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

Project 30-L: Mechanisms of Grain Refinement in Laser Powder Bed Fusion of In-Situ Metal Matrix Composite 6061 Aluminum Alloys

Summer 2020 Videoconference

June 29 – July 1, July 8 – 10 2020

Student: Chloe Johnson (Mines)

Faculty: Amy Clarke (Mines)

Industrial Mentors: Paul Wilson (Boeing), Clarissa Yablinsky (LANL), John Carpenter (LANL), Jeremy Iten (Elementum 3D)

Other Participants: Joe McKeown (LLNL), Jonah Klemm-Toole (Mines)

Project 30: Mechanisms of Grain Refinement in Laser Powder Bed Fusion of In-Situ Metal Matrix Composite 6061 Aluminum Alloys

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- Student: Chloe Johnson (Mines)
- Advisor(s): Amy Clarke (Mines)

Project Duration

PhD: August 2017 to May 2021

- Problem: While inoculation presents a method to eliminate hot tearing and columnar growth in additive manufacturing (AM) of aluminum alloys, the mechanisms of grain refinement under rapid solidification conditions are not well understood.
- Objective: Understand how solidification conditions, solute content, and nucleant site density affect mechanisms controlling grain refinement in inoculated alloys in AM.
- Benefit: Inform alloy design and grain size prediction for inoculated alloys used in AM solidification conditions.

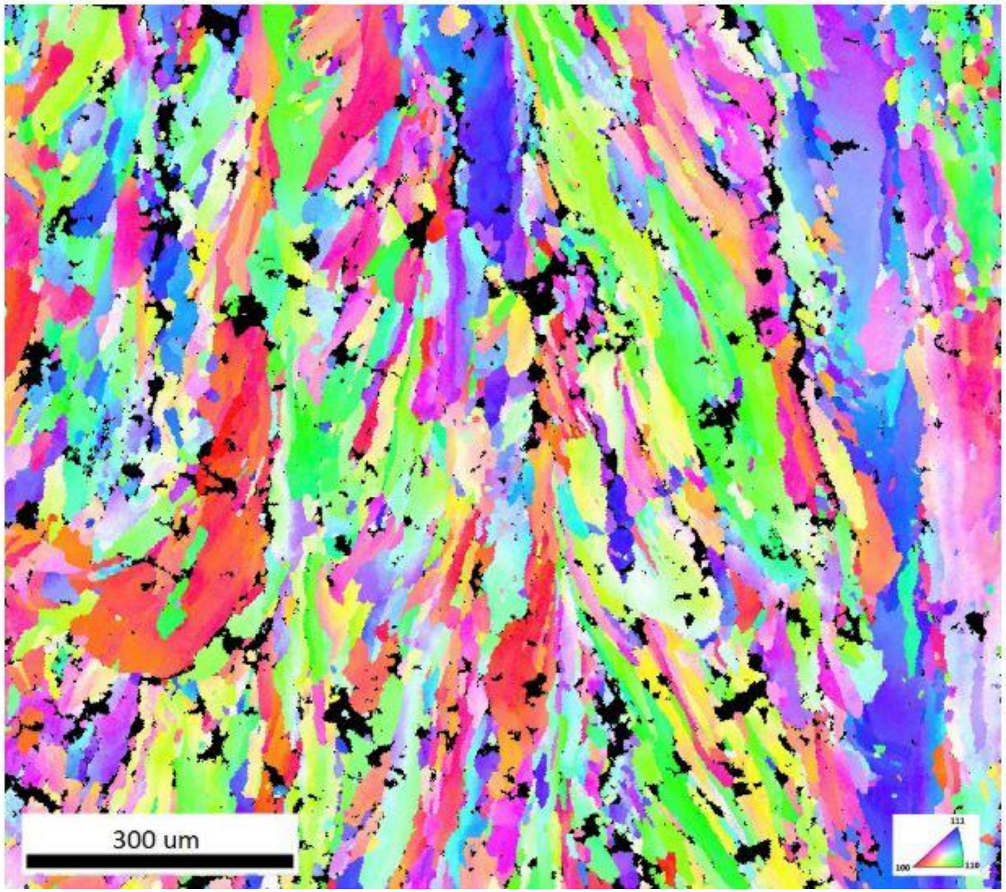
Recent Progress

- Proposal Completed at the end of May
- Characterization of grain size in A6061-RAM2 alloys from in-situ experiments at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL)
- NSF sponsored internship at Elementum 3D

Metrics

Description	% Complete	Status
1. Literature review	70%	●
2. Investigation of RAM (reactive additive manufacturing) reaction on grain refinement mechanisms	10%	●
3. Correlation of measured and modeled solidification conditions to microstructural features and grain refinement	25%	●
4. Effect of inoculants and unreacted particles on post-processing heat treatment	5%	●

