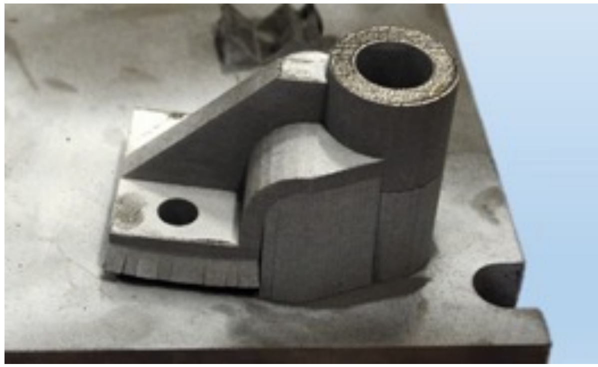
- Established in 2015
- 2,000 sq ft lab space

Build Failures - Laser Powder Bed Fusion





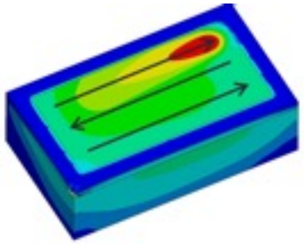




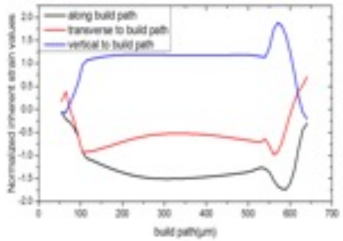
Modified Inherent Strain Method

Detailed model

- meso-scale (~0.1mm)
- sequentially coupled thermomechanical analysis



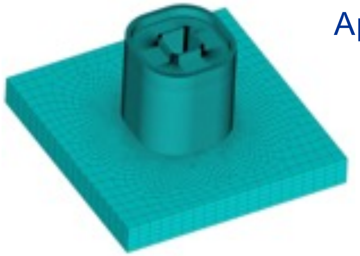
Extract inherent strains (element by element)



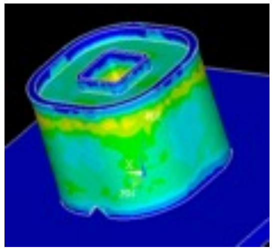
$$\varepsilon^{In} = \varepsilon_{t_i}^{Plastic} + (\varepsilon_{t_i}^{Elastic} - \varepsilon_{t_s}^{Elastic})$$

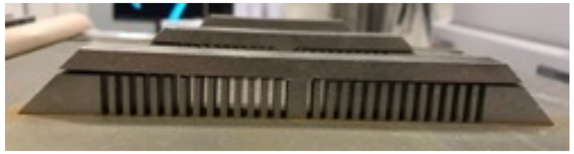
Inherent strain model

- macro-scale (~100mm)
- Quasi-static mechanical analysis

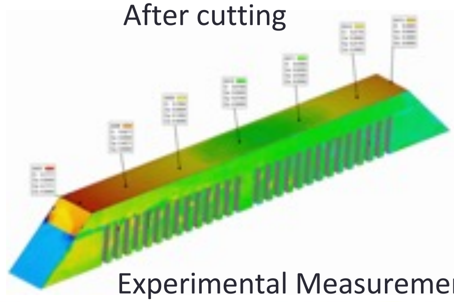


Apply inherent strains (layer-by-layer)

