Center for Advanced Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

Project 52-L: Data Driven Qualification (DDQ) Framework for Metals Additive Manufacturing (AM)

Semi-annual Fall Meeting
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Student: Charles Smith (Mines)
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Participant: Craig Brice (Mines)
Sponsor: National Center for Defense Manufacturing and Machining (NCDMM)

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- Student: Charles Smith (Mines)
- Advisor: Jonah Klemm-Toole (Mines)
  Amy Clarke (Mines)

Project Duration
M.S. January 2021 to December 2022

- Problem: The range of equipment suppliers that use their own proprietary feedstock and process parameters makes each AM system and qualification protocol unique.
- Objective: Use a data driven qualification approach to form relationships across platforms and alloy systems using intelligent machine learning algorithms and physics-based modeling.
- Benefit: Accelerated qualification and adoption of AM parts into military vehicles.

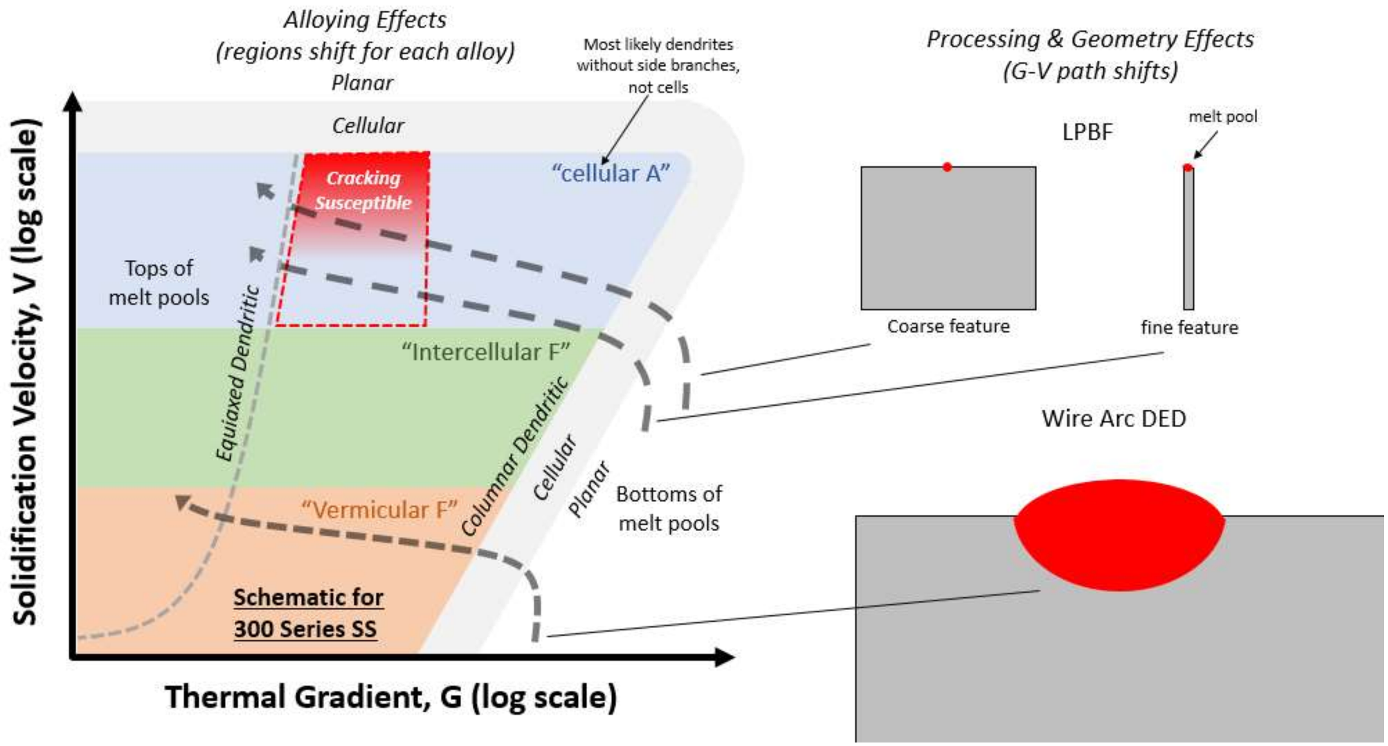
Recent Progress:
- Basic thermodynamic (heat transfer) modeling to model melt pool geometry and fusion characteristics has continued.
- Simulations to model thermal gradients and heating characteristics has been furthered developed.
- Microstructure characterization has begun.

Metrics		
Description	**% Complete**	**Status**
1. Literature review	40%	●
2. Development of metallographic preparation techniques	90%	●
3. Preliminary thermodynamic modeling/simulations	50%	●
4. Microstructure Characterization	10%	●
5. Development of G (temperature gradient) and V (solidification velocity) diagram	0%	●

Overview

- **Proposed Project Methodology**
- **Modeling and Simulation**
  - *Effects of laser powder bed fusion processing parameters on microstructure and defects in the as-built conditions*
  - *Heat transfer/thermodynamic process maps to predict process windows*
  - *Moving point heat source to model laser powder bed fusion processes*
- **Metallography and Characterization**
- **Challenges & Opportunities**

Proposed Processing – Microstructure Mapping Methodology



The map can predict the resulting microstructure (solidification + solid state transformation) if the solidification velocity and thermal gradient are known for a process.

J. Klemm-Toole, unpublished, 2020

Process Parameters Effect on Build Properties

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- Optimal energy density (E_{d0}) of about 100-105 J/mm^3 for 316L
  - Results in the least porosity, good surface finish, and hardness
- $E_d < 0.5E_{d0}$ - reduction in density
- $0.5E_{d0} < E_d < 0.7E_{d0}$ - inconsistent density
- $0.7E_{d0} < E_d < 1.3E_{d0}$ - optimum processing

$$E_d = \frac{P}{v * h * l}$$

$Where$:

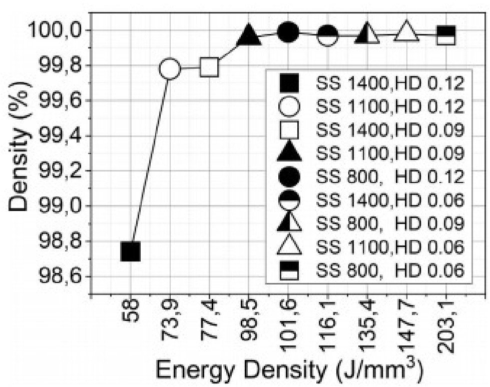
E_d = total volumetric energy (J/mm^3)