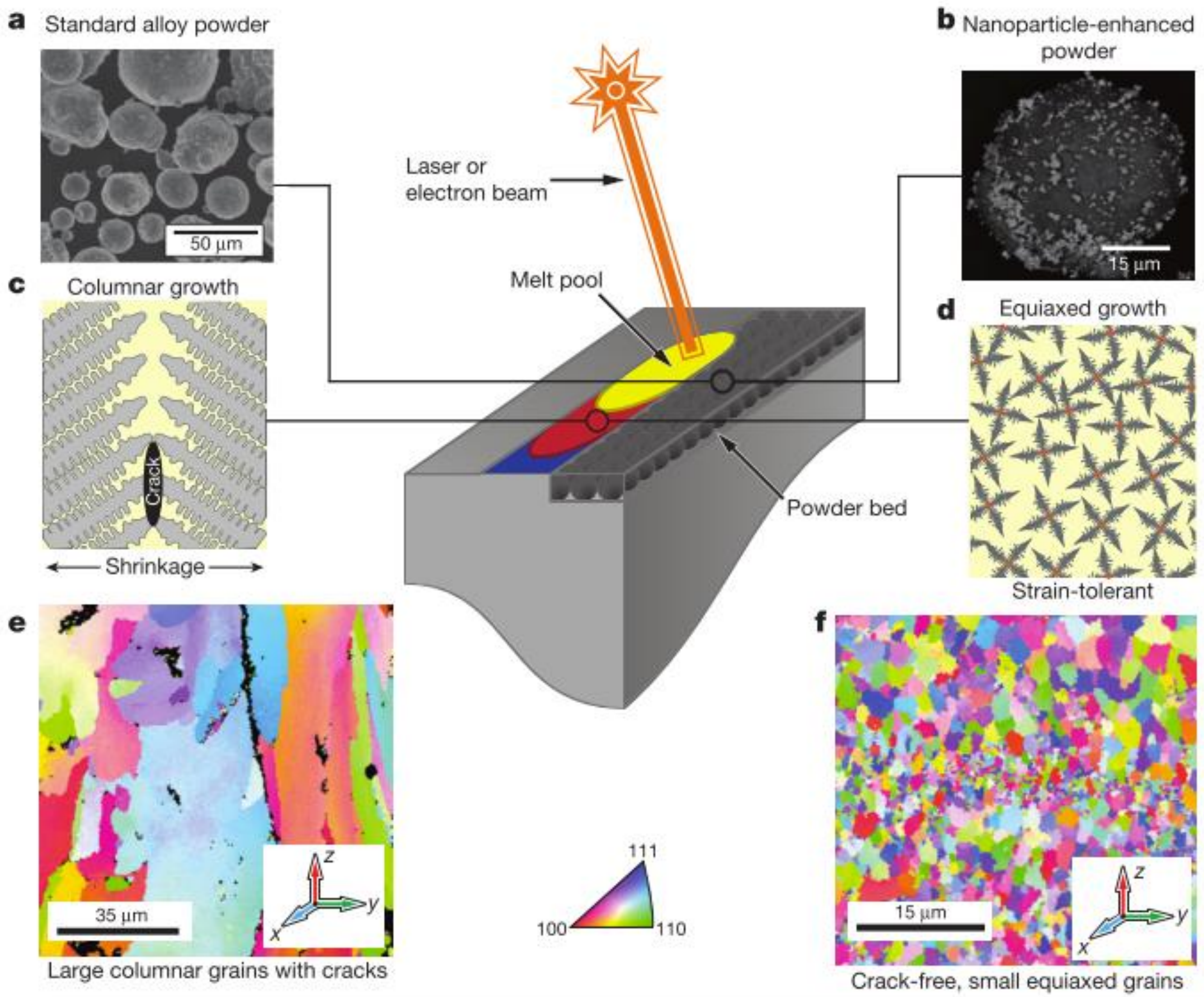
Industrial Relevance



Inverse pole figure of 3D-printed stock 7075, build direction is vertical to the page. Taken from J. H. Martin et al. *Nature,* 549 (2017) 365-369.

- Aluminum alloys currently used in AM are mostly traditional stock alloys (e.g. 7075, 6061, 2024)
- Under AM conditions these alloys tend to form columnar grains, and are subject to solidification cracking
- These results imply a need for alloys designed specifically for AM

Grain Size Control via Innoculants in AM Alloy Powders



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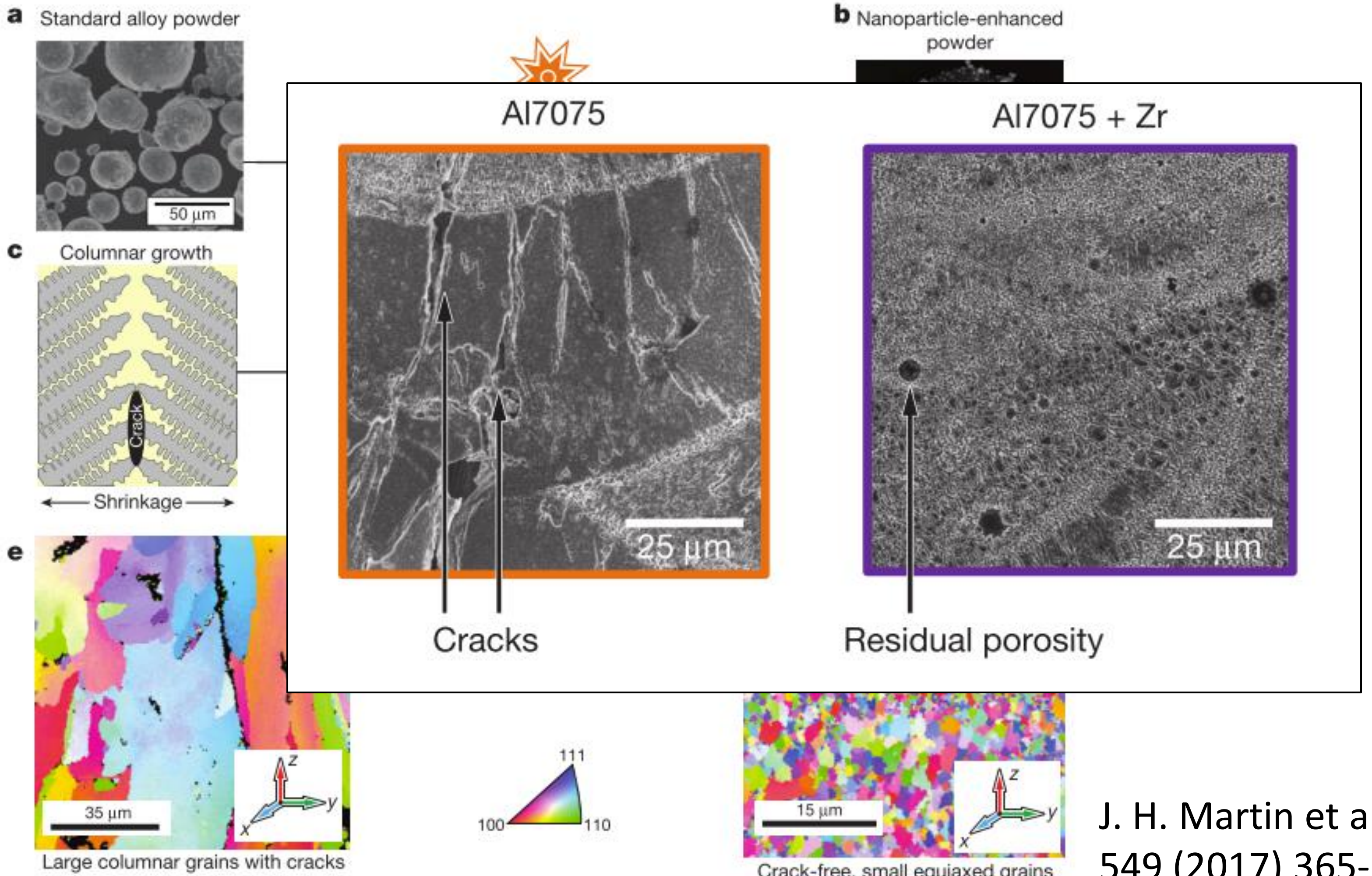
Grain Size Control via Innoculants in AM Alloy Powders



