CANFSA

Center for Advanced Non-Ferrous Structural Alloys

An Industry/University Cooperative Research Center

Project 36E-L: In-Situ Characterization of Microstructural Evolution During Simulated Additive Manufacturing in Model Alloys

Spring Meeting

April 7th – 9th 2020

- Student: Brian Rodgers (Mines)
- Faculty: Dr. Amy Clarke (Mines)
- Industrial Mentors: TBD
- Other Participants: Dr. Jonah Klemm-Toole

Office of Naval Research Science & Technology · NSF · Colorado School of Mines · Iowa State University

Project 36E-L: *In-Situ Characterization of Microstructural Evolution During Simulated Additive Manufacturing in Model Alloys*

- Student: Brian Rodgers (Mines)
- Advisor: Amy Clarke (Mines)

Project Duration

PhD: September 2019 to March 2023

- Problem: Aerospace components are difficult to produce conventionally, but the effects of additive manufacturing (AM) on microstructural evolution are not understood enough to replace conventional manufacturing.
- Objective: Develop an understanding of solidification behavior in model alloys under AM conditions by *in-situ* characterization.
- Benefit: Microstructural control for additive manufacturing of aerospace components.

Recent Progress

- *In-situ* experiments at the Advanced Photon Source (APS).
- Analysis of APS *in-situ* radiography.
- Rosenthal-type simulations of experiments at the APS.

Metrics		
Description	**% Complete**	**Status**
1. Literature review	10%	●
2. Analysis of APS beam line data	10%	●
3. Analysis of Dynamic Transmission Electron Microscopy (DTEM) of rapid solidification	0%	●
4. Simulation of experimental conditions	10%	●
5. Complementary *ex-situ* microstructural characterization	0%	●

Industrial Relevance

Enhanced microstructure/properties:

- Control during AM

Applications:

- Turbine components
- Aerospace components

Benefits:

- Faster production time
- Greater geometric flexibility
- Reduced processing cost
- Enhanced performance
- Low volume / lean manufacturing and customization

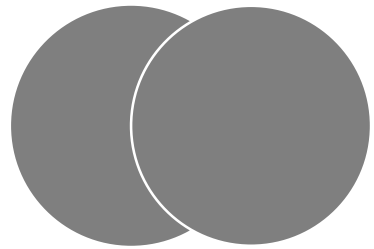
Left photo courtesy of wikimedia, right photo courtesy of NASA

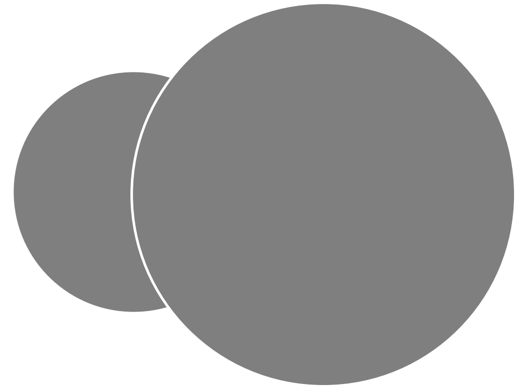
Model Alloys of Choice

- Two alloy systems:
  - Ni-Al-Mo
  - Al-Ag
- Ni-base system consists of two alloys with same equilibrium γ' volume fraction supplied as single crystals
  - R2: Ni-6.6Al-1.9Mo (wt%)
  - R4: Ni-2.8Al-22.2Mo (wt%)
- Al-Ag binary system consists of two different fractions of silver
  - Al-10Ag (wt%)
  - Al-18Ag (wt%)

APS Experiments

- R2 and R4 alloys:
  - Rasters at constant heat input
  - Overlapping spot melts
- Al-Ag system:
  - Rasters and re-rasters for DTEM comparison