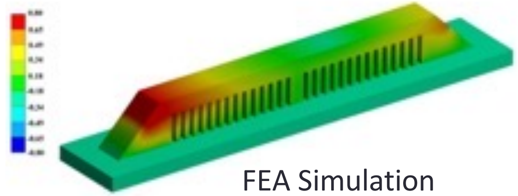




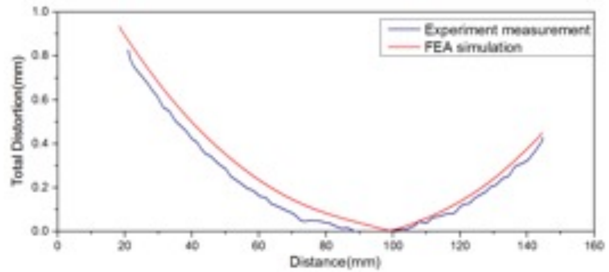
After cutting



Experimental Measurement



FEA Simulation

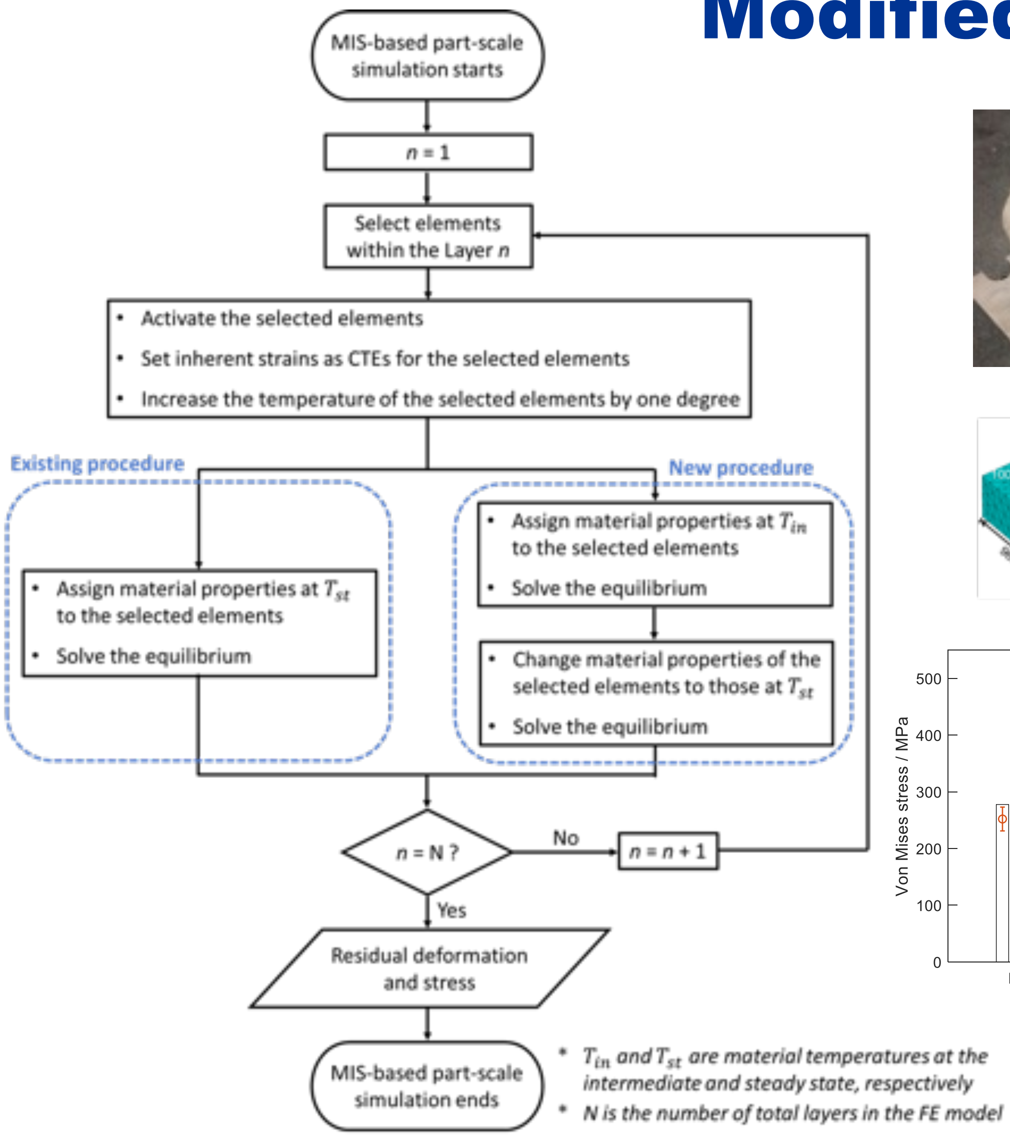


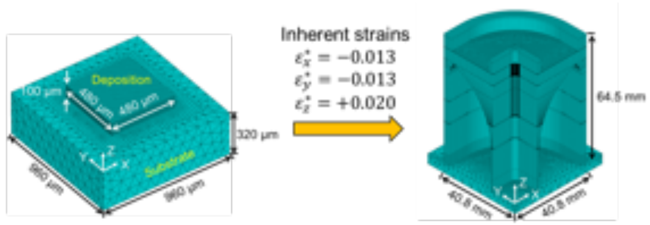
➢ **Reduce error in deformation from 40% to 10% compared to original inherent strain model**

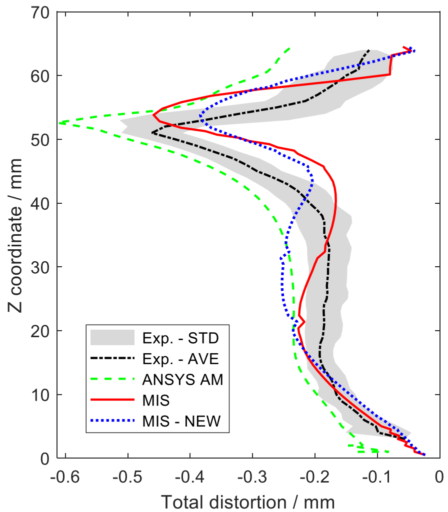
Q. Chen, A. C. To, et al., “An inherent strain based multiscale modeling framework for simulating part-scale residual deformation for direct metal laser sintering,” *Additive Manufacturing*, vol. 28, 406-418, 2019.

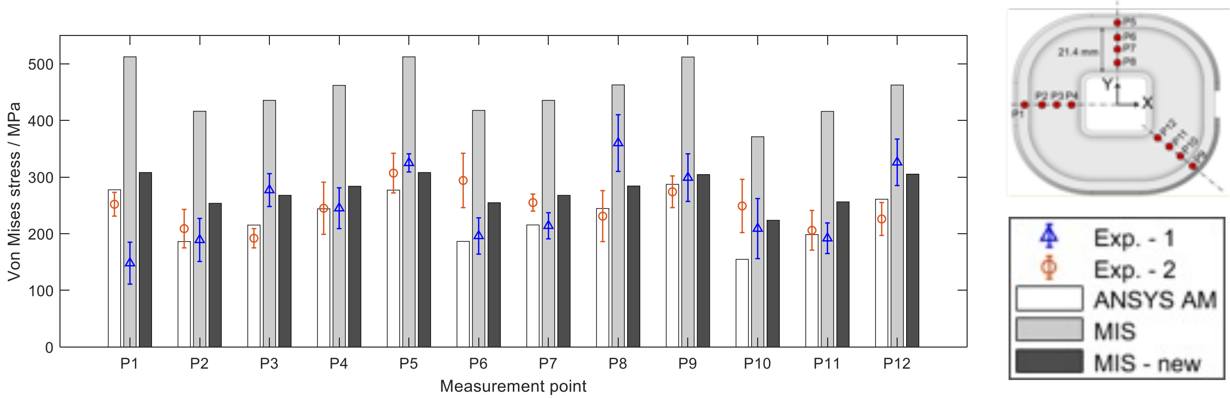
X. Liang, A. C. To, et al., “Modified inherent strain method for fast prediction of residual deformation in direct metal laser sintered components,” *Computational Mechanics*, vol. 64, 1719-1733, 2019.

Modified Inherent Strain Method





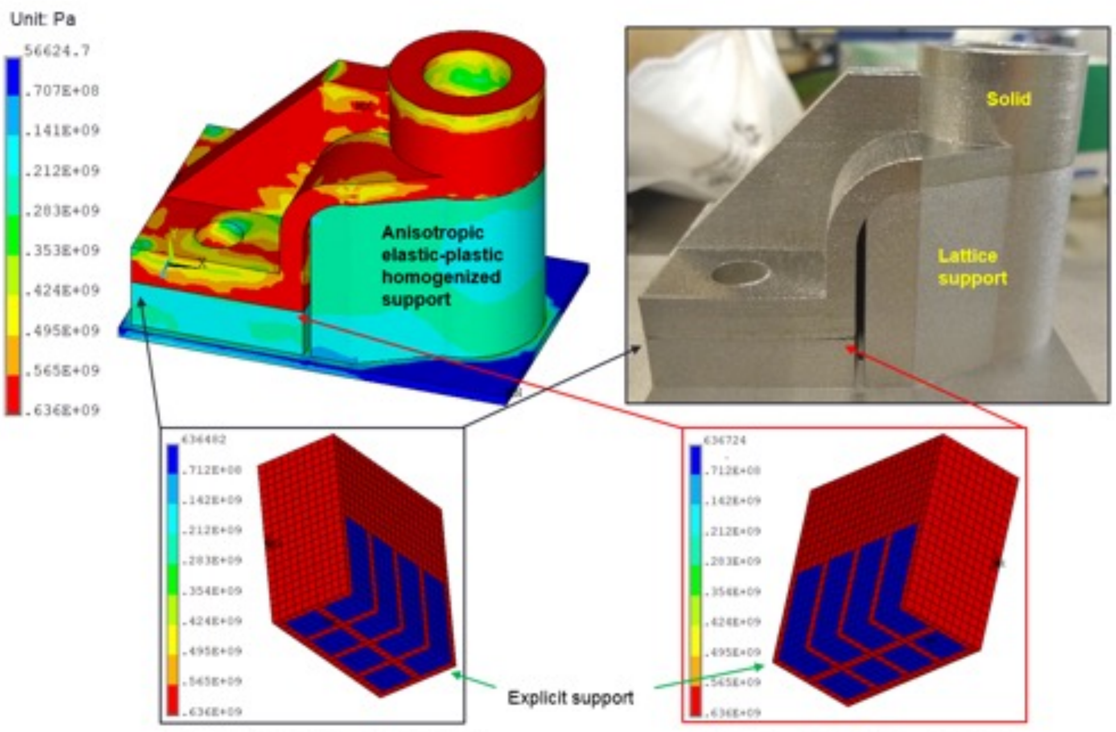




W. Dong, **A. C. To**, et al "A new procedure of implementing modified inherent strain model for improving prediction accuracy of both residual stress and deformation in laser powder bed fusion parts", *Additive Manufacturing*, in press.