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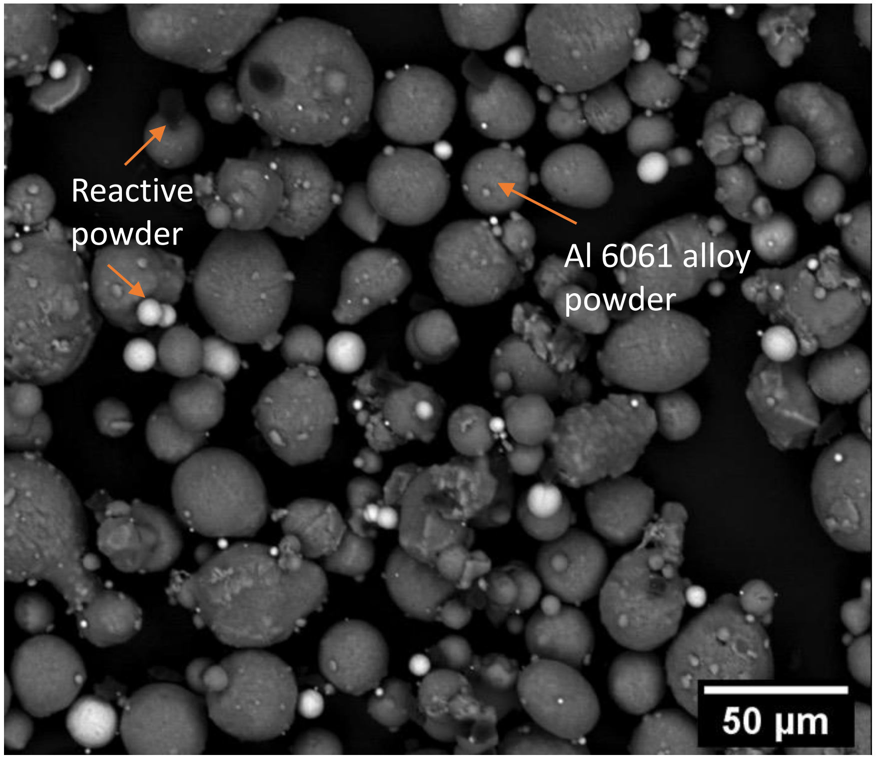
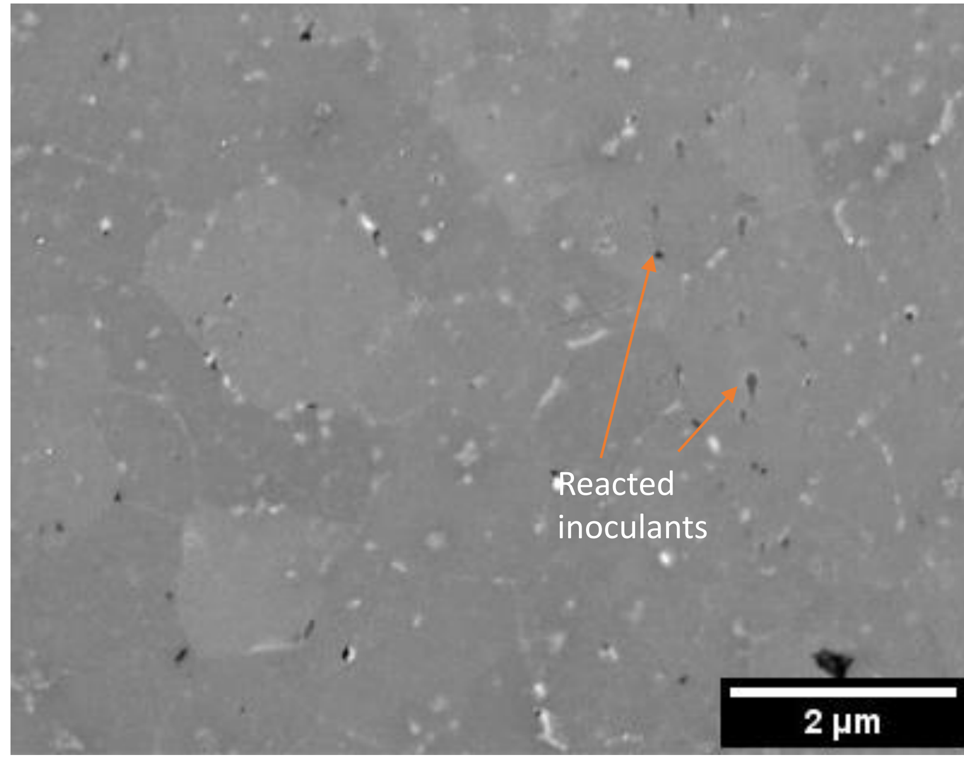
Al 6061 Reactive Additive Manufacturing (RAM) Alloy Designed for AM: Initial Characterization

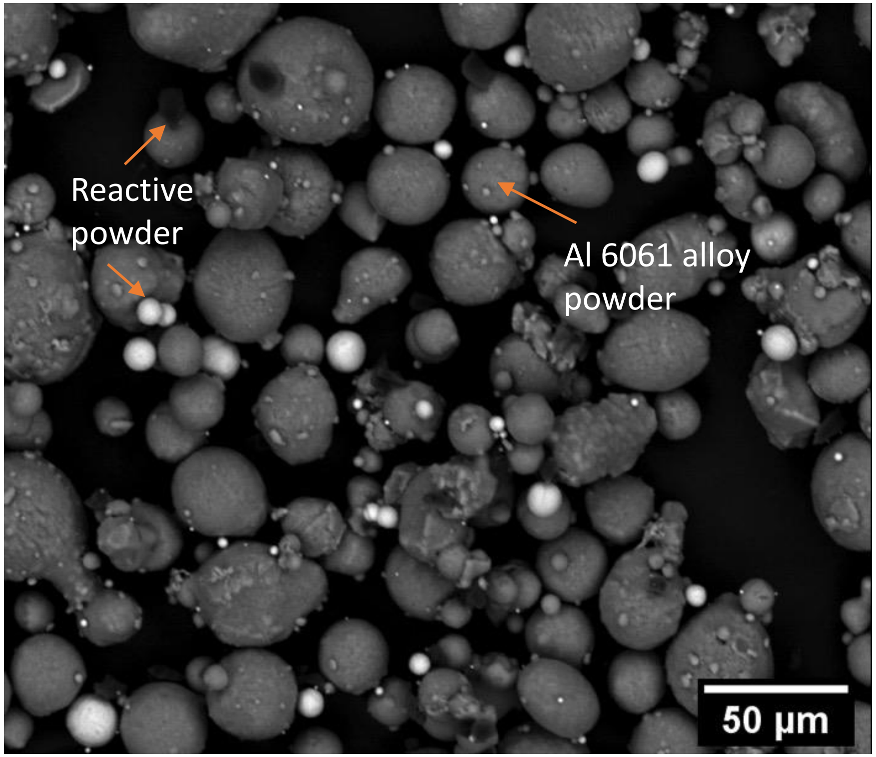


BSE SEM image of Al 6061 RAM 2% alloy powder



SEM image of as built Al 6061 RAM 2%

Al 6061 Reactive Metal Powder (RAM) Alloy Designed for AM: Initial Characterization