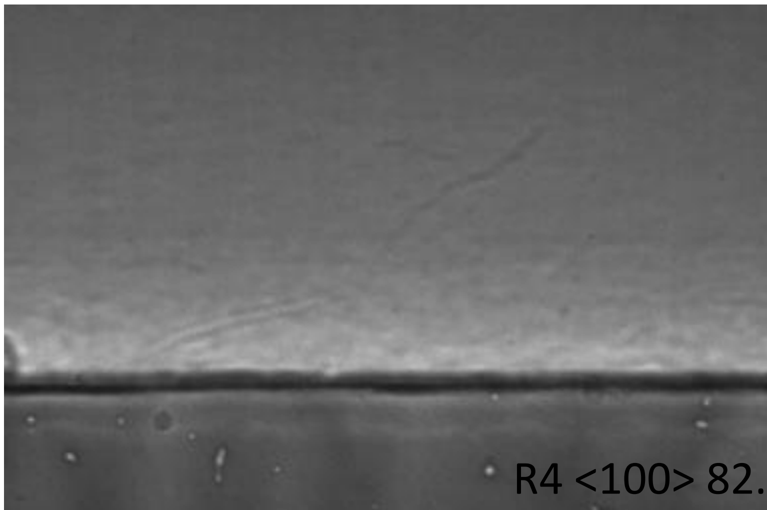




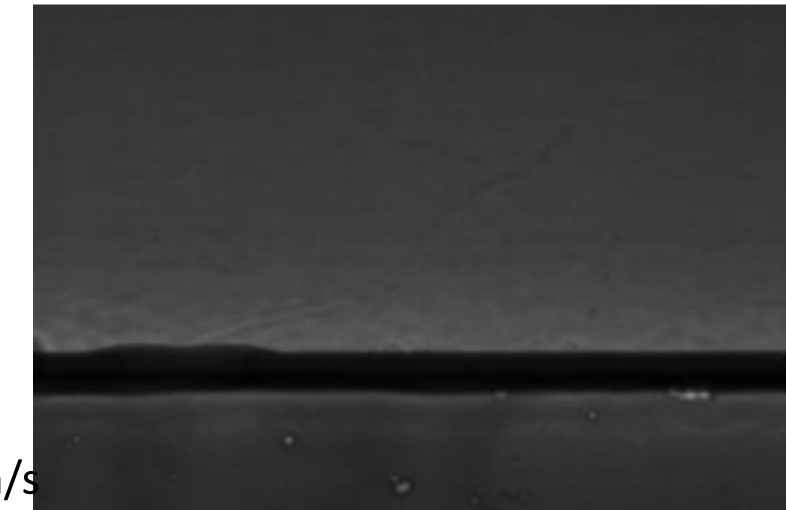
Alloy	Beam power [W]	Raster speed [m/s]	Notes
R2 [110], R2 [111], R4[100], R4 [110]	253.9	1.6	
	139.4	0.5	
	47.8	0.1	
	82.1/82.1	Spot melt	Edge of second pool intersects middle of first
	82.1/253.9	Spot melt	
R2 [110]	517.1	1.6	
	253.9	1	
R4 [100]	517.1	1.6	
	368.3	1.6	
	253.9	Spot melt	
Al-10Ag & Al-18Ag	282.5/282.5	0.1/0.1	Re-rasters with 100% overlap
	368.3/368.3	2/2	
	282.5	0.1	
	368.3	2	