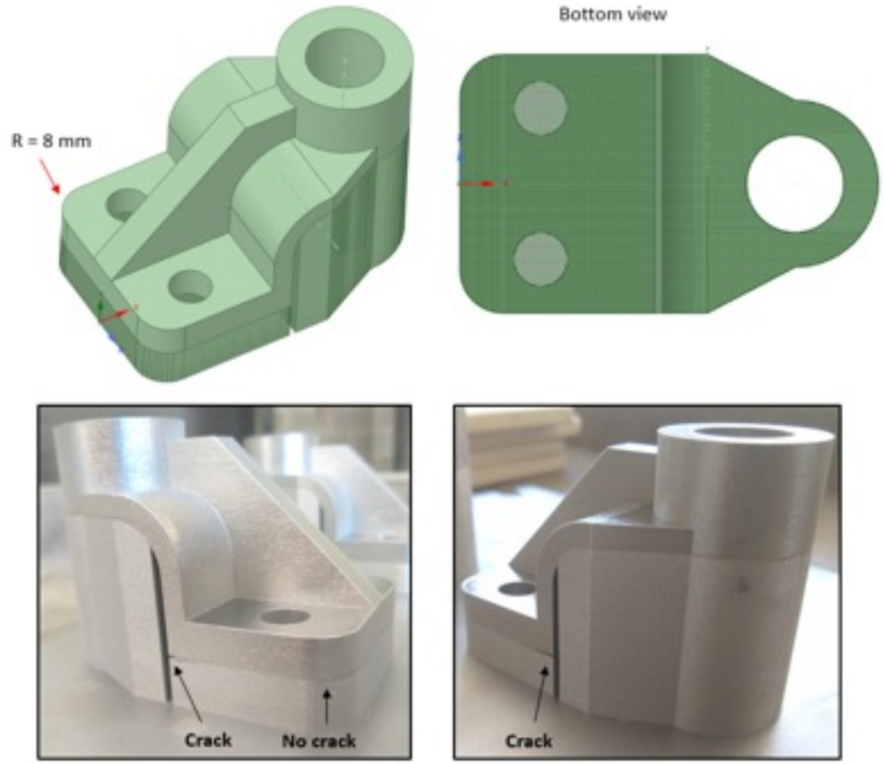
Bearing Bracket Support (Re)-Design

- Combine global-local analysis, J-integral, and modified inherent strain method to predict interfacial cracking between solid component and support structure



J-integral = 7.6 KJ/m^2 > J_C = 7.2 KJ/m^2
→ cracking

J-integral = 9.3 KJ/m^2 > J_C = 7.2 KJ/m^2
→ cracking



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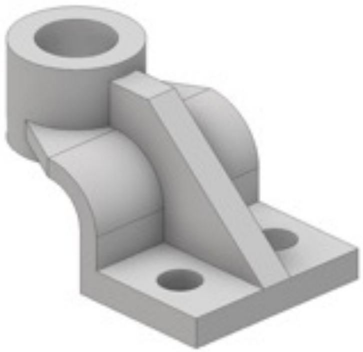
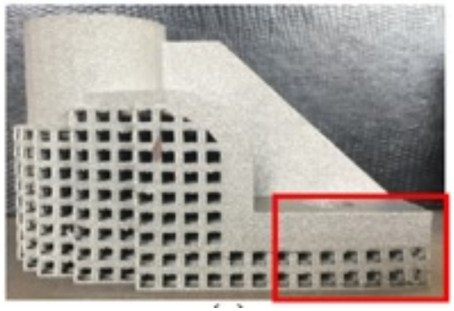
H. Tran, X. Liang, and A. C. To, "Efficient prediction of cracking at solid-lattice support interface during laser powder bed fusion via global-local J-integral analysis based on modified inherent strain method and lattice support homogenization," *Additive Manufacturing*, vol. 36, 101590, 2020.

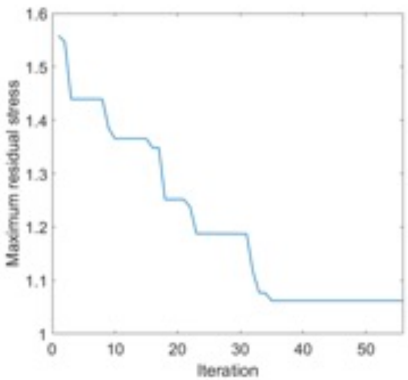
Build Orientation Optimization

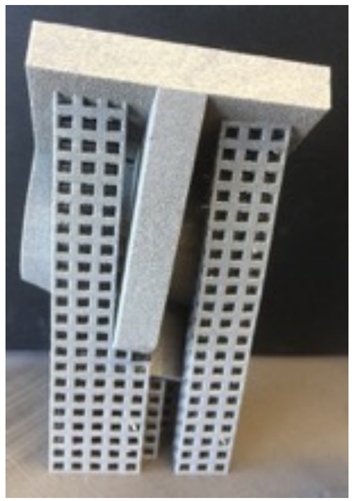
- Combine particle swarm optimization and modified inherent strain method to efficiently optimize build orientation for residual stress





Optimal Orientation





- **Reduce maximum residual stress by 40-50%**

No cracking!