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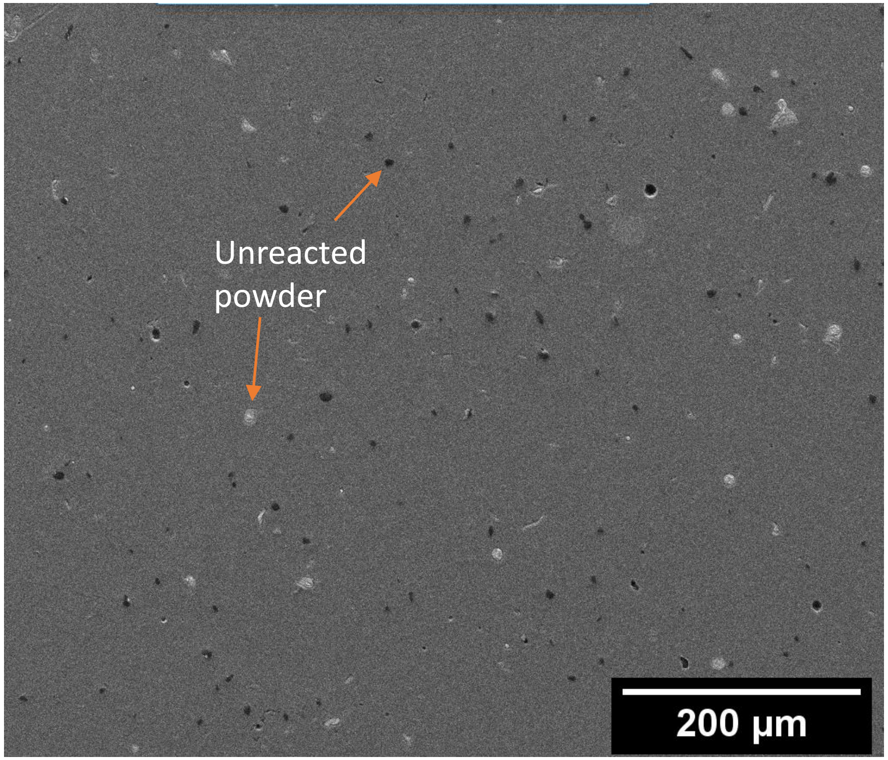

SEM image of as built Al 6061 RAM 2%

Project Focus

Overall Focus: What are the grain refinement mechanisms in AM of Al 6061 RAM alloys?

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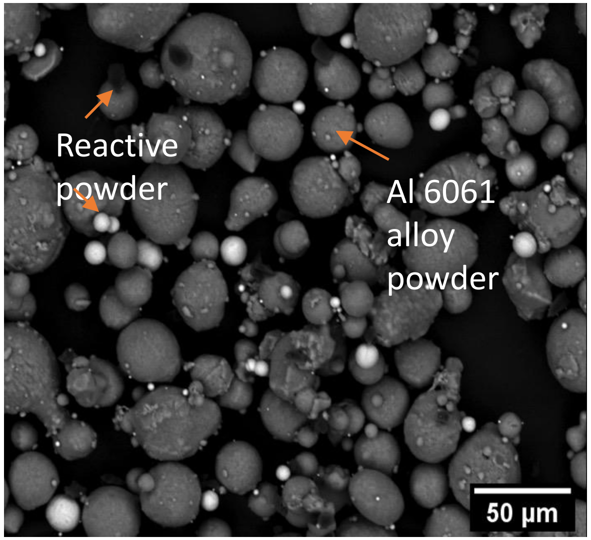
RAM process/reactant particles



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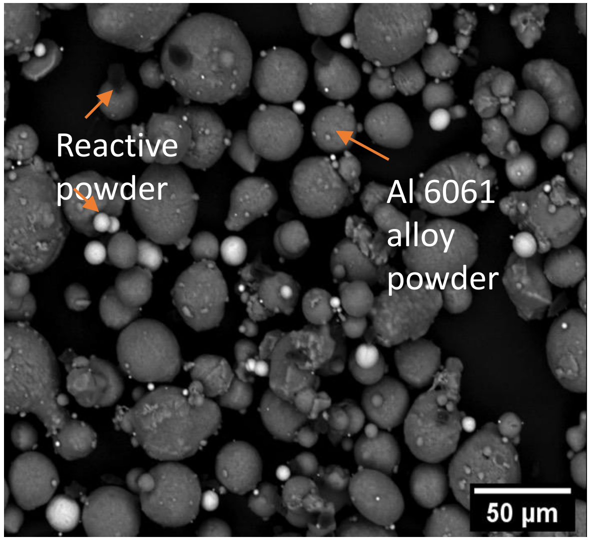
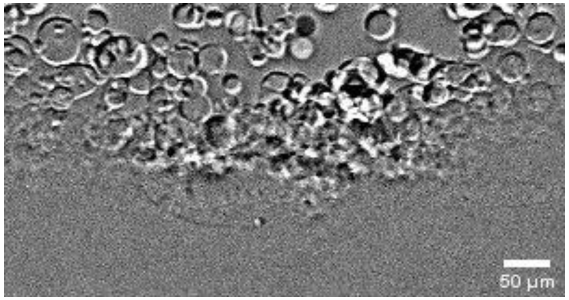


Solidification conditions experienced in AM



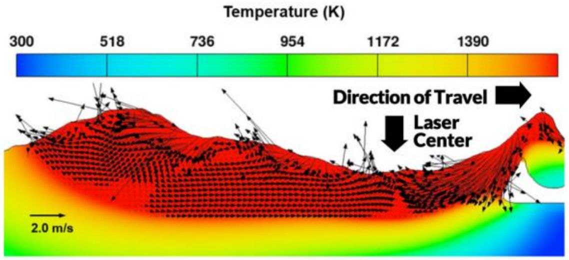
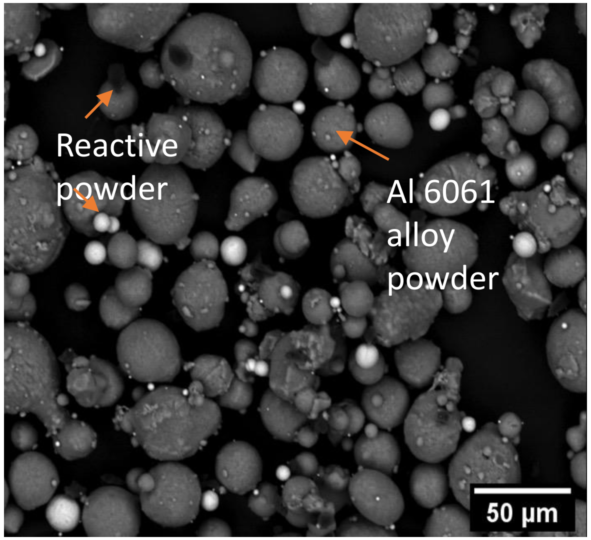


Image taken from Flow 3D website

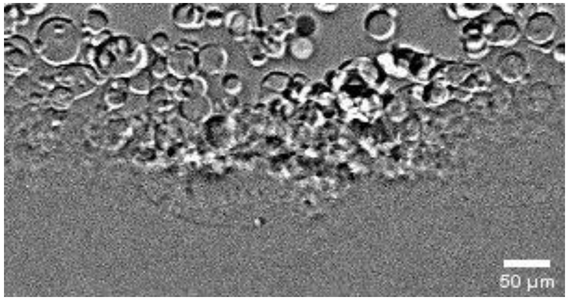
Project Focus

Overall Focus: What are the grain refinement mechanisms in AM of Al 6061 RAM alloys?

