Project 36F-L: Microstructure and Processing Links in Beta-Titanium during Additive Manufacturing

Semi-annual Fall Meeting
October 2021

- Student: Chris Jasien (Mines)
- Faculty: Dr. Amy Clarke (Mines)
- Industrial Mentors: Adam Pilchak (MRL), Lee Semiatin (AFRL)
- Other Participants: Jonah Klemm-Toole (Mines)

COLORADO SCHOOL OF MINES · NSF · IOWA STATE UNIVERSITY

Project 36F-L: Microstructure and Processing Links in Beta-Titanium during Additive Manufacturing

- Student: Chris Jasien (Mines)
- Advisor(s): Amy Clarke (Mines)

Project Duration
PhD: August 2020 to May 2024

- Problem: Common titanium alloys for additive manufacturing (AM) undergo solid-state phase transitions during cooling that inhibit understanding of solidification.
- Objective: Subject beta-titanium alloys to conditions representative of AM and understand retention of the metastable beta phase and microstructure evolution.
- Benefit: The development of solidification models and knowledge base of titanium alloys for AM.

Recent Progress
- Completion of models for spot-melt and raster scenarios in *FLOW-3D*
- Development of Columnar-to-Equiaxed (CET) model for Ti-10V-2Fe-3Al
- Design, fabrication, and set-up of AM simulator chamber for Sigmajig solidification crack testing

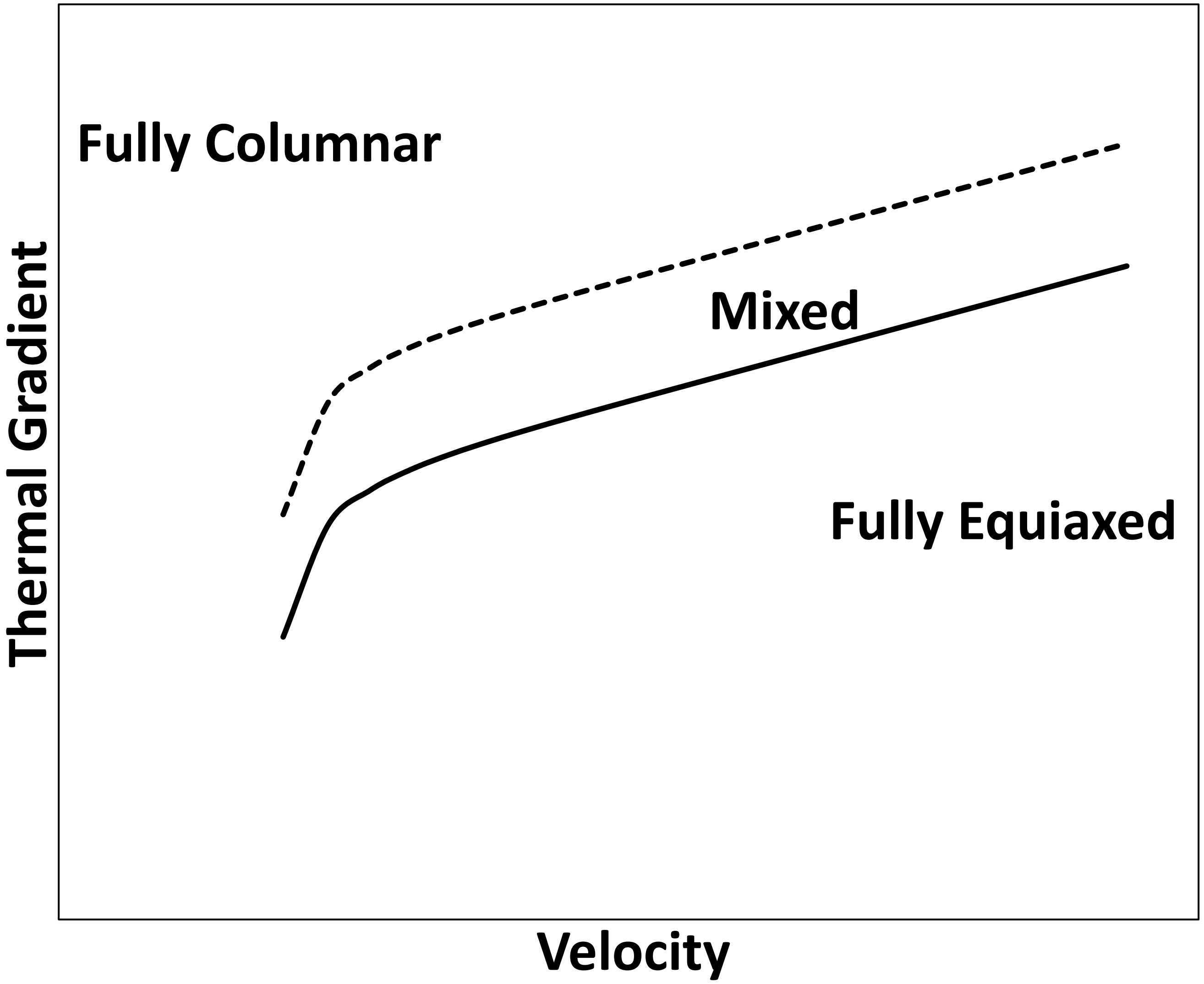
Metrics		
Description	**% Complete**	**Status**
1. Literature review	40%	●
2. Analyze APS data (solidification velocities)	100%	●
3. Determination of thermal history using simulations	50%	●
4. Supporting material characterization	20%	●
5. Crack susceptibility using Sigmajig test	20%	●

Overview

- Solidification Map for Ti-1023
- APS Simulations
  - Solidification Velocity
  - Estimated Thermal Gradients
- Sigmajig Crack Susceptibility Testing – Capability Development

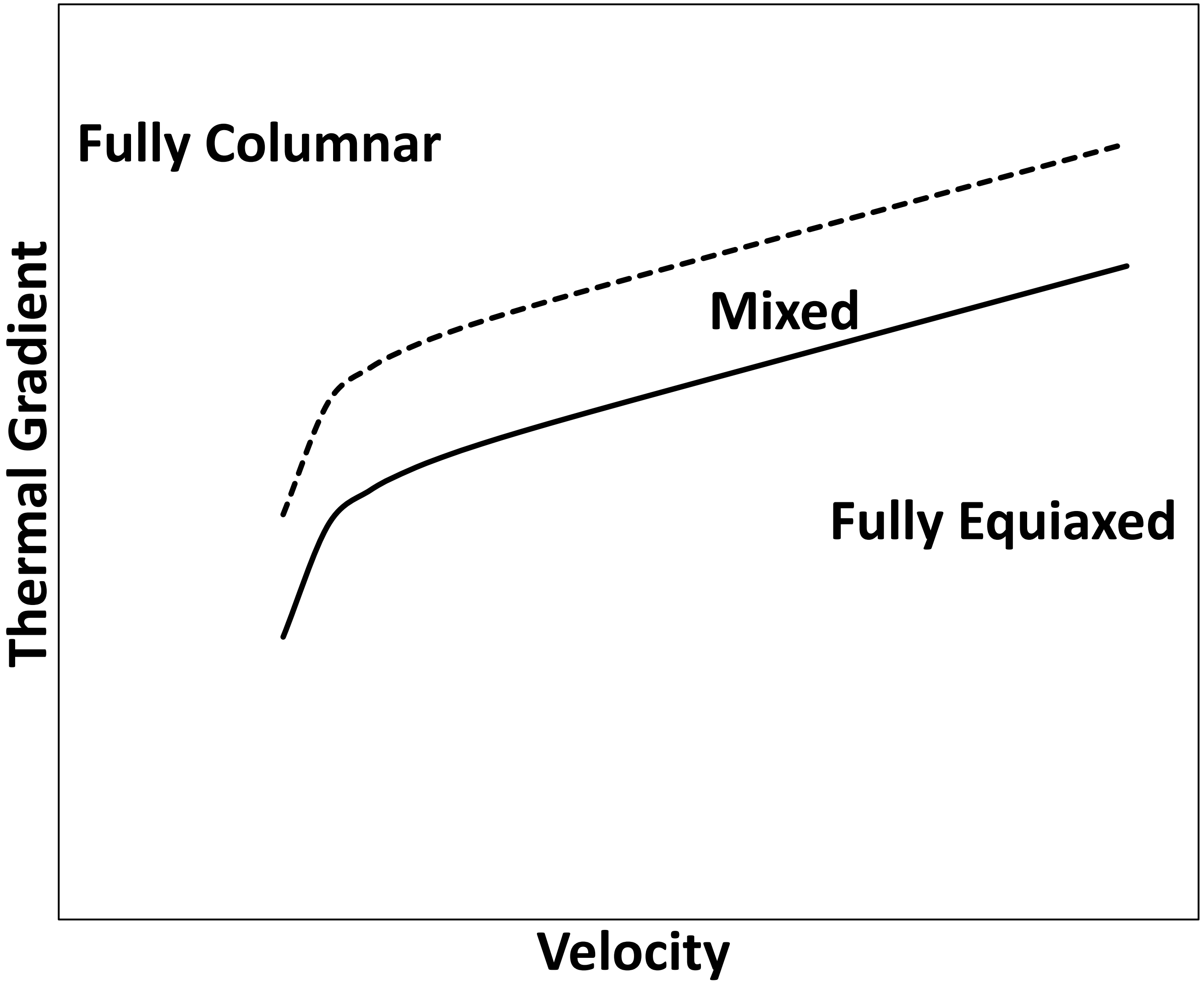
Solidification Map for Ti-1023

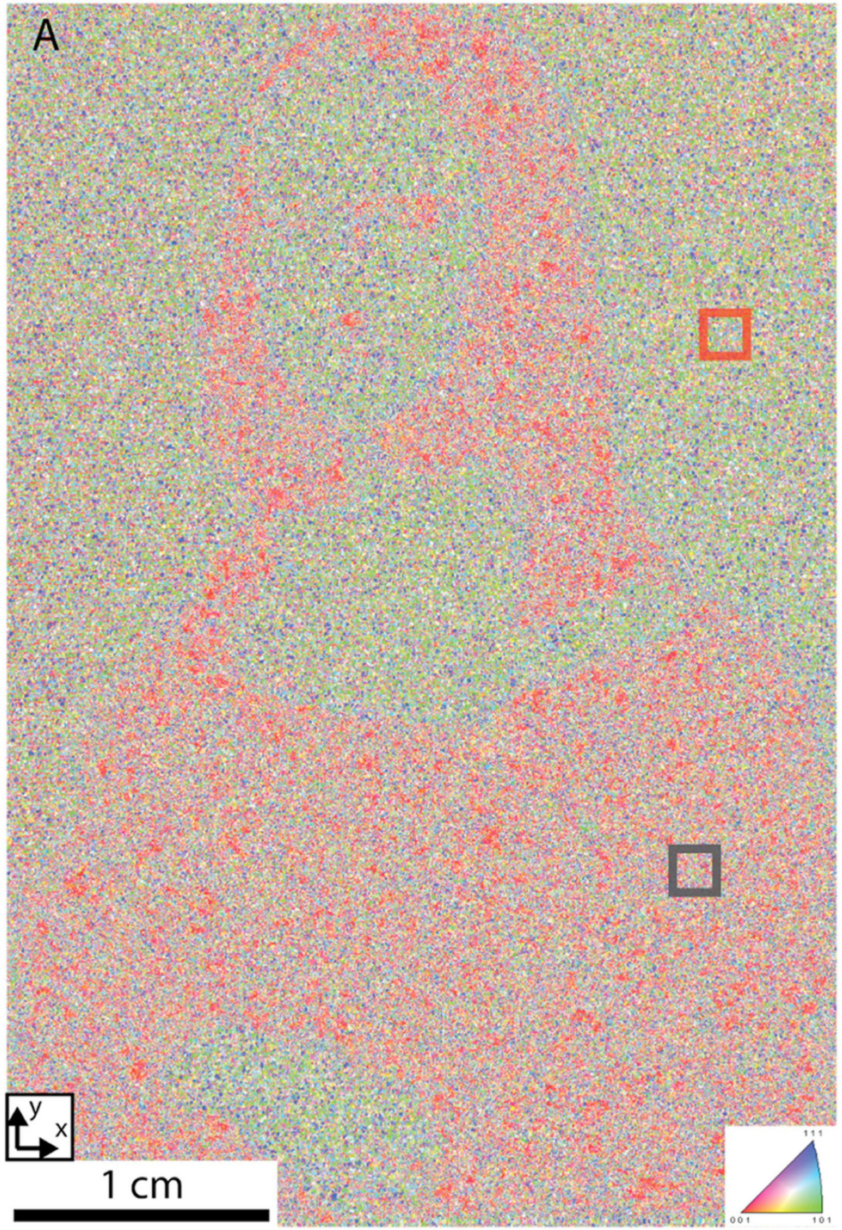
Solidification Maps



- What solidification conditions promote certain grain morphologies over another?
  - Correlated to Process Parameters