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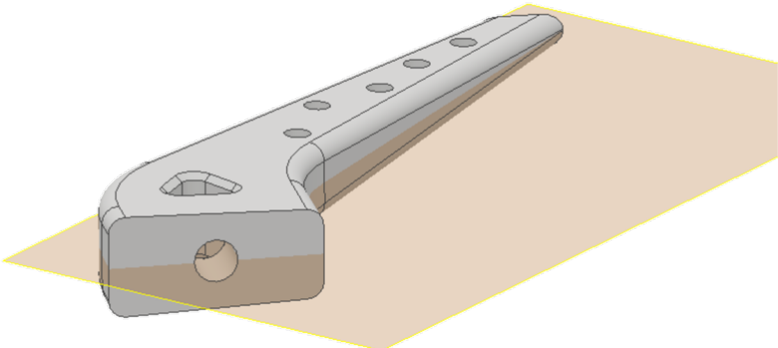
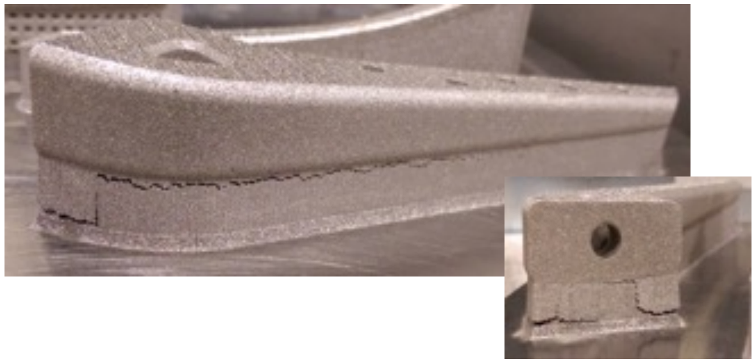
L. Cheng and A. C. To, "Part-scale build orientation optimization for minimizing residual stress and support volume for metal additive manufacturing: theory and experimental validation," *Computer-Aided Design*, vol. 113, 1-23, 2019.

Support Structure Optimization

- Combine modified inherent strain method and topology optimization to design support structure



Un-optimized support



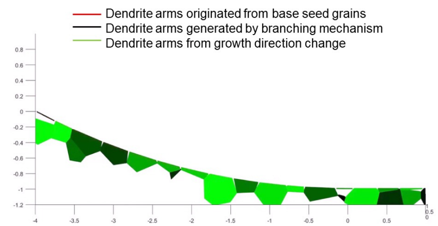
L. Cheng, A. C. To, et al., “On utilizing topology optimization to design support structure to prevent stress induced build failure in laser powder bed fusion,” *Additive Manufacturing*, vol. 27, 290-304, 2019.

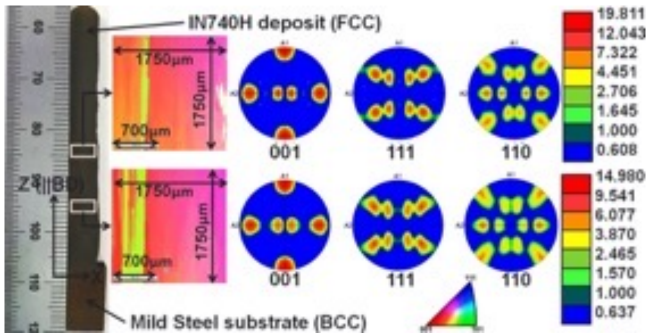
Optimized support

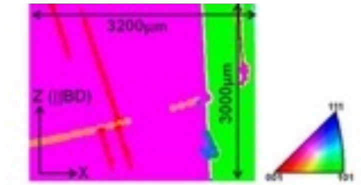
- **Reduce maximum residual stress by 30-40%**

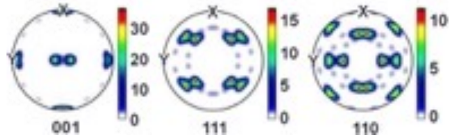
Fast Grain Growth Model

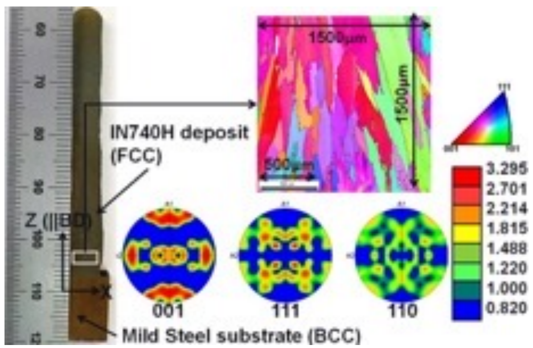
- Assumes epitaxial columnar dendrite is the dominant growth mechanism
- Each epitaxial columnar dendrite is modeled by a line segment
- Each dendrite is grown according to the local thermal gradient

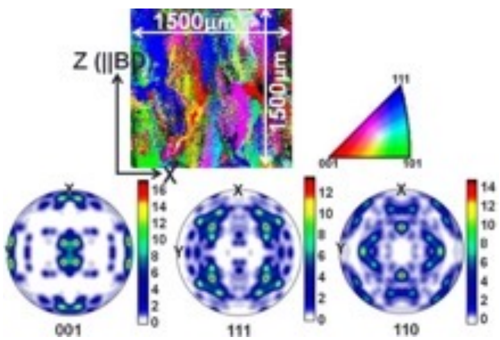


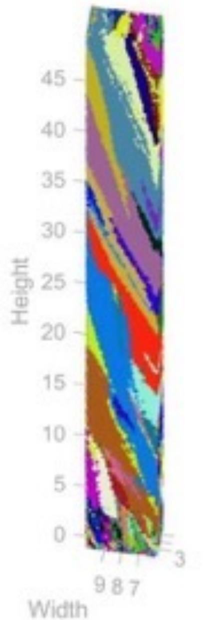






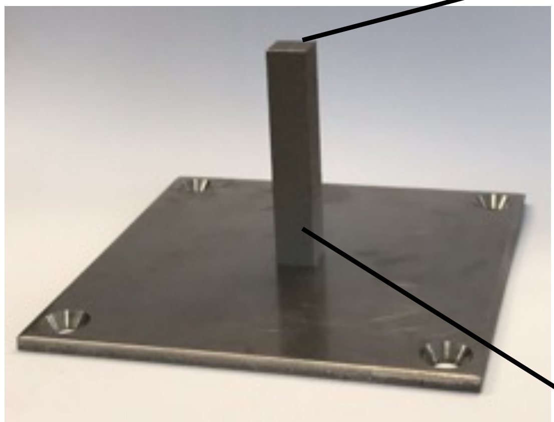




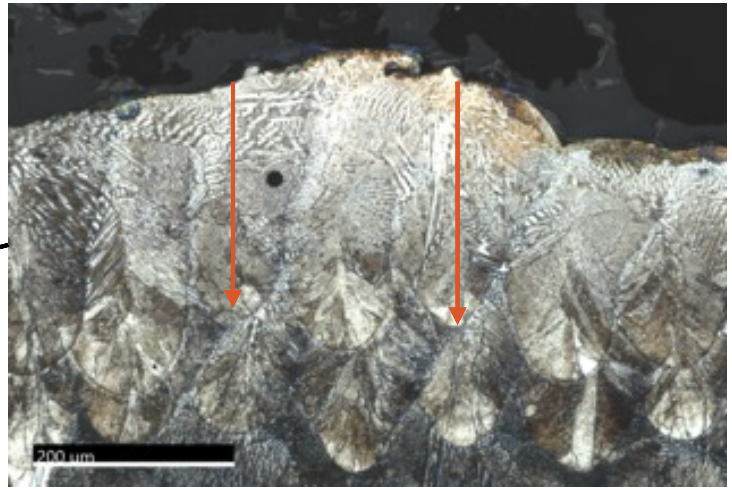


S. Paul, A. C. To, et al., “Discrete Dendrite Dynamics Model for Epitaxial Columnar Grain Growth in Metal Additive Manufacturing with Application to Inconel,” *Additive Manufacturing*, vol. 36, 101611, 2020.

