08/13/2019
SFF 2019
1400 – 1420 Hrs.
Salon A

Experimental Validation of the Thermal Distribution Predicted by the Graph Theory Approach Application to Laser Powder Bed Fusion

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Acknowledgements

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CMMI 1752069

Outline

- Introduction
  - Research goal
  - Introduction of graph theoretic thermal modeling
- Experiment and simulation procedure
  - Experimental Setup
  - Build Strategies
- Result
  - Simulations vs. experiment
  - Graph Theory vs FEA
- Conclusion and Future Works
  - Distortion and microstructure prediction

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Validate the graph theory model using experimental laser powder bed fusion data

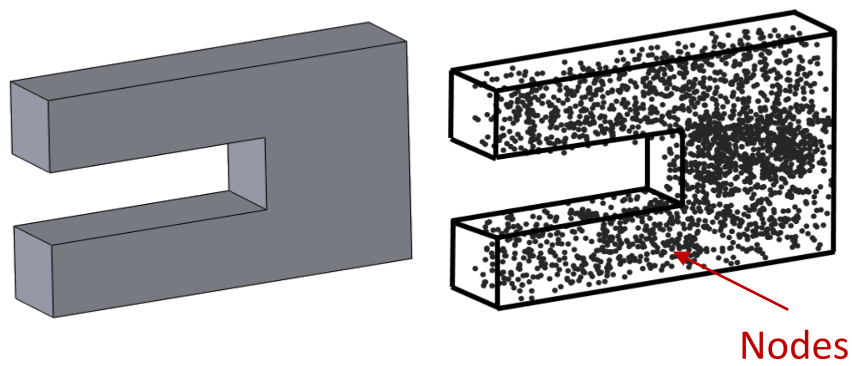
Approach

Yavari, M. R., Cole, K., and Rao, P., 2019, "Thermal Modeling in Metal Additive Manufacturing using Graph Theory," ASME Transactions, *Journal of Manufacturing Science and Engineering*, 141(7)

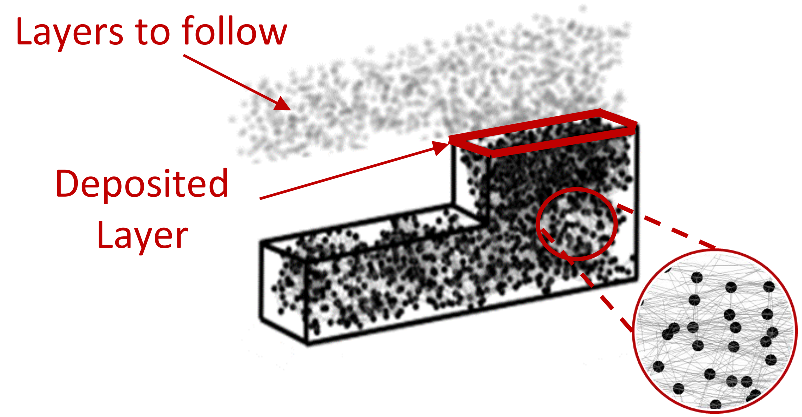
Data

Williams, R., Piglione, A. , Ronneberg, T. , Pham, M. S., Davis, C. M. and **Hooper, P. A.** , 2019, "In-situ thermography for laser powder bed fusion: effects of layer temperature on porosity, microstructure and mechanical properties", *Additive Manufacturing*, In Press

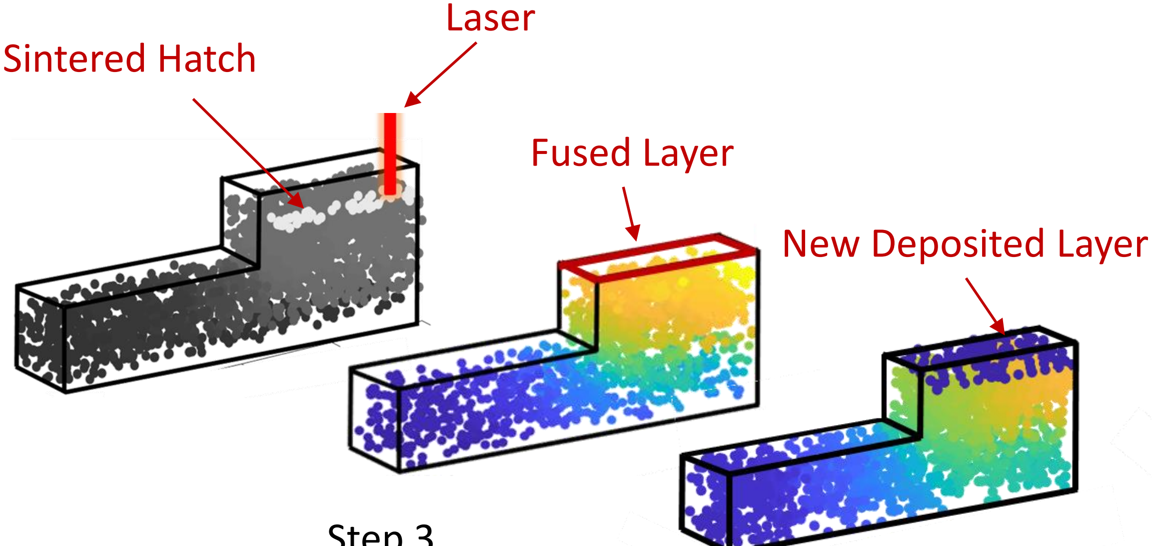
Graph Theoretic Thermal Modeling in AM

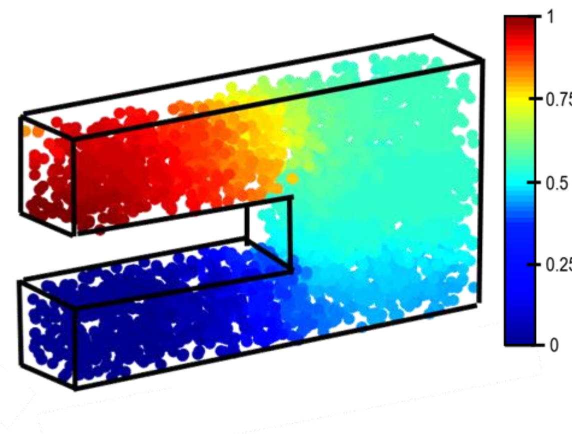


<u>Step 1</u>- Convert the part into a set of discrete nodes



<u>Step 2</u>- Network graph construction





<u>Step 3</u>

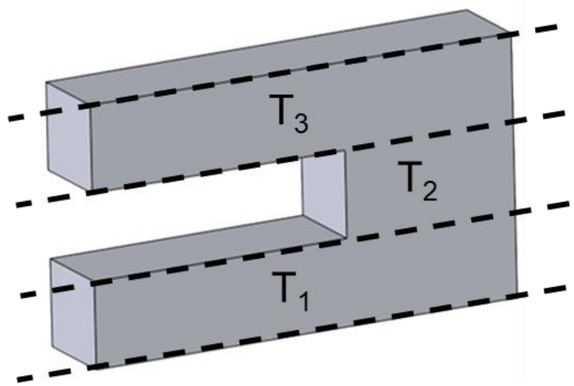
- Heating a layer, hatch by hatch,
- Diffusion of the heat through the part
- Deposition of a new layer

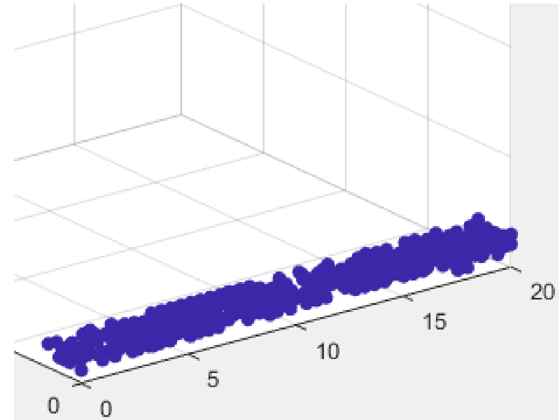
<u>Step 4</u>

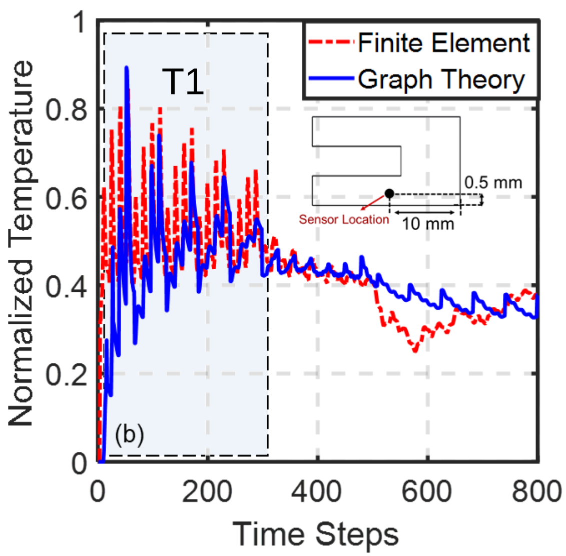
Result as temperature matrix which shows the temperature history of the part

Recap: Verification with FEA

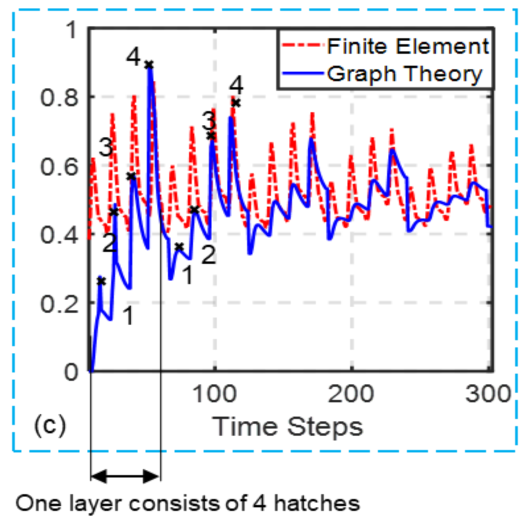
Graph theory simulates the AM process in C-shaped part.

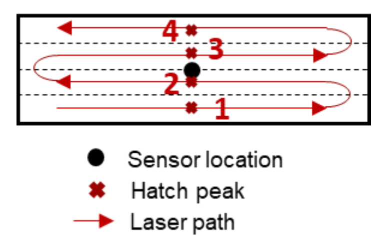






T1 Zoomed-In





Graph theory solution converges to similar trends as finite element analysis.

Yavari, M. R., Cole, K., and Rao, P., 2019, "Thermal Modeling in Metal Additive Manufacturing using Graph Theory," ASME Transactions, *Journal of Manufacturing Science and Engineering*, 141(7), pp. 071007-071027

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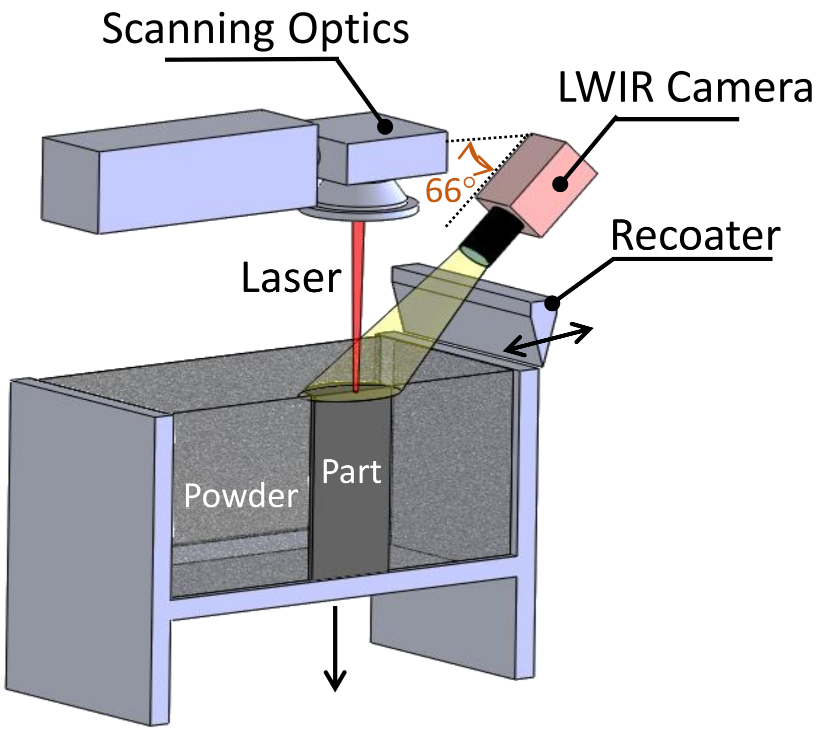
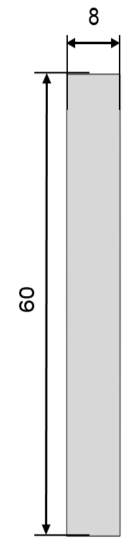
Experiment Setup

A thermal camera is used to measure the surface temperature on the top surface.

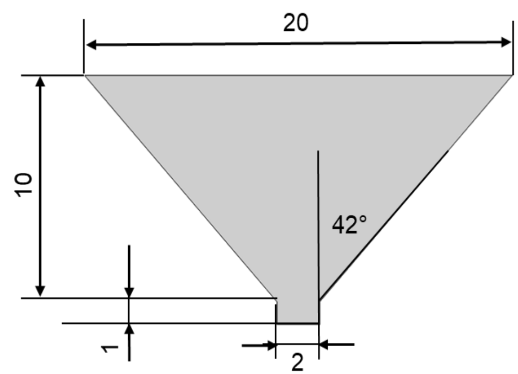


Laser Powder Bed Fusion (LPBF)



Build 1
(Cylinder)

Laser power: 50 W



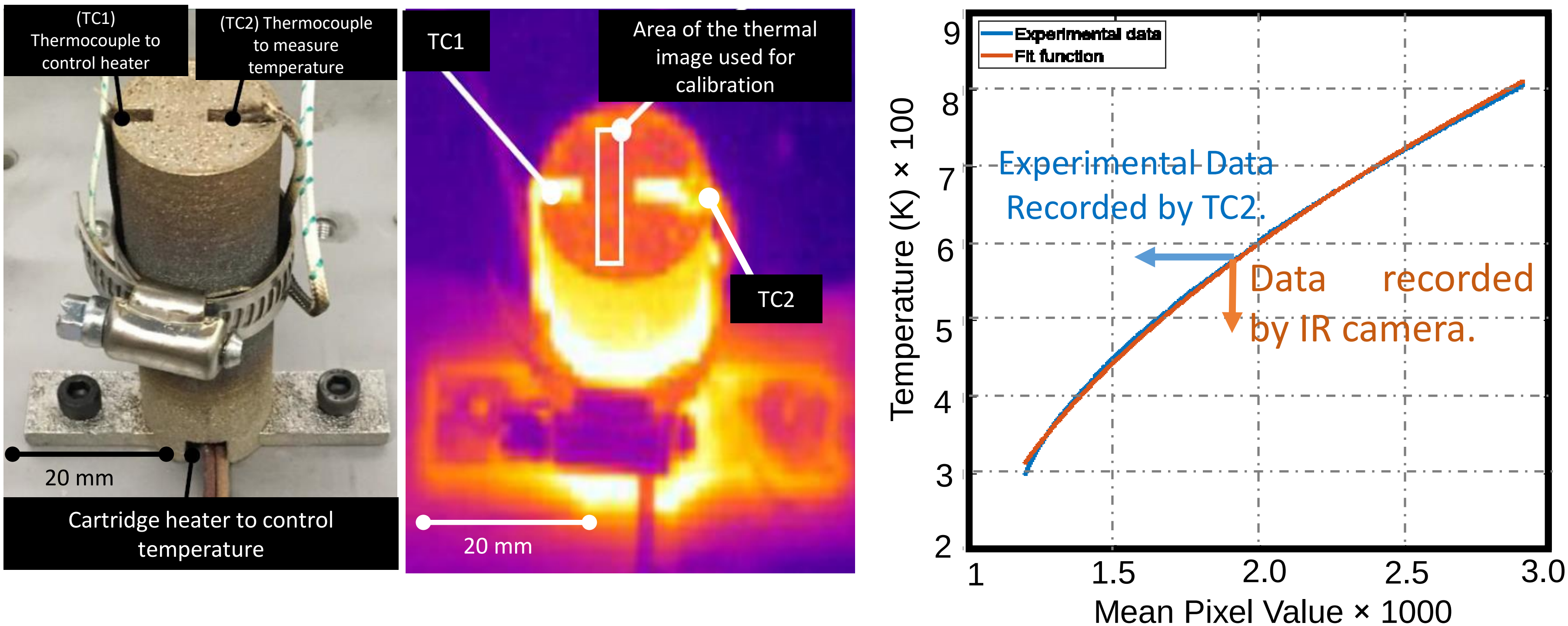
Build 2
(Inverted Cone)

Laser power: 200 W

Layer thickness: 50 µm
point distance: 40 µm, exposure time: 50 µs

Calibration of IR Camera Measurements

- Calibration function applied to convert the raw IR camera data to temperature values.
- IR camera was calibrated empirically for both solid and powder.
- AM part temperature was controlled using a cartridge heater.
- Absolute temperature trends captured using thermocouples embedded in a cavity.