RAM process/reactant particles



Solidification conditions experienced in AM



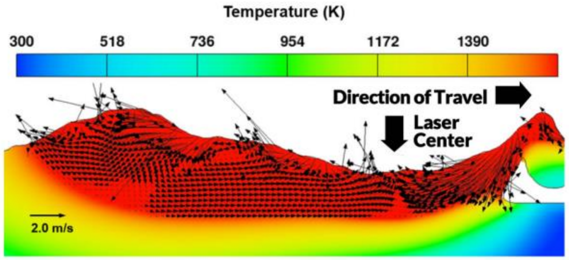
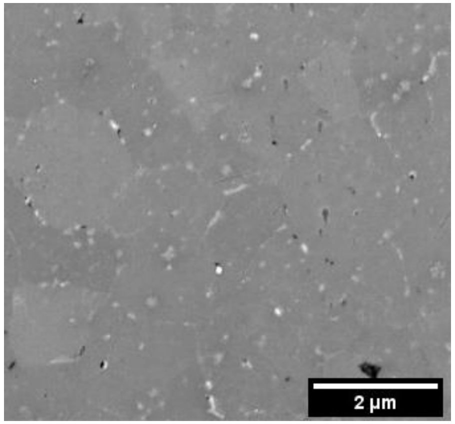


Image taken from Flow 3D website

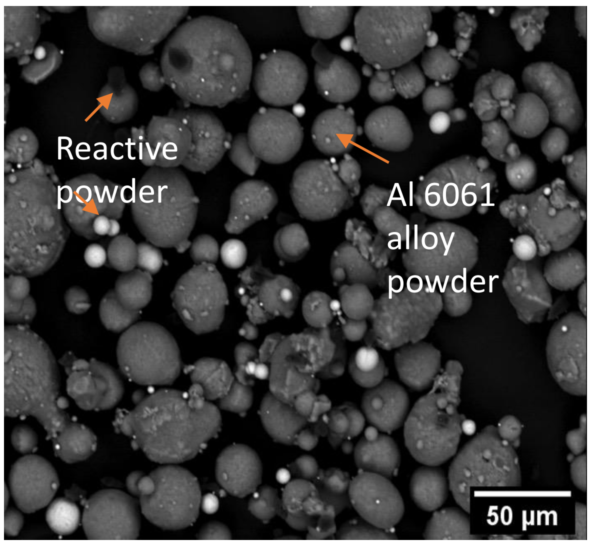
Effect of particles on final structure after heat treatment

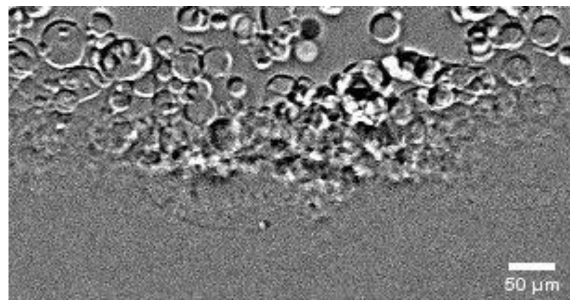


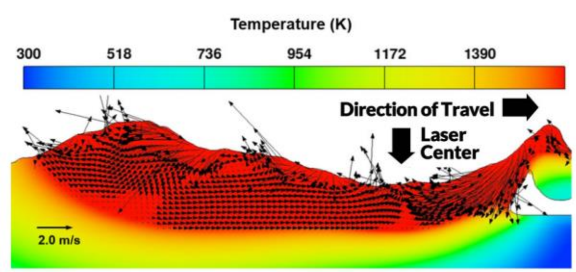
Project Focus

Overall Focus: What are the grain refinement mechanisms in AM of Al 6061 RAM alloys?

RAM process/reactant particles	Solidification conditions experienced in AM	Effect of particles on final structure after heat treatment







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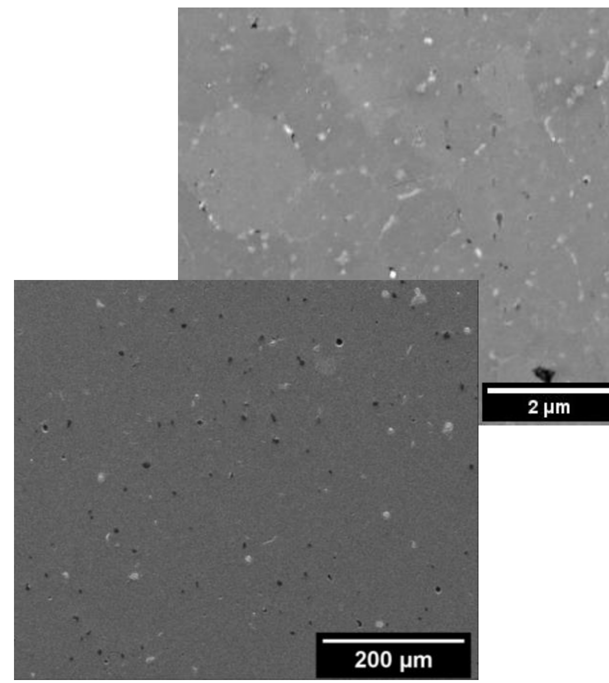
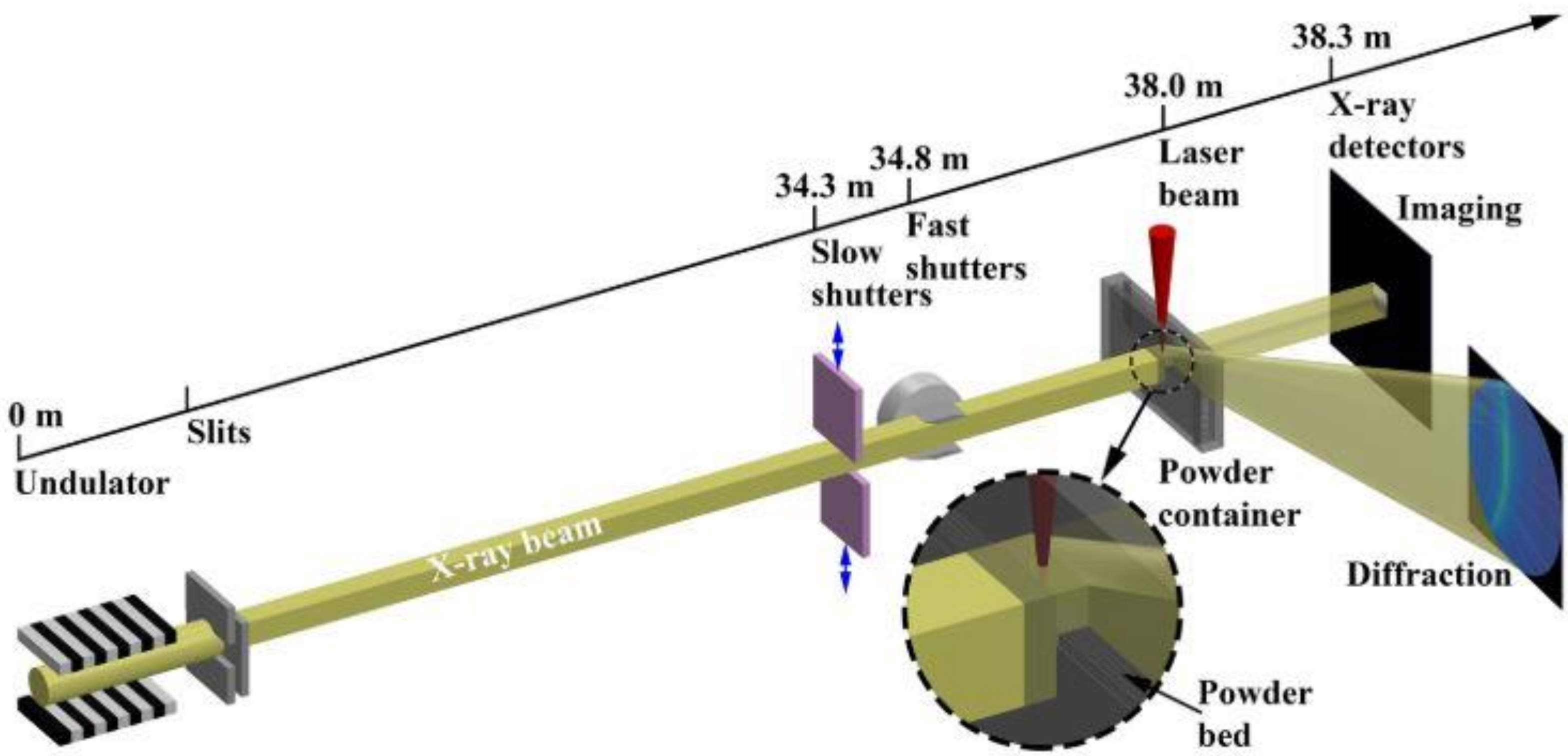