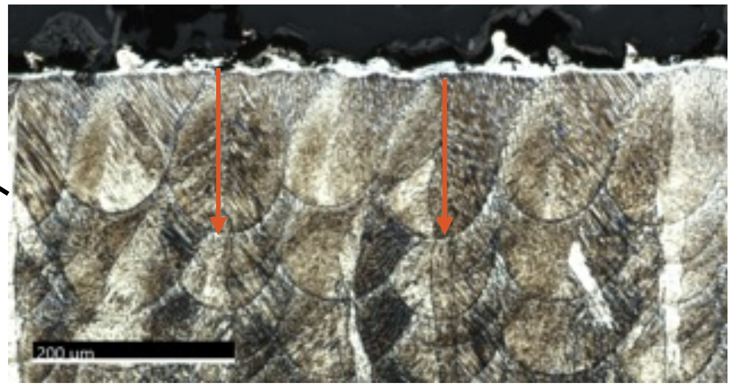
Melt Pool Variation and Defect Formation

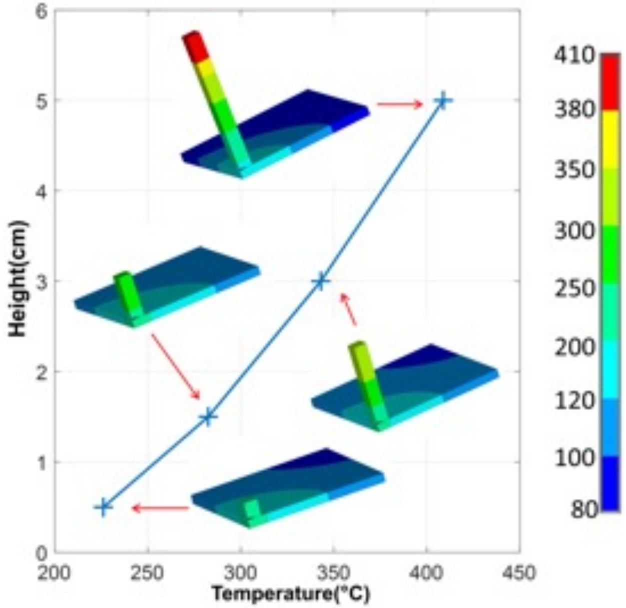


5 cm height



1 cm height





Pre-deposition temperature profile along building height

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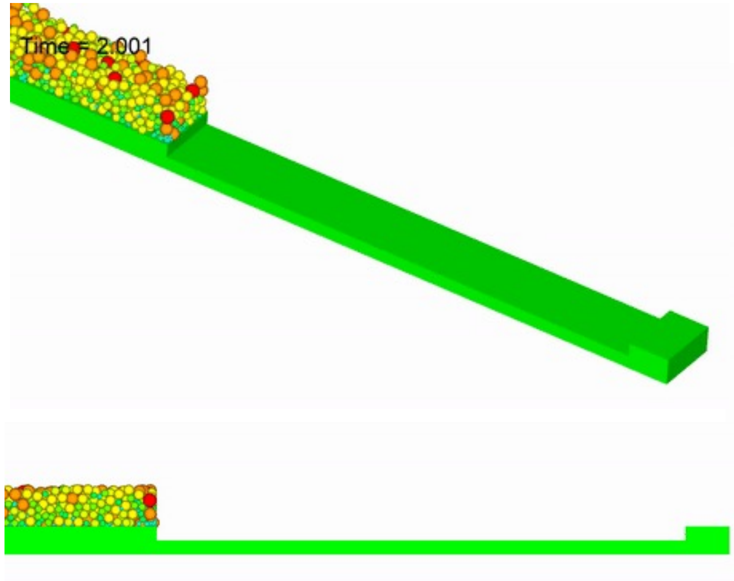
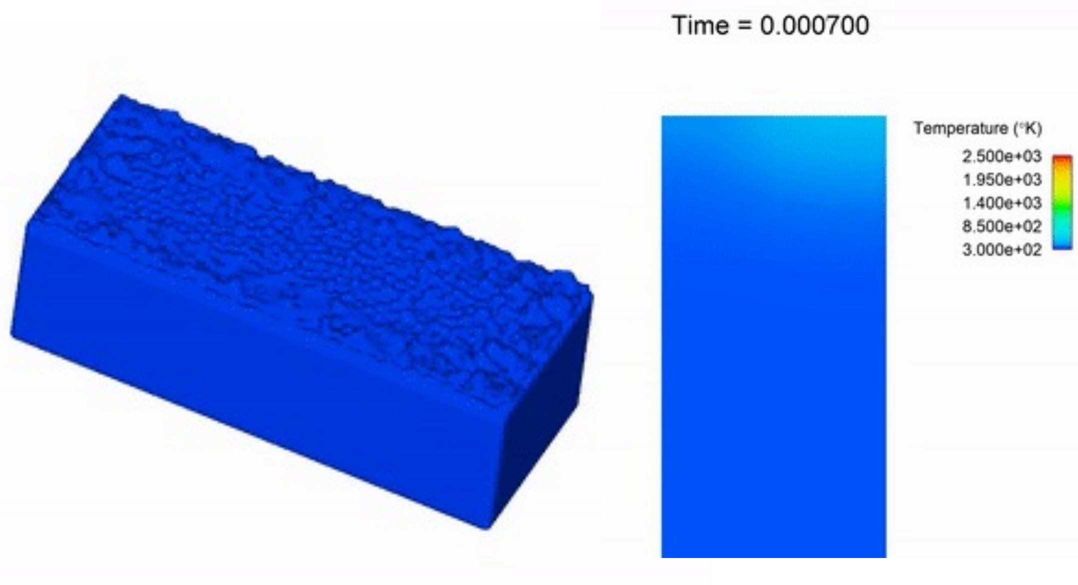
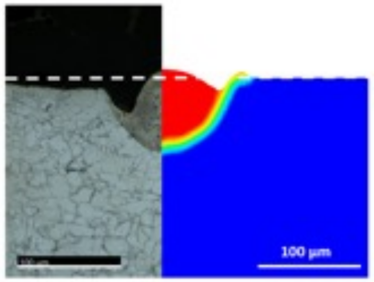
Melt Pool and Defect Prediction