Williams, R., Piglione, A. , Ronneberg, T. , Pham, M. S., Davis, C. M. and Hooper, P. A. , 2019, "In-situ thermography for laser powder bed fusion: effects of layer temperature on porosity, microstructure and mechanical properties", *Additive Manufacturing*, In Press

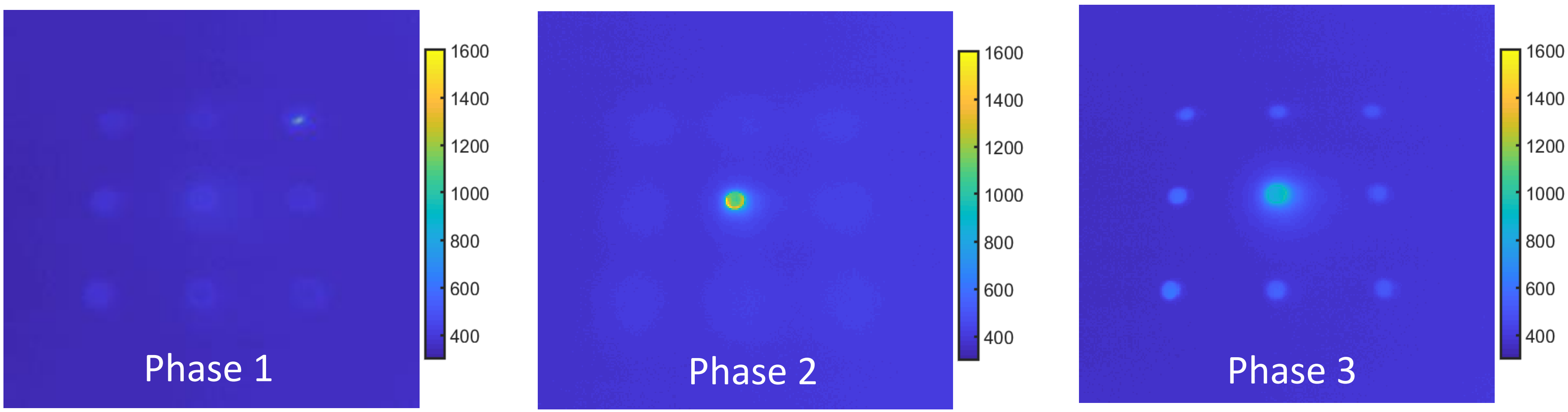
Build 1 (Cylinder)

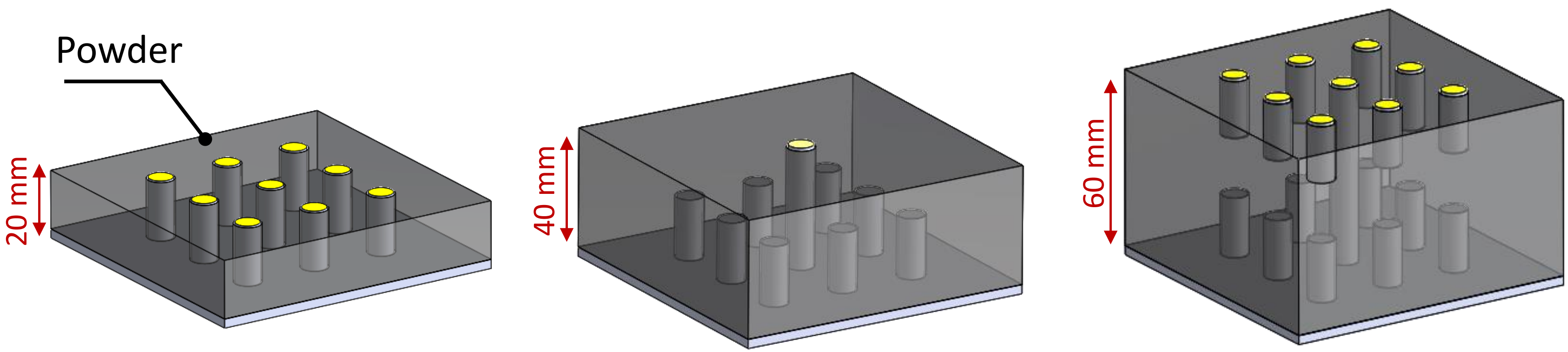
Build 1 includes of 3 different phases:

Phase 1: Print 9 cylinders (dia. 8 mm, L = 60 mm).

Phase 2: Print only the middle cylinder.

Phase 3: Print all 9 cylinders again.

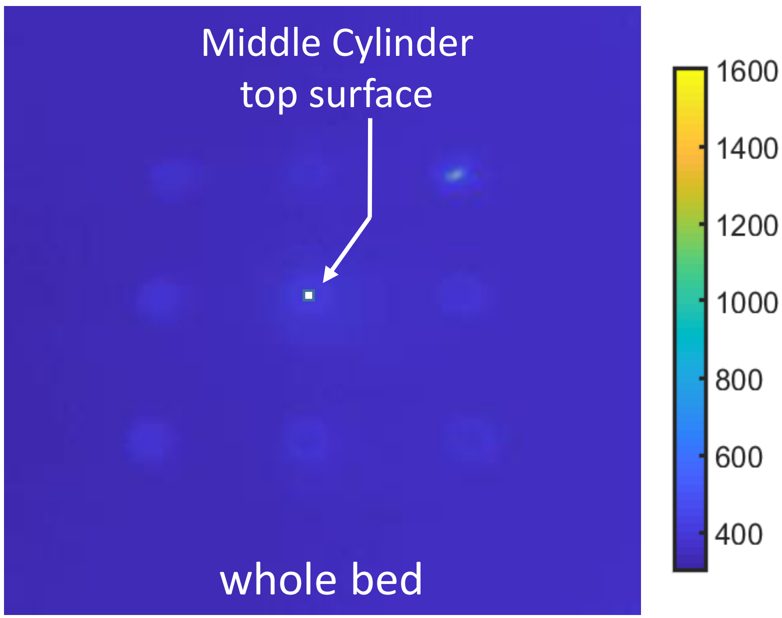


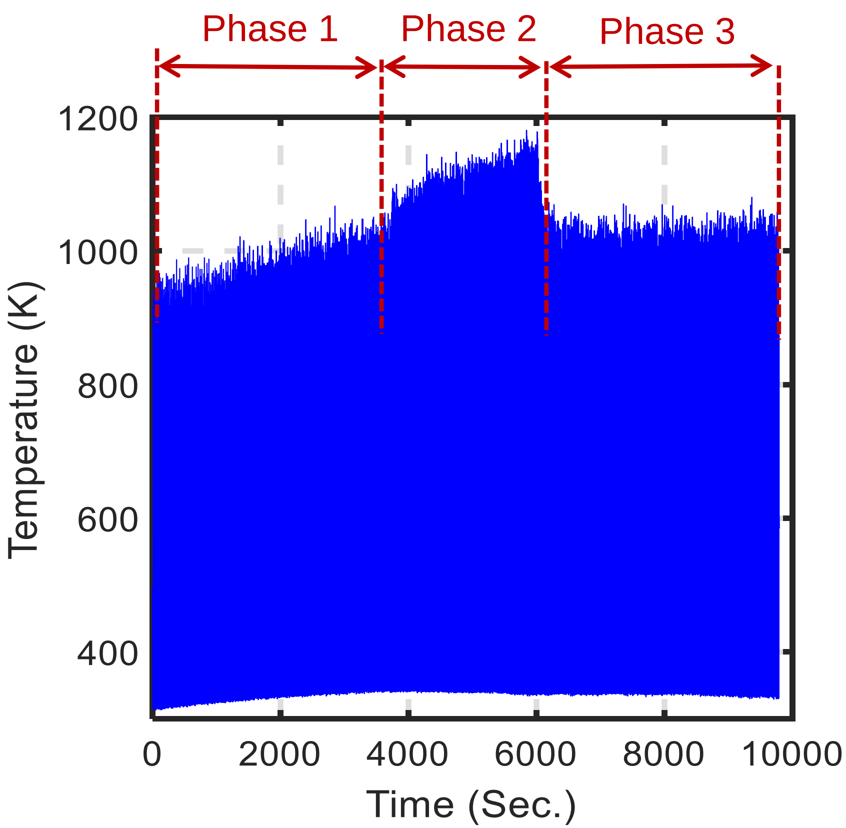


Change in the build plan causes variation in the inter-layer cooling time (ILCT).

Build 1 (Cylinder) Thermal Data

The temperature recorded at center pixel of the middle cylinder.





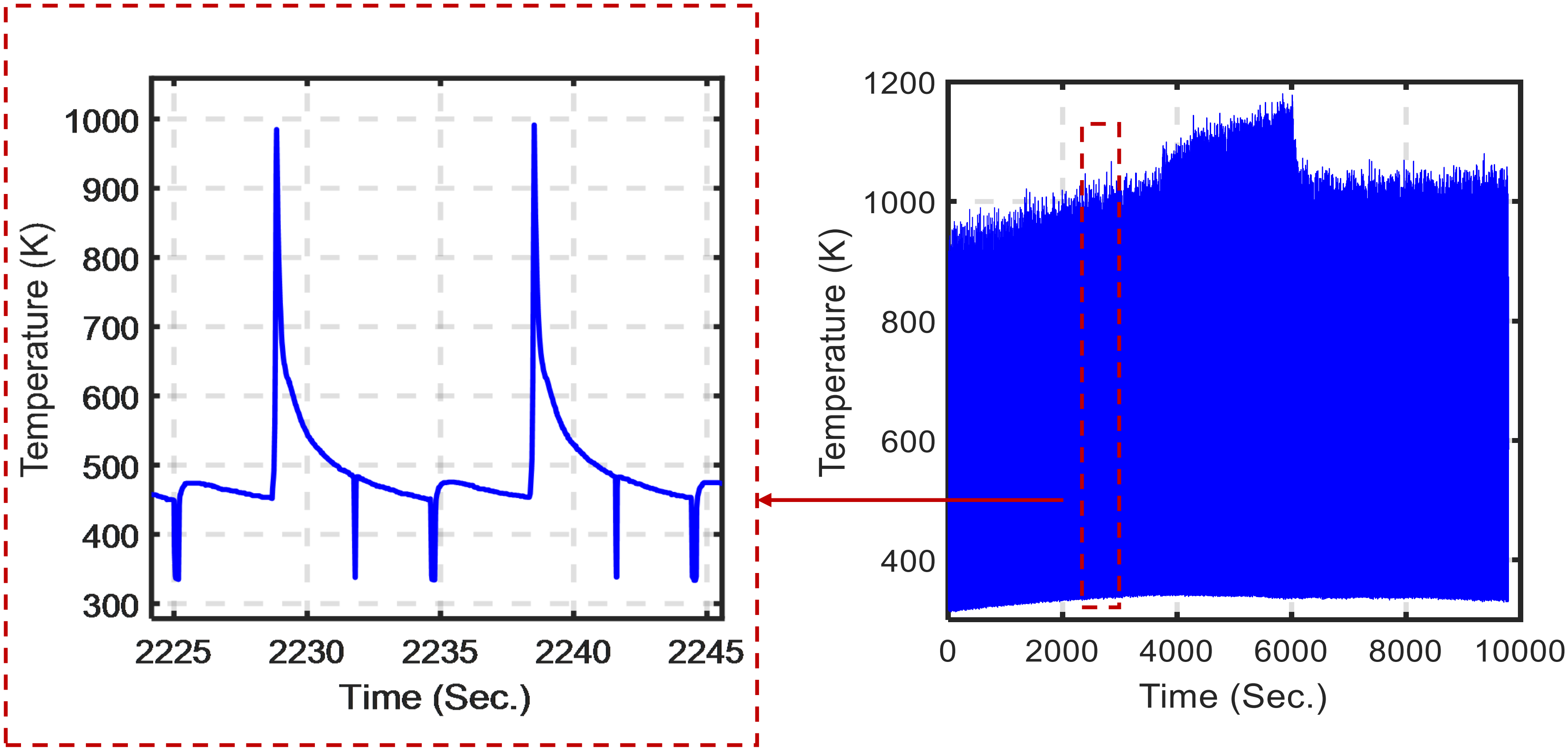
600,000 frames, 60 frames per second.

3 hours build time.

Thermal data need to be filtered to remove IR transients.

Build 1 (Cylinder) Thermal Data

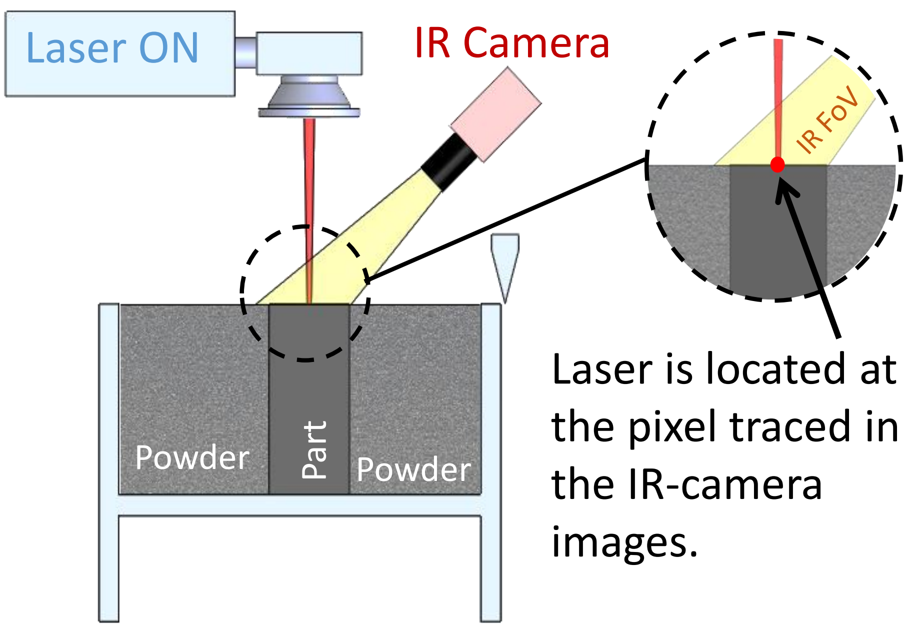
Raw IR camera measurements includes of several high and low peaks.