Advanced Photon Source (APS) Additive Manufacturing Simulator Set-up



Schematic of AM simulator used for in-situ experiments at ANL.
Taken from: C. Zhao et al., *Scientific Reports,* 7 (2017) 1-11.

Image Processing: Tracking of S/L Interface

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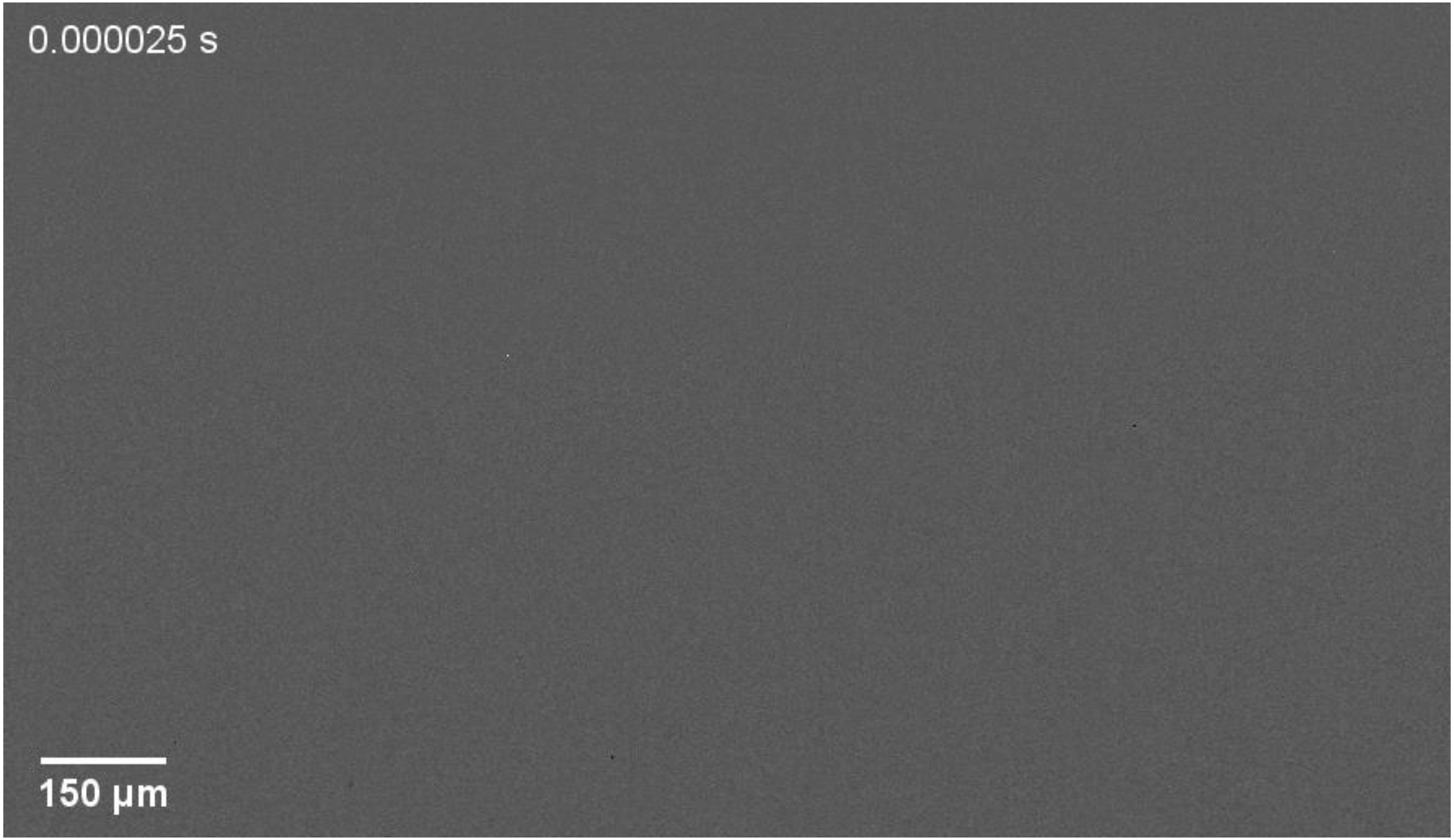

Animation of laser pass on 6061 wrought + 6061 powder, 416 W, 0.5 m/s

Acknowledgement to Gus Becker for image processing

Changes in Grain Size with Laser Parameters

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Base Plate	Powder
A6061-RAM2 Build	A6061-RAM2
Wrought 6061	A6061-RAM2