Solidification Maps

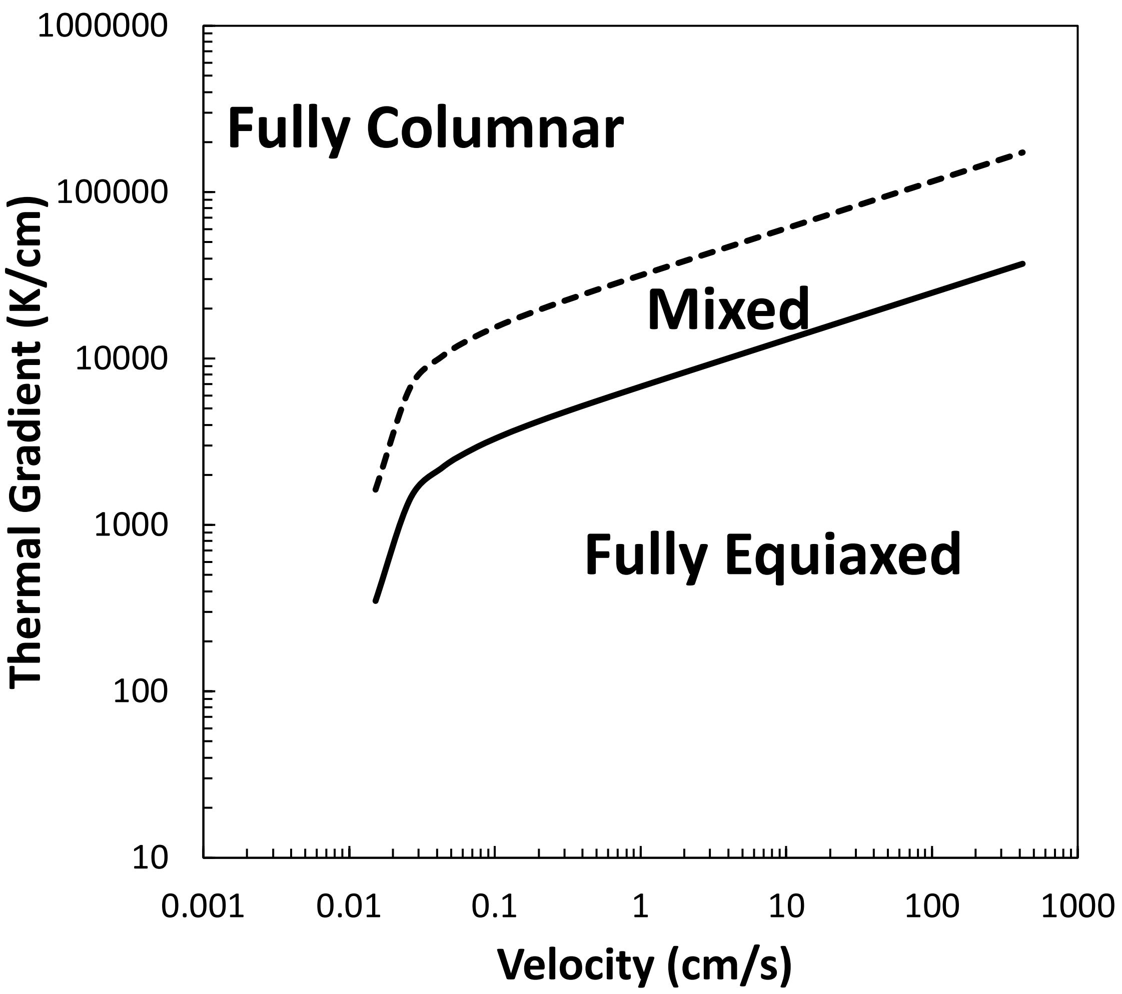




Plotkowski, A., et al., "A stochastic scan strategy for grain structure control in complex geometries using electron beam powder bed fusion", *Additive Manufacturing*, Vol. 46, 2021

Solidification Map – Ti-10V-2Fe-3Al

- Need alloy specific solidification map to predict microstructure
  - Kobryn and Semiatin developed one for Ti-6Al-4V
- Used KGT model to approximate fully columnar and equiaxed regions for the alloy
  - Calculated liquidus slopes and partition coefficients using *Thermo-calc*
  - Diffusivities and Gibbs-Thomson coefficient pulled from literature
  - Top-down images of melt pools used to help calibrate model

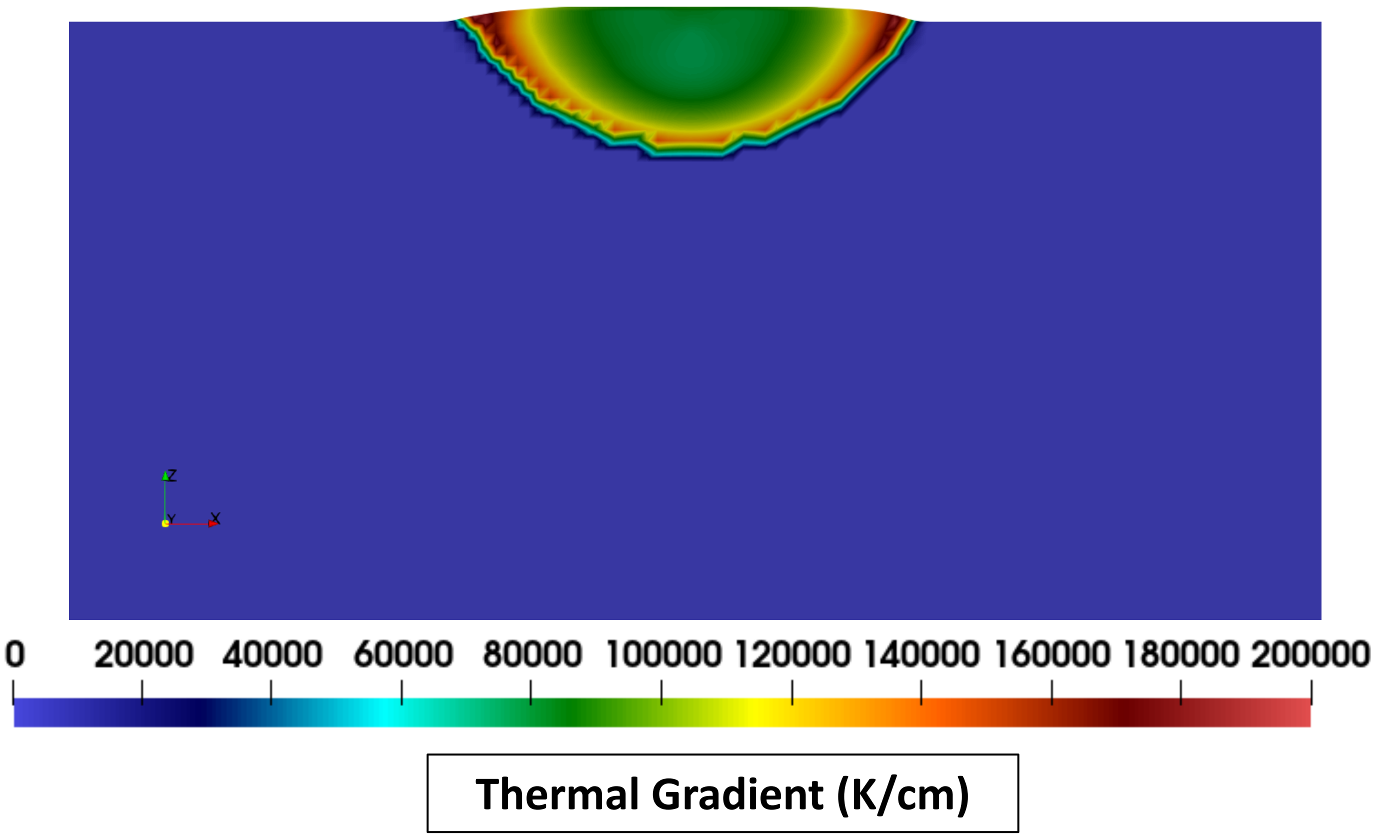


APS Simulations

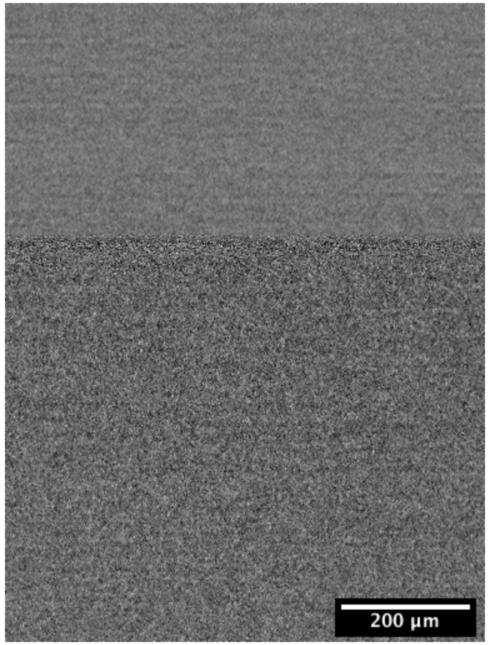
Why Simulations?