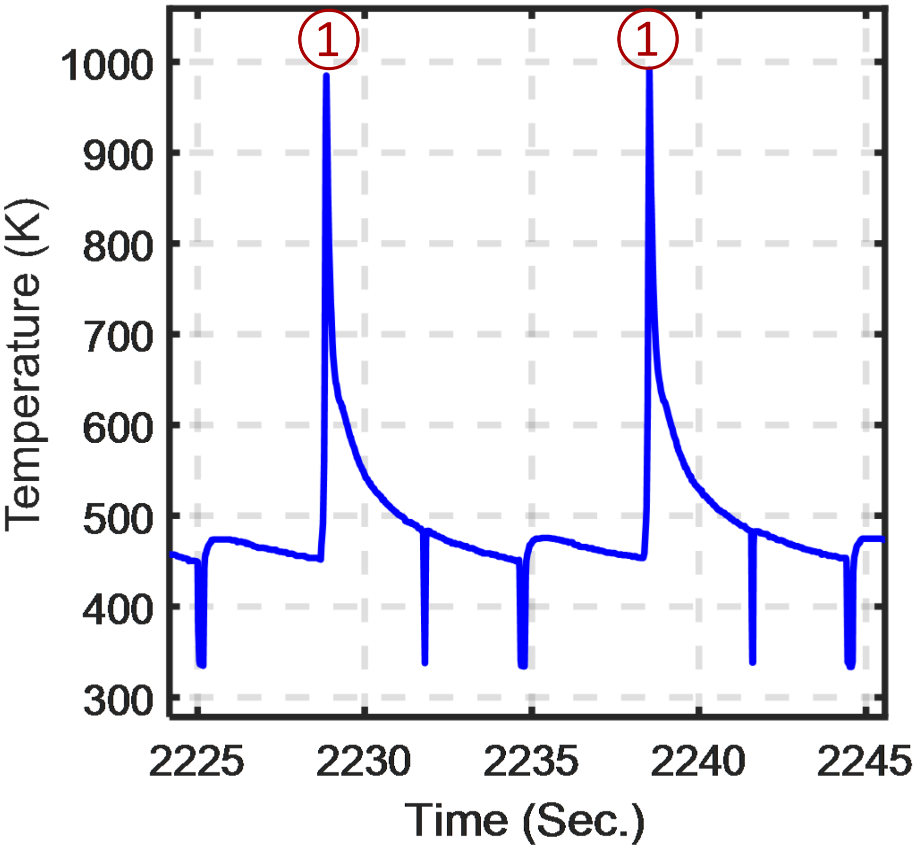
Raw IR camera measurements includes of several high and low peaks.

Removing Transients from IR Data

① : Laser is located at the pixel traced by the IR-camera images

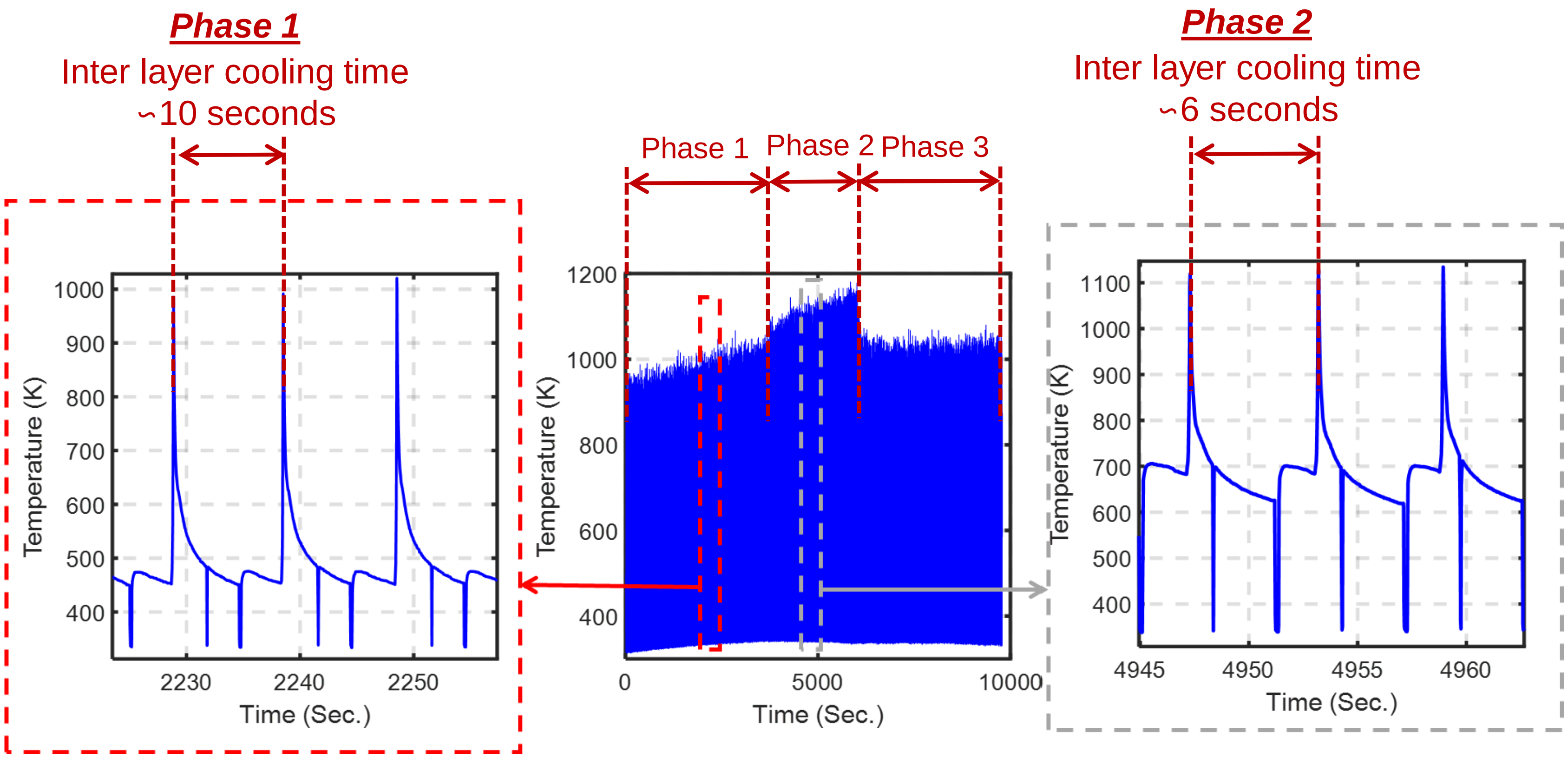


Laser is located at the pixel traced in the IR-camera images.



Removing Transients from IR Data

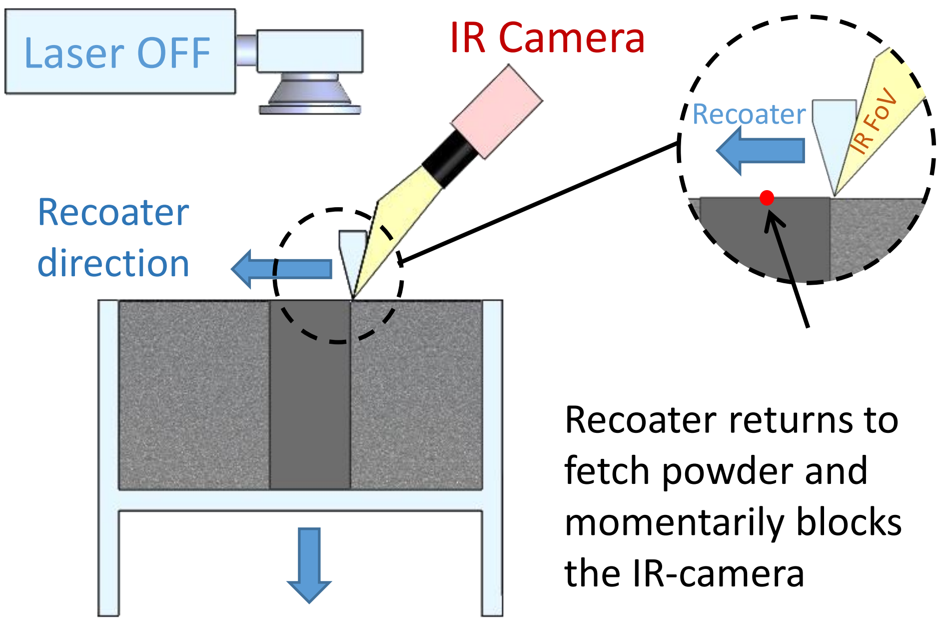
Inter-layer cooling time (ILCT): The time between successive scans, layer-to-layer.



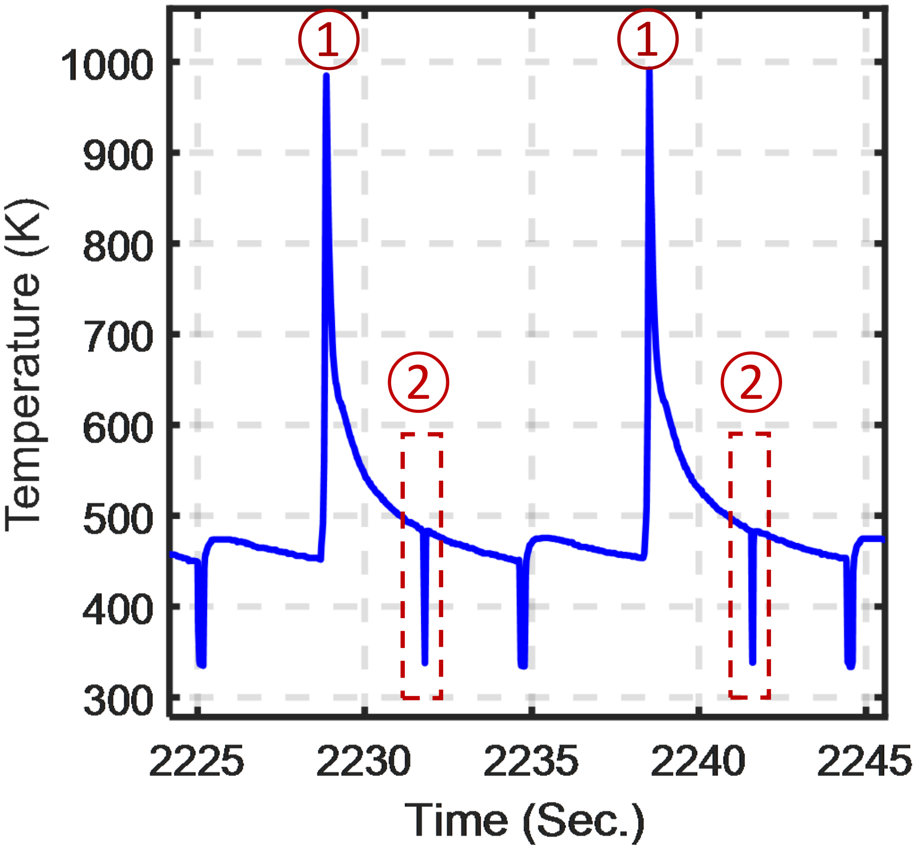
- Phase 1: 10 seconds
- Phase 2: 6 seconds
- Phase 3: 10 seconds