Example Radiography

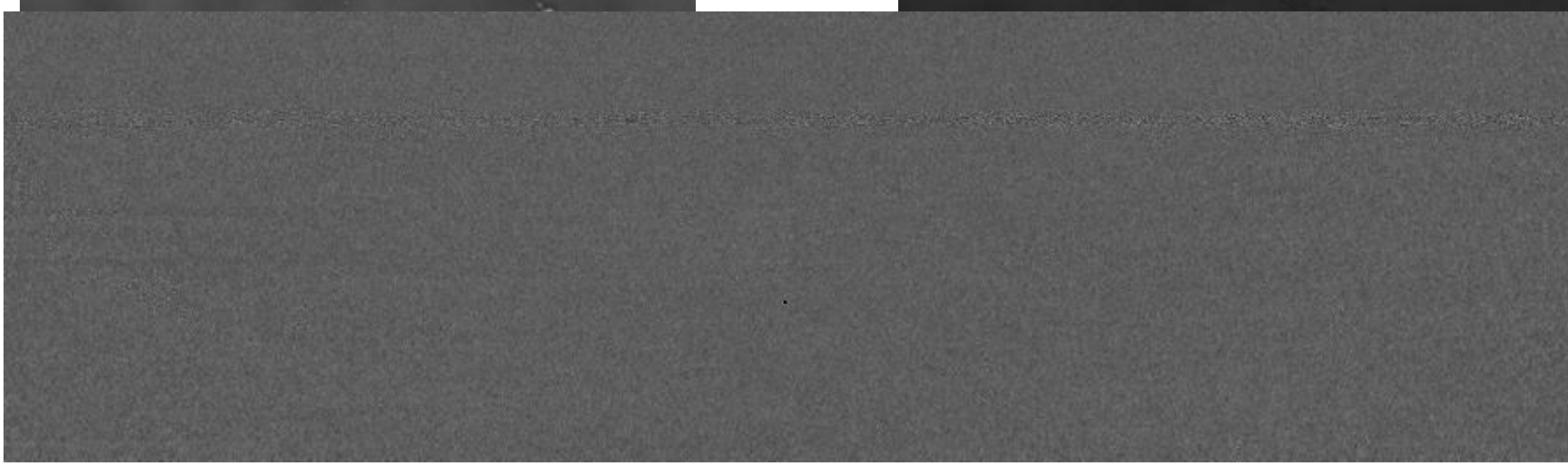
R4 <100> 82.2 W



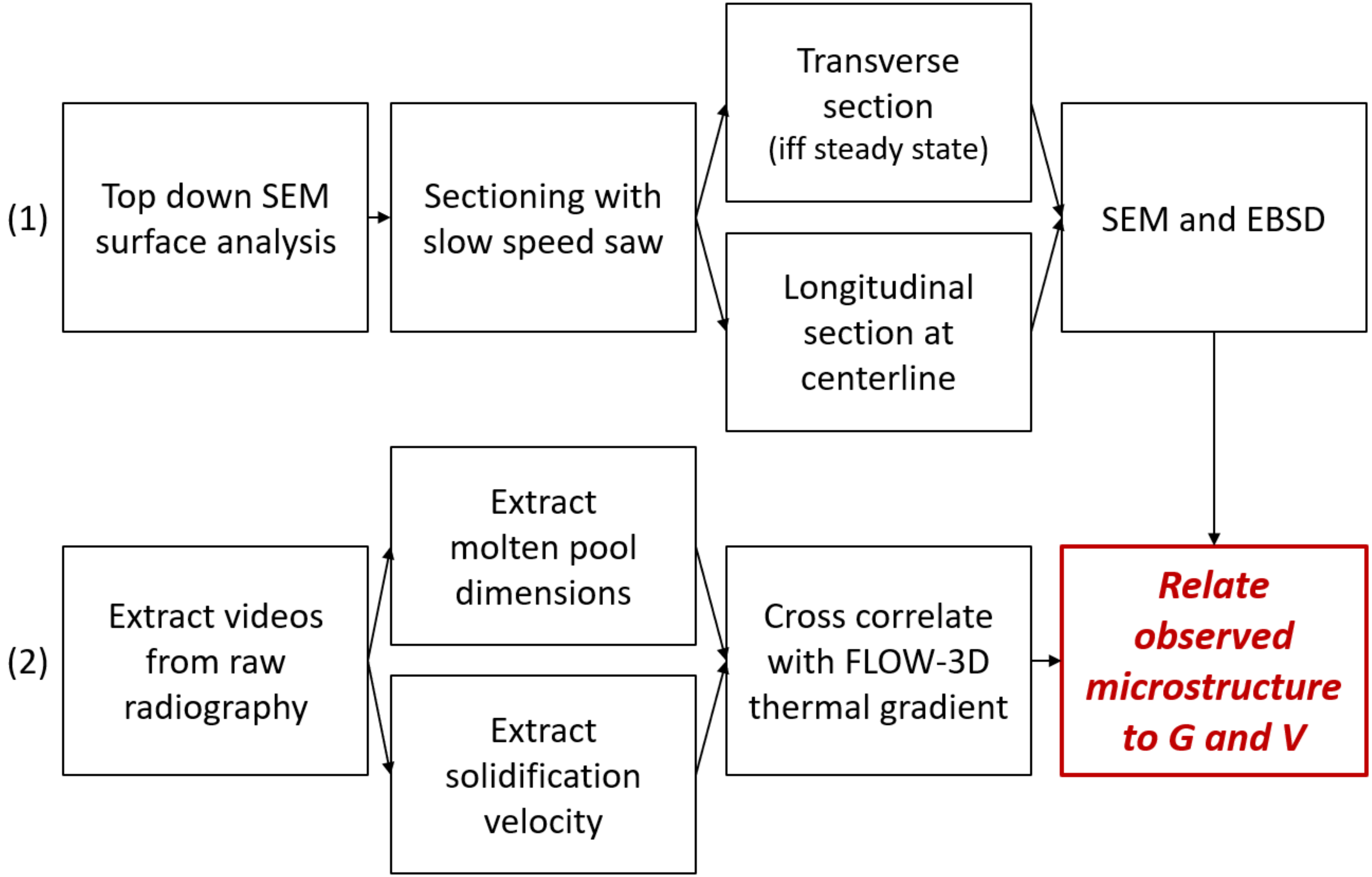
R4 <100> 253.9 W



R4 <100> 82.2 W, 0.1 m/s



Ex-Situ Analysis Plan



MATLAB Simulations

- Program using Rosenthal-type equations to simulate temperature, thermal gradient, cooling rate, and solidification rate
- Filtering logic added to exclude values outside regions of interest and to remove singularity from consideration
- Assumptions include:
  - Point heat source
  - No convection
  - Semi-infinite boundary conditions
  - Steady-state
  - Same thermophysical properties between solid and liquid

Rosenthal Solutions

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Inputs:

- Absorptivity
- Power
- Travel speed
- Thermal conductivity
- Thermal diffusivity

$$T = T_o + \frac{\lambda P}{2\pi k r}\exp\left(-\frac{v(r+x)}{2\alpha}\right)$$

$$\frac{\partial T}{\partial x} = -\frac{\lambda P v}{4\pi k \alpha r}\left[1 + \frac{x}{r} + \frac{2\alpha x}{v r^2}\right]\exp\left(-\frac{v}{2\alpha}(x+r)\right)$$

$$\frac{\partial T}{\partial y} = -\frac{\lambda P v y}{4\pi k \alpha r^2}\left[1 + \frac{2\alpha}{v r}\right]\exp\left(-\frac{v}{2\alpha}(x+r)\right)$$

$$\frac{\partial T}{\partial t} = \frac{\lambda P v^2}{4\pi k \alpha r}\left[1 + \frac{x}{r} + \frac{2\alpha x}{v r^2}\right]\exp\left(-\frac{v}{2\alpha}(x+r)\right)$$

$$R_\theta = \frac{\partial T / \partial t}{\sqrt{\left(\partial T / \partial x \cos(\theta)\right)^2 + \left(\partial T / \partial y \sin(\theta)\right)^2}}$$

Outputs:

- Temperature
- Thermal gradient
- Cooling rate
- Solidification velocity

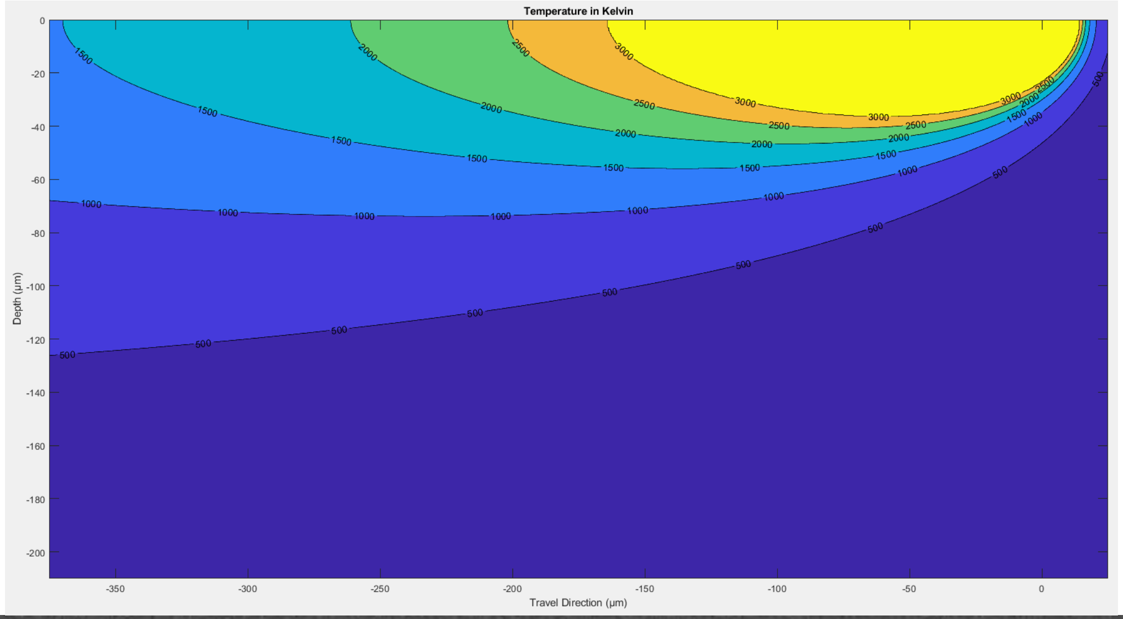
P. Promoppatum et. al., Engineering

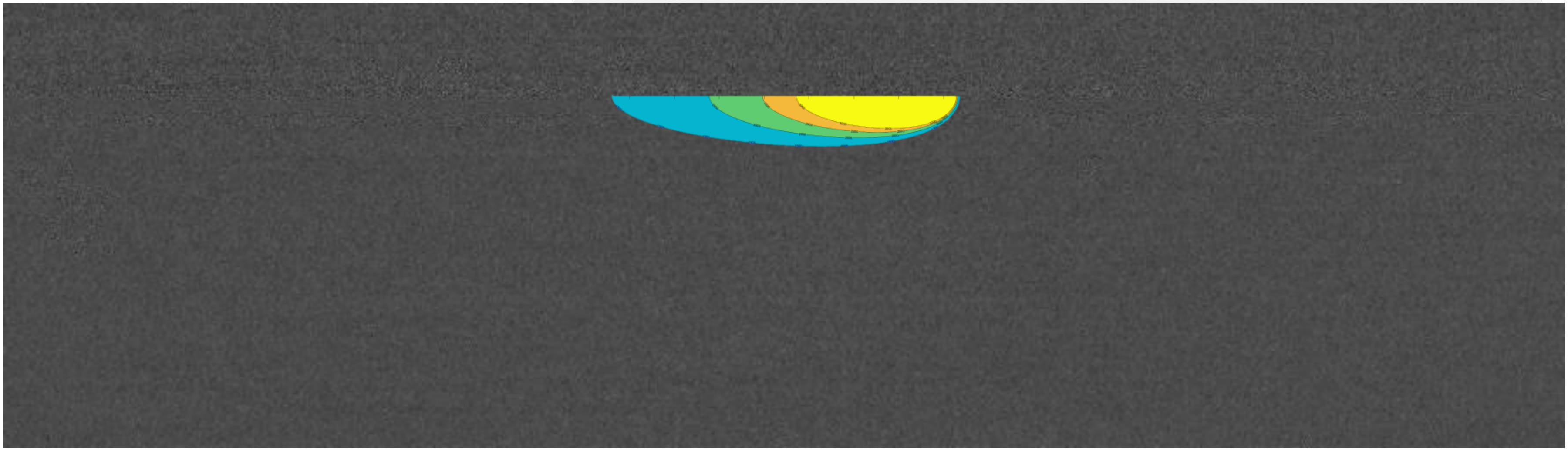
Real-Simulated Comparison

- Absorptivity adjusted so real and simulated pool depth matches
- Real and simulated pool lengths tend to differ, most egregious cases due to keyholing or non-steady-state behavior
- Ni rasters remain in conduction mode, but some do not appear to be fully steady-state
- Al-Ag melt pools seemingly steady-state conduction mode towards start then abruptly transition to keyhole mode