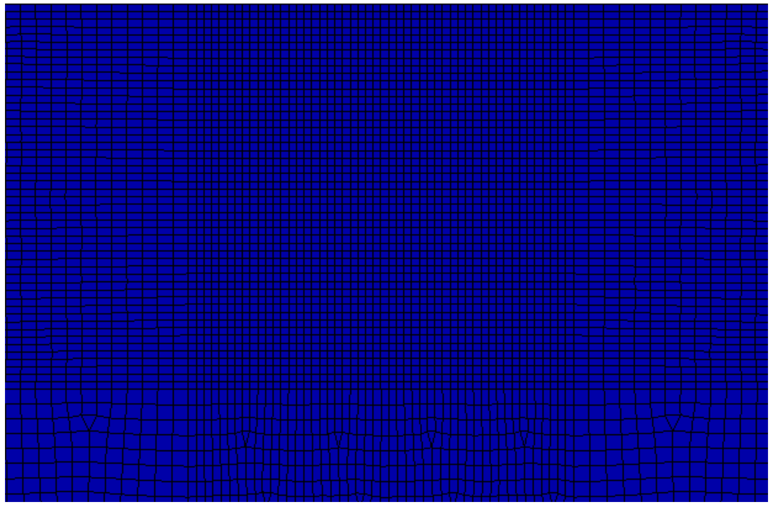
CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

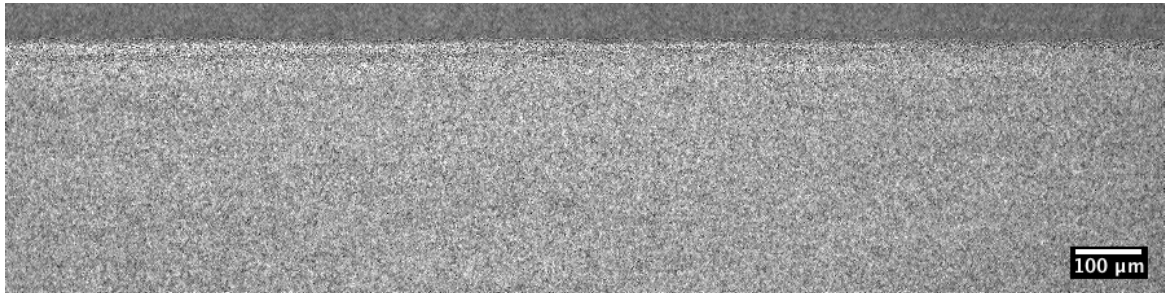
- To use solidification map to predict microstructure, we need **velocity (V)** and **thermal gradient (G)**
  - Velocities can be obtained from controlled experiments
  - Thermal gradients can't…
- Need simulations to predict thermal gradients throughout the melt pool