Removing Transients from IR Data

② : Recoater returns to back for powder

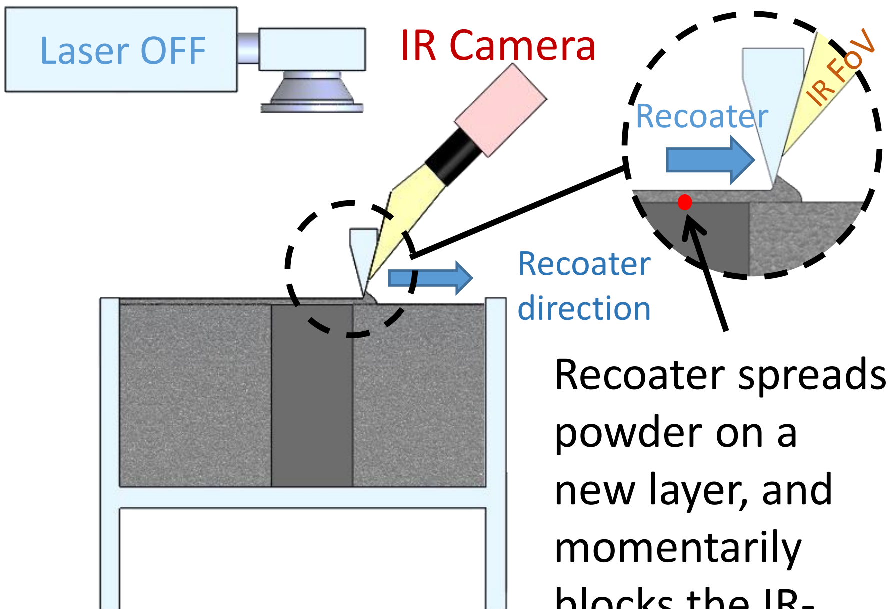


Recoater returns to fetch powder and momentarily blocks the IR-camera

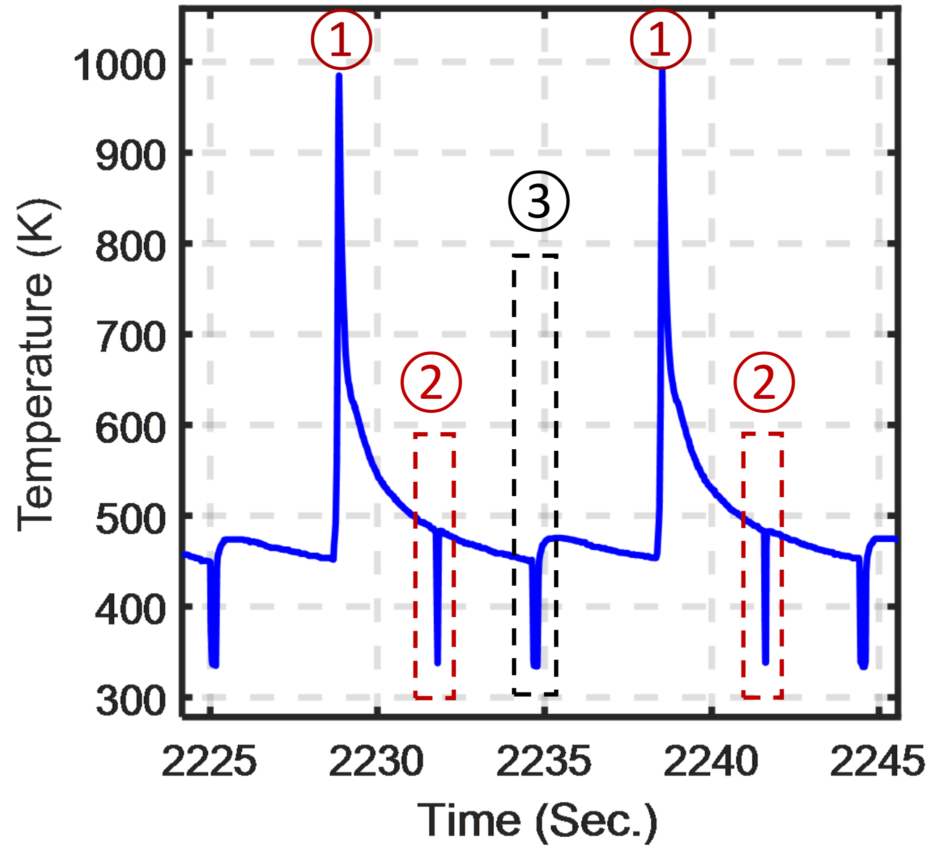


Removing Transients from IR Data

③ : Recoater spreads powder for a new layer

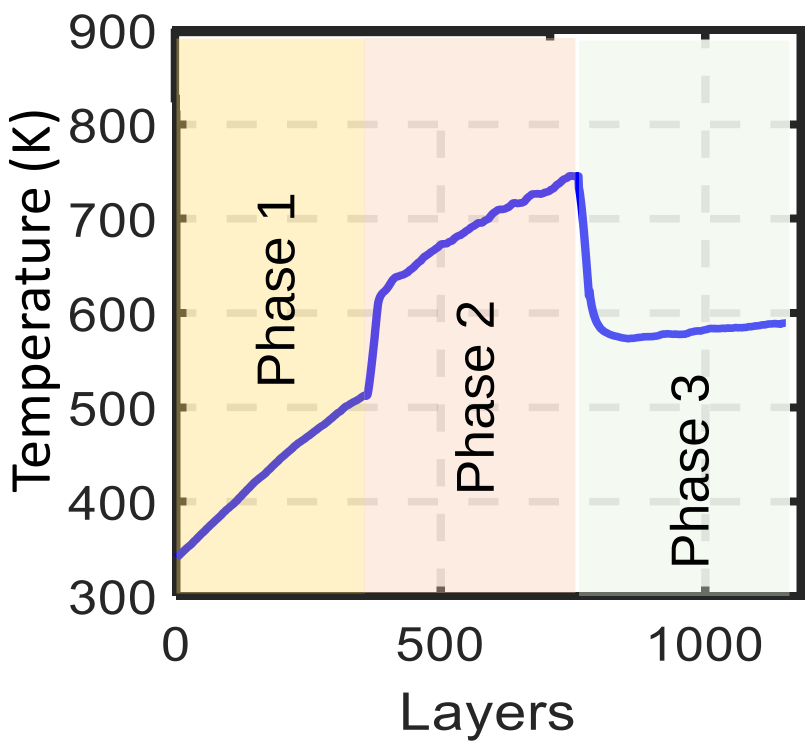


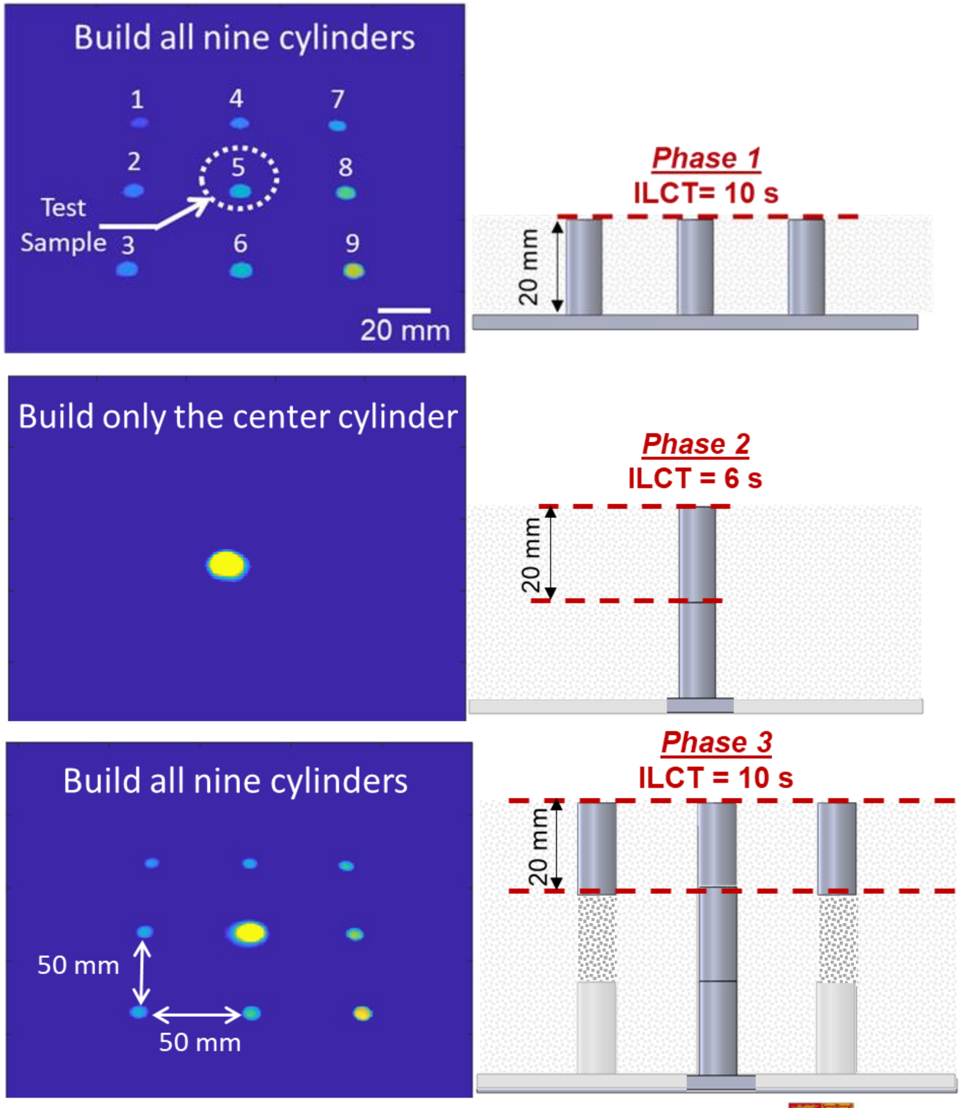
Recoater spreads powder on a new layer, and momentarily blocks the IR-camera.



Layer-wise Experiment Thermal Data

Top surface temperature for 1200 layers.





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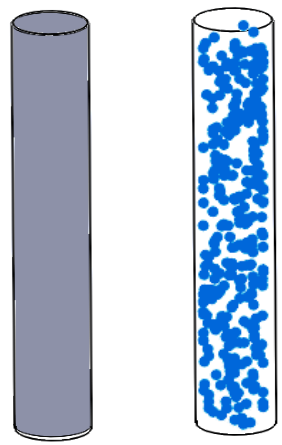
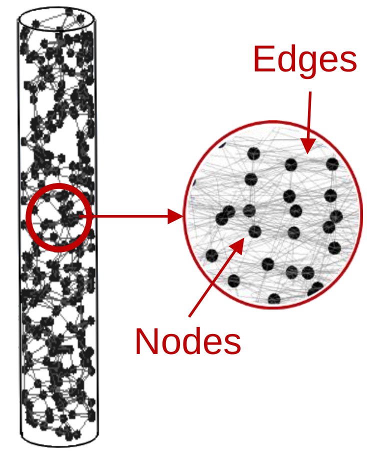
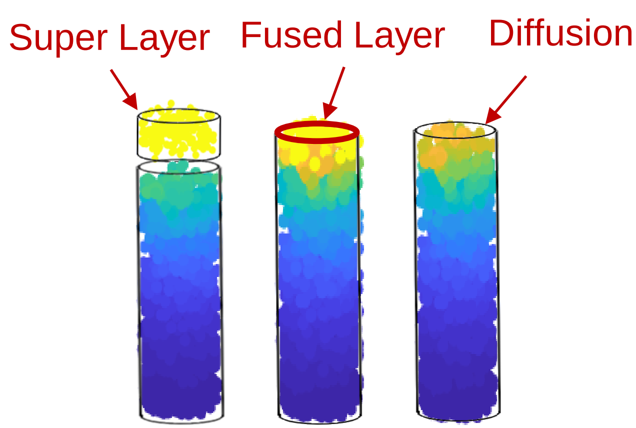


Step 1- Convert the part into a set of discrete nodes



Step 2- Network graph construction



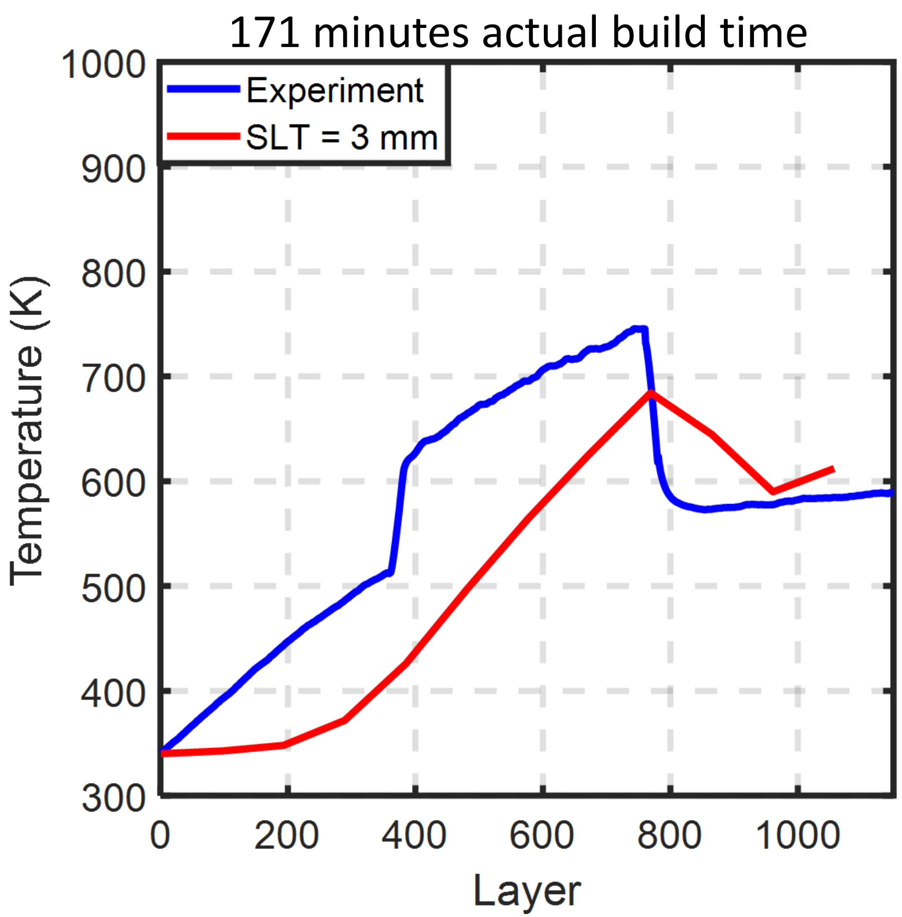
Step 3

- Deposition of super layers
- Diffusion of the heat through the part

Step 4- Obtaining the result

Effect of Super Layer Thickness

Super layer thickness = 3 mm (60 actual layers)
Computational time= 75 seconds ∽ (1 minutes)
Mean Absolute Percentage Error (MAPE) = 29 %

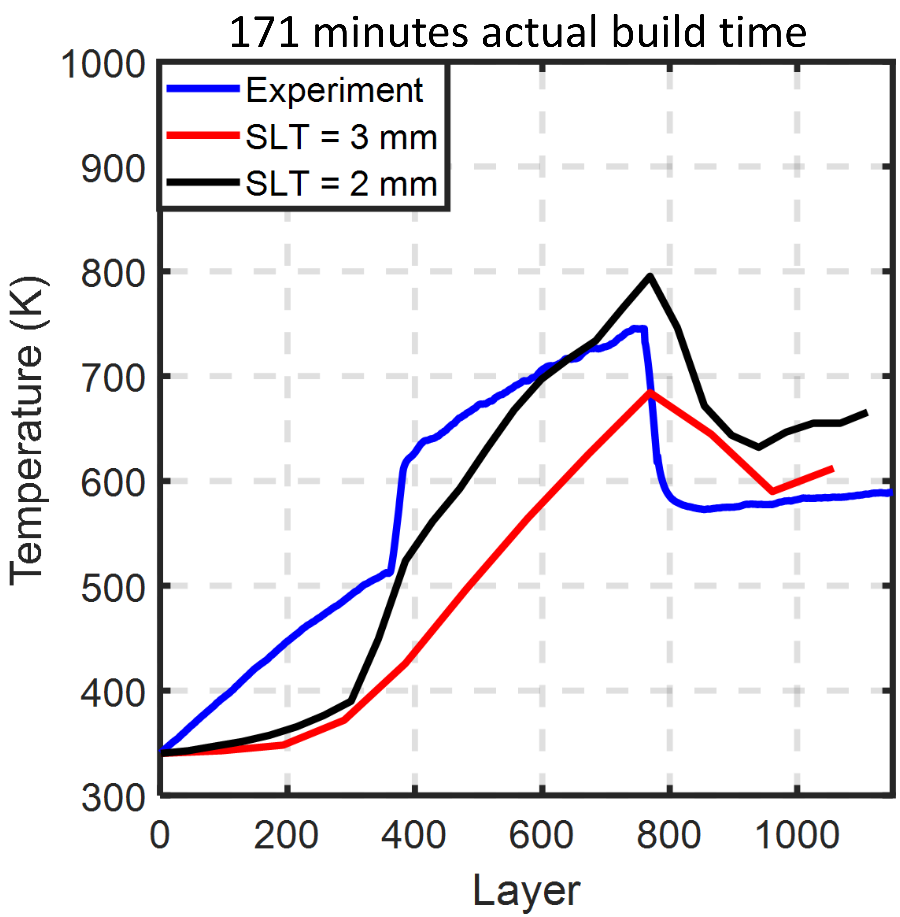


Effect of Super Layer Thickness

Super layer thickness = 2 mm (40 actual layers)

Computational time= 166 seconds ∽ (3 minutes)

Mean Absolute Percentage Error (MAPE) = 24 %

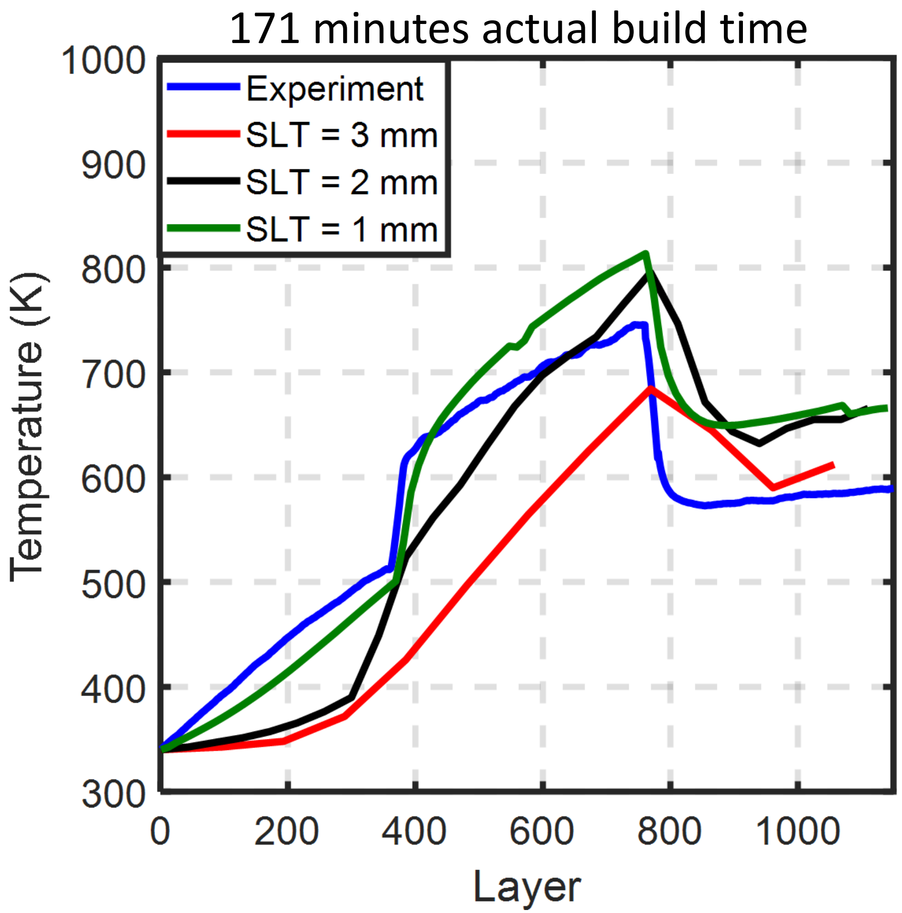


Effect of Super Layer Thickness

Super layer thickness = 1 mm (20 actual layers)