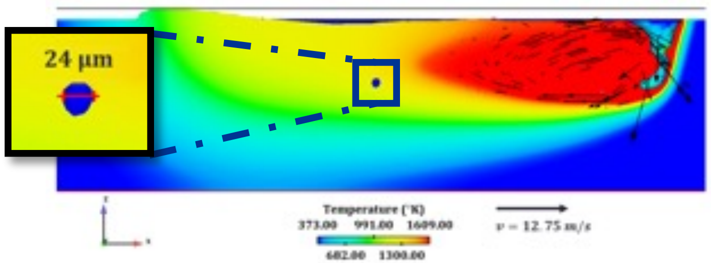




- Mesoscale computational fluid dynamics to model the heat transfer and fluid flow
- Predict the melt pool morphology and anticipated defects



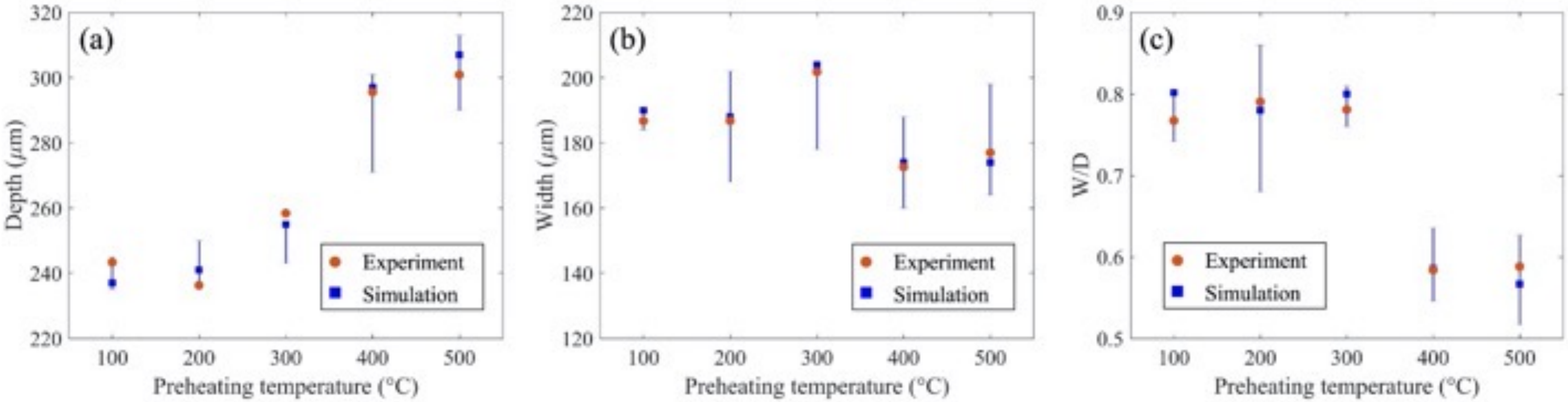
Melt pool geometry

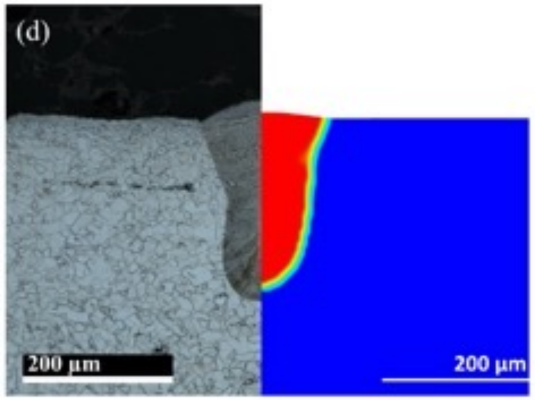


Keyhole pore generation

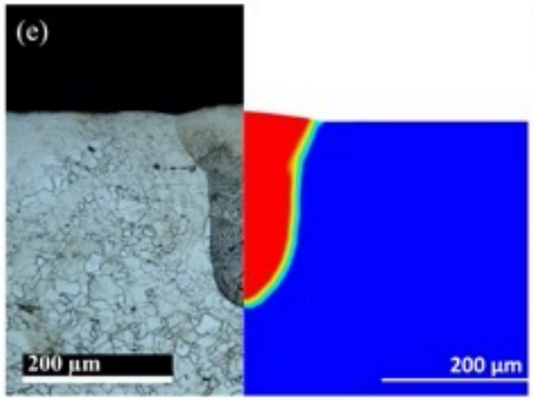
Effect of Preheating Temperature

Keyhole regime (P = 250 W and V = 0.5 m/s)

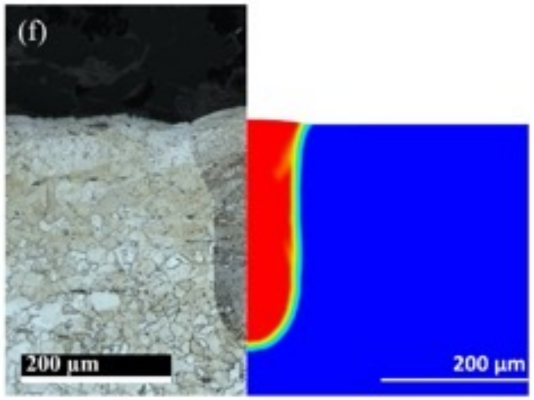




Preheating temperature: 100 °C



Preheating temperature: 300 °C



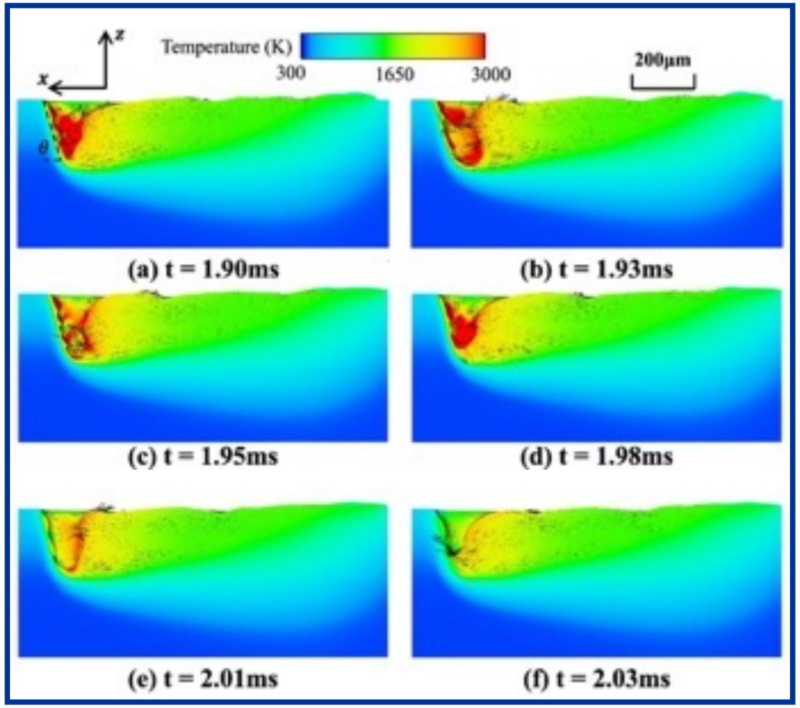
Preheating temperature: 500 °C

Q. Chen, **A. C. To**, et al. “Elucidating the effect of preheating temperature on melt pool morphology variation in Inconel 718 laser powder bed fusion via simulation and experiment,” *Additive Manufacturing*, vol. 37, 101642, 2021