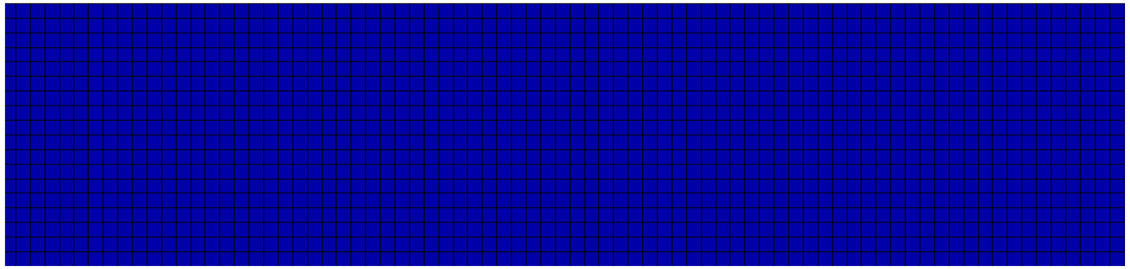


Previous Work

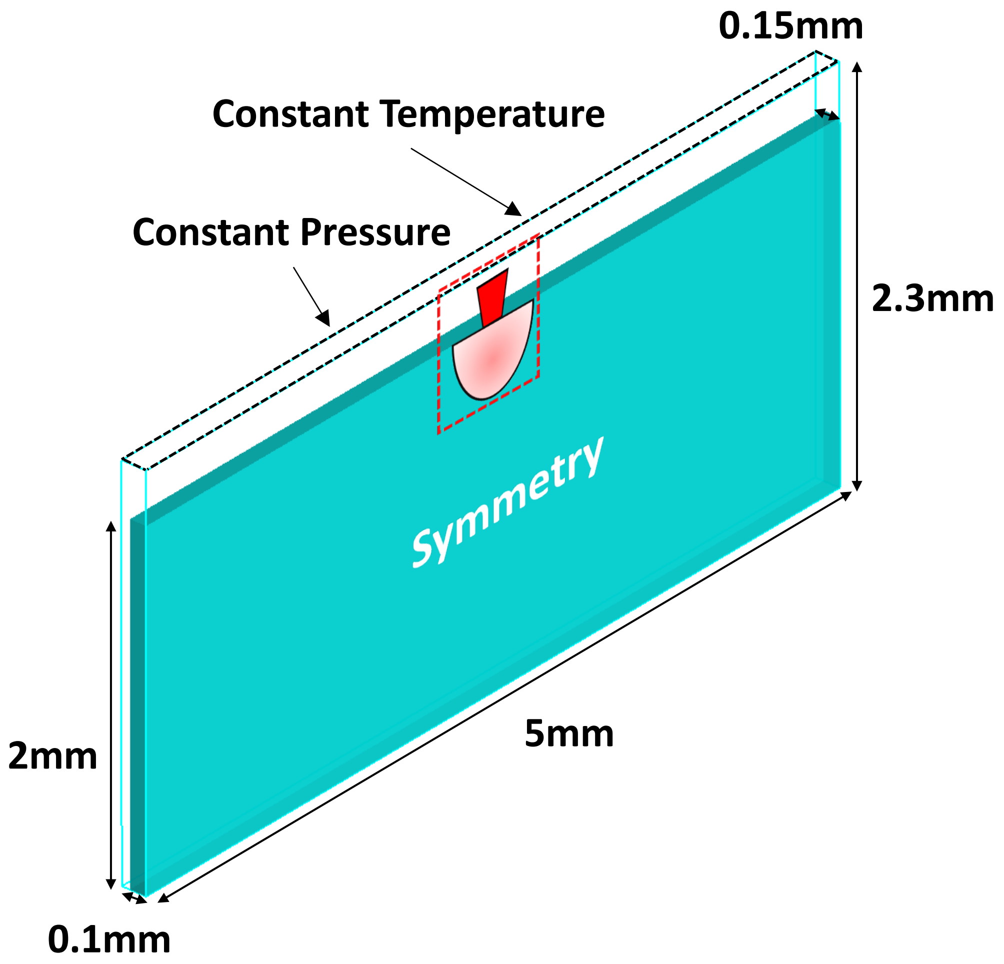


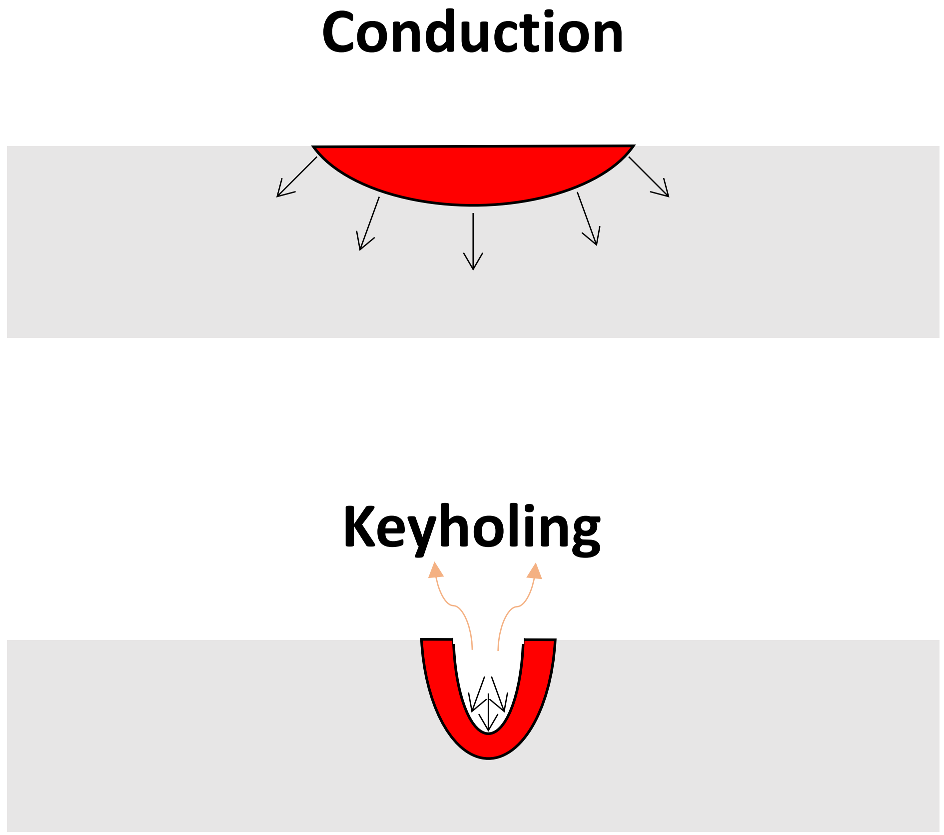




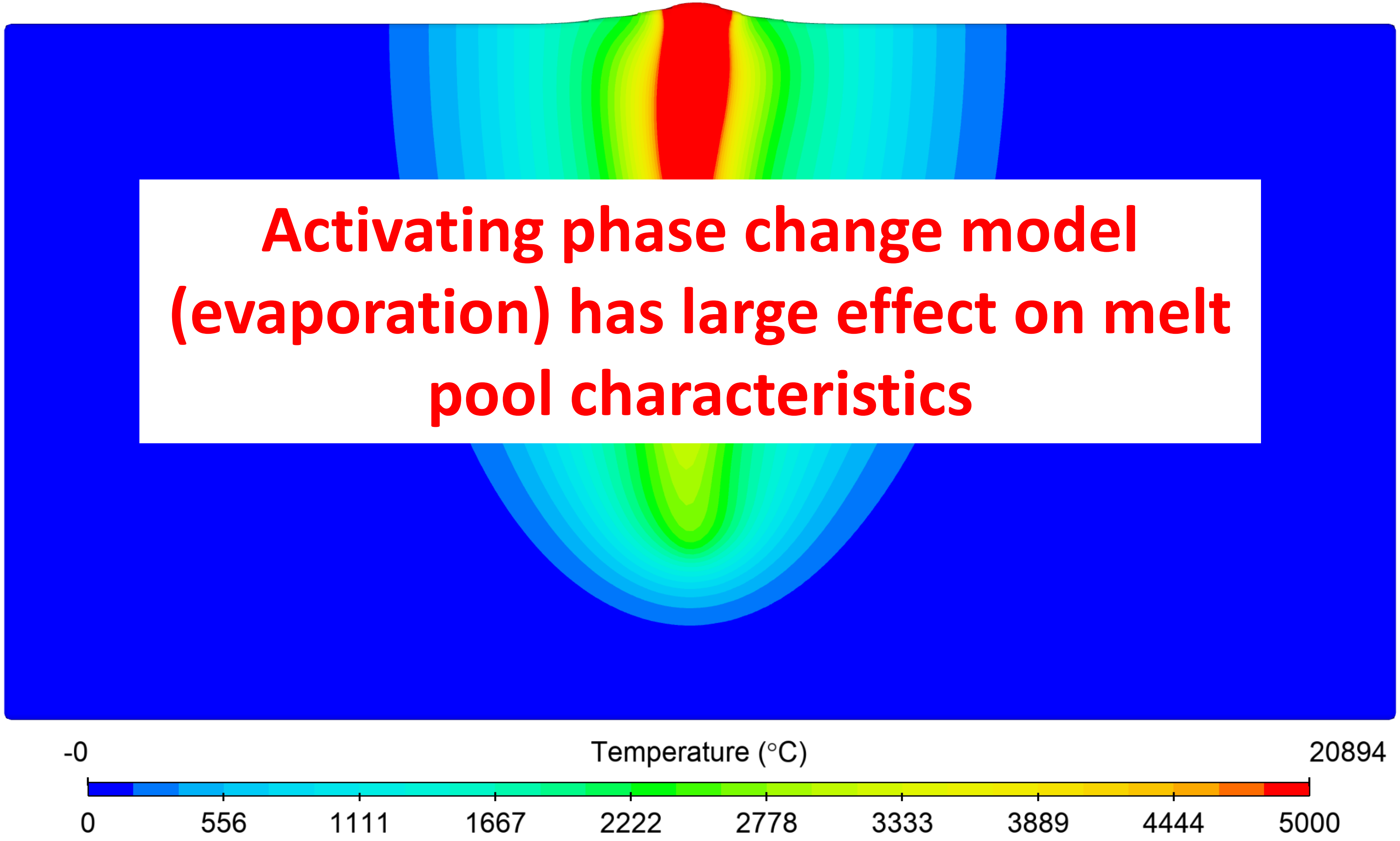


Simulations – FLOW3D





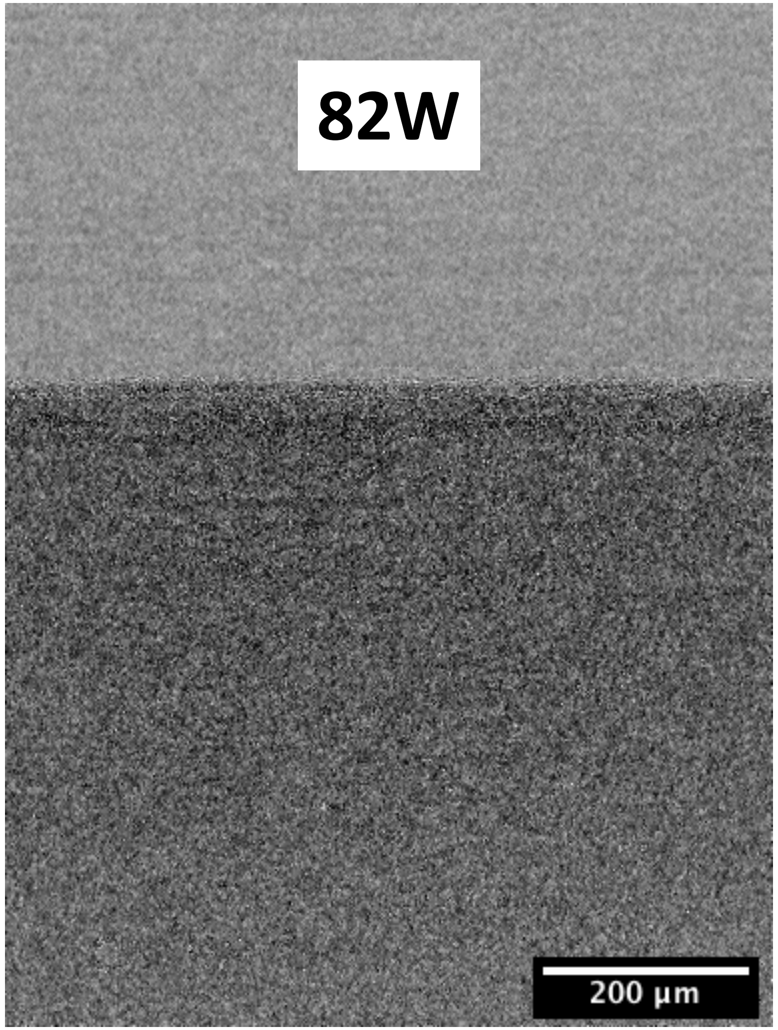
Simulations – FLOW3D

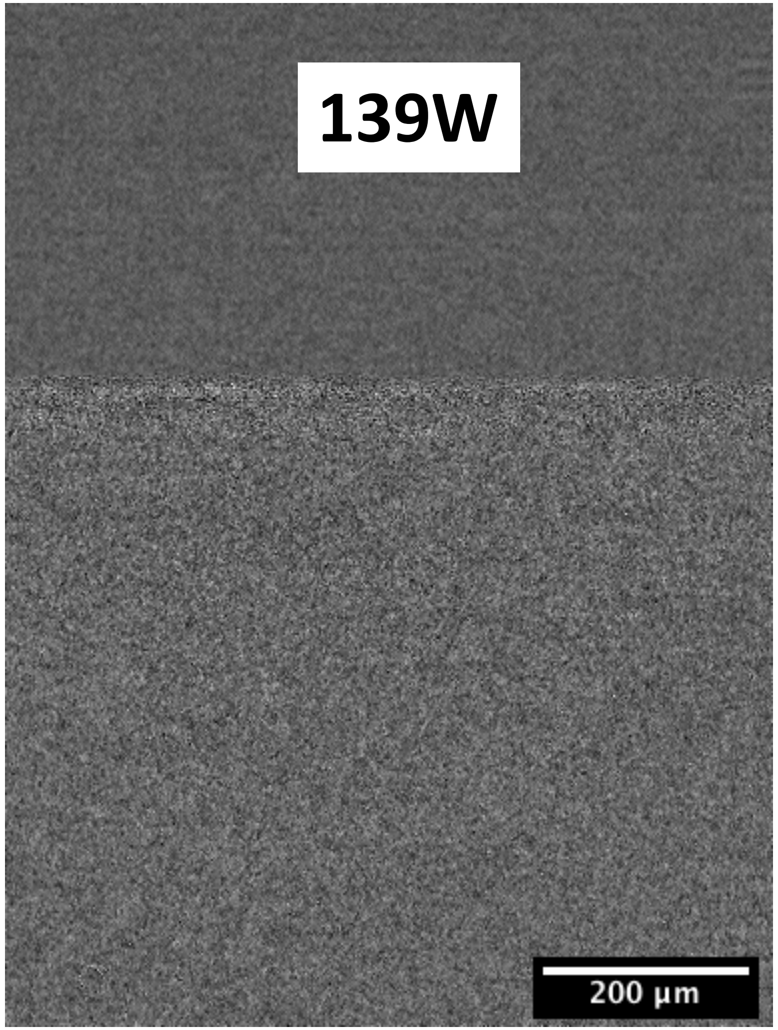


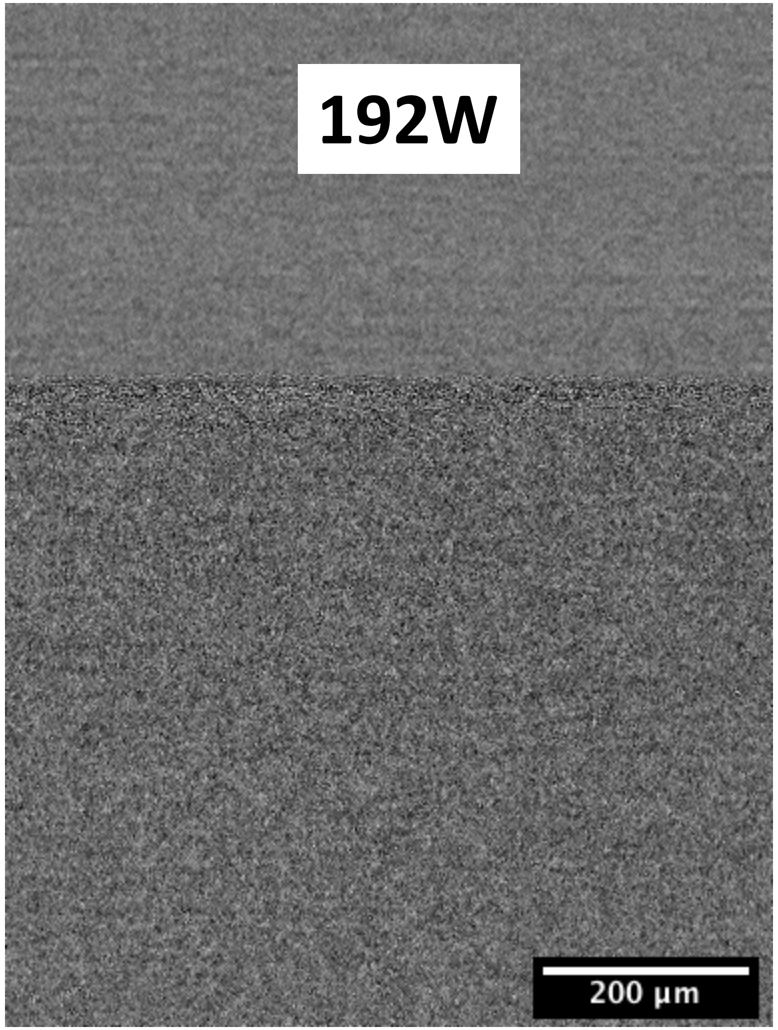
Activating phase change model (evaporation) has large effect on melt pool characteristics