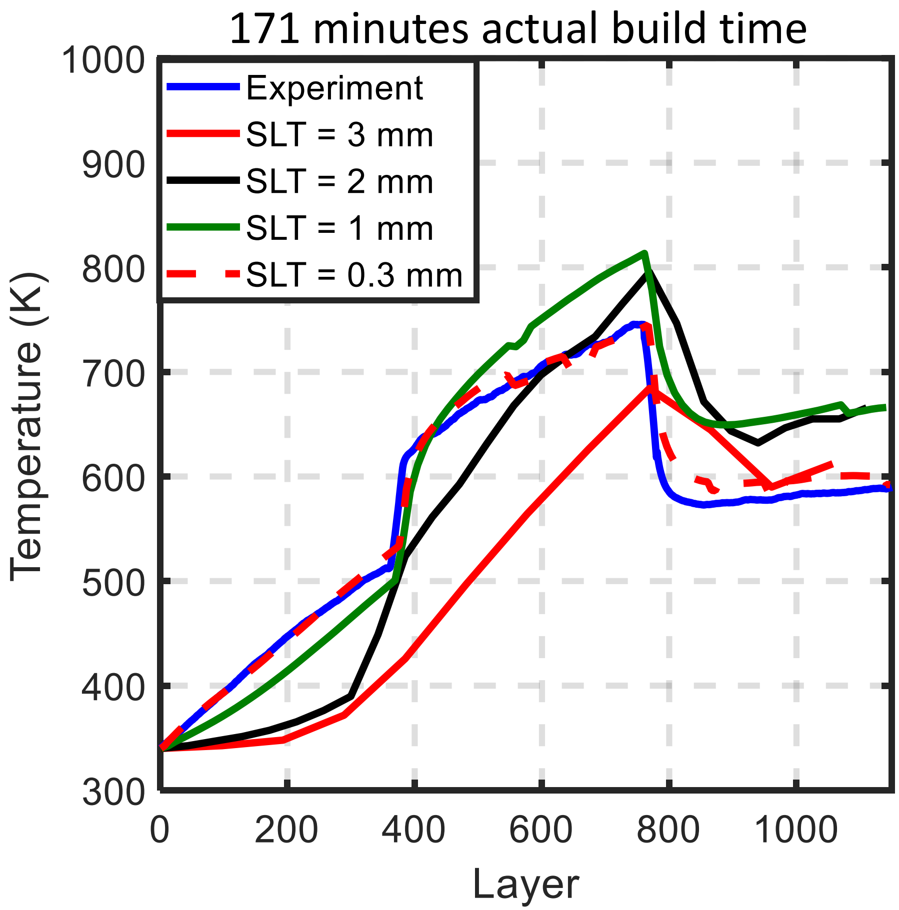
Computational time= 481 seconds ∽ (8 minutes)

Mean Absolute Percentage Error (MAPE) = 16 %



Effect of Super Layer Thickness

Super layer thickness = 0.3 mm (6 actual layers)
Computational time= 1,655 seconds ~ (27 minutes)
Mean Absolute Percentage Error (MAPE) = 6 %

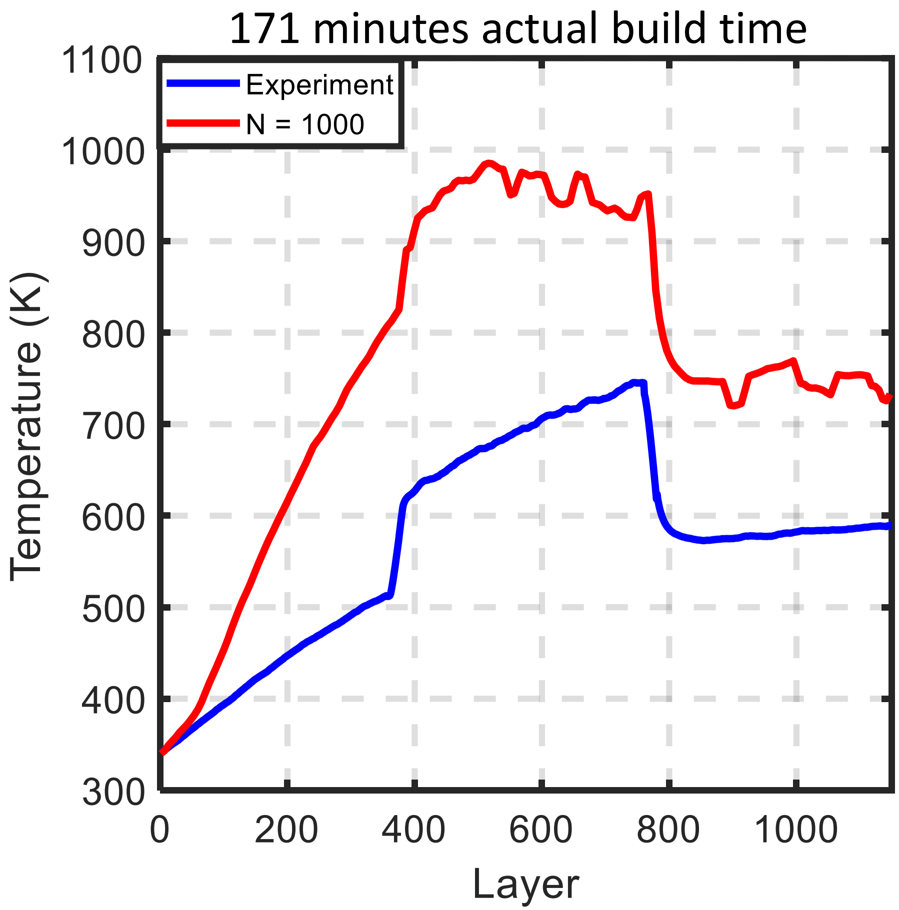


Effect of Number of Nodes

Number of Nodes= 1,000

Computational time= 92 seconds ~ (1 minutes)

Mean Absolute Percentage Error (MAPE) = 42 %

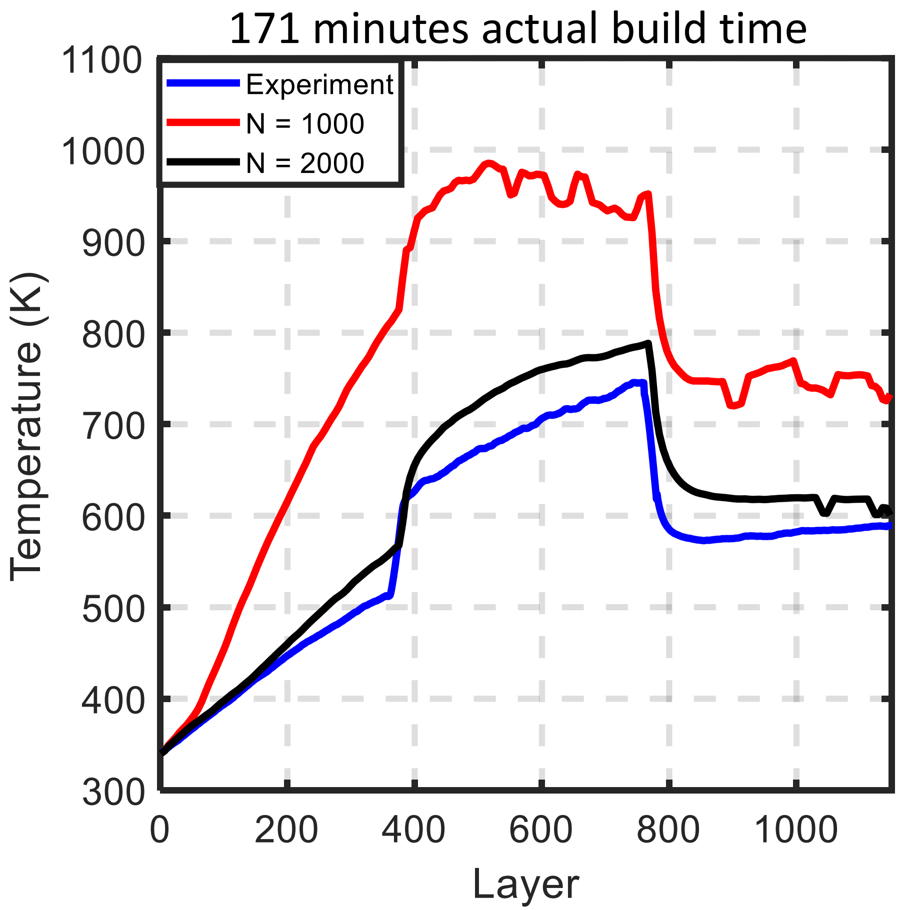


Effect of Number of Nodes

Number of Nodes= 2,000

Computational time= 501 seconds ∽ (8 minutes)

Mean Absolute Percentage Error (MAPE) = 15 %

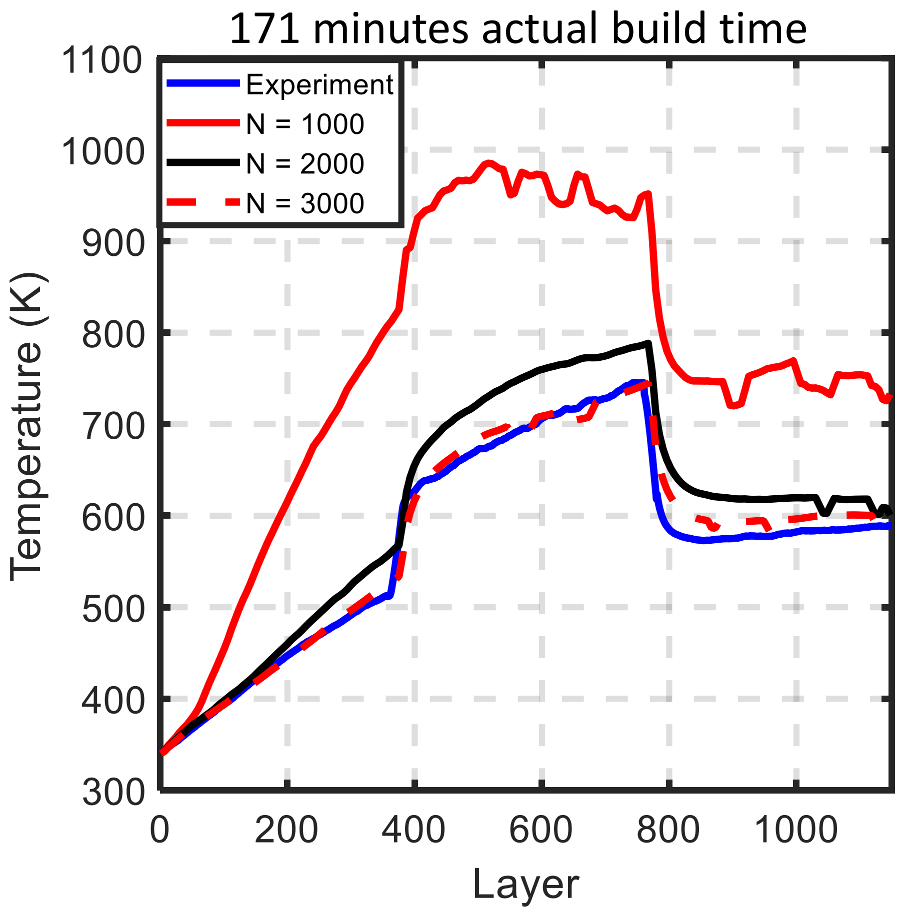


Effect of Number of Nodes

Number of Nodes= 3,000

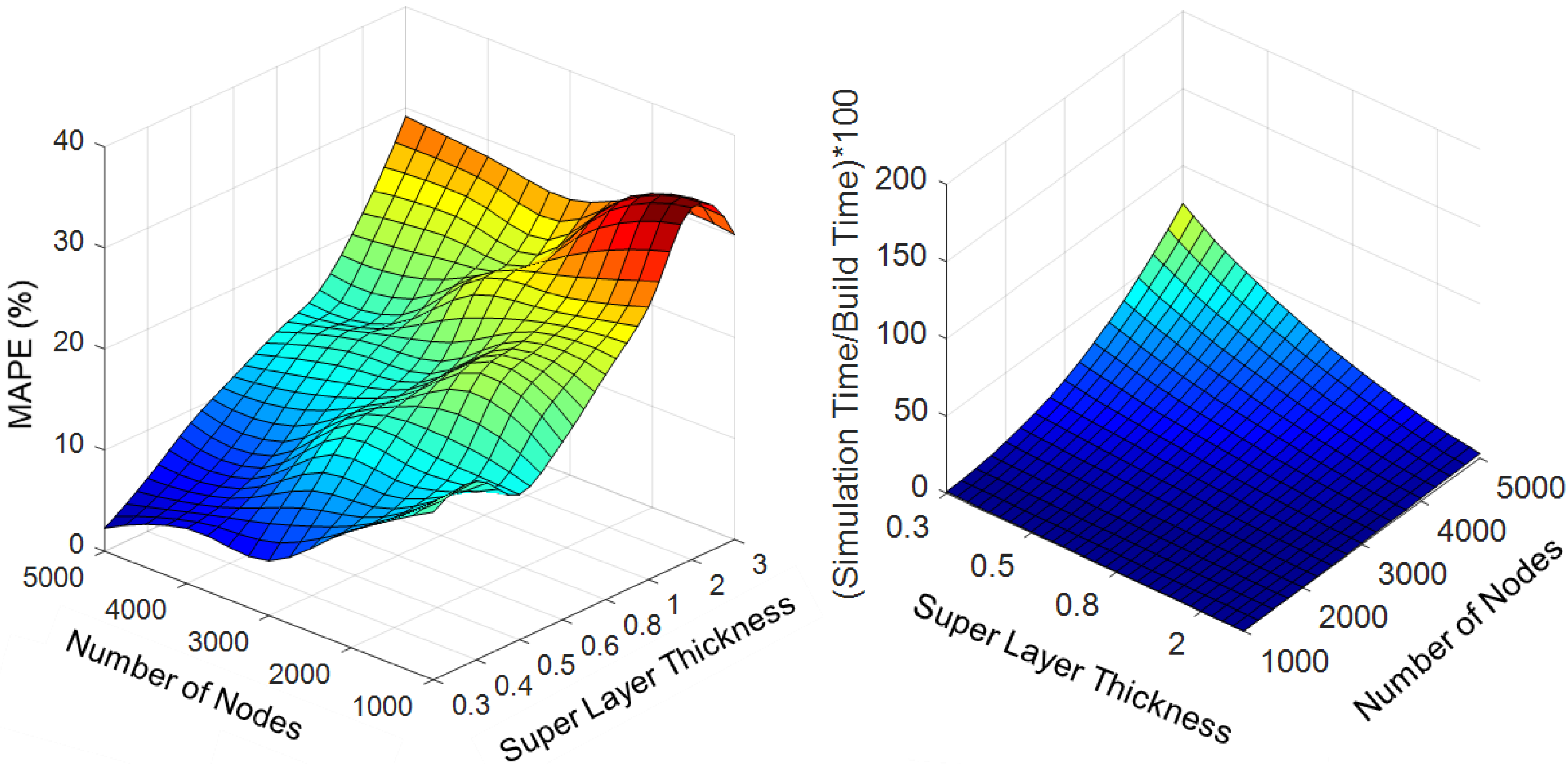
Computational time= 1,655 seconds ~ (27 minutes)