Closely Matched R4 Raster

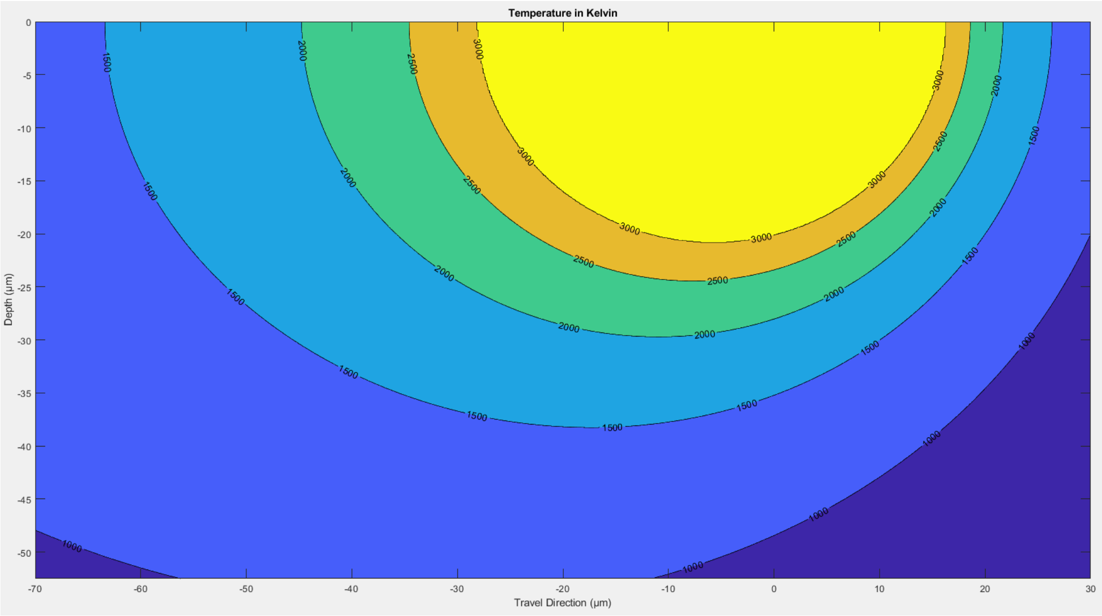
- 139.4 W, 0.5 m/s
- <100> orientation

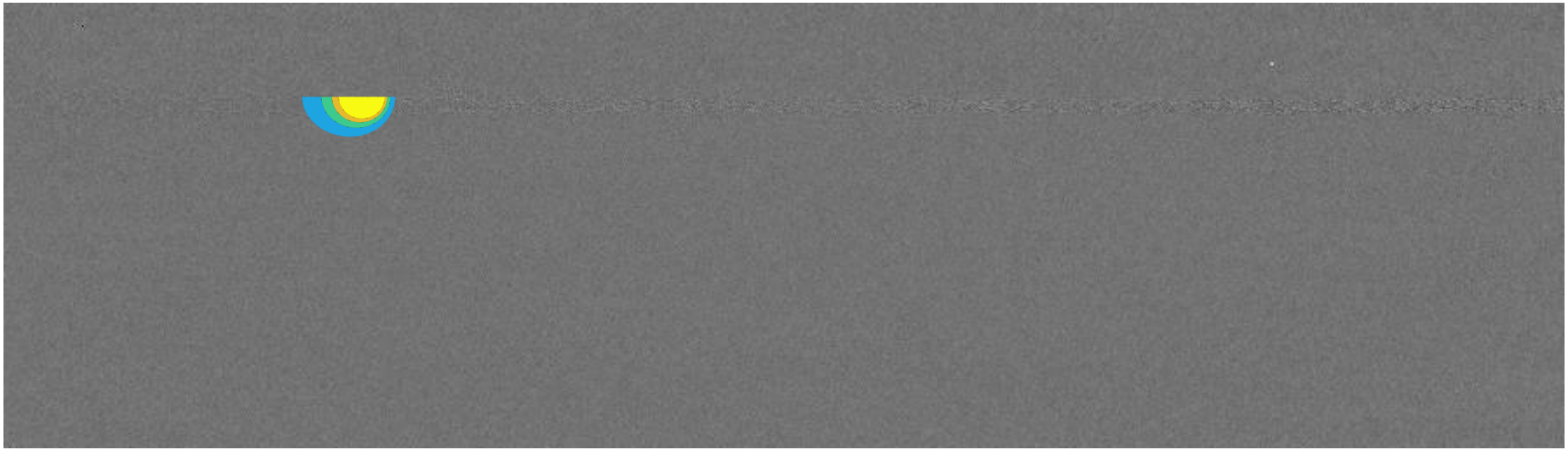




Underestimated R2 Raster

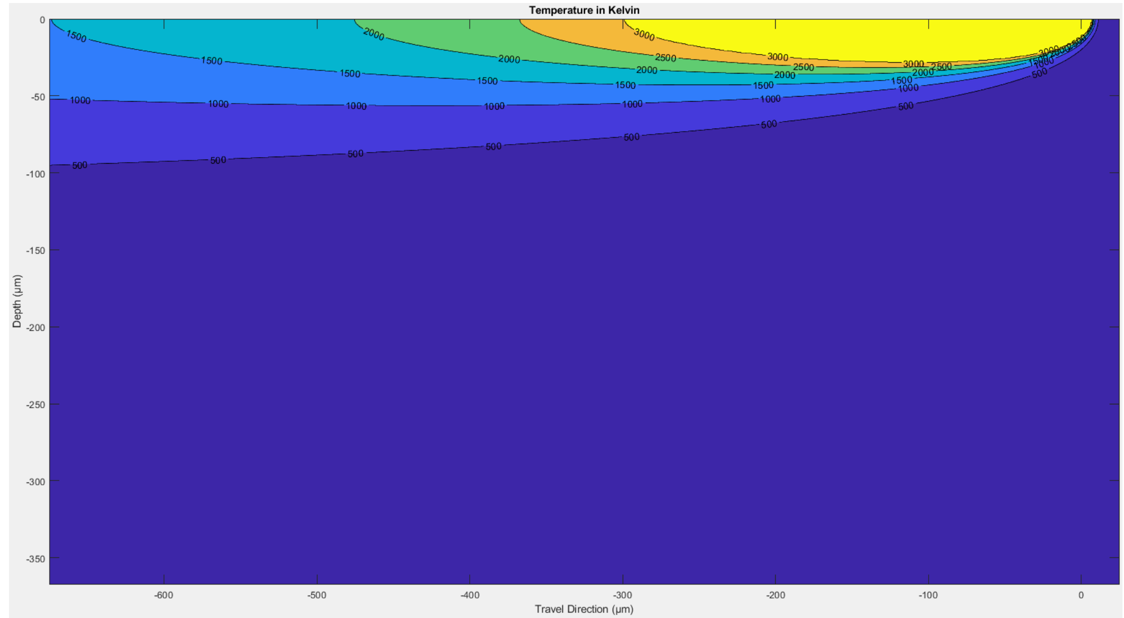
- 47.8 W, 0.1 m/s
- <111> orientation

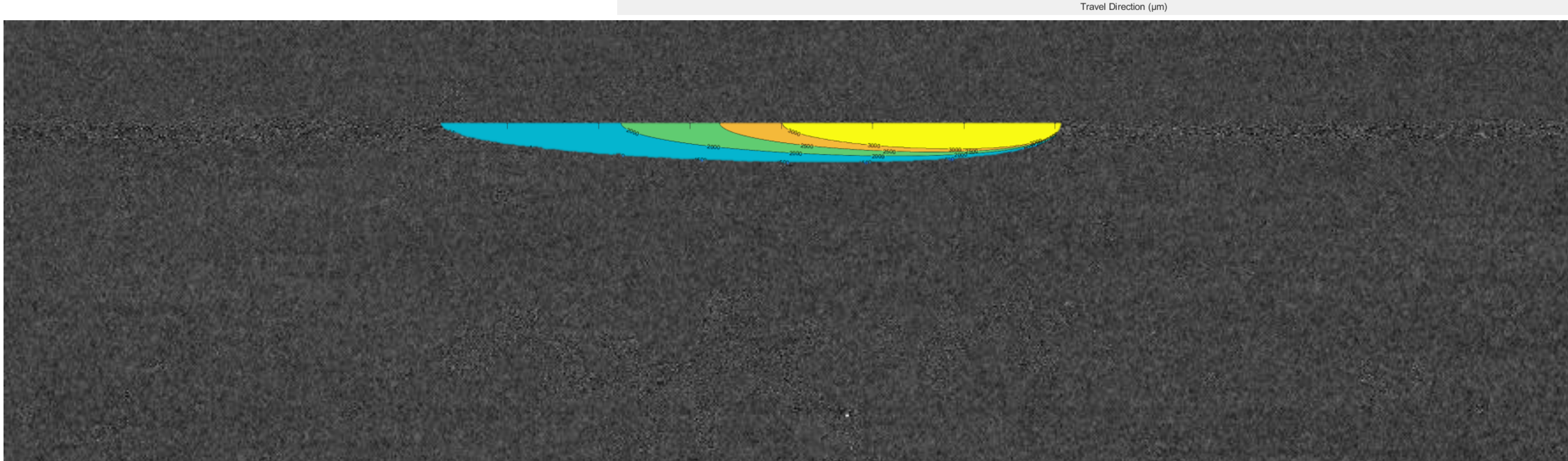




Overestimated R4 Raster

- 253.9 W, 1.6 m/s
- <100> orientation