Sample Number	Power (W)	Speed (m/s)	Linear Energy Density (J/m)
1	311	0.5	622
2	397	1	397
3	397	1.5	265
4	540	1.5	360
5	540	2	270

Changes in Grain Size with Laser Parameters (RAM2 Build/RAM2 Powder)

Sample Number	Power (W)	Speed (m/s)	Linear Energy Density (J/m)
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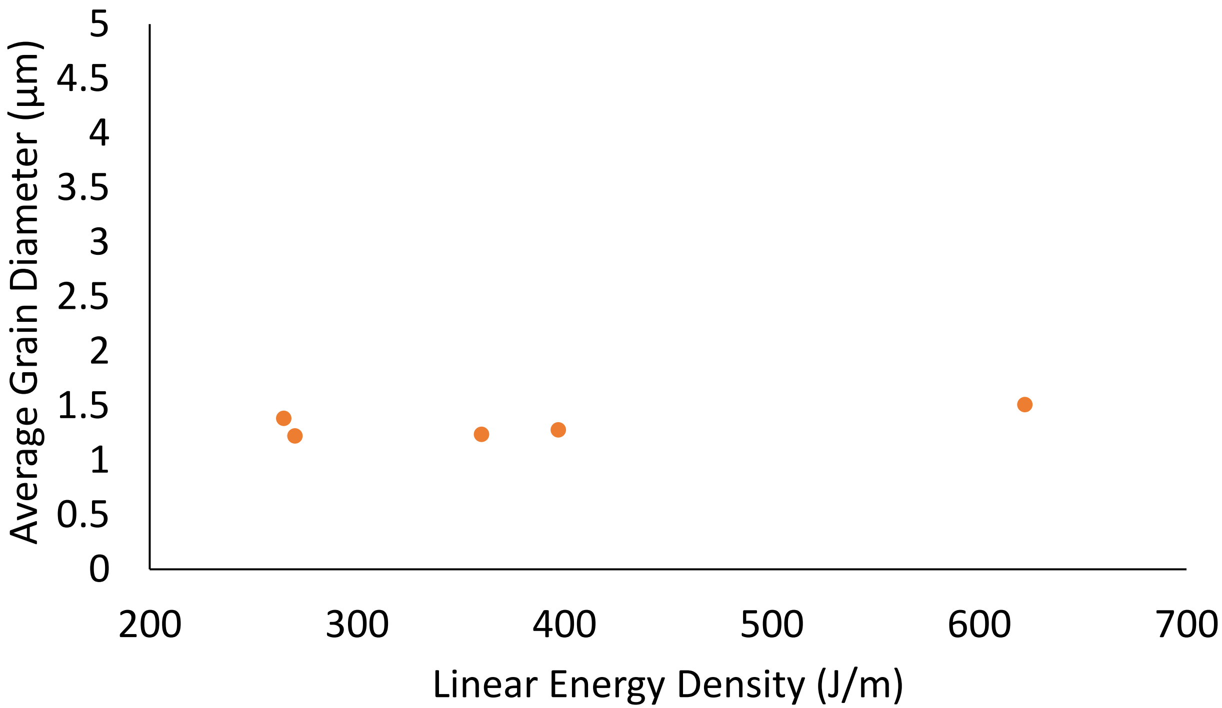