Mean Absolute Percentage Error (MAPE) = 6 %



Sensitivity Analysis

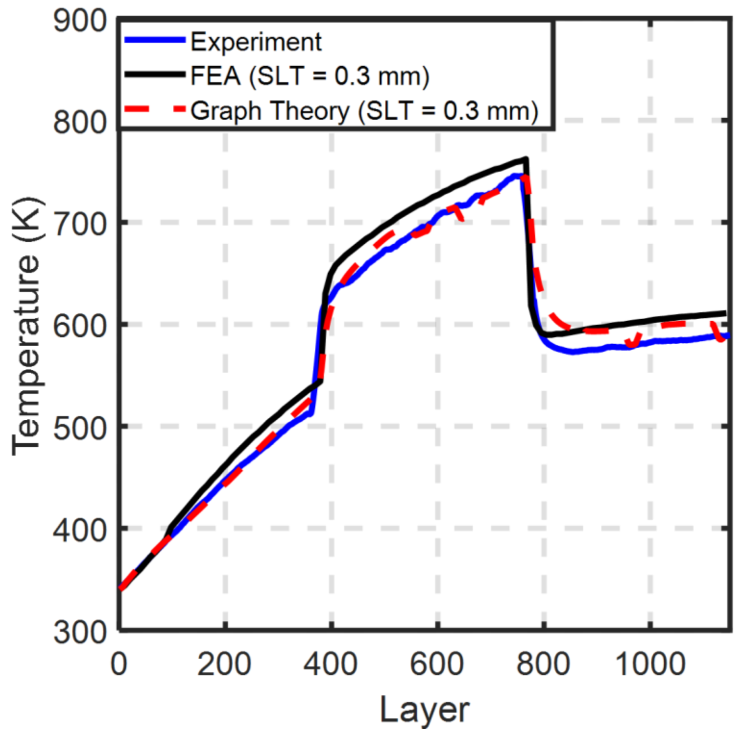
Effect of number of nodes and super layer thickness on accuracy and computation time.



Increasing number of nodes and decreasing super layer thickness reduces error and inflates computation time.

Comparison with FEA (Build 1)

Graph theory approach and FE approach were compared.

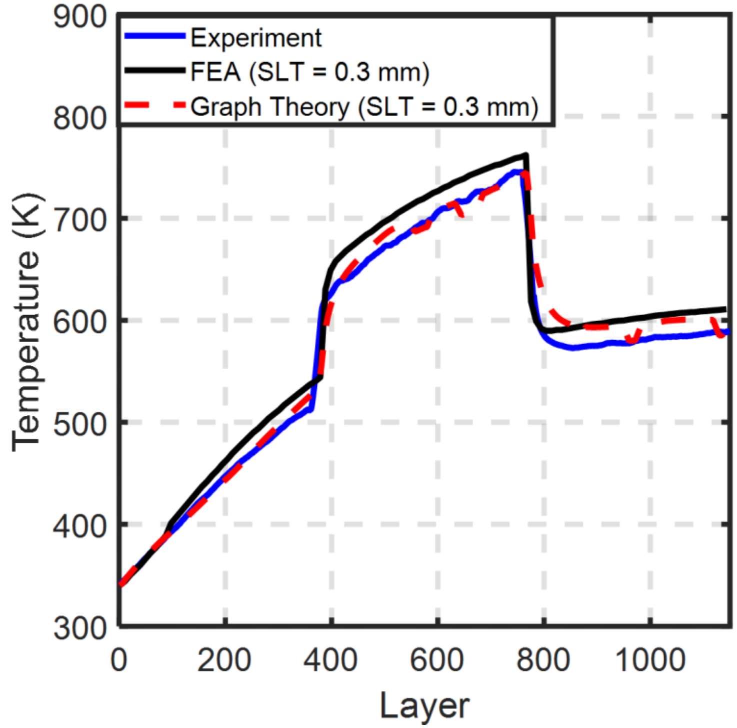


Actual Build Time 171 minutes	Finite Element		Graph Theory	
Super Layer Thickness	0.3 mm	0.5 mm	0.3 mm	0.5 mm
Computation Time	34 minutes	22 minutes	27 minutes	15 minutes
MAPE	8 %	18 %	6 %	14 %
RMSE (Kelvin, K)	33.8	48.1	14.5	33.8

Graph theory converges faster than FE, and slightly smaller error.

Comparison with FEA (Build 1)

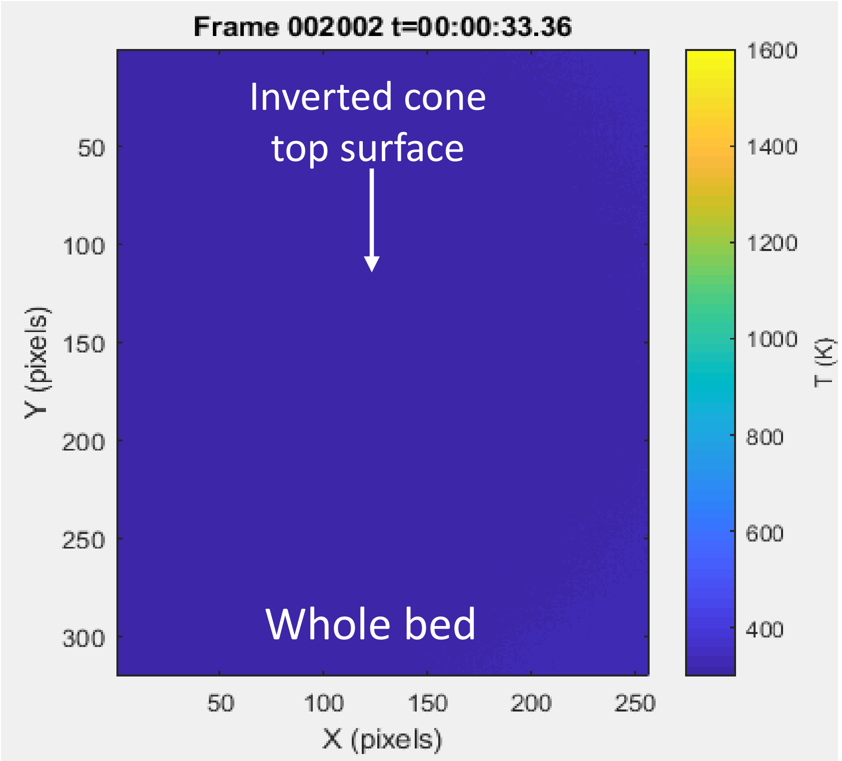
Graph theory approach and FE approach were compared.



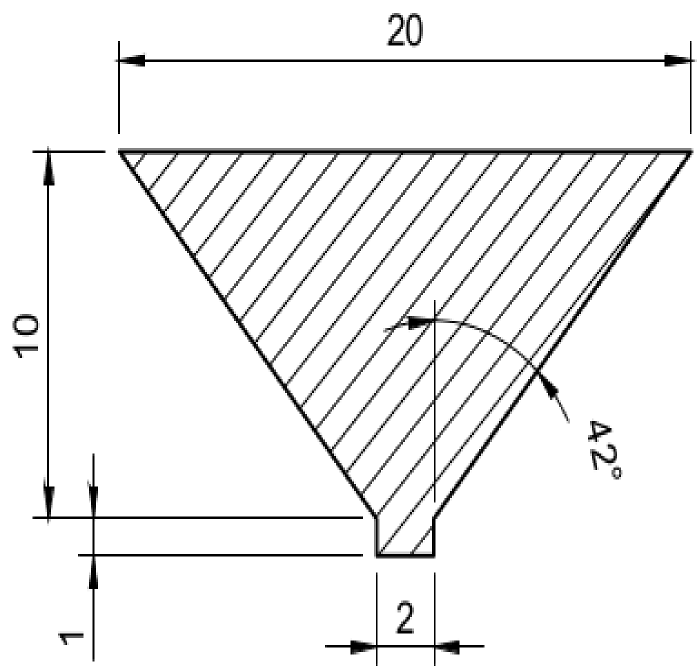
- Both the FE model and graph theory approach use super layer.
- Number of nodes are similar (N = 4000)
- Graph theory algorithm has not yet optimized for parallel processing
- Algorithm is currently implemented in a derived computation language Matlab (single core processing)

Build 2 (Inverted Cone)

Same calibration methods and temperature data characterization.



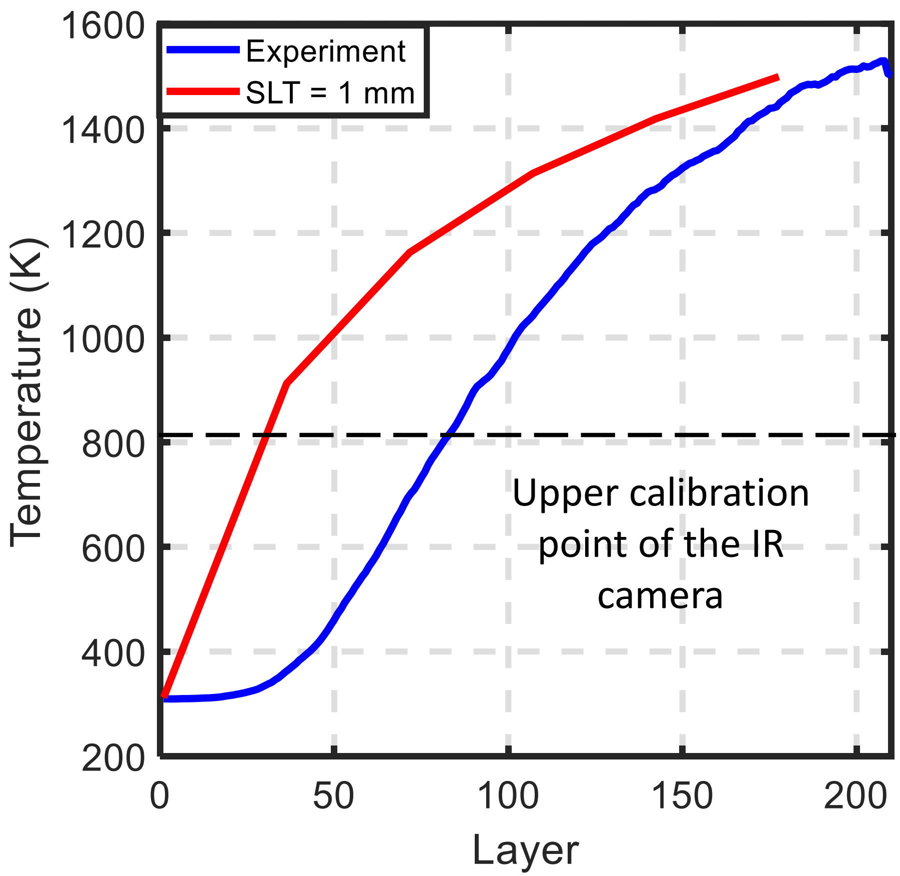
180,000 frames, 60 frames per second.



316L Stainless Steel
Build time: 51 minutes
Laser power: 200 W

Effect of Super Layer Thickness

Super layer thickness = 1 mm (20 actual layers)
Computational time= 237 seconds ~ (4 minutes)
Mean Absolute Percentage Error (MAPE) = 43 %

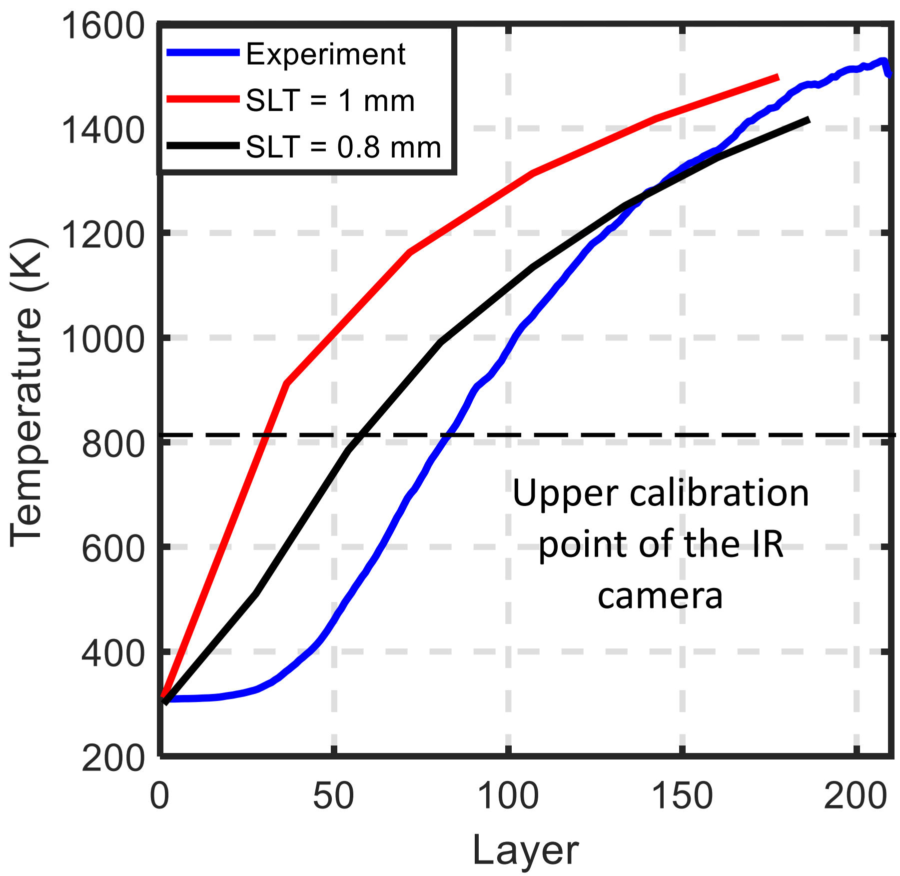


Effect of Super Layer Thickness

Super layer thickness = 0.8 mm (16 actual layers)

Computational time= 721 seconds ~ (12 minutes)