Simulations – FLOW3D

1ms Dwell

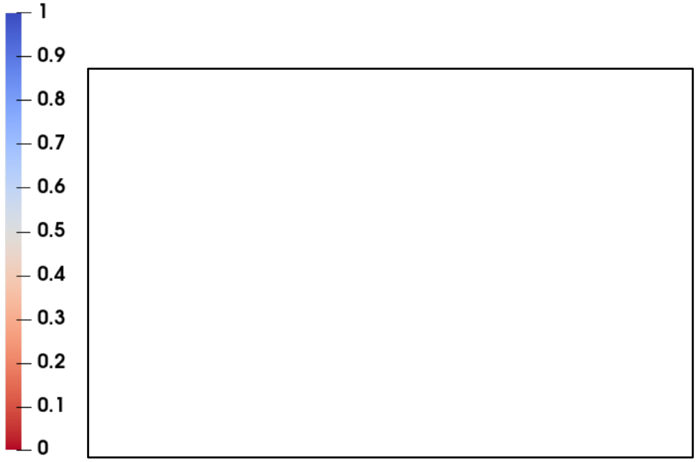




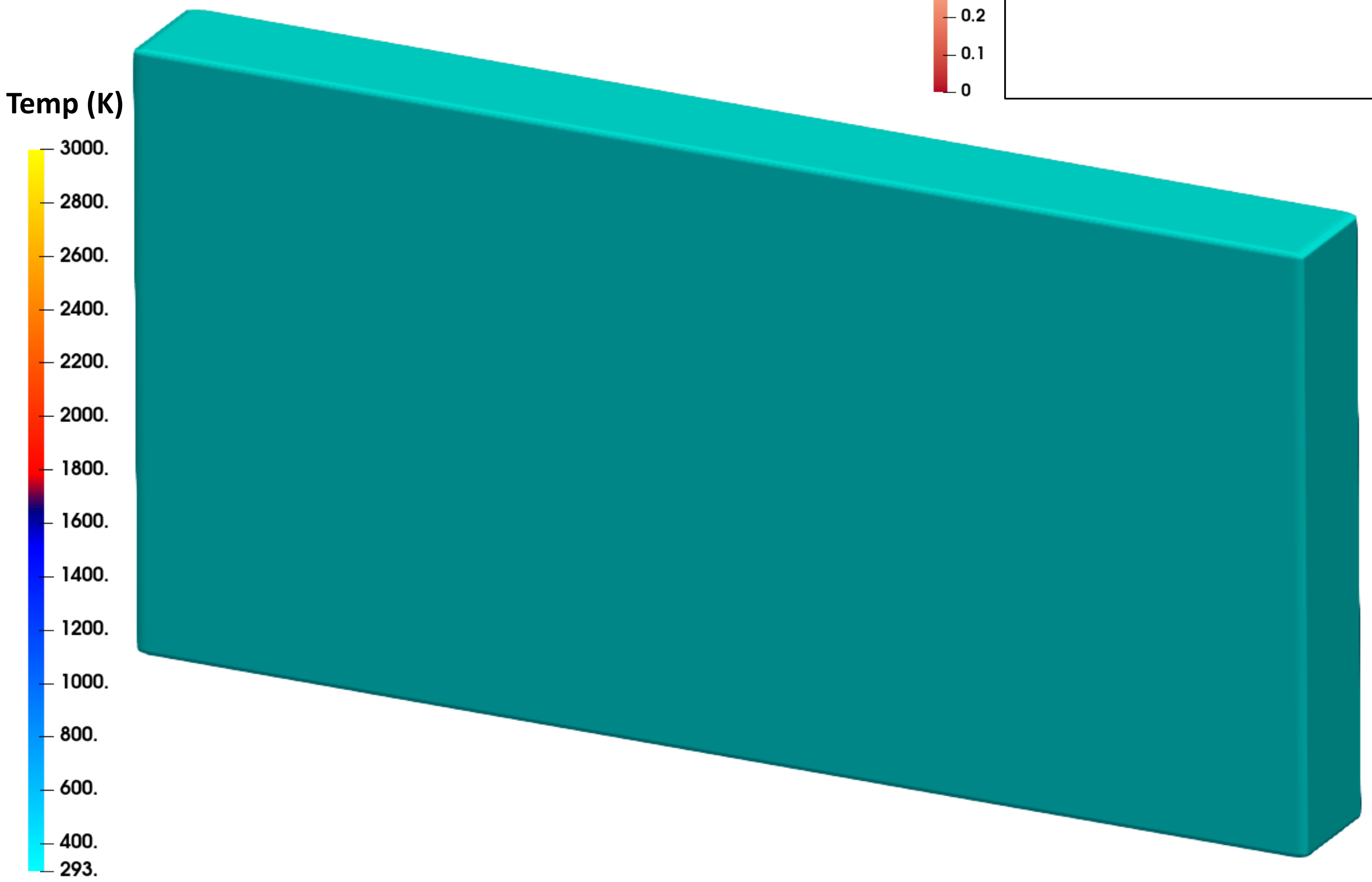


Simulations – FLOW3D

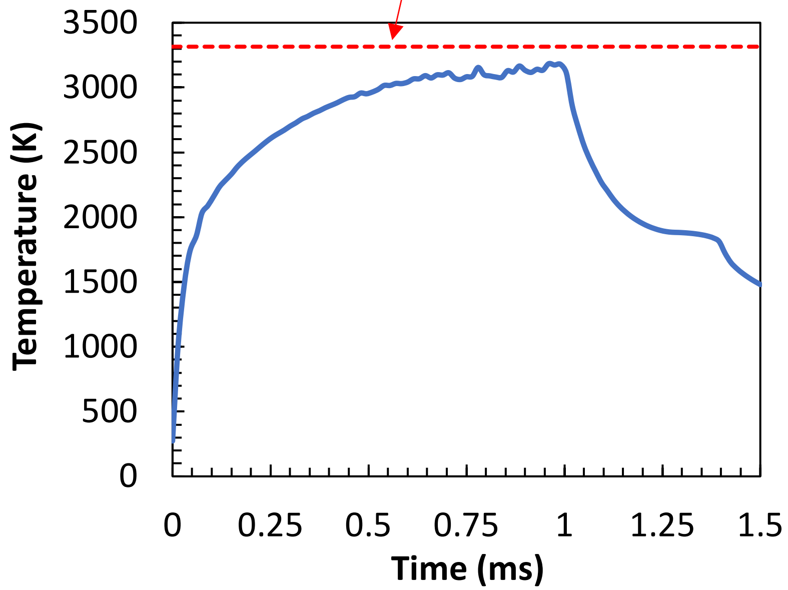
Solid Fraction



Time: 0.00000 **82W**

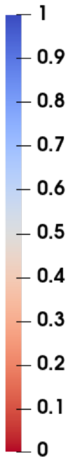


Evap Temperature



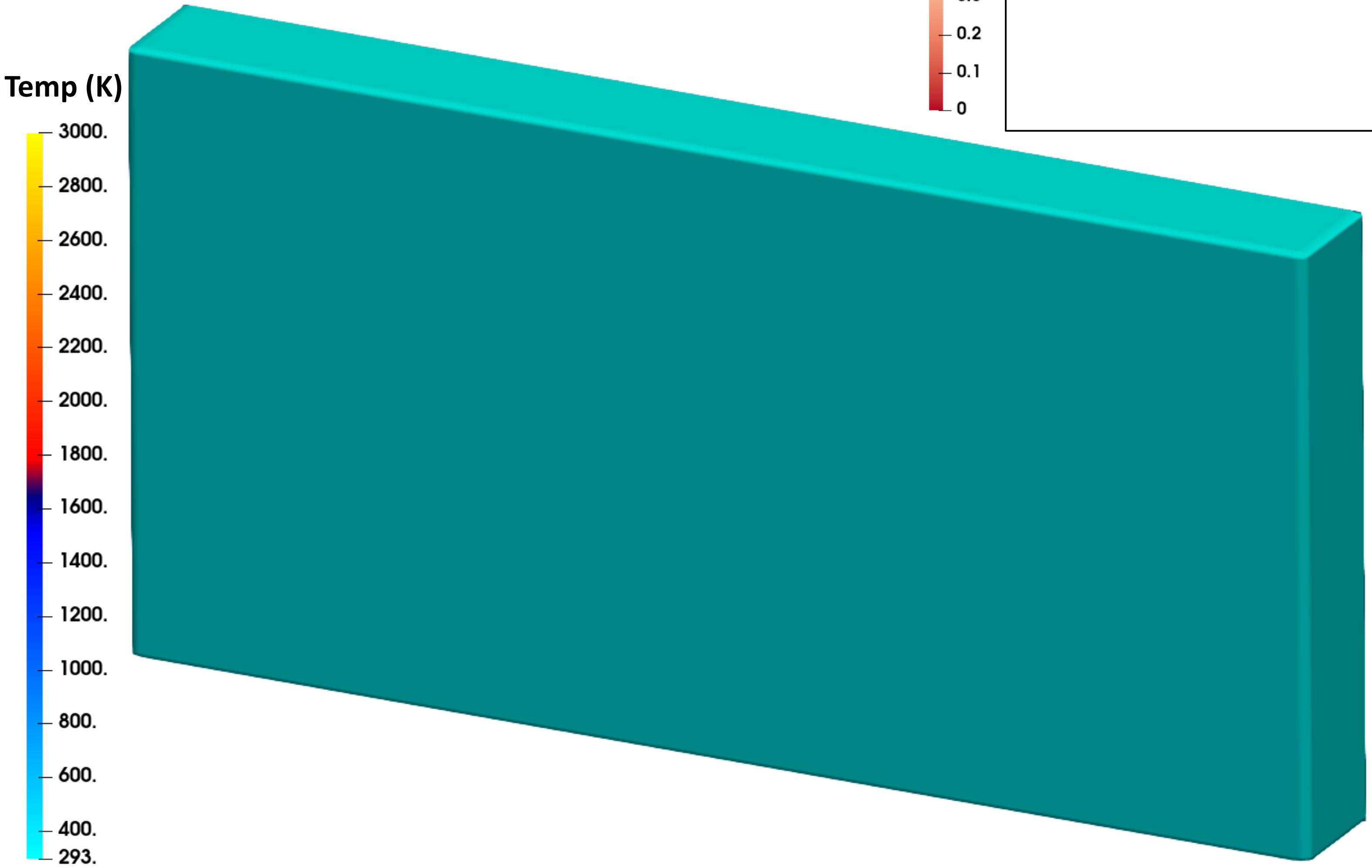
Simulations – FLOW3D

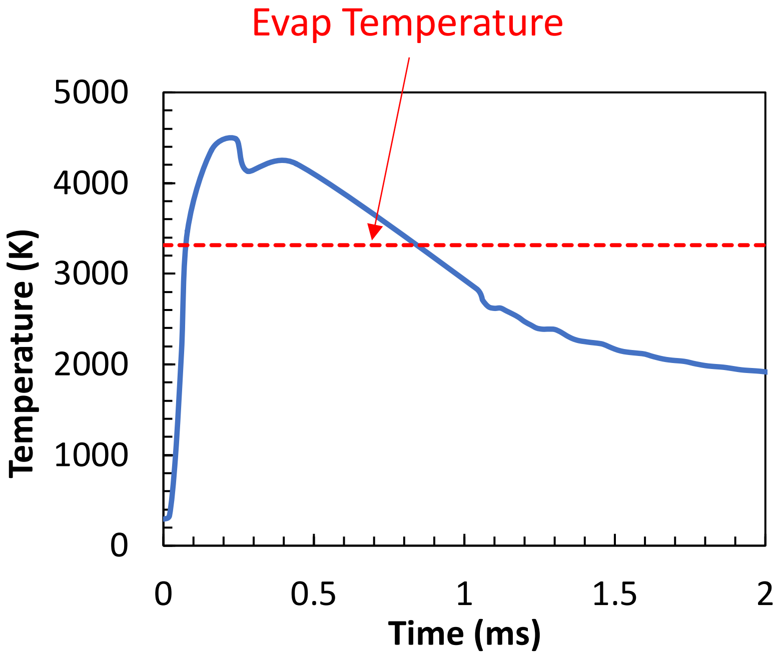
Solid Fraction



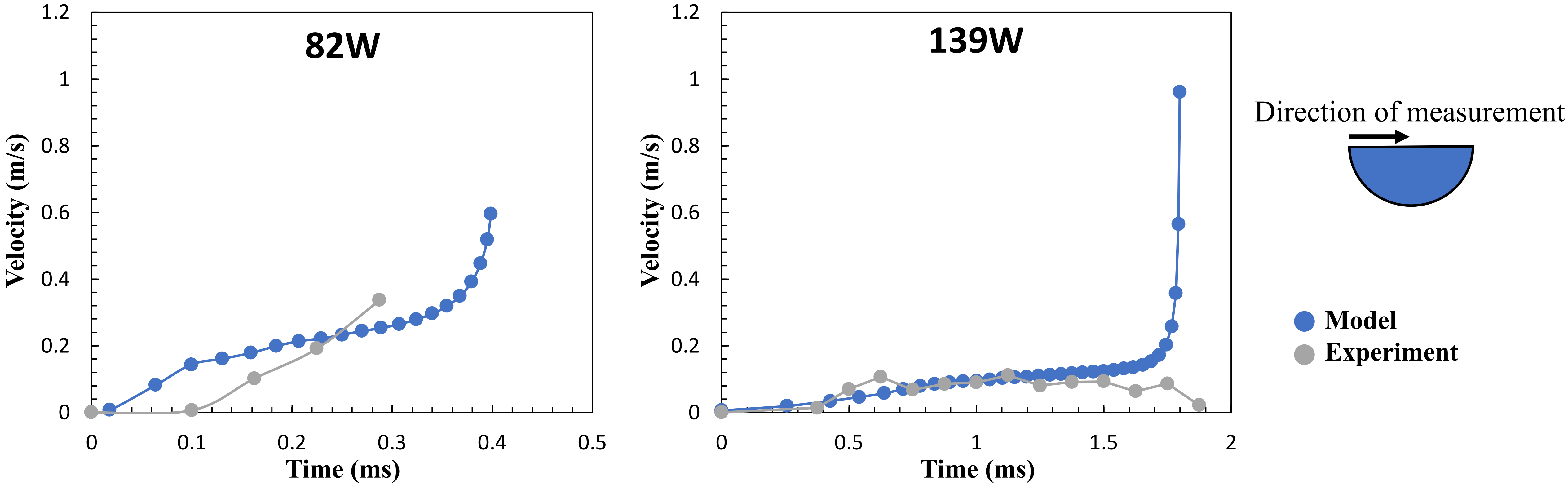
Time: 0.00000 139W

Temp (K)