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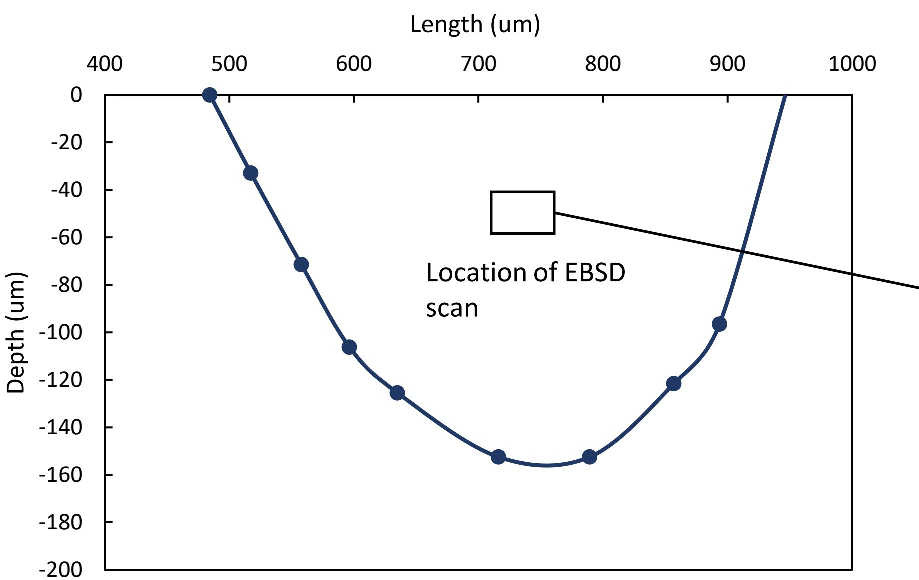
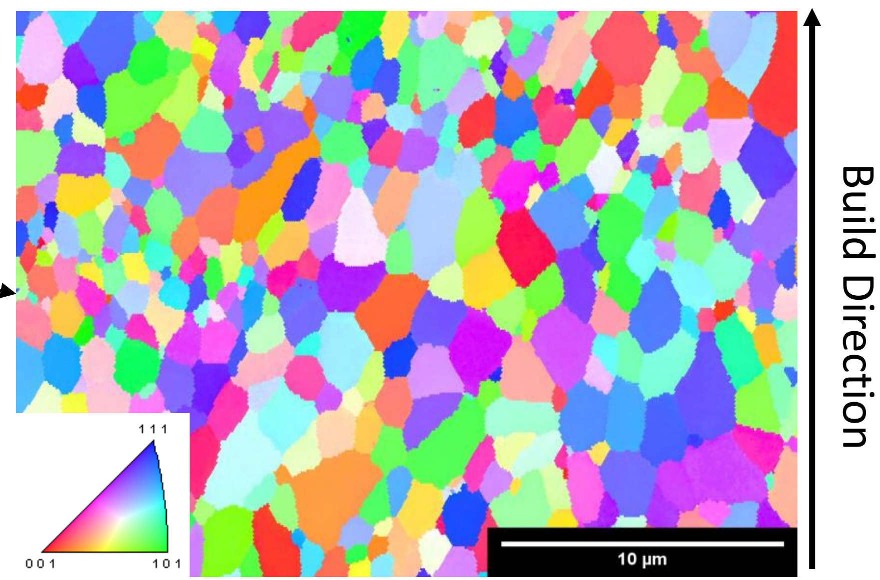
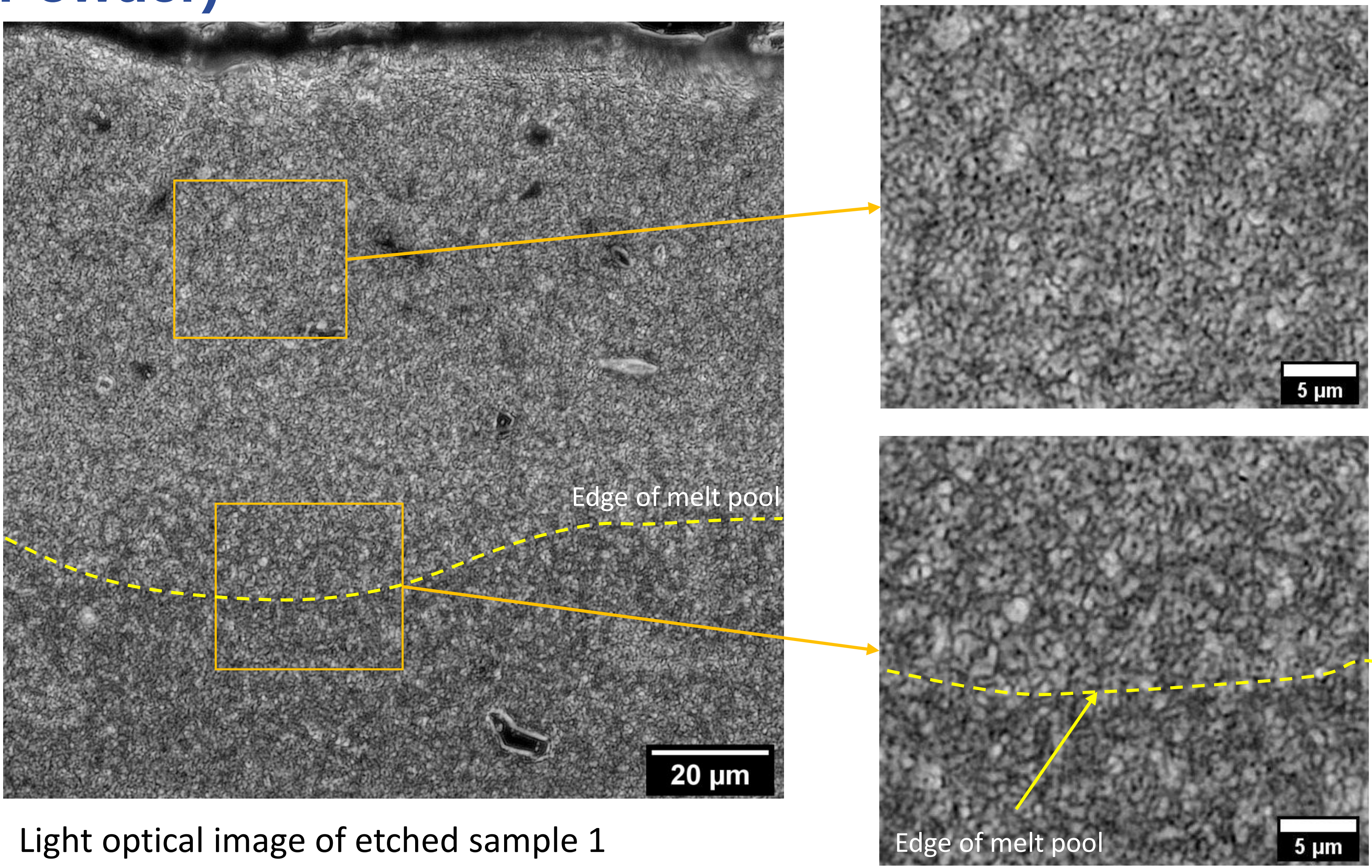


Location of EBSD scan relative to melt pool depth for sample 1; the scan was taken in the middle section of the raster.



Inverse pole figure map of sample 1 (see above) for an A6061-RAM2 Build with A6061-RAM2 powder produced using in-situ experiments at APS

Changes in Grain Size with Laser Parameters (RAM2 Build/RAM2 Powder)



Light optical image of etched sample 1

Changes in Grain Size with Laser Parameters (6061 wrought/ A6061-RAM2)

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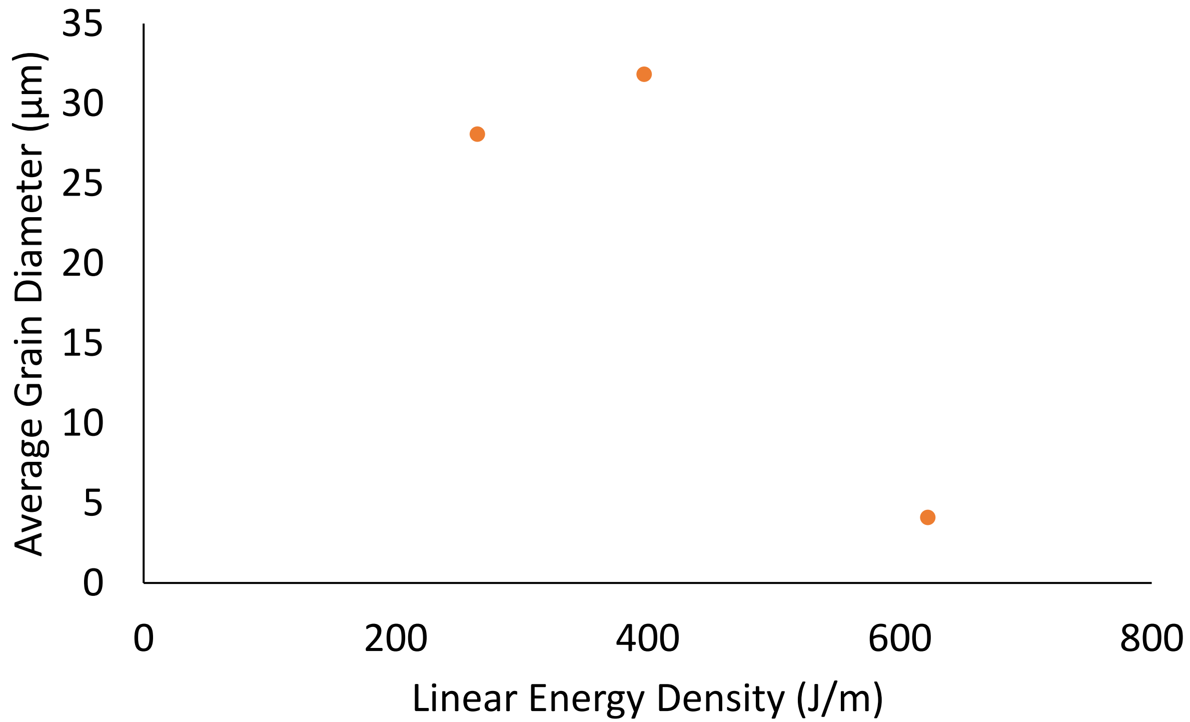

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