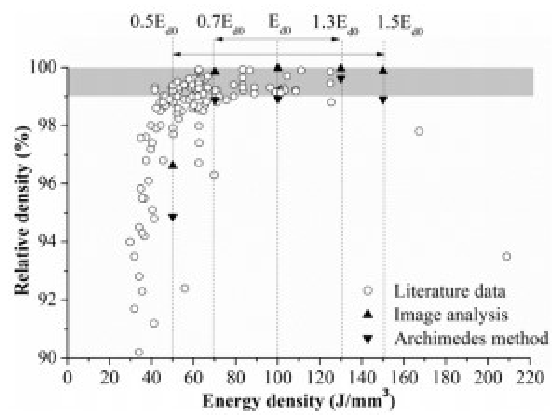
P = laser power (W)

v = scan speed (mm/s)

h = hatch distance (mm)

l = layer thickness



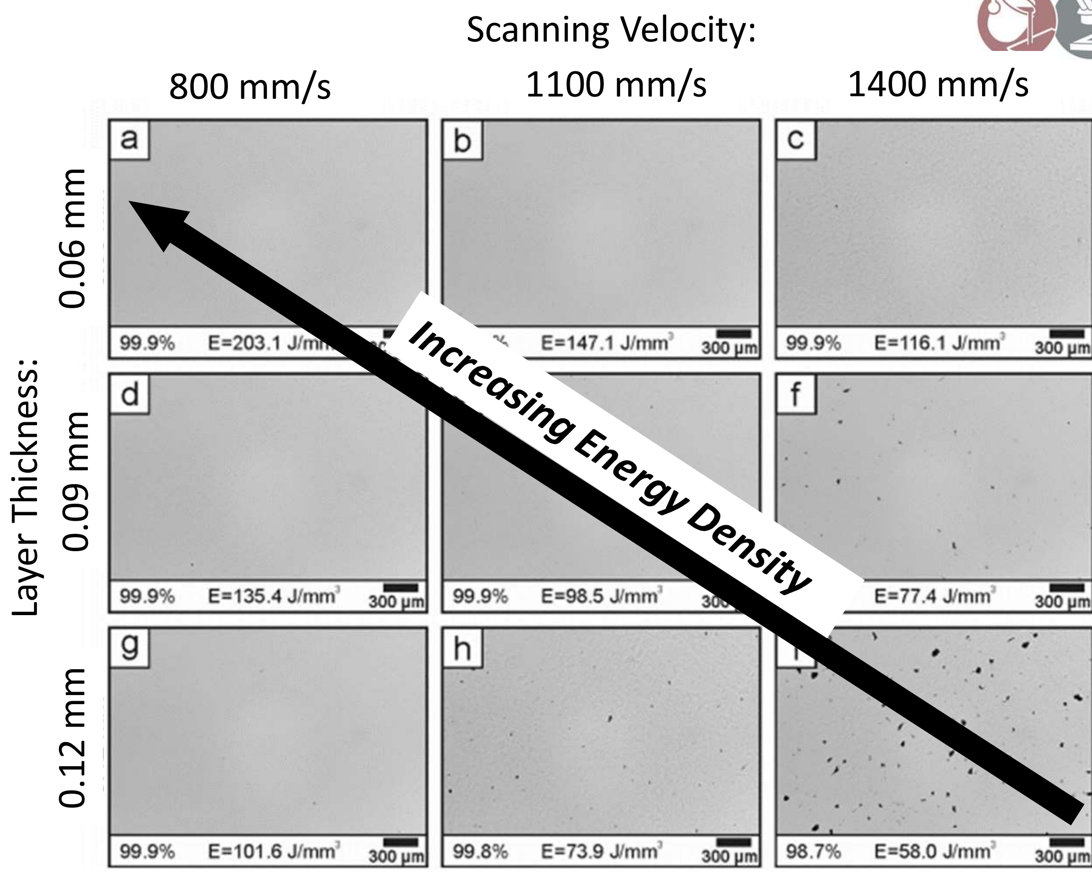


Increasing energy density leads to a decrease in porosity

A. Leicht et al, Materials Characterization, 2019

M. Zhang et al, Materials Science and Engineering A, 2017

Process Parameters on Build Density

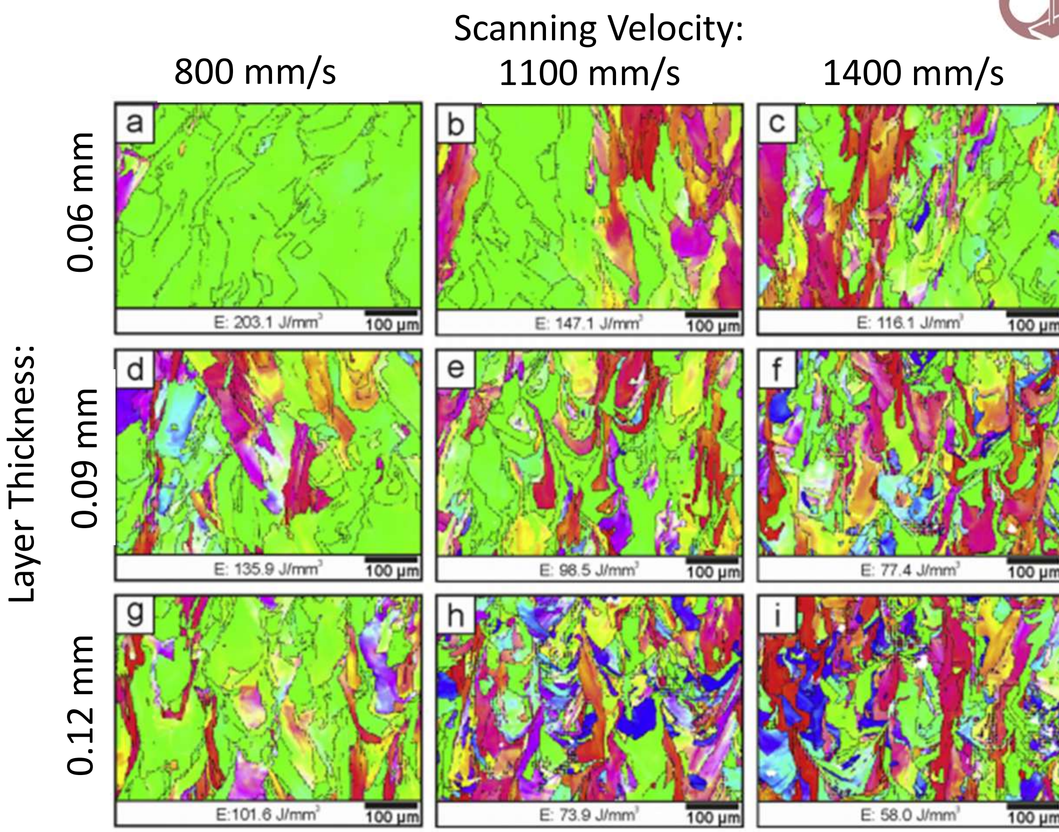


Optimal process parameters combination would be figures c, e, and g.