Non-Steady-State Sample

- R2 <100>, 517 W, 1.6 m/s
- Highest power used, later samples all use lower power

Nickel Raster Conclusions

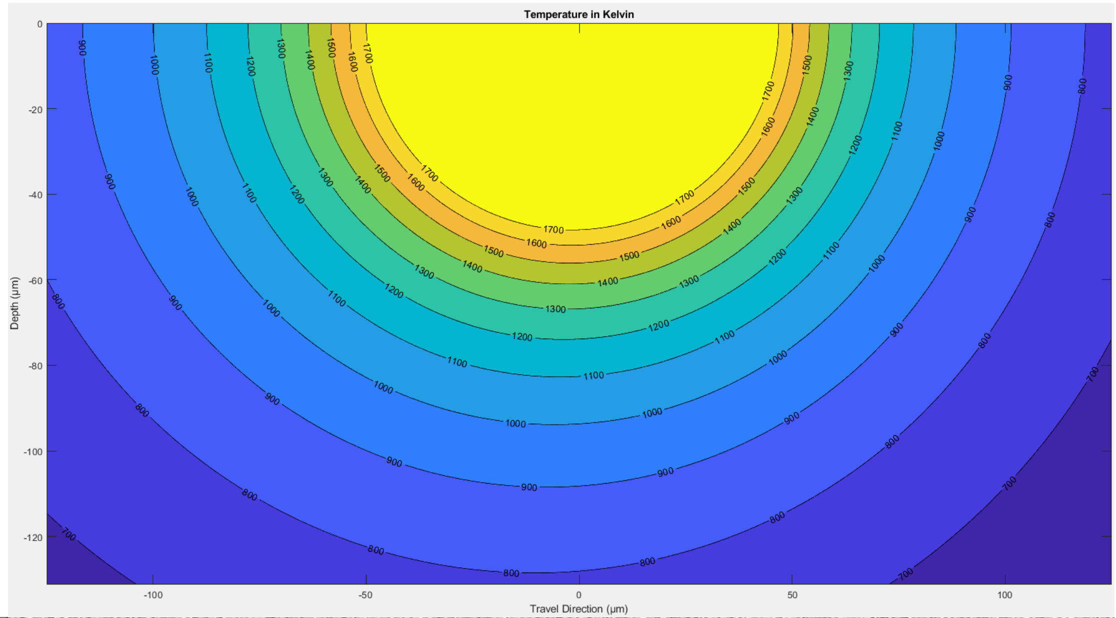
- Simulation underestimates slow rasters and overestimates fast rasters
- Keyholing invalidates model
  - Pool shape mismatches
  - Increase in absorptivity not accounted for