Mean Absolute Percentage Error (MAPE) = 32 %

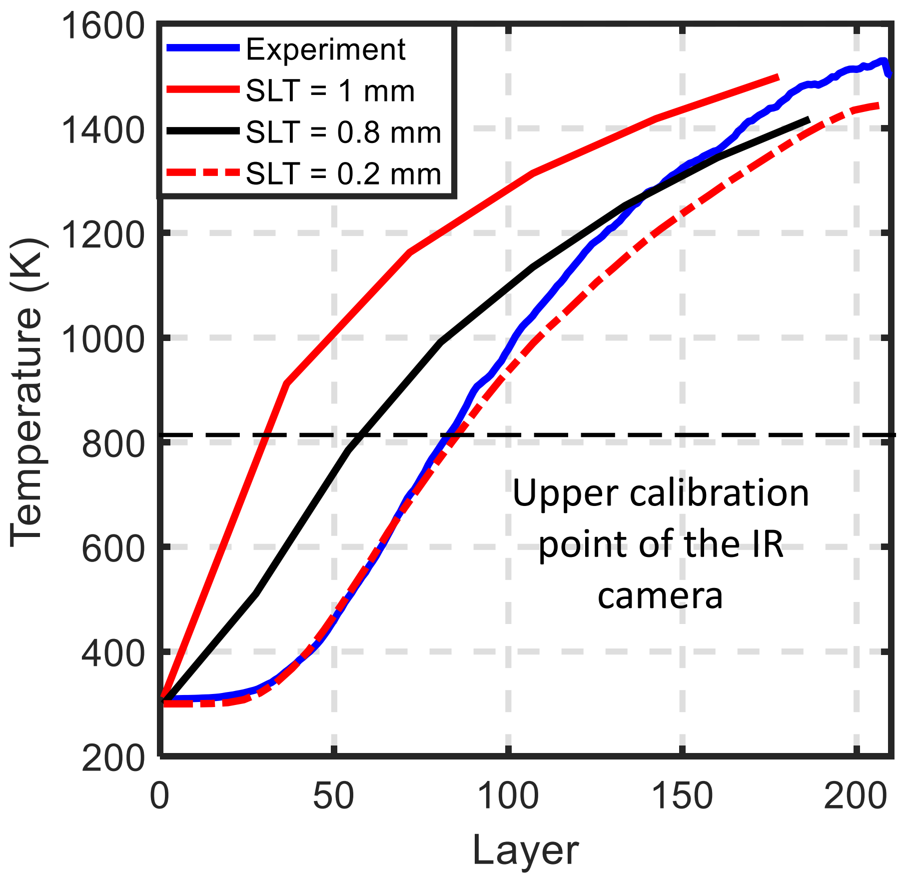


Effect of Super Layer Thickness

Super layer thickness = 0.2 mm (4 actual layers)

Computational time= 2,471 seconds ~ (41 minutes)

Mean Absolute Percentage Error (MAPE) = 8 %

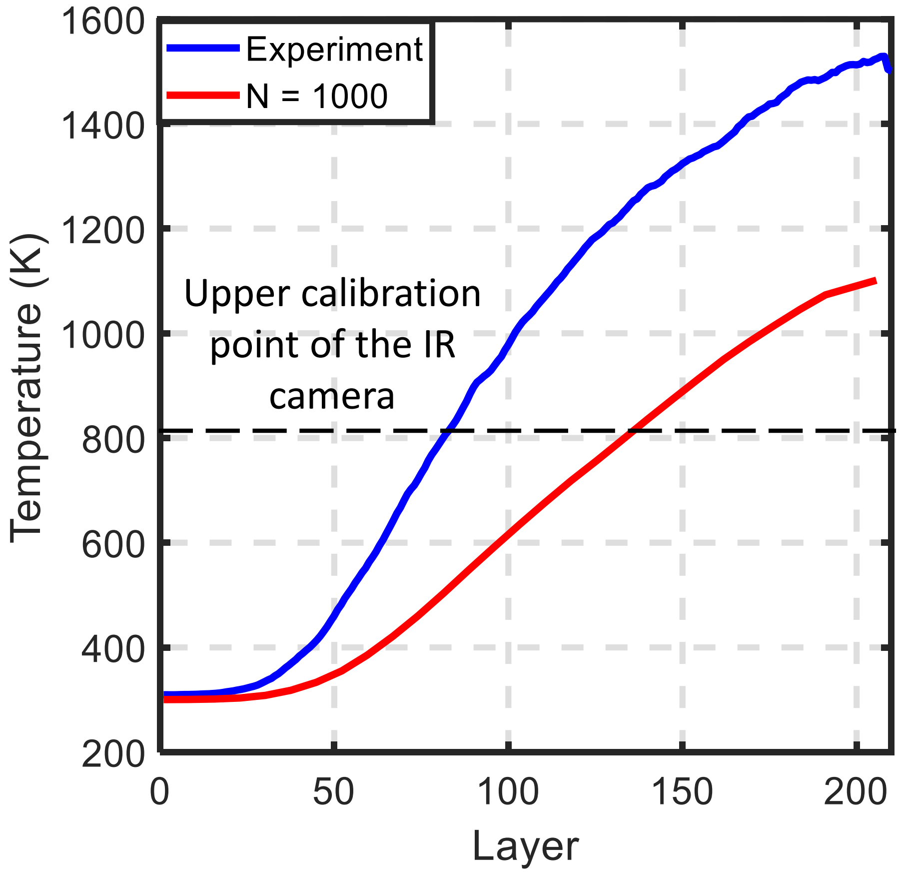


Effect of Number of Nodes

Number of Nodes= 1,000

Computational time= 104 seconds ∽ (2 minutes)

Mean Absolute Percentage Error (MAPE) = 34 %

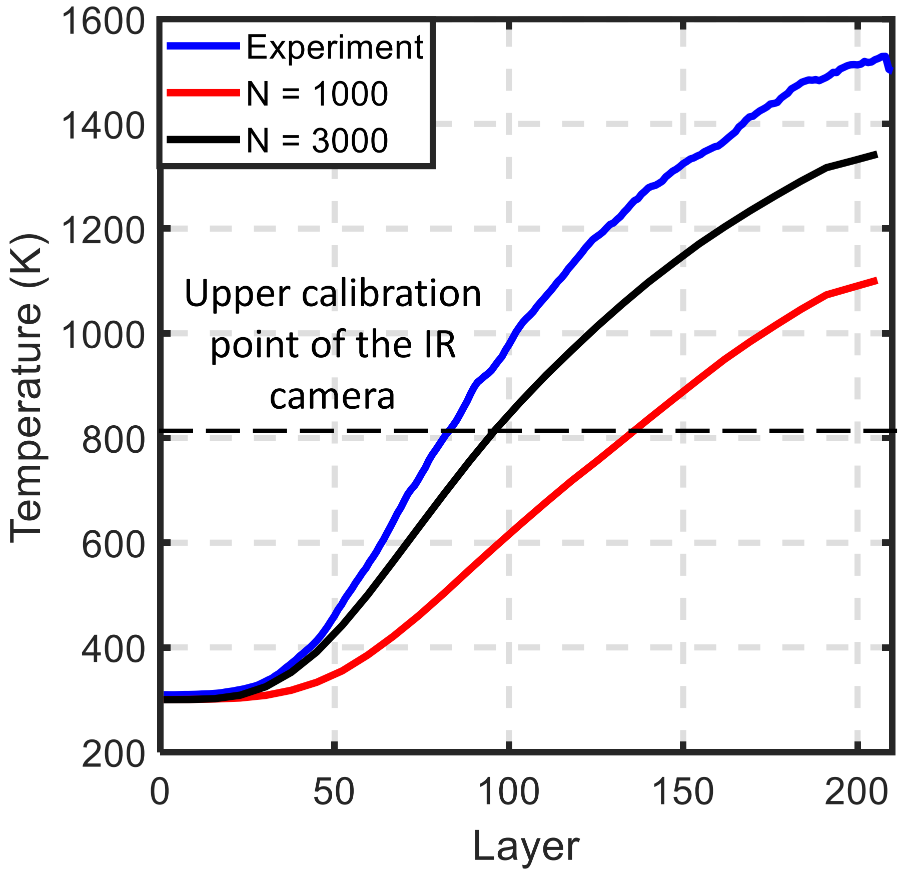


Effect of Number of Nodes

Number of Nodes= 3,000

Computational time= 1,017 seconds ∽ (17 minutes)

Mean Absolute Percentage Error (MAPE) = 20 %

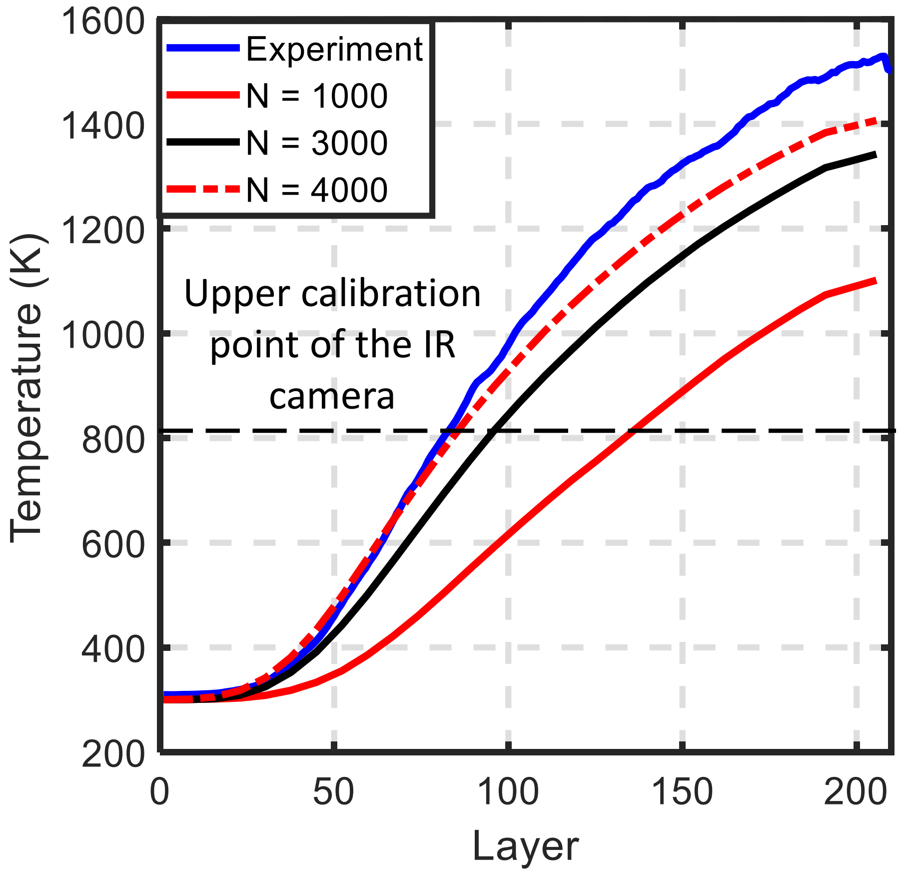


Effect of Number of Nodes

Number of Nodes= 4,000

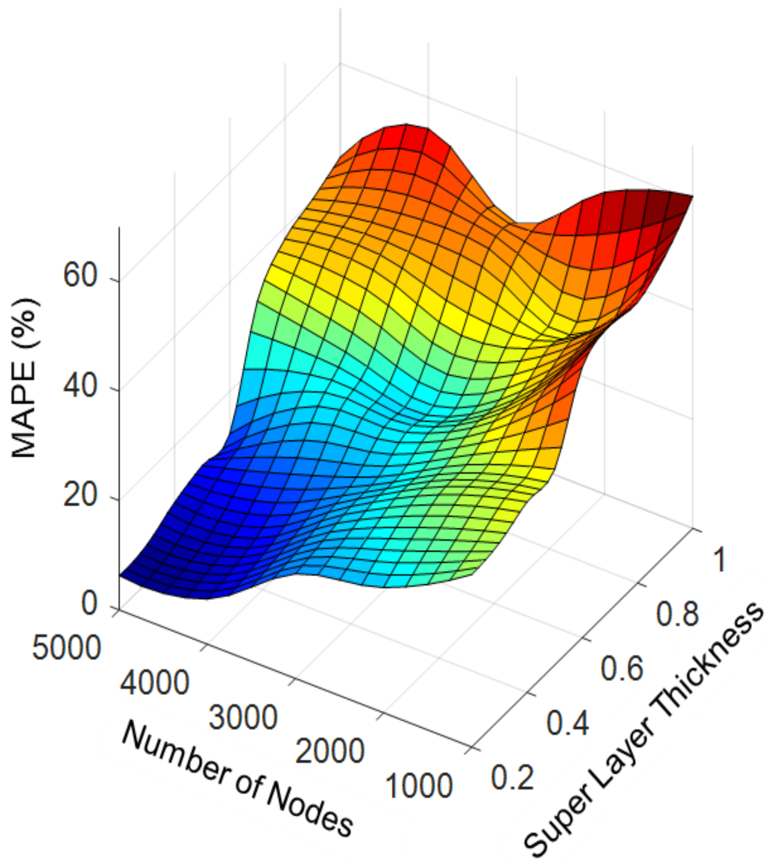
Computational time= 2,471 seconds ∽ (41 minutes)

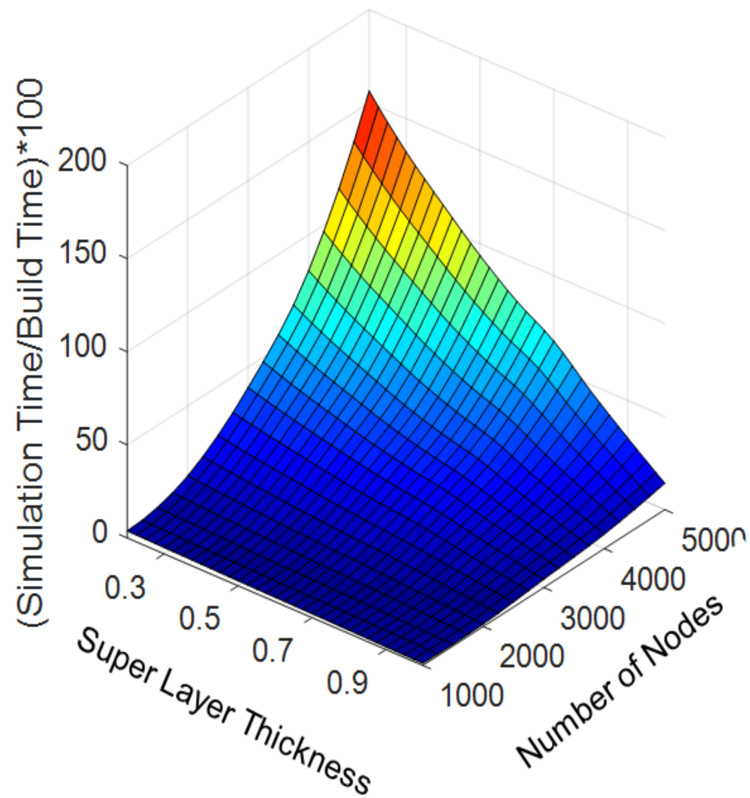
Mean Absolute Percentage Error (MAPE) = 8 %



Sensitivity Analysis

Effect of number of nodes and super layer thickness on accuracy and computation time.