Negligible changes in porosity are observed above an energy density of ~ 98 J/mm³

A. Leicht et al, Materials Characterization, 2019

Process Parameters on Grain Orientation

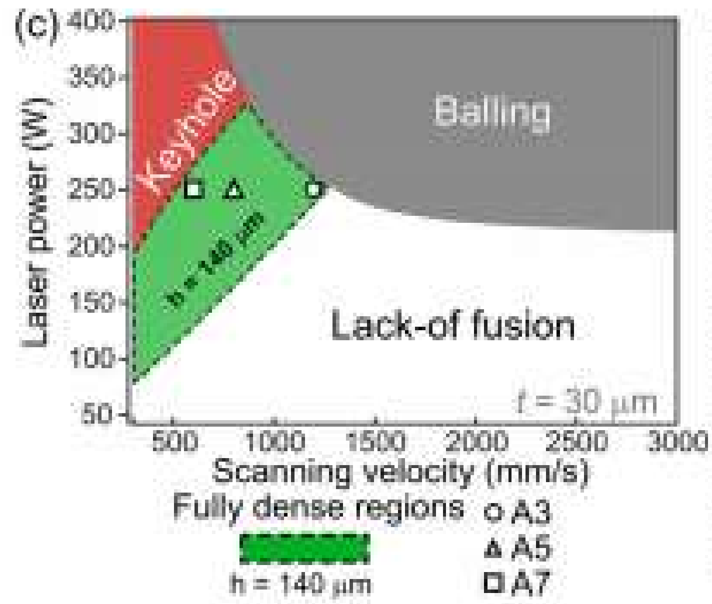


Higher energy densities are correlated with coarser microstructures likely leading to lower strengths in the as-built condition

A. Leicht et al, Materials Characterization, 2019

Defect Maps

- Each region represents parameter sets that could experience solidification defects
- These maps were developed using the Rosenthal Model along criteria proposed through literature

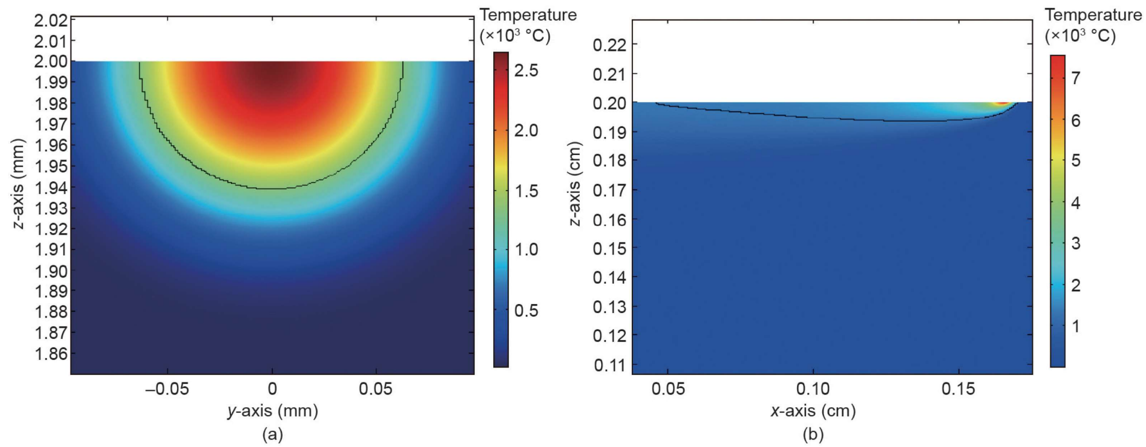


By using process parameters along with predicted melt pool geometry, it is possible to predict and control defects and solidification behavior

J. Zhu et al, Additive Manfacting, 2021

Rosenthal Model

- Assumptions
  - Thermophysical properties are temperature independent.
  - Scanning speed and power input are constant.
  - Point heat source
  - The heat transfer is governed purely by conduction.
- The Rosenthal model predicts semi-circular melt pool cross-sections.



$$T = T_o + \frac{\lambda P}{2\pi k r} \exp\left[-\frac{V(r+\xi)}{2\alpha}\right]$$

The Rosenthal model predicts semi-circular melt pool cross-sections whose depths and widths are deeper and narrower respectively compared to many additive manufacturing techniques.

P. Promoppatum et al, Engineering, 2017

Criteria for Defect Maps

- Balling:

$$\frac{\pi W}{L} < \sqrt{\frac{2}{3}}$$

- Lack of fusion:

$$\left(\frac{h}{W}\right)^2 + \frac{t}{t+D} \geq 1$$

- Keyhole-induced pore formation:

$$\frac{\Delta H}{h_s} = \frac{AP}{\pi h_s \sqrt{\alpha v a^3}} > \frac{\pi T_b}{T_m}$$

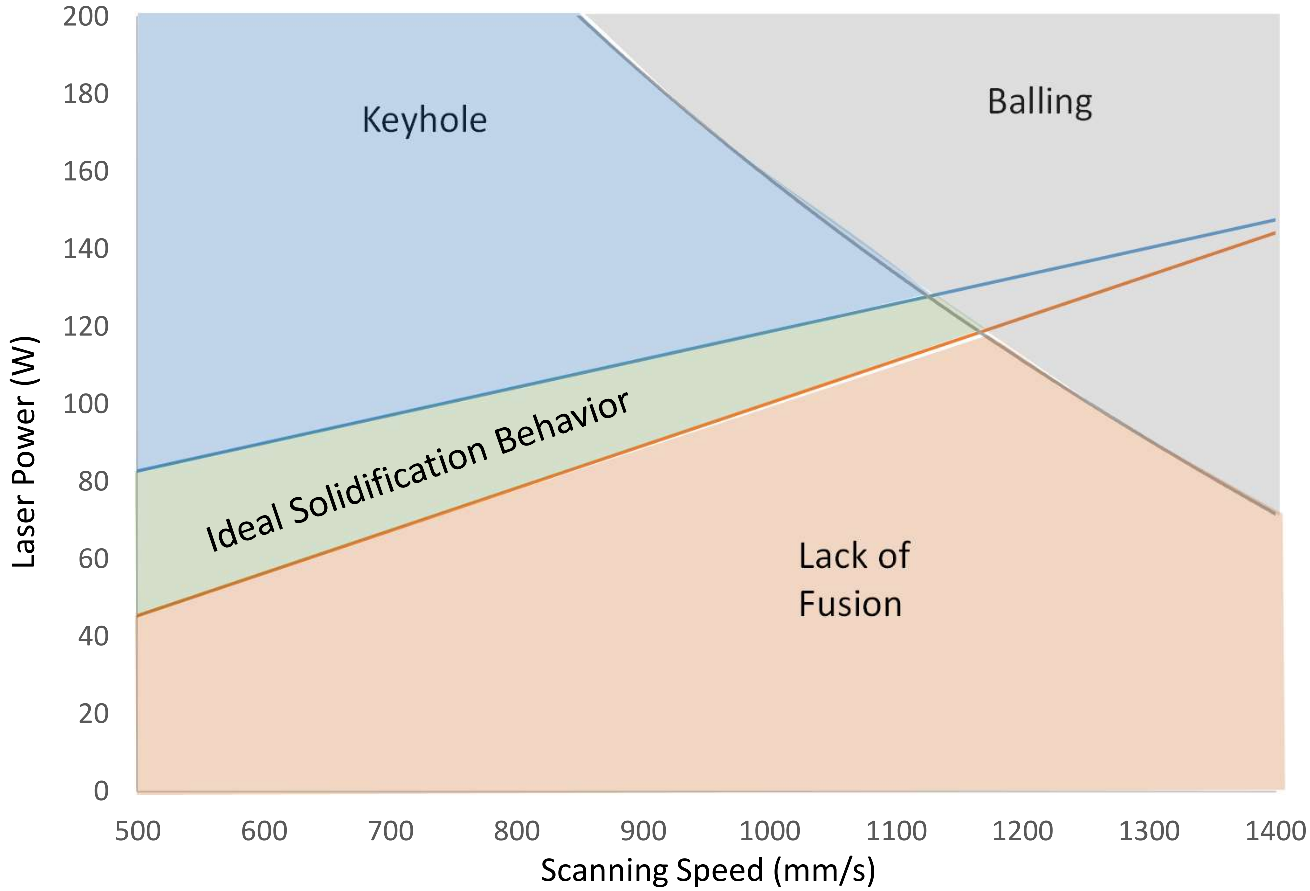
Where:

- W = melt pool width
- D = melt pool depth
- L = melt pool length
- h = hatch distance
- t = layer thickness
- P = laser power
- a = beam radius
- v = scanning velocity

The solidification behavior and defect formation can be predicted using process parameters and melt pool geometry

J. Zhu et al, Additive Manfacting, 2021

Defect Map

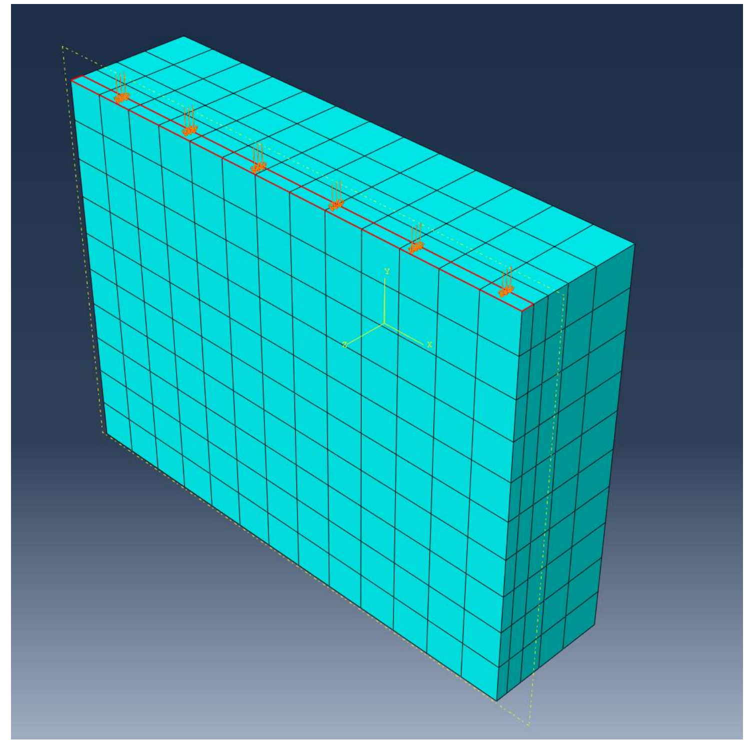


Spot Size: 0.1 mm
Hatch Distance: 0.1 mm
Layer Thickness: 0.04 mm

The green area gives optimal process parameters for solidification behaviors

ABAQUS Simulations

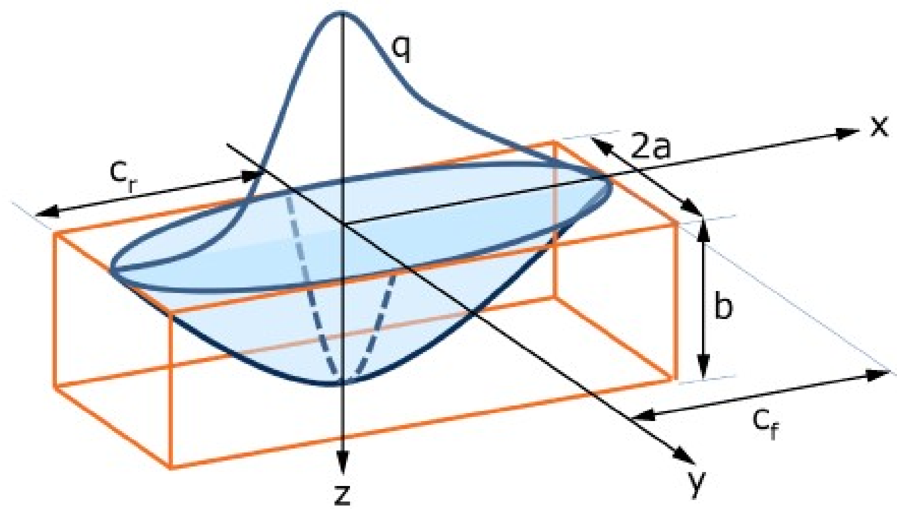
- Simulates a single-track moving heat source on a 316L steel plate
- Uses a Goldak heat distribution to model a moving heat source
- Accounts for convection and radiation loss to the environment, but only conduction in the melt pool
- Possible to do more complex processes including material depositing, multi-passes, and different scanning strategies.



ABAQUS simulations are used to model thermal gradients and temperature histories during the build process

Goldak Distribution and ABAQUS Simulation Set Up

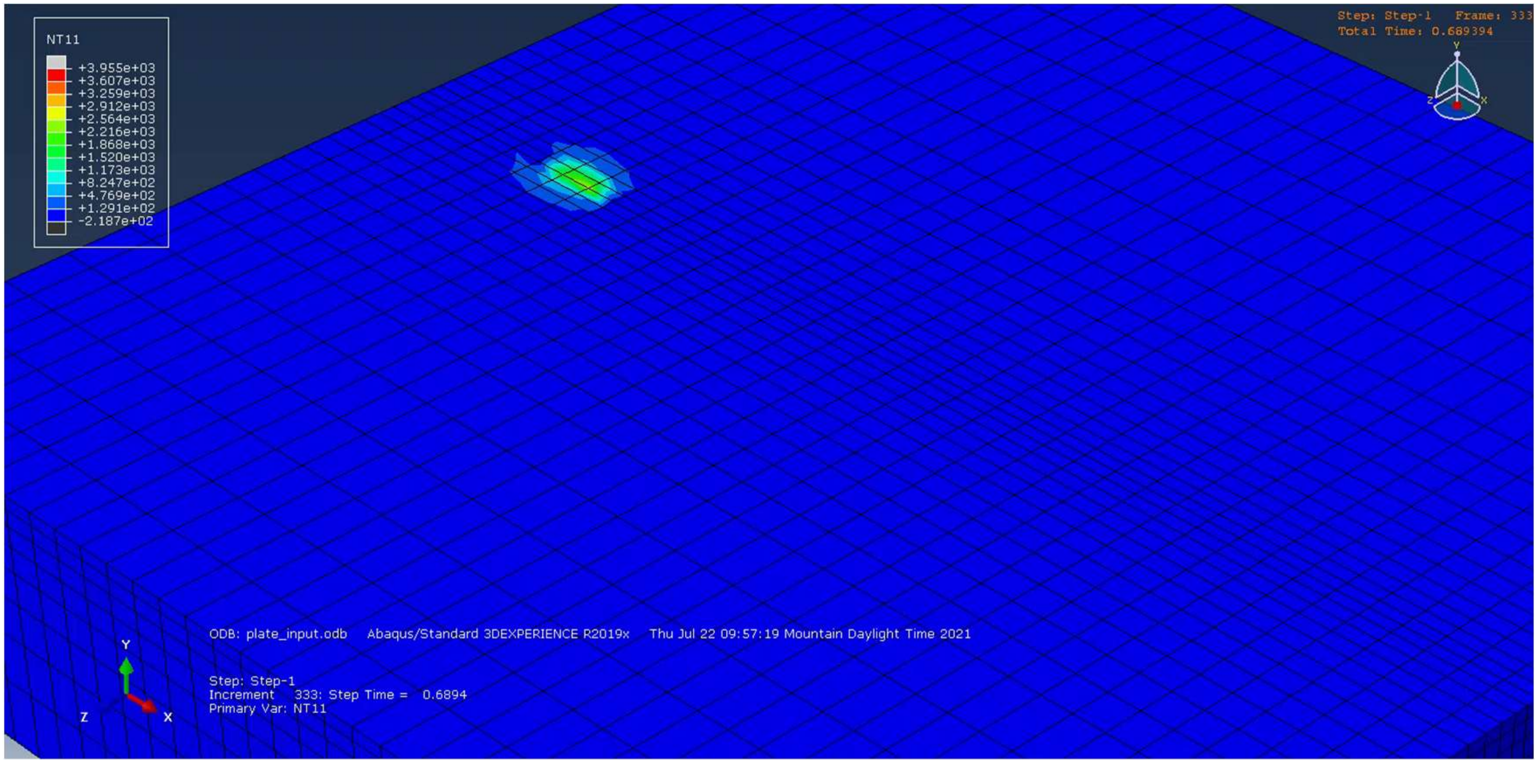
- Developed in 1984 by John Goldak for welds
- Aimed to expand on the Rosenthal model to overcome some of the limiting assumptions
- Model is based on a double ellipsoid configuration