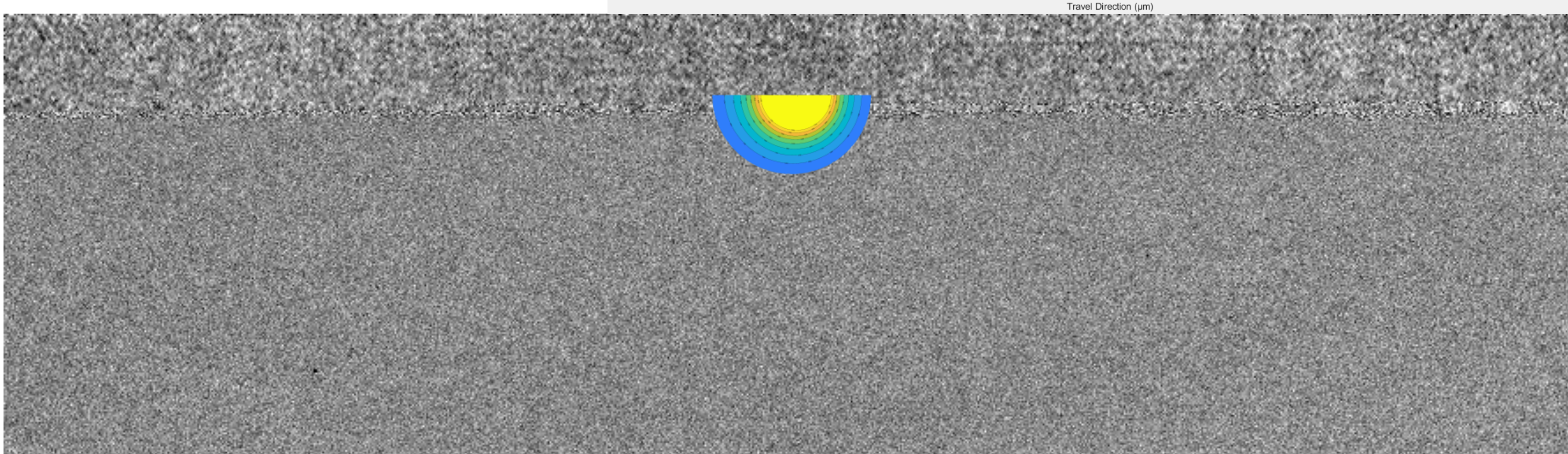
Al-Ag Only Underestimated

- Real-simulated comparison done only for steady-state region before onset of keyholing
- Consistent underestimation likely caused by thermal soaking
- Thermal soaking also explains the transition from conduction to keyhole
- Pools also steadily grow during raster