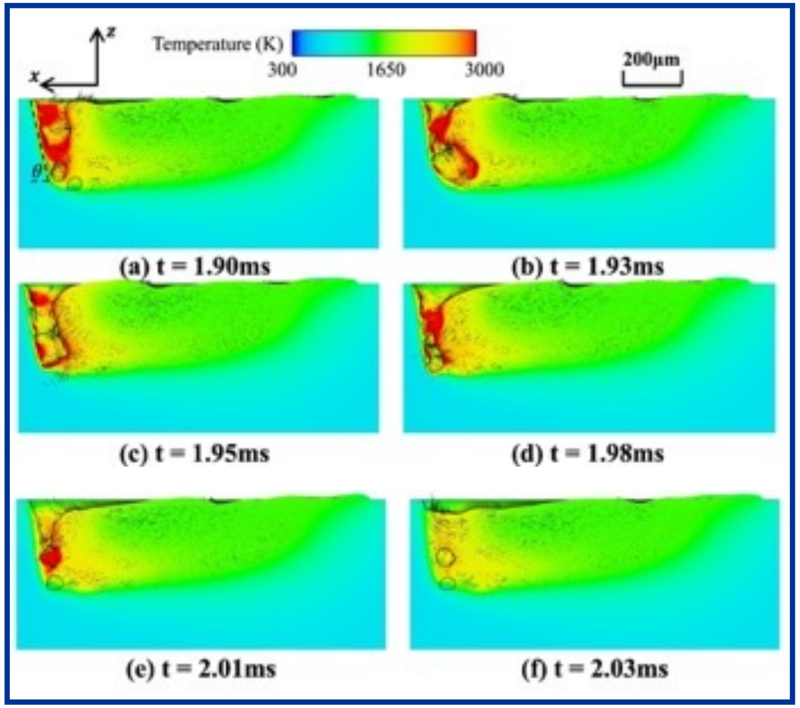
Keyhole Pore Generation

For melt pool in keyhole regime (P = 250 W, V = 0.5 m/s):

- Increasing the preheating temperature leads to deep melt pool
- Probability of porosity occurrence is increased at higher preheating temperature



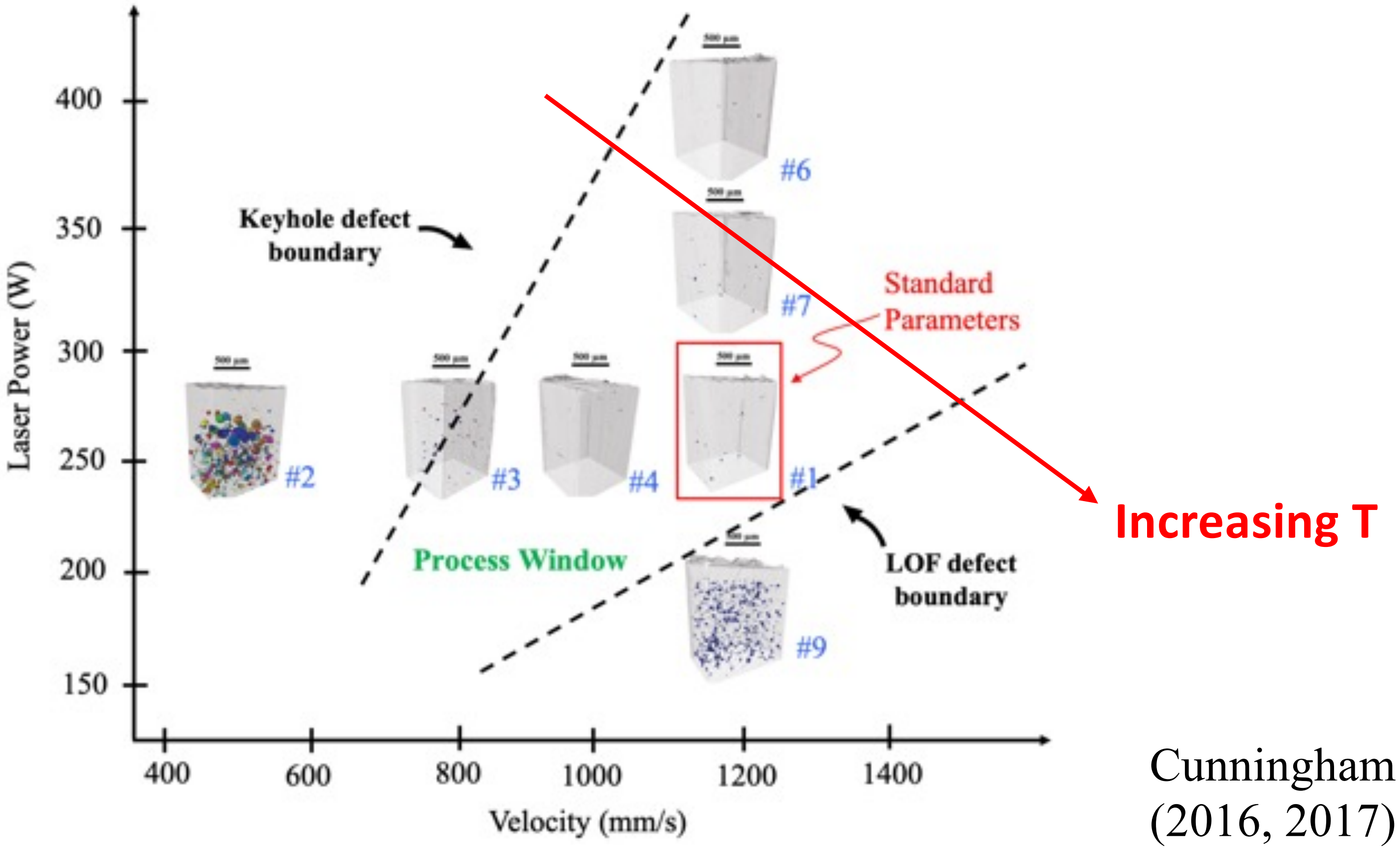
Preheating temperature: 100 °C



Preheating temperature: 500 °C

Q. Chen, **A. C. To**, et al. "Elucidating the effect of preheating temperature on melt pool morphology variation in Inconel 718 laser powder bed fusion via simulation and experiment," *Additive Manufacturing*, vol. 37, 101642, 2021