The Goldak distribution was developed for larger melt pool geometries and the applicability to LPBF is being evaluated

J. Goldak et al, Metallurgical Transaction, 1984
Abaqus software documentation

Example Simulations – Preliminary



First 316L Build

- First build was designed to evaluate effects of part sizes and proximity of nearby builds on microstructure
- This build was done using baseline parameters from 3D Systems using the Mines DMP Flex 350

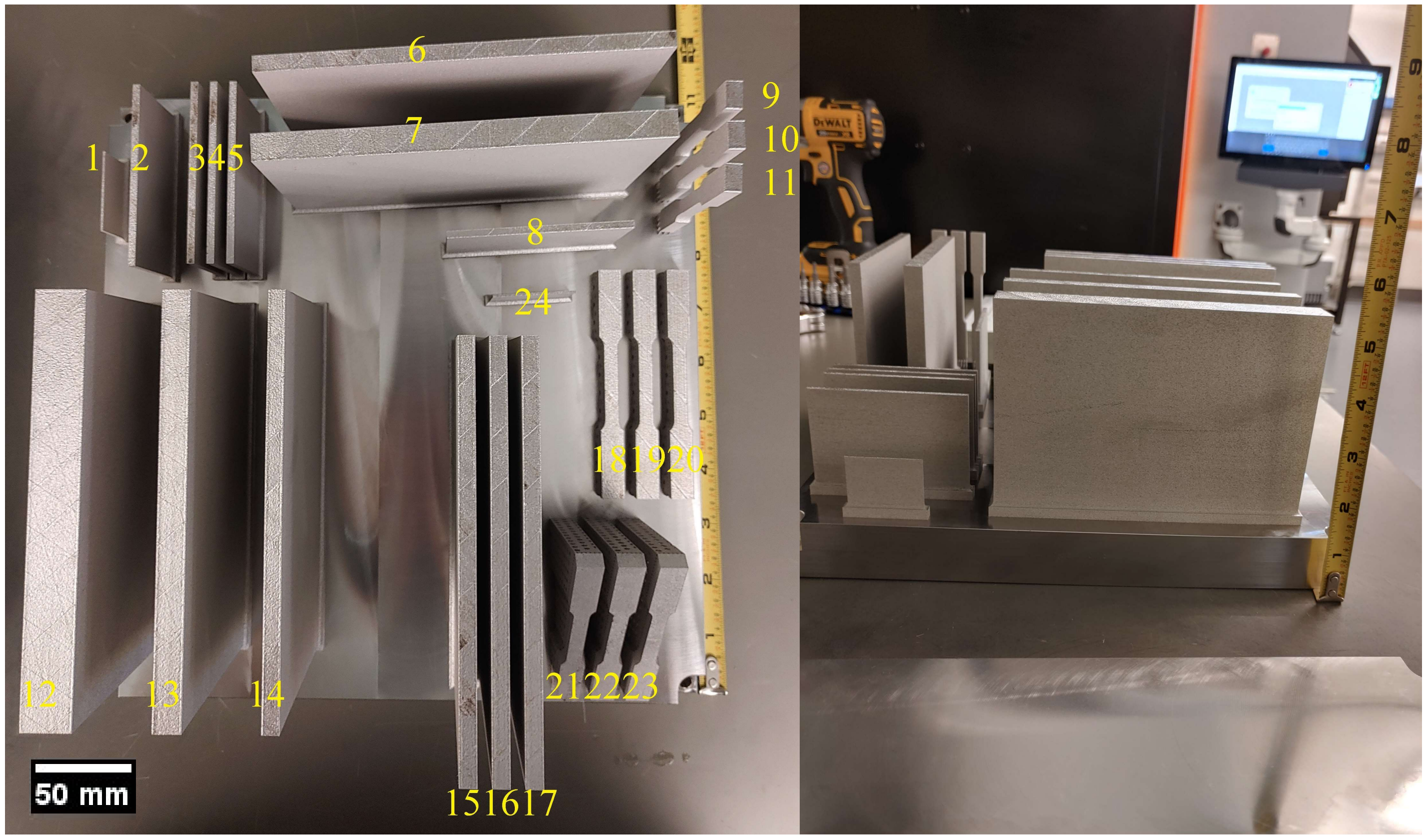


Plate 1

- Plate 1 – 35 mm x 1.25 mm x 23.5 mm
- Plate 1 was isolated in the build and designed to assess the thinnest feature that would be made
- The top section or top layer would experience the smallest amount of remelting and reheating which would give the most meaningful results to compare to solidification models
- ABAQUS simulations were done to predict the thermal gradients and solidification velocity