Al-10Ag Closer Matching Raster

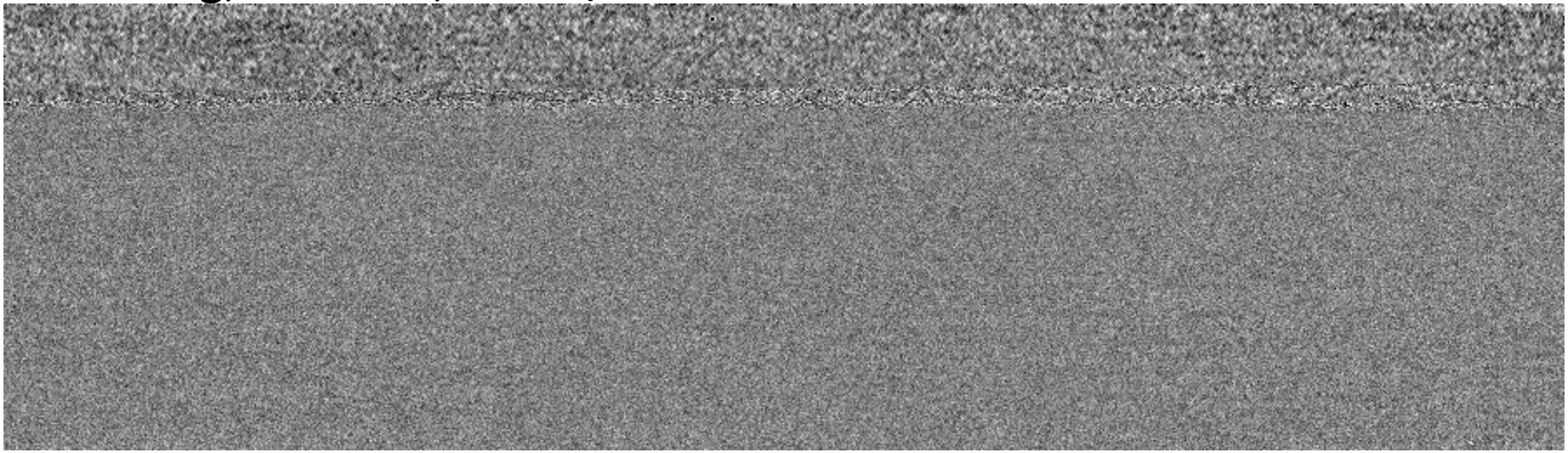
- 282.5 W, 0.1 m/s

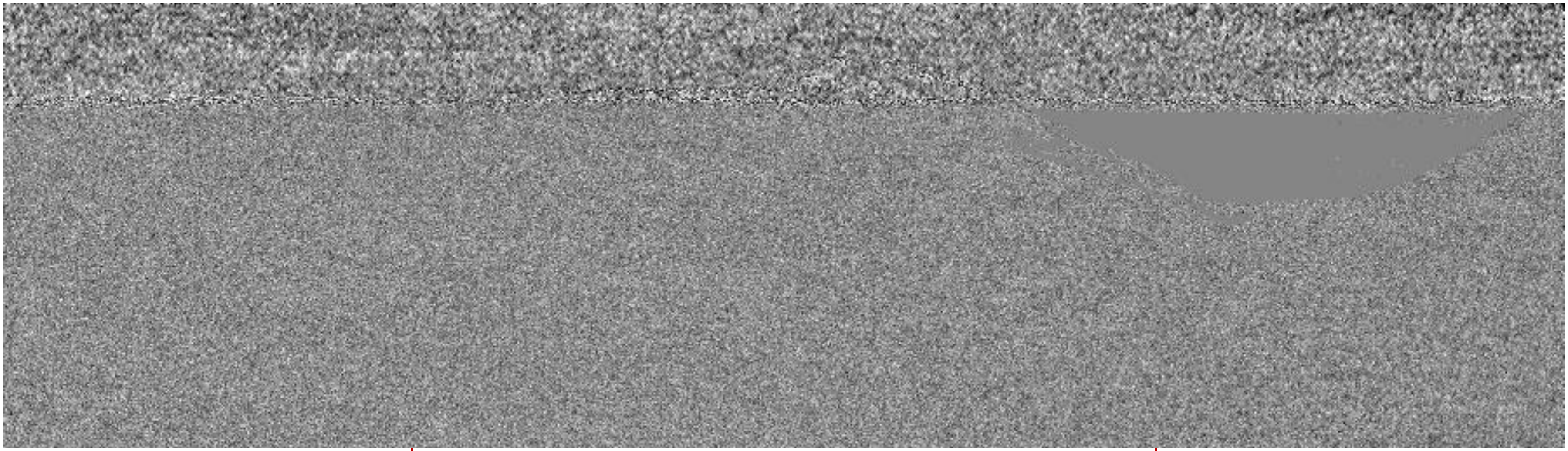




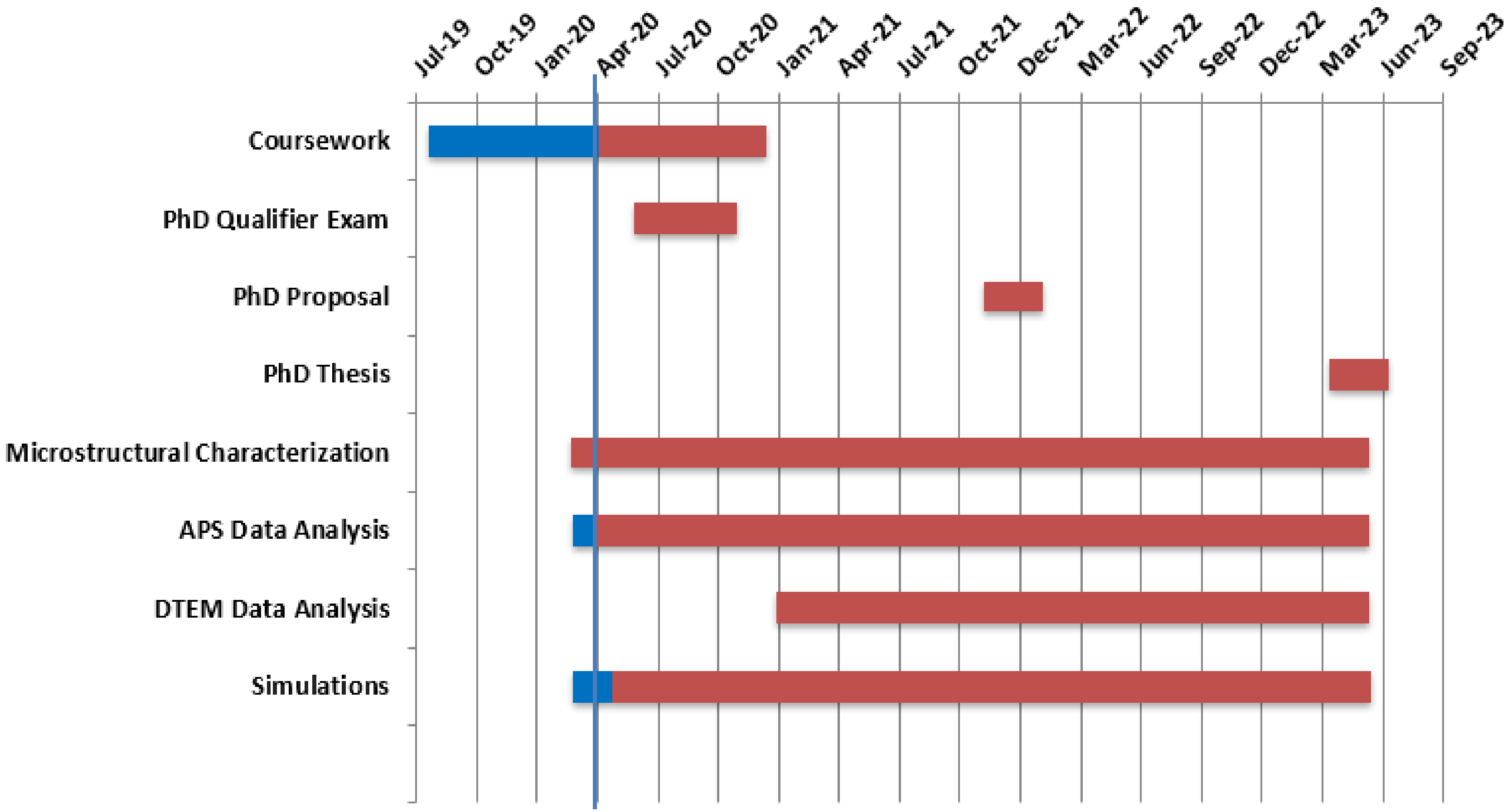
Re-Raster with Interesting Keyhole Behavior

- Al-10Ag, 282.5 W, 0.1 m/s





Progress



Jul-19
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Jan-21
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Oct-21
Dec-21
Mar-22
Jun-22
Sep-22
Dec-22
Mar-23
Jun-23
Sep-23
Coursework
PhD Qualifier Exam
PhD Proposal
PhD Thesis
Microstructural Characterization
APS Data Analysis
DTEM Data Analysis
Simulations

Challenges & Opportunities

- Analysis of *in-situ* APS data
  - Tracking solid-liquid interface velocity manually is slow
  - Ongoing discussion about potential for automation

- More sophisticated simulations
  - Application of FLOW-3D to account for additional effects

- Microstructural analysis
  - Sample preparation

Thank you!

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References

[1] P. Promoppatum, S.-C. Yao, P.C. Pistorius, A.D. Rollett, A Comprehensive Comparison of the Analytical and Numerical Prediction of the Thermal History and Solidification Microstructure of Inconel 718 Products Made by Laser Powder-Bed Fusion, Engineering. 3 (2017) 685–694. doi:10.1016/j.eng.2017.05.023.