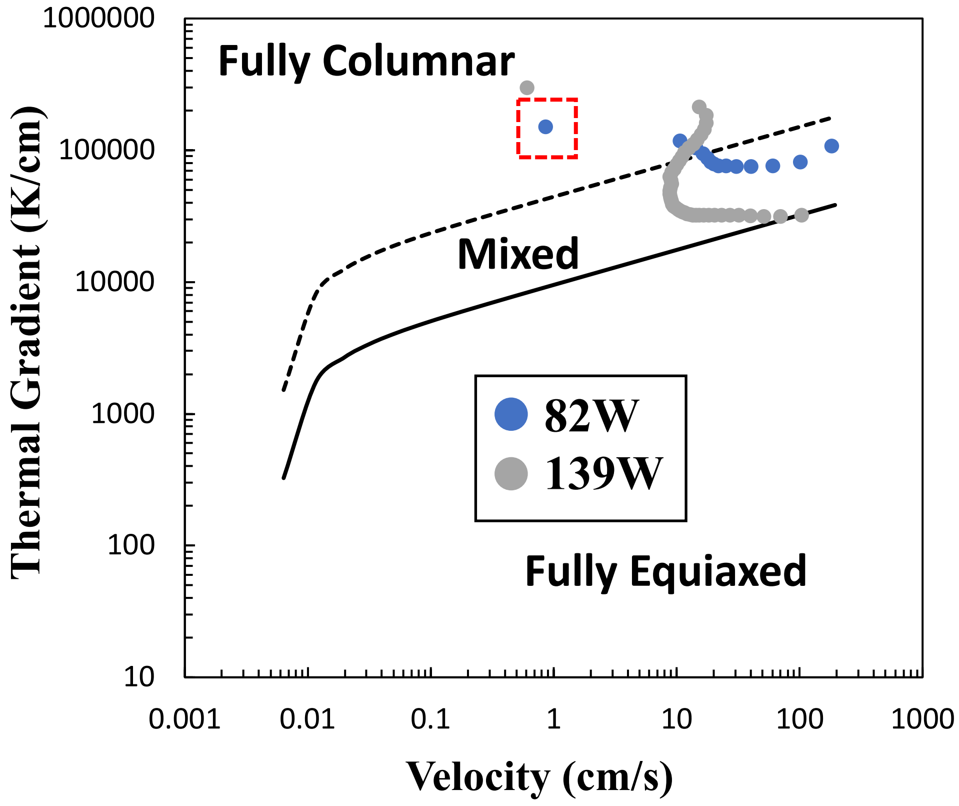


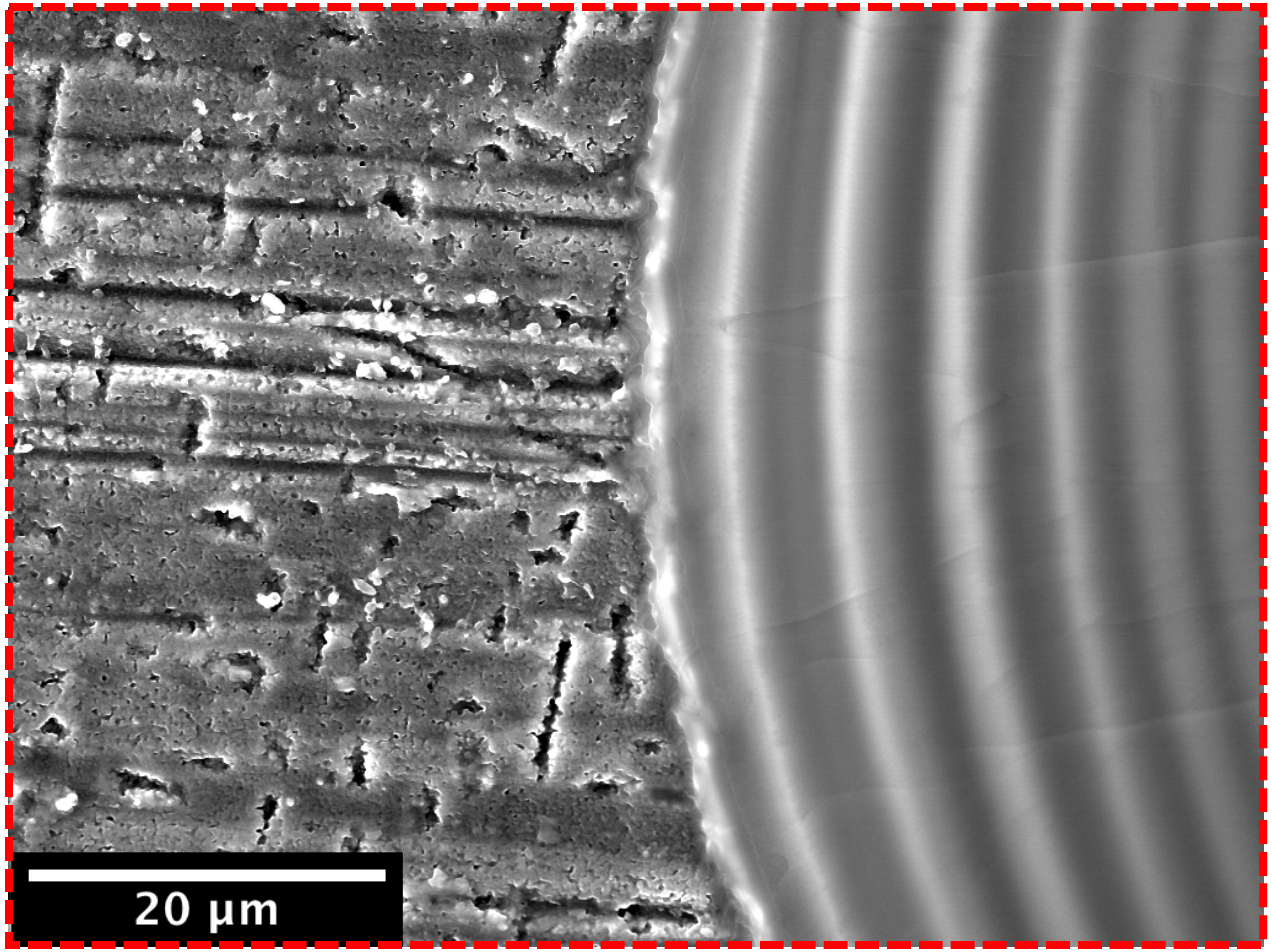


Simulations – FLOW3D

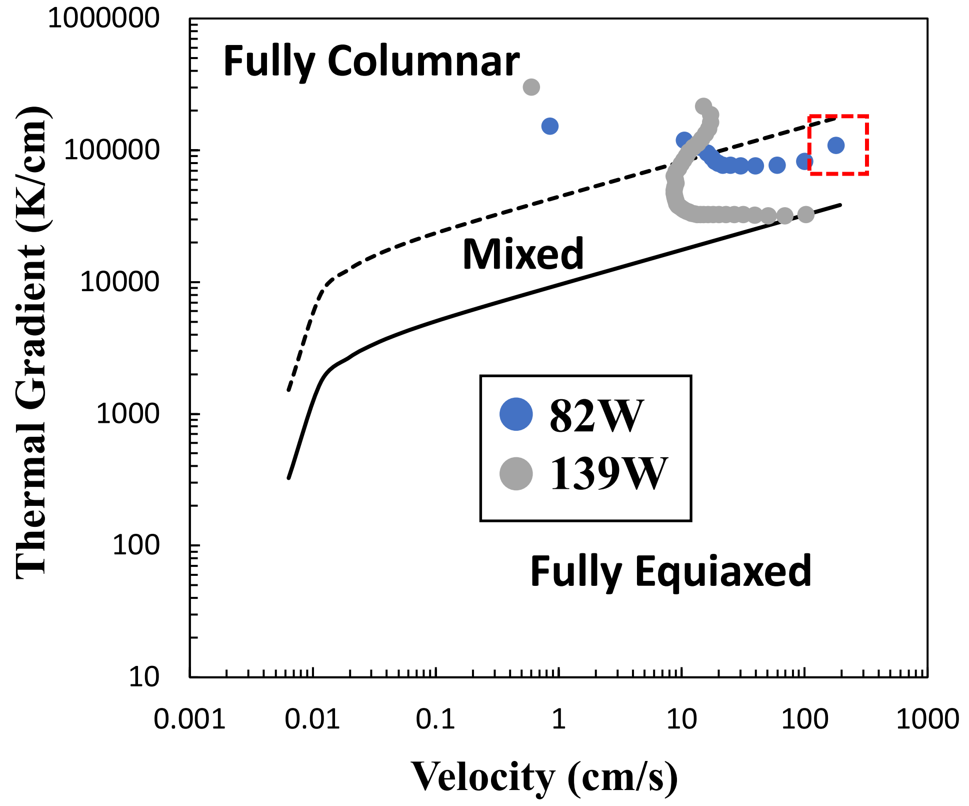


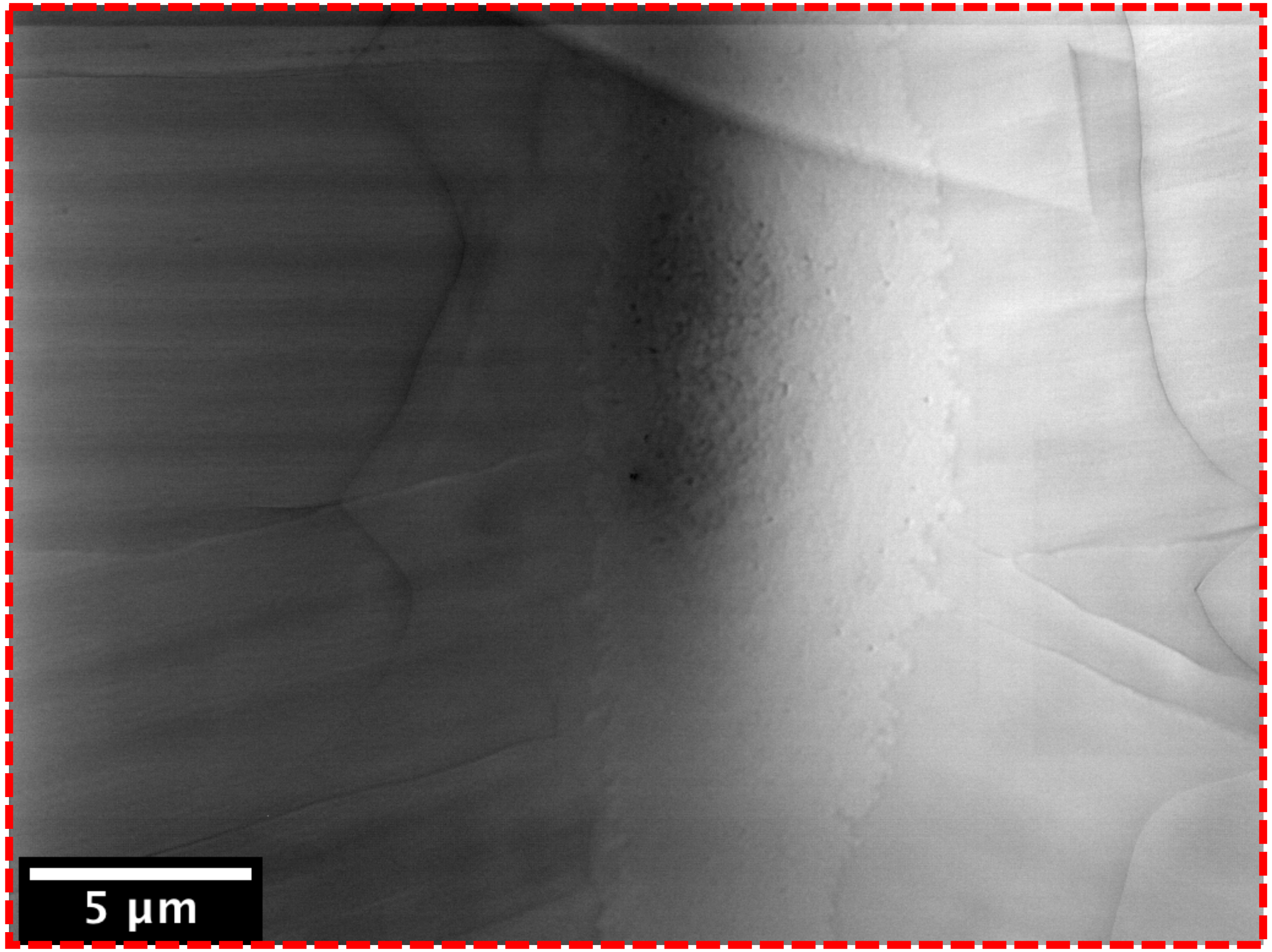
Simulations – FLOW3D



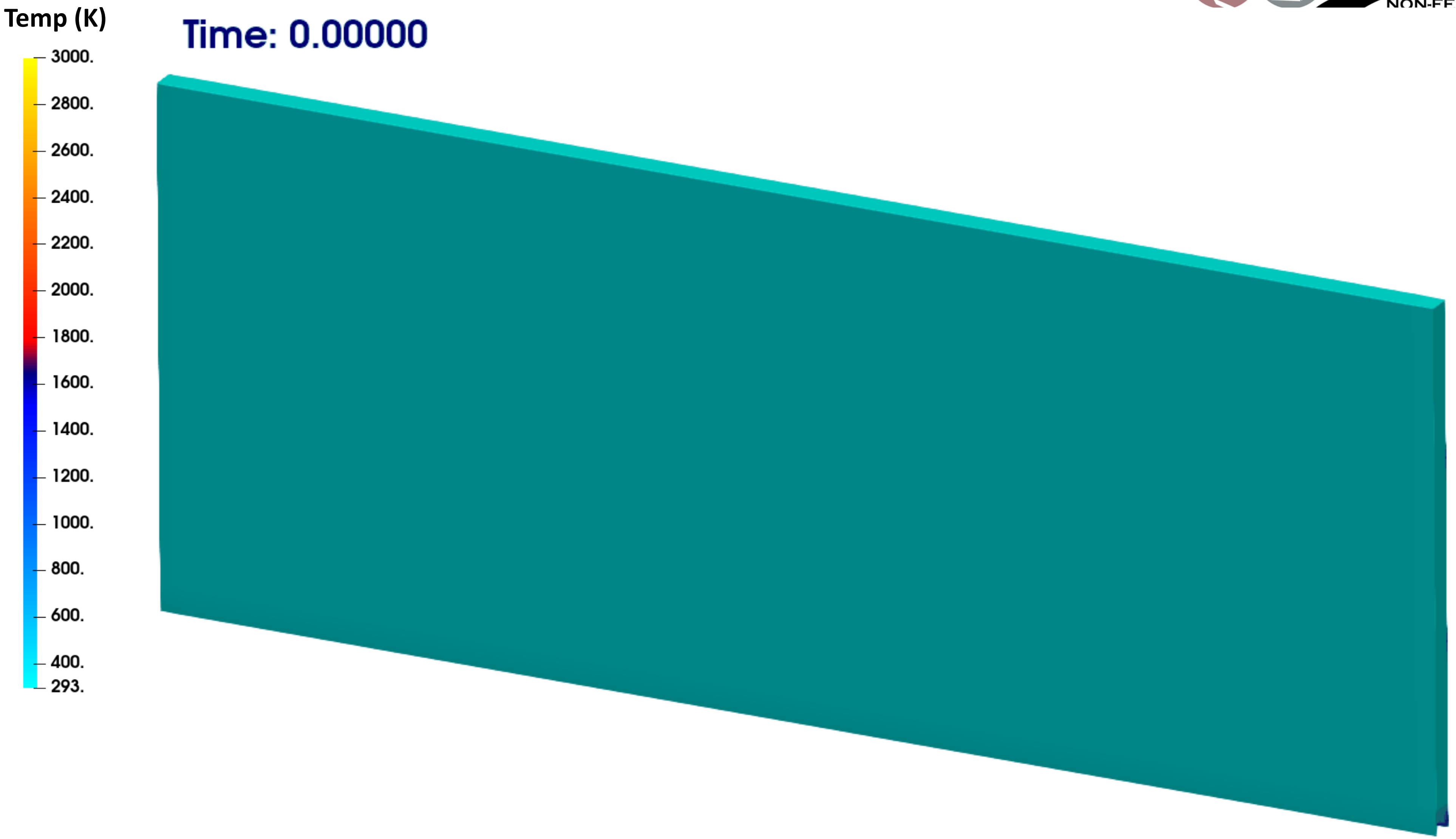


Simulations – FLOW3D

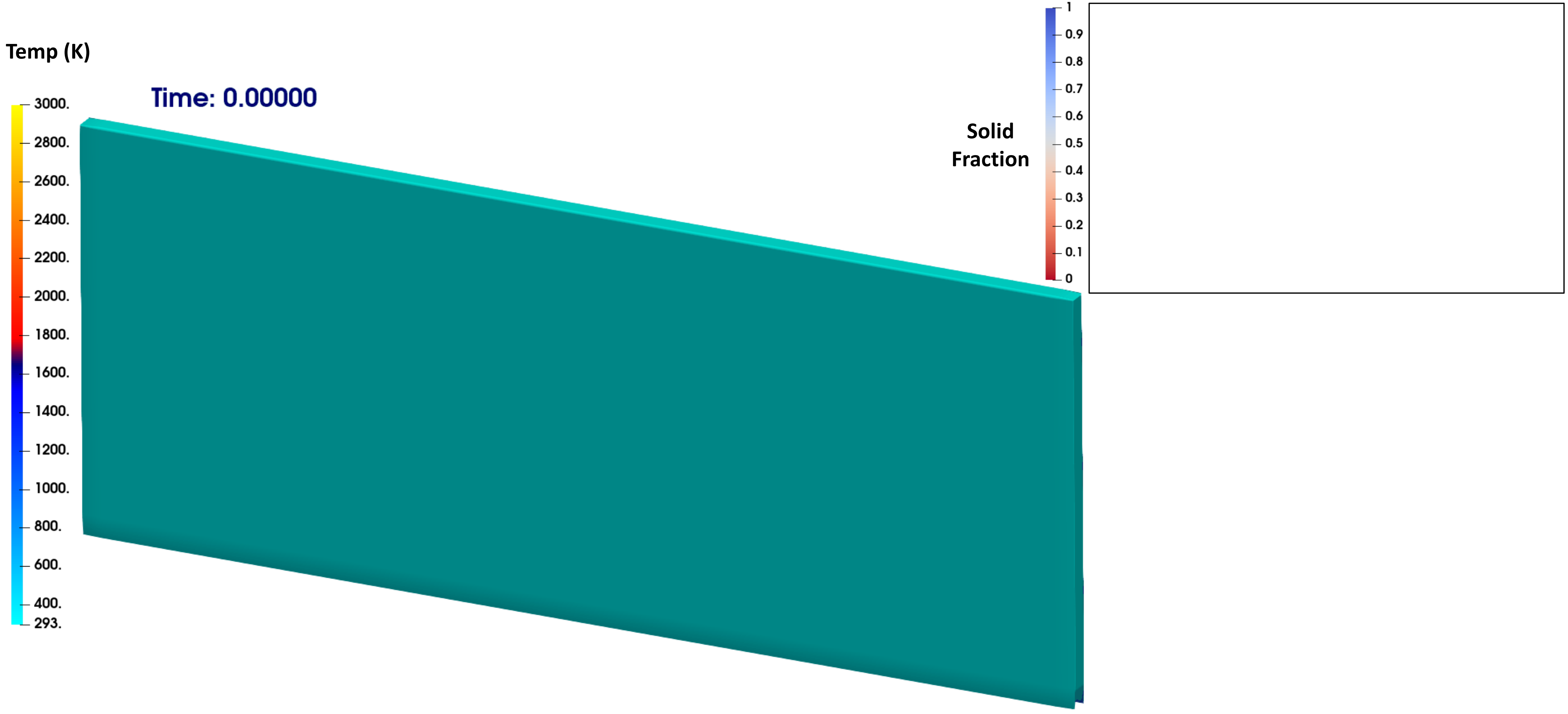




Next Steps: Simulations – FLOW3D



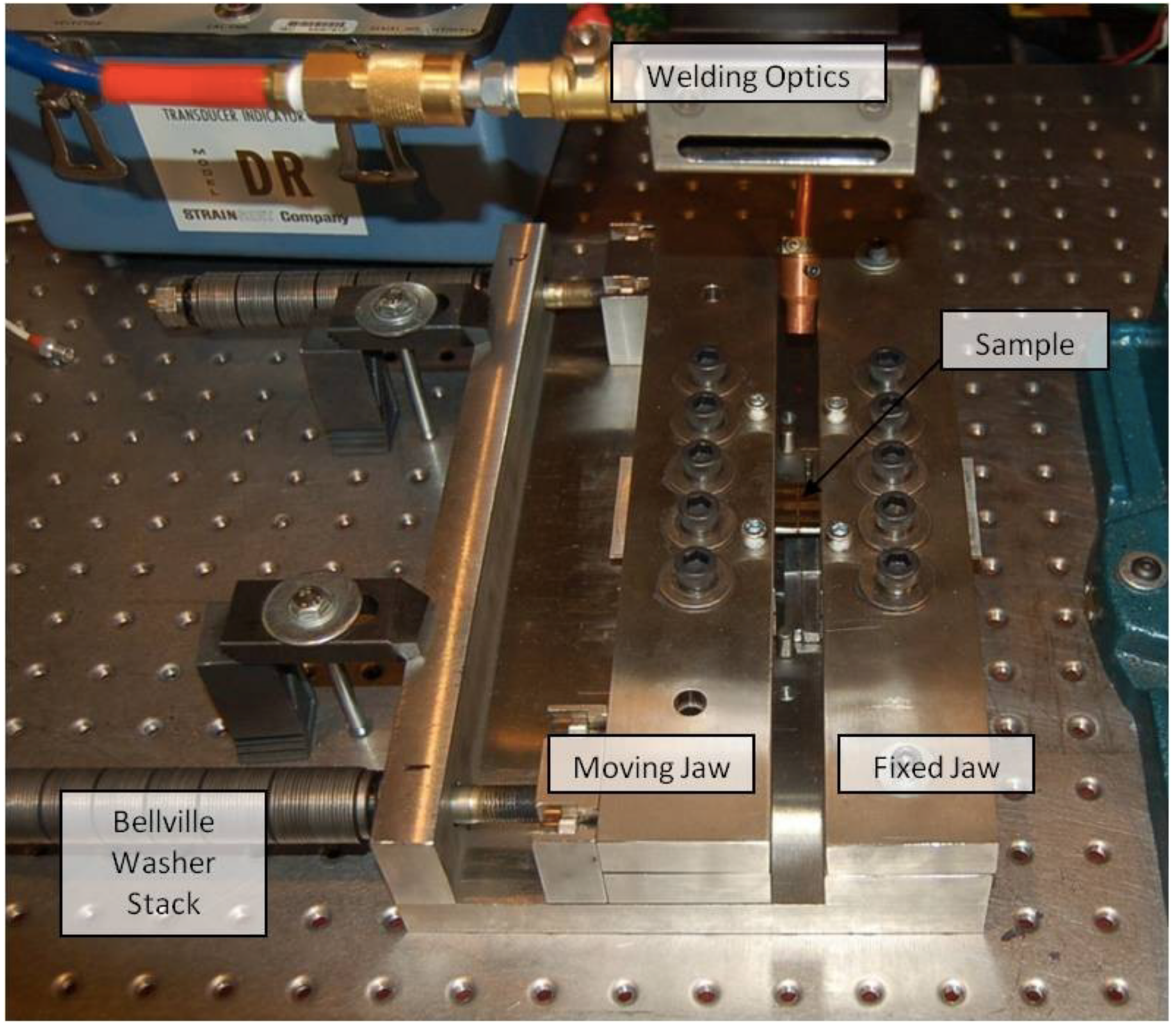
Next Steps: Simulations – FLOW3D



Sigmajig Crack Susceptibility Testing Capability Development

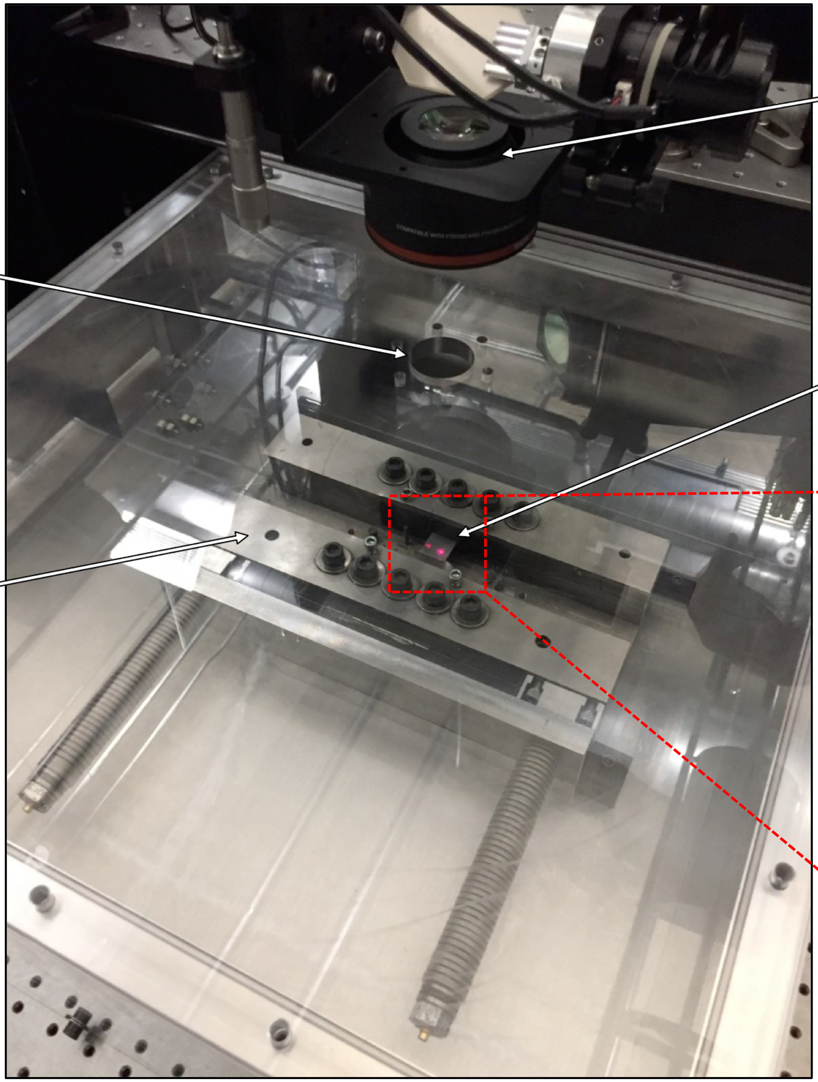
Sigmajig Crack Susceptibility Testing – Capability Development

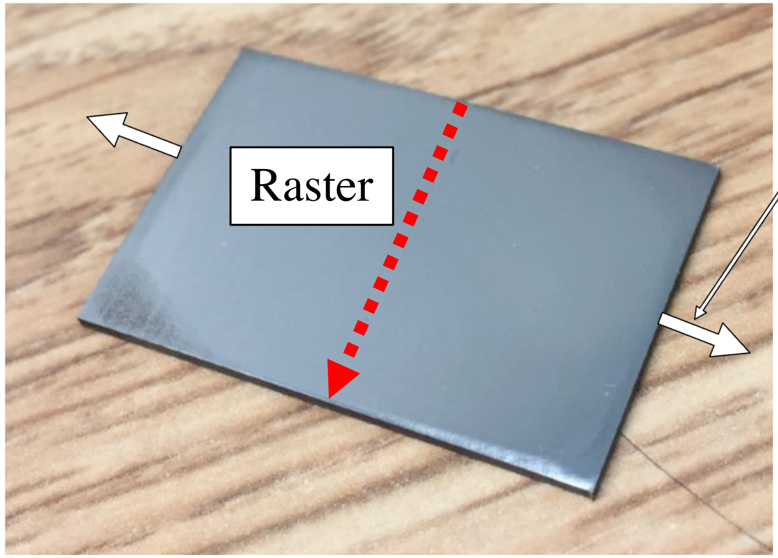
- Sigmajig test originally a weldability test developed by Goodwin
  - Apply tensile stress to sample while running an autogenous weld across the surface
  - Assess cracking behavior
- Modified to turn into an "AM-ability" test
  - Quantify effects of different factors
    - Process parameters