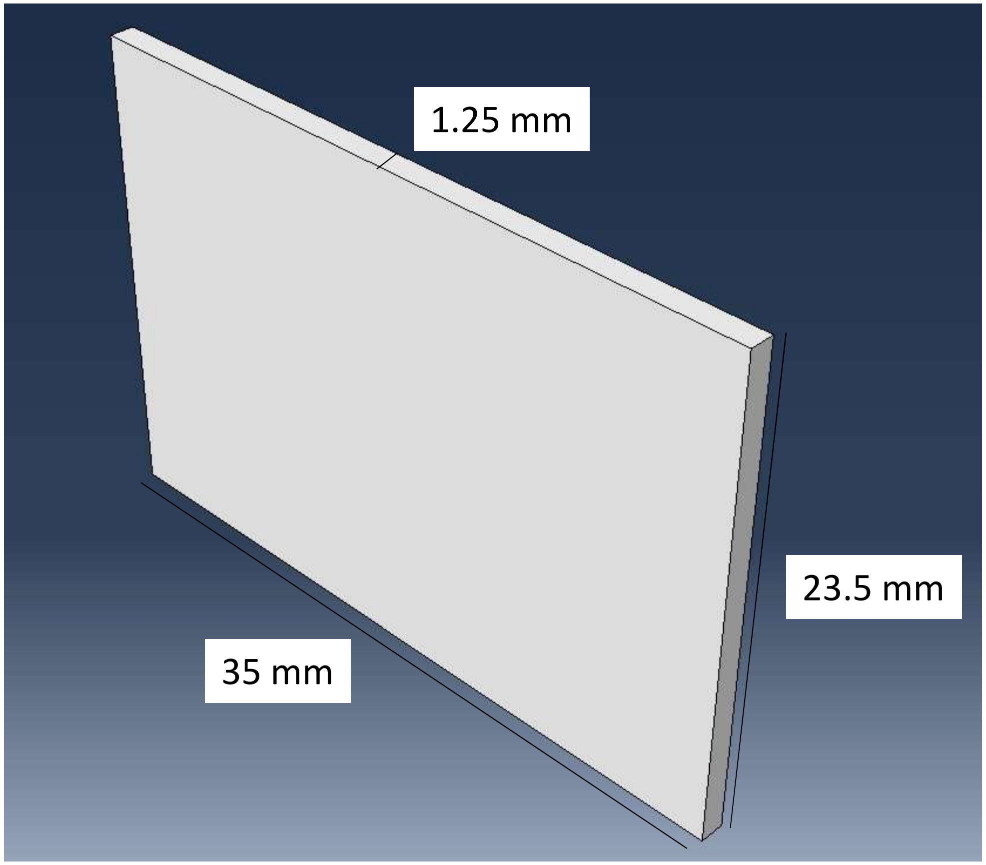
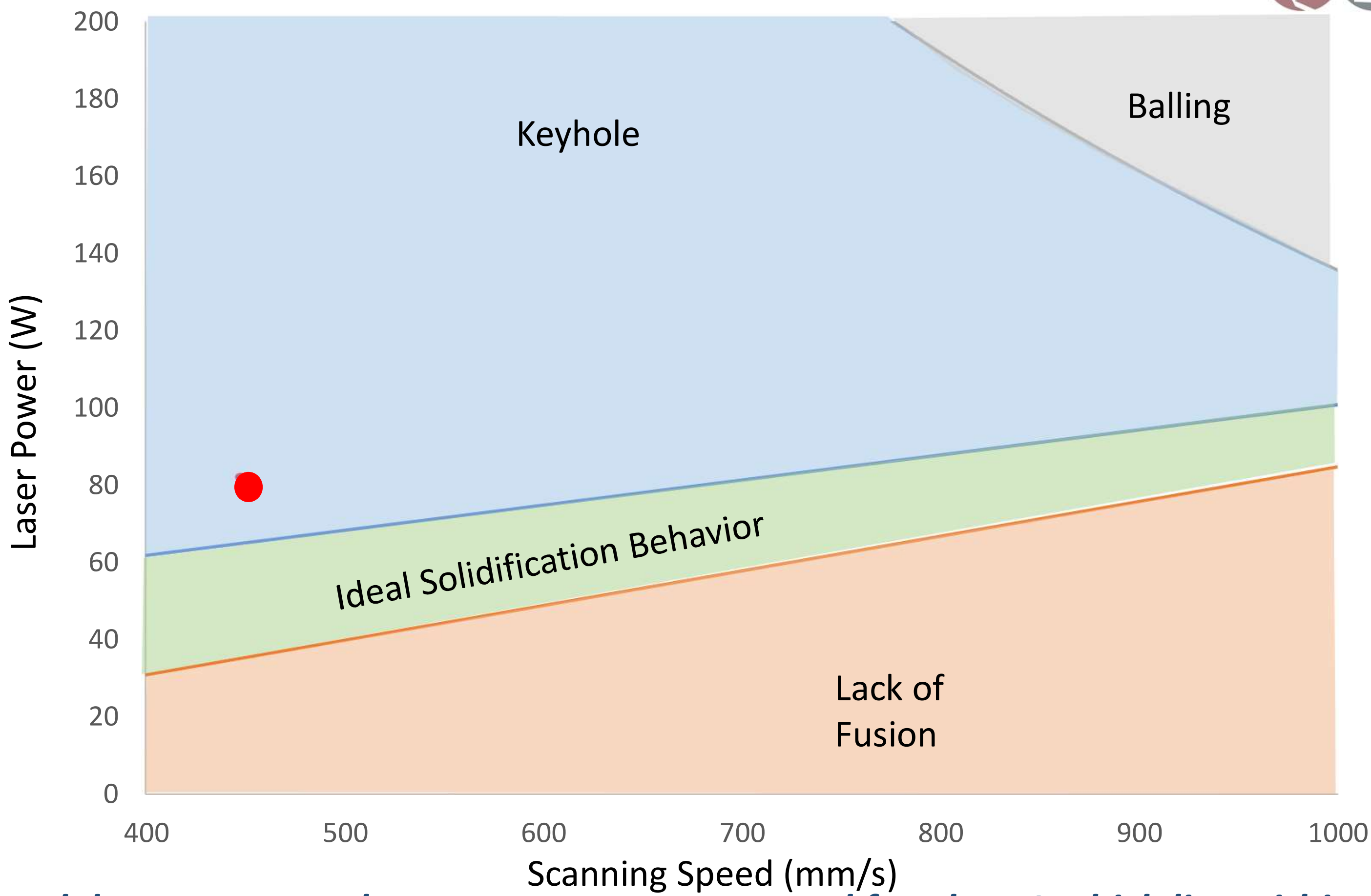


Plate 1 Melt Pool Analysis

- The melt pool dimensions were predicted using the Rosenthal model
- The melt pool is predicted, using the Rosenthal model, to have a width of 108 µm and a depth of 34.4 µm
- Measurements show an average width of 156 µm and an average depth 48 µm respectively