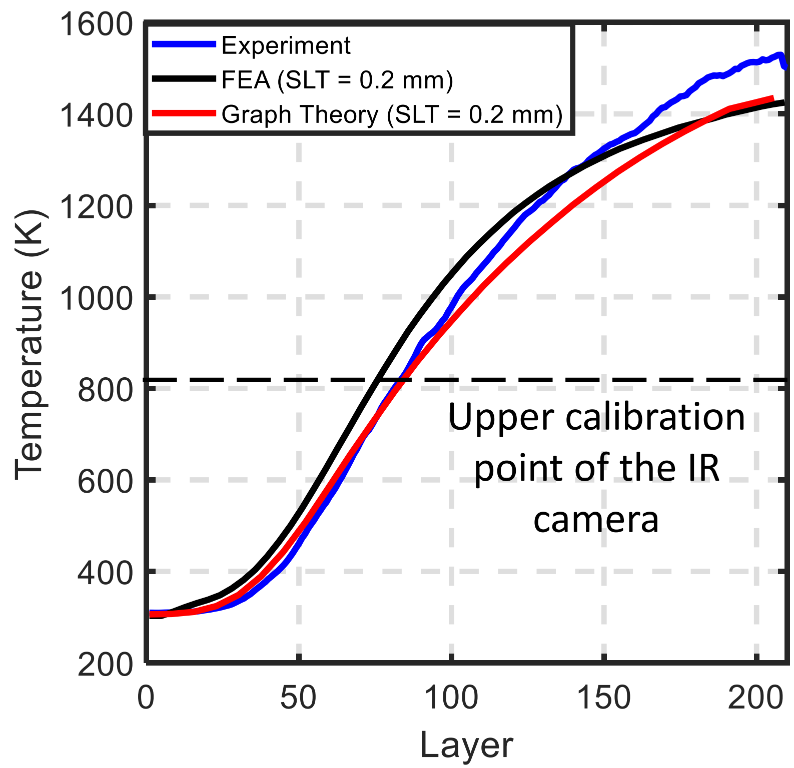




Comparison with FEA (Build 2)

Table and plot shows the finite element and graph theory results comparison

Actual Build Time 53 minutes	Finite Element		Graph Theory	
Super Layer Thickness	0.2 mm	0.3 mm	0.2 mm	0.3 mm
Computation Time	54 minutes	48 minutes	41 minutes	35 minutes
MAPE	9 %	14 %	8 %	9 %
RMSE (Kelvin, K)	37.7	73.0	26.0	35.4



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Conclusion and Future Works

- Graph theoretic simulation is able to simulate the top surface temperature of the part in Laser Powder Bed Fusion process.
- Use graph theoretic thermal filed to predict part distortion.
- Use graph theoretic thermal filed to predict microstructure.

Speaker Information

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https://engineering.unl.edu/lamps/

University of Nebraska Lincoln

Nebraska Engineering Additive Technology Labs

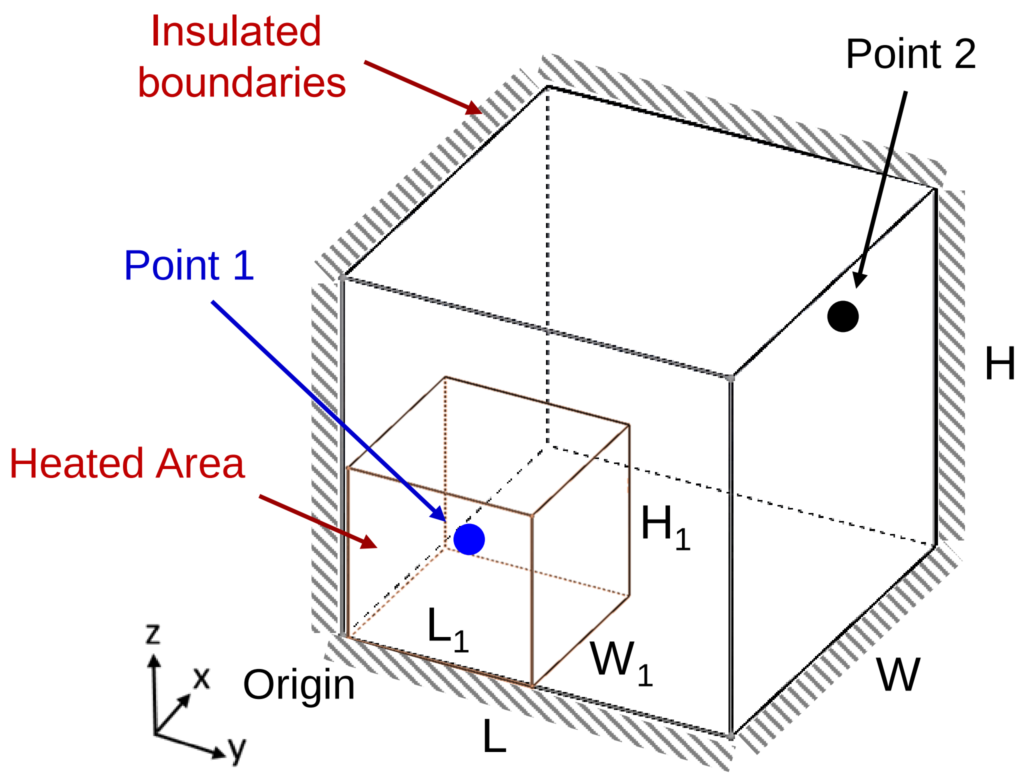
LAMPS Laboratory for Advanced Manufacturing Processes and Sensing

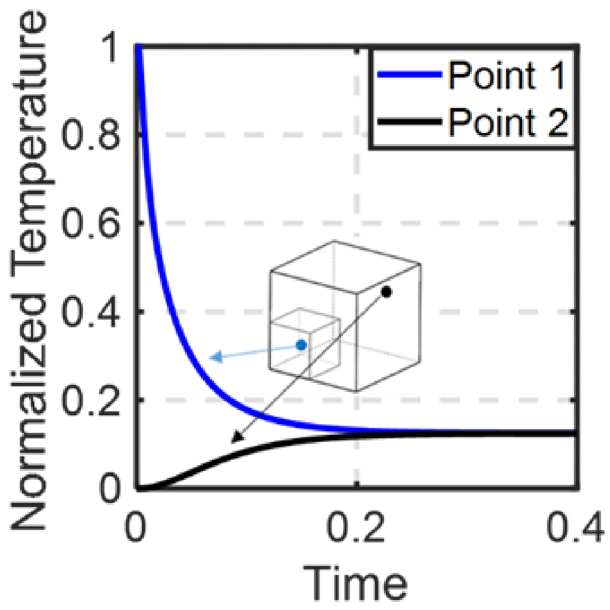
Comparison with Exact Analytical Solution

Purpose: Quantify the accuracy of graph theory diffusion with analytical solution

Geometry condition: ($W = L = H = 1$) and ($W_1 = L_1 = H_1 = 0.5$)

Observation points: Point 1 = (0.25H, 0.25L, 0.25W), Point 2 = (0.75H, 0.75L, 0.75W).

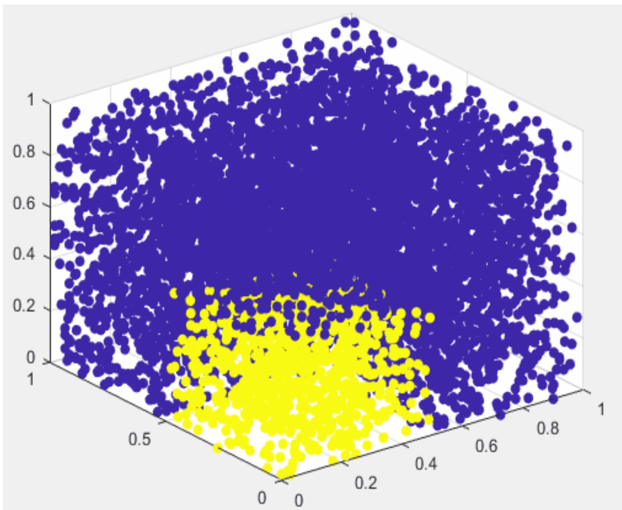


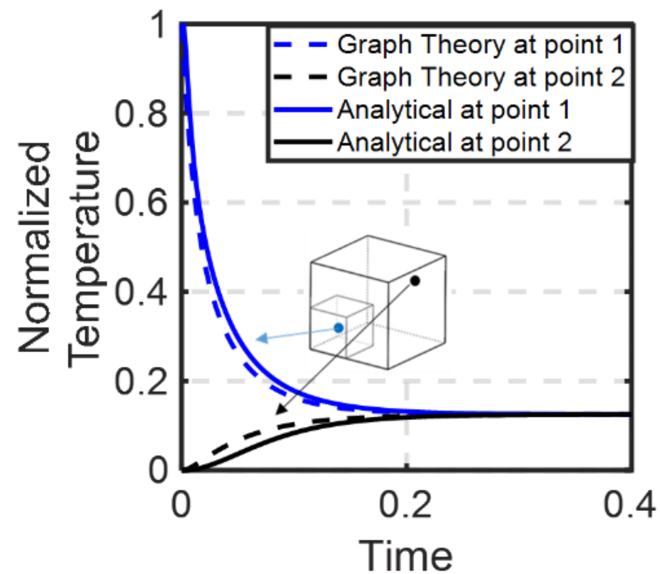


Cole et al., 2011, chap. 3. Heat Conduction Using Green's Functions, Exact Analytical Conduction Toolbox (EXACT) at UNL
www. exact.unl.edu

Comparison with Exact Analytical Solution

Graph theory captures the physics of the heat transfer for an ideal case.



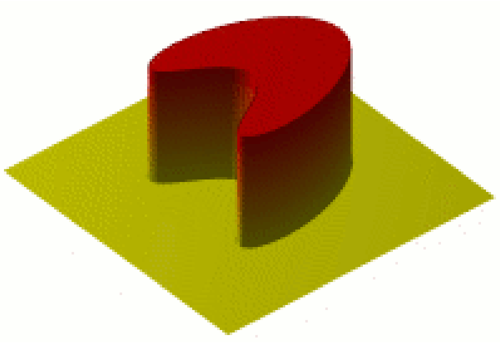


Error	Graph theoretic approach time (sec.)	FE analysis time (sec.)
~ 5%	237	3,540
	4 mins	59 mins

The Scientific Problem

Temperature (T) is a function of space (x, y, z) and time (t)

$\mathrm{T}(x, y, z, t)$



The Heat Equation (Fourier's Law of Conduction)

$$\rho c_p \frac{\partial \mathrm{T}(x,y,z,t)}{\partial t} - k\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\mathrm{T}(x,y,z,t) = 0$$

$$\rho c_p \frac{\partial \mathrm{T}}{\partial t} - k\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\mathrm{T} = 0$$

K = thermal conductivity ρ = density C_p = specific heat

Yavari, M. R., Cole, K. D., & Rao, P. (2019). Thermal Modeling in Metal Additive Manufacturing Using Graph Theory. Journal of Manufacturing Science and Engineering, 141(7), 071007.

Solving the Heat Equation with Graph Theory

$$\frac{\partial \mathrm{T}}{\partial t} - \frac{k}{\rho c_p}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\mathrm{T} = 0$$

Laplacian operator

$$\Delta \stackrel{\text{def}}{=} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$$

Continuum heat equation

$$\frac{\partial \mathrm{T}}{\partial t} - \alpha(\Delta)\mathrm{T} = 0$$

$k/\rho\, c_p = \alpha$ (Thermal diffusivity)

Hypothesis

The Heat Equation is solved as a function of the
Eigenvalues (Λ) and Eigenvectors (ϕ) of the Discrete Laplacian Matrix ($\mathcal{L}$)

$$\frac{\partial T}{\partial t} - \alpha(\Delta)T = 0$$

The continuous Laplacian operator is approximated by the Graph Laplacian.

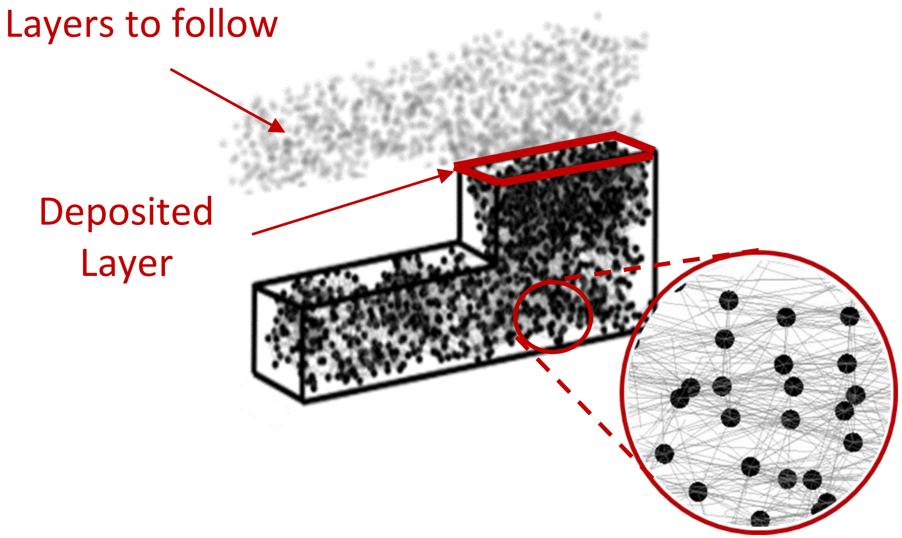
$$\Delta \approx -\mathcal{L}$$

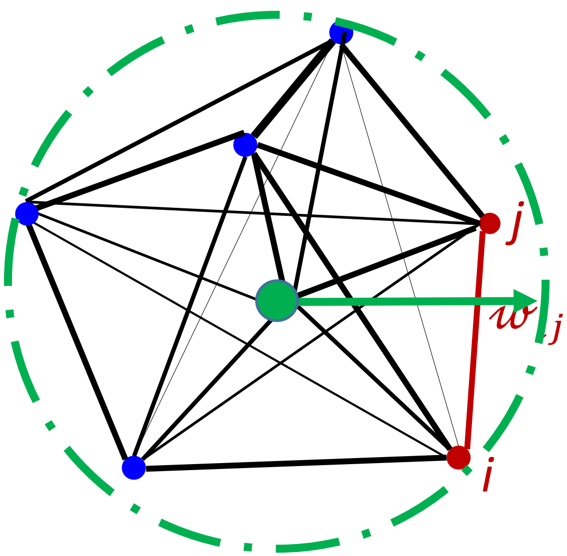
Describing the Laplacian matrix by its eigenspectrum:

$$\mathcal{L} = \phi\lambda^{*}\phi^{-1}$$

$$T = e^{-\alpha g(\phi\Lambda\phi')t}$$

Obtaining the Laplacian Matrix ($\mathcal{L}$)





Step 2- Network graph construction

Find the Gaussian distance between nodes (Closer nodes have higher edge weights)

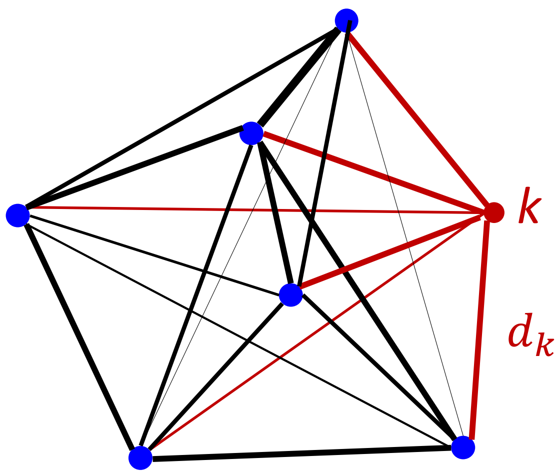
$$w_{ij} = e^{-\frac{(\vec{x}_i - \vec{x}_j)(\vec{x}_i - \vec{x}_j)^{\mathrm{T}}}{\sigma^2}}$$

Similarity matrix $S^{M \times M} \stackrel{\text{def}}{=} [w_{ij}]$

Obtaining Eigenvectors (ϕ) and Eigenvalues (Λ)

Similarity matrix

$$S^{M\times M} \stackrel{\text{def}}{=} [w_{ij}]$$



$$d_k = \sum_{j=1}^{j=M} w_{kj}$$

Degree matrix

$$\mathcal{D} \stackrel{\text{def}}{=} \begin{bmatrix} d_1 & 0 & 0 \\ 0 & d_k & 0 \\ 0 & 0 & d_M \end{bmatrix}$$

Matrix of Real positive numbers

Laplacian matrix

$$\mathcal{L} \stackrel{\text{def}}{=} (\mathcal{D} - S)$$

$$\mathcal{L}\phi = \Lambda\phi$$

Simulation Calibration

- Test has been done for Phase 1 of the cylinder (Build 1).
- Best gain factor calculated and used for the the Build 1 and 2.