    - Alloy composition
    - Atmosphere
- Designed a chamber to house Sigmajig and simulate L-PBF environment



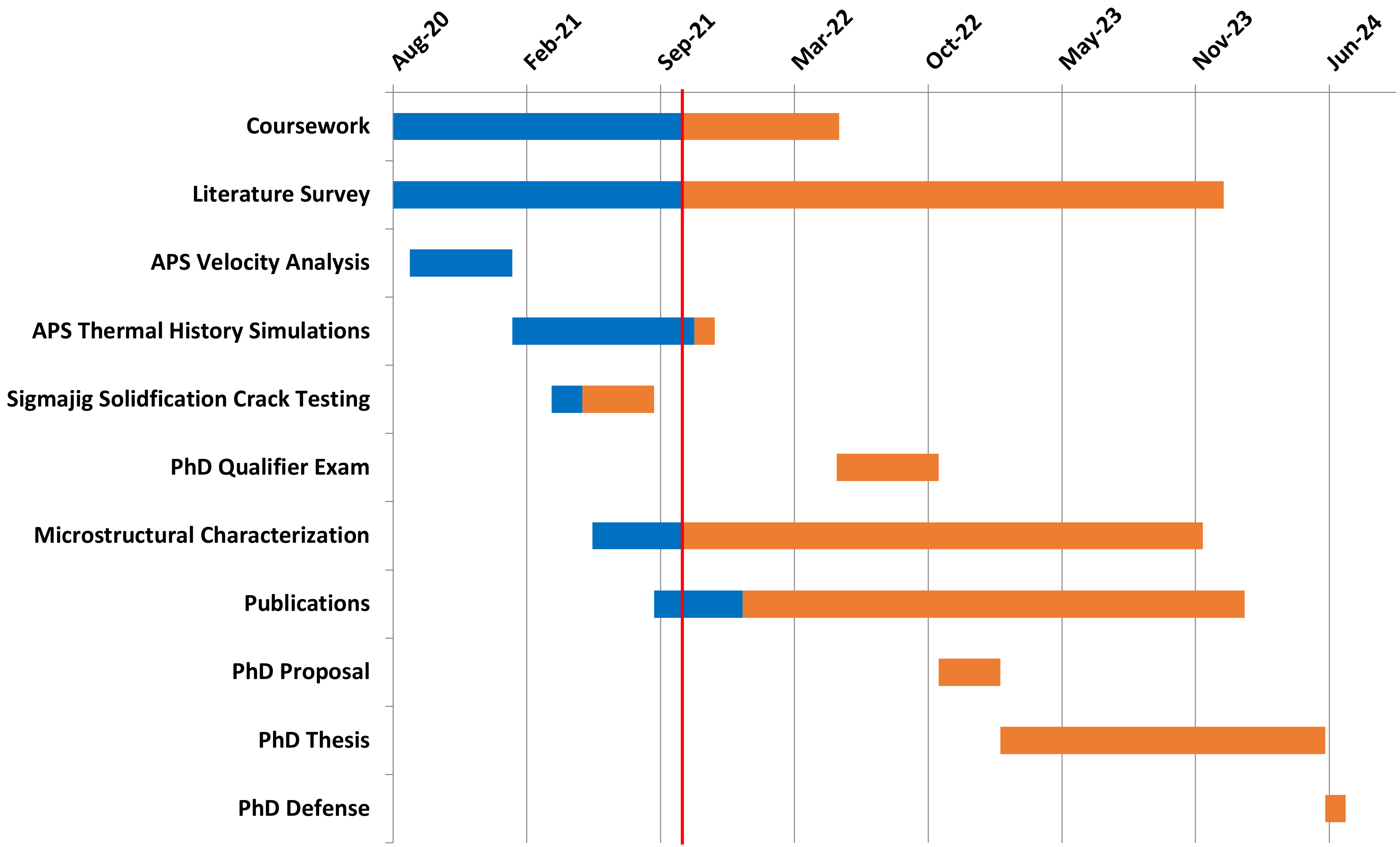
Tate,S., "LASER WELDABILITY OF TYPE 21CR-6NI-9MN STAINLESS STEEL," Ph.D. Thesis, Colorado School of Mines

Sigmajig Crack Susceptibility Testing – Capability Development





Gantt Chart



Aug-20
Feb-21
Sep-21
Mar-22
Oct-22
May-23
Nov-23
Jun-24
Coursework
Literature Survey
APS Velocity Analysis
APS Thermal History Simulations
Sigmajig Solidfication Crack Testing
PhD Qualifier Exam
Microstructural Characterization
Publications
PhD Proposal
PhD Thesis
PhD Defense

Challenges & Opportunities

- Complicated nature of APS AM-simulator experiments (AM in general) require more computationally intensive models to predict representative solidification conditions

- Development of first beta-Ti solidification map published in literature that predicts grain morphology during AM

- Sigmajig test can quantify factors that cause solidification cracking in alloys during AM
  - Also helpful in speeding up alloy design for AM (ie new hot-crack resistant Ni-based superalloys)

Thank you!

Chris Jasien
jasien@mines.edu

References

[1] Plotkowski, A., et al., 2021. A stochastic scan strategy for grain structure control in complex geometries using electron beam powder bed fusion, Additive Manufacturing, Vol. 46.

[2] Kobryn, P.A., Semiatin, S.L., 2003. Microstructure and texture evolution during solidification processing of Ti–6Al–4V. J. Mater. Process. Technol., 135, 330-339

[3] Kurz, W., Giovanola, B., Trivedi, R., 1986. Theory of Microstructural Development during Rapid Solidification, Acta Metall., 34, 823-830.

[4] Goodwin, G.M., 1987. Development of a New Hot-Cracking Test – The Sigmajig, Welding Research Supplement, 33-38.

[5] Tate, S., Laser Weldability Of Type 21Cr-6Ni-9Mn Stainless Steel, Ph.D. Thesis, Colorado School of Mines.