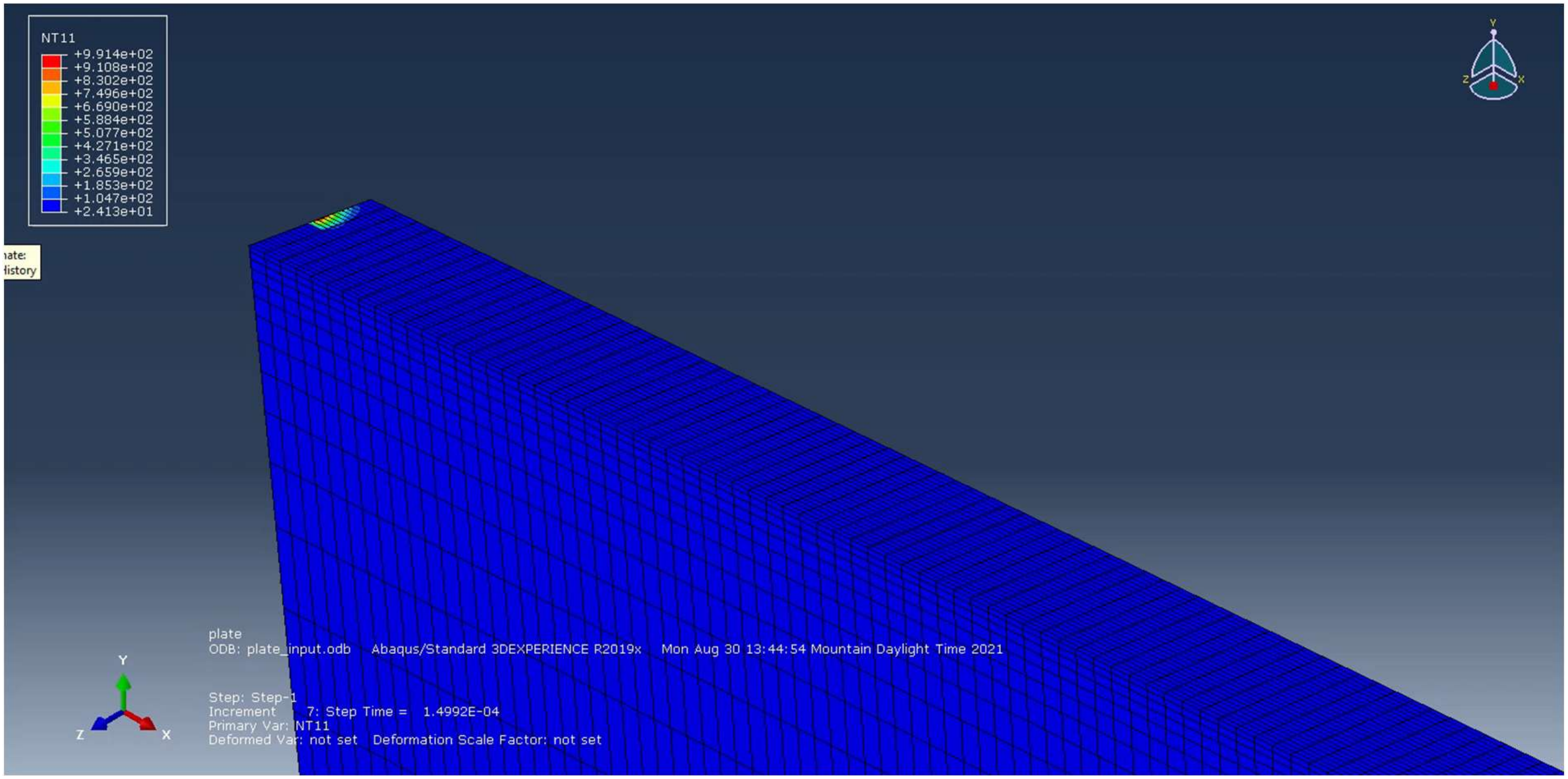
Discrepancies between Rosenthal model predictions and experiments are likely due to a combination of sectioning effects and the limiting assumptions in the model.

Updated Defect Map



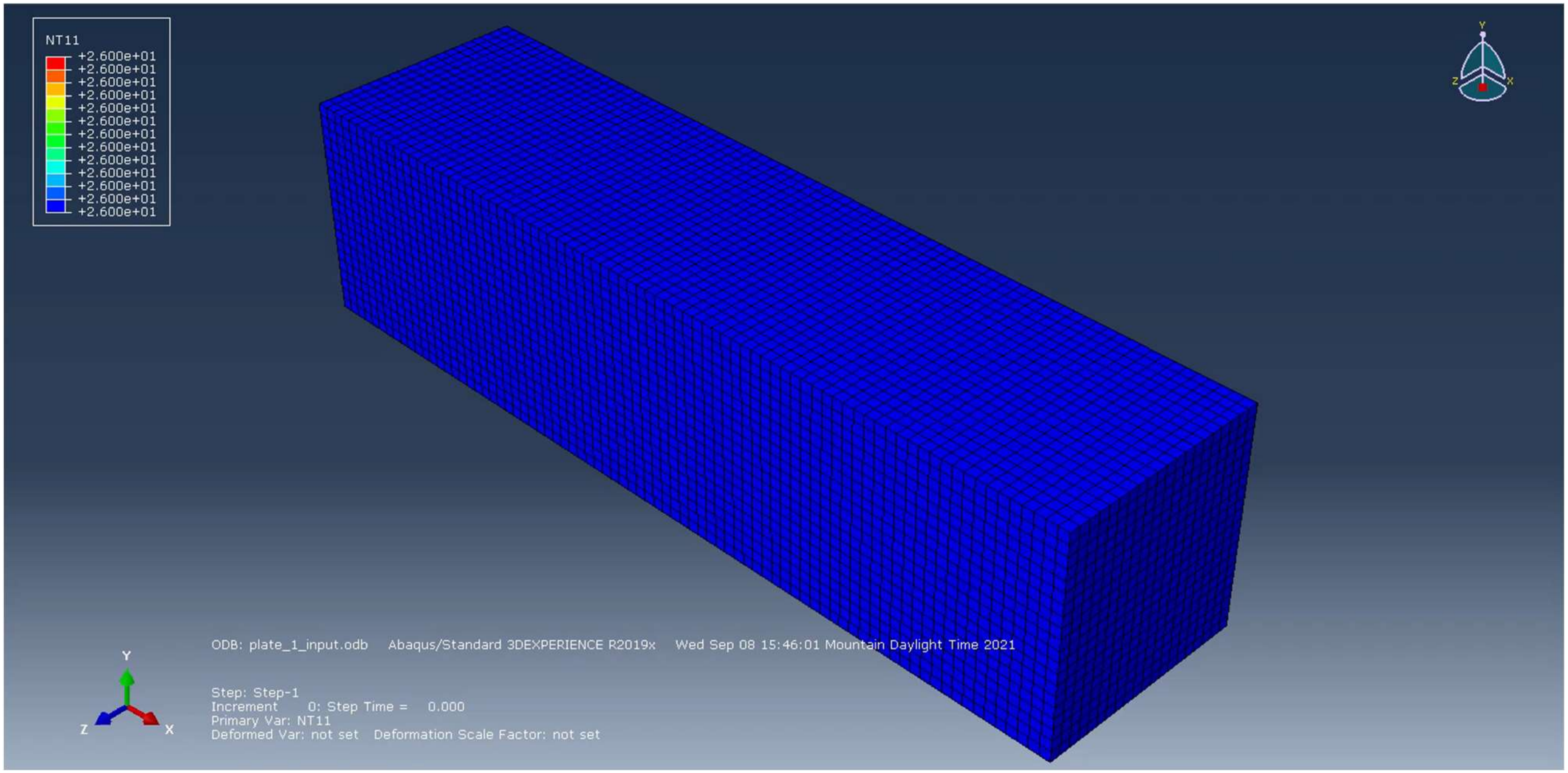
The red dot represents the process parameters used for plate 1 which lies within the Keyholing region.