Process Window (P-V Map)



Cunningham *et al.* (2016, 2017) JOM

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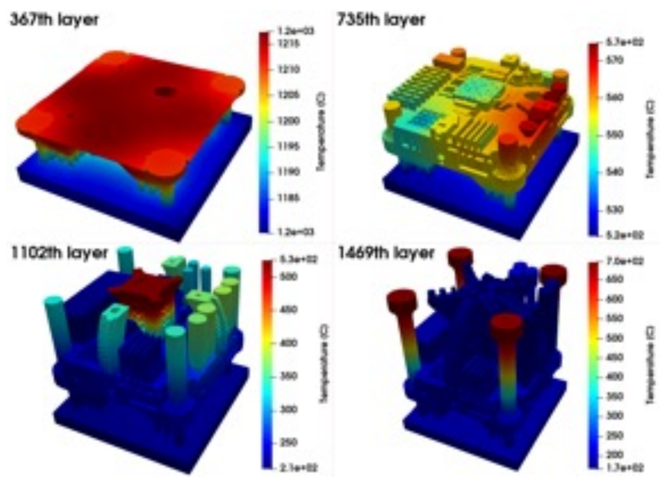
GPU-based AM Process Simulator

Key Features:

- Based on ***voxel mesh*** and ***matrix-free finite element formulation***
- Runs on a $10-30k workstation but with supercomputer performance
- Handles highly complex geometry
- **300 times faster** running on 1 GPU than running on 1 CPU core



Layer-by-layer simulation of the "UTEP QTA block" on multi-GPUs

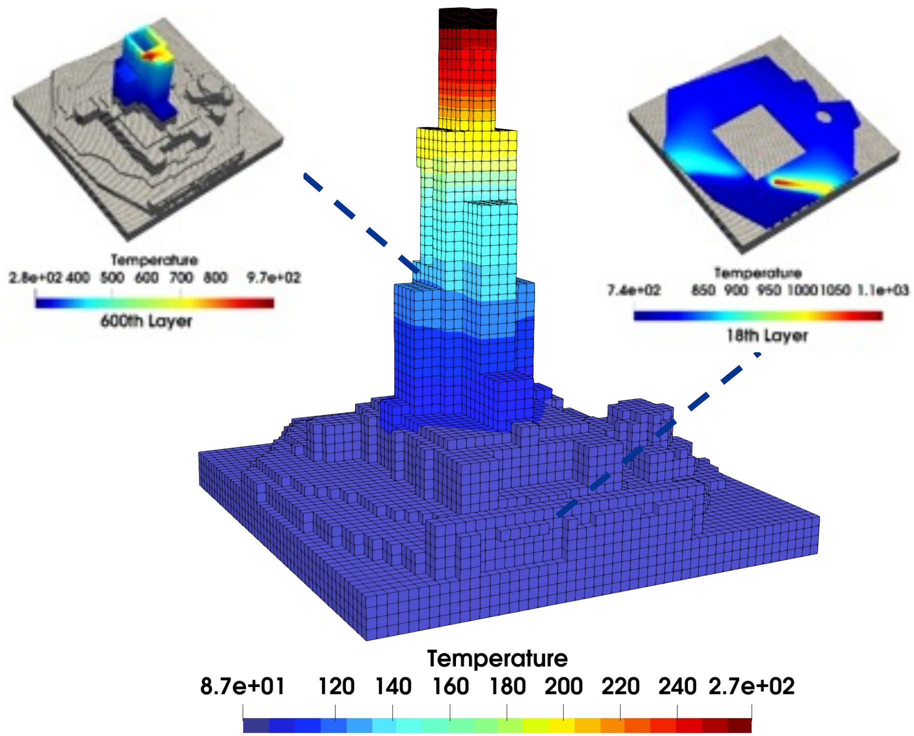
	Simulation time	Speedup
1 GPU	17h	-
2 GPU	10h 51 min	1.57
3 GPU	8h 50 min	1.92
4 GPU	7h 40 min	2.22
Actual build time	14 hours	-

Physical domain: 41x41x41 mm^3 Number of nodes: 206x206x206
Element resolution in x and y direction: 200 microns
Layer thickness: 30 microns
Material properties: Ti64 (temperature dependent)

F. X. Dugast, A. C. To, et al. "Part-scale thermal process modeling for laser powder bed fusion with matrix-free method and GPU Computing," *Additive Manufacturing*, vol. 37, 101732, 2021.

Multiscale Process Simulation

- Layerwise simulation is fast and can be used to detect “hot spots”
- Scanwise simulation is time-consuming and should be restricted to small millimeter-scale region
- Developing a global-local process simulation to simulate thermal history, melt pool geometry, and microstructure including porous defects



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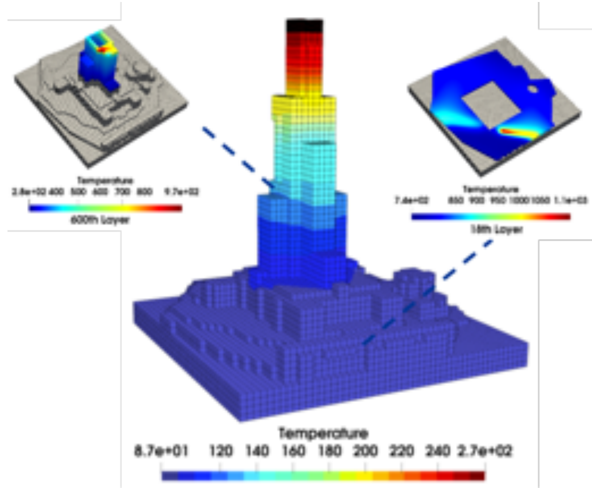
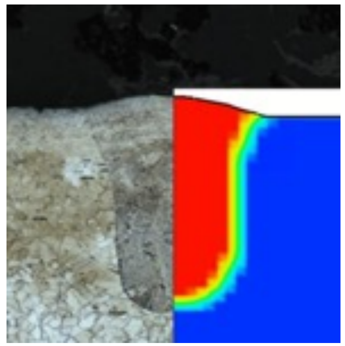
Challenges and Opportunities

- Predicting detailed temperature history and microstructure/property everywhere in a part
  - Phase field and cellular automaton limited to 1-mm region
  - Property prediction beyond static strength is challenging, and experimental data is limited
- Capturing melt pool variability
  - Laser diameter dependency on location
  - Spatter shadowing in laser path
  - Laser power/focus varies over time and differ between machines
- Predicting porosity in the “allowable process window” within a part
  - Porosity caused by spattering difficult to predict
- Data curation, storage, and mining
  - In-situ monitoring, ex-situ characterization, simulations
  - Many terabytes of data





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Thank you

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