Simulation of Plate 1



Scale model of plate 1 from build 1 showing a moving heat source across the top layer

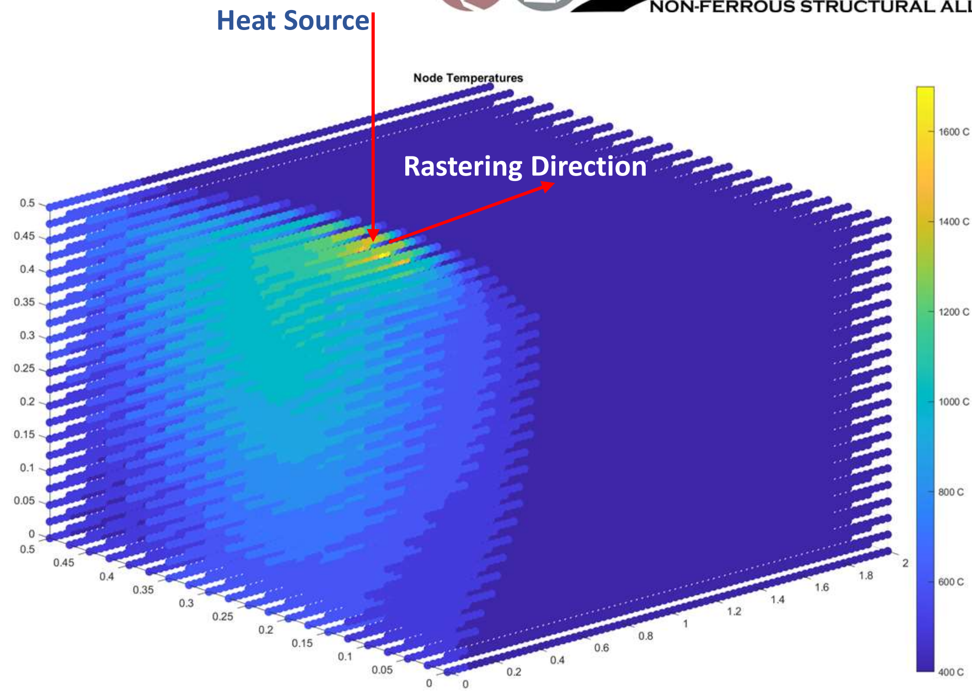
Scaled Down Model of Plate 1



A scaled down model allows quicker simulations and a finer mesh

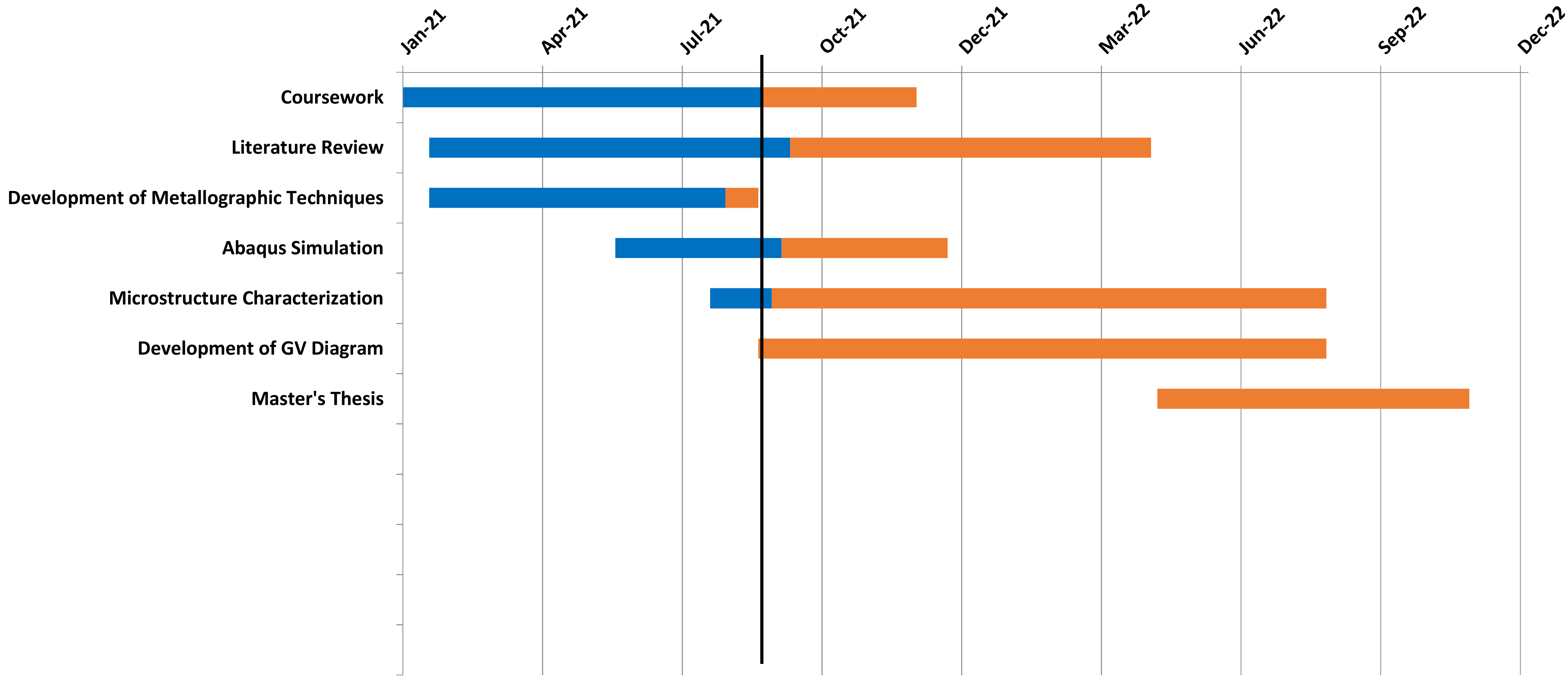
Predictions of G and V

- The thermal gradient (G) and solidification velocity (V) can be calculated by observing the melt pool boundary
- The nodal temperatures of the model were plotted at a set time
- The surface of the melt pool was also plotted



The next step is to overlay the melt pool surface with the nodal temperature plots and observe the movement of the solidification boundary to determine V and observe the thermal gradients across the solidification boundary to determine G.

Progress



Jan-21
Apr-21
Jul-21
Oct-21
Dec-21
Mar-22
Jun-22
Sep-22
Dec-22
Coursework
Literature Review
Development of Metallographic Techniques
Abaqus Simulation
Microstructure Characterization
Development of GV Diagram
Master's Thesis

Challenges & Opportunities

- ***The defect maps should provide insight on ideal process parameters, but they do not provide insight on effects of component geometry and solidification conditions.***
- ***Progress is being made with ABAQUS simulations, and more work needs to be done to simulate more complex situations.***
- ***Other simulation programs such as SYSWELD and/or Flow3D will be evaluated to compare the thermal gradients and history.***
- ***Metallography and melt pool analysis has begun***
  - *Are there any particular microstructural features of interest to the sponsors (other than dendrite arm spacing, grain size, and grain morphology)?*
- ***There are many other aspects of AM that these microstructure maps will not take into consideration.***
  - *Are there any recommendations from the sponsors about critical variables or microstructure features that should be included?*

Thank you!

Charles Smith

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References

- A. Leicht, M. Rashidi, U. Klement, and E. Hryha, “Effect of process parameters on the microstructure, tensile strength and productivity of 316L parts produced by laser powder bed fusion,” *Mater. Charact.*, vol. 159, no. August 2019, p. 110016, 2020, doi: 10.1016/j.matchar.2019.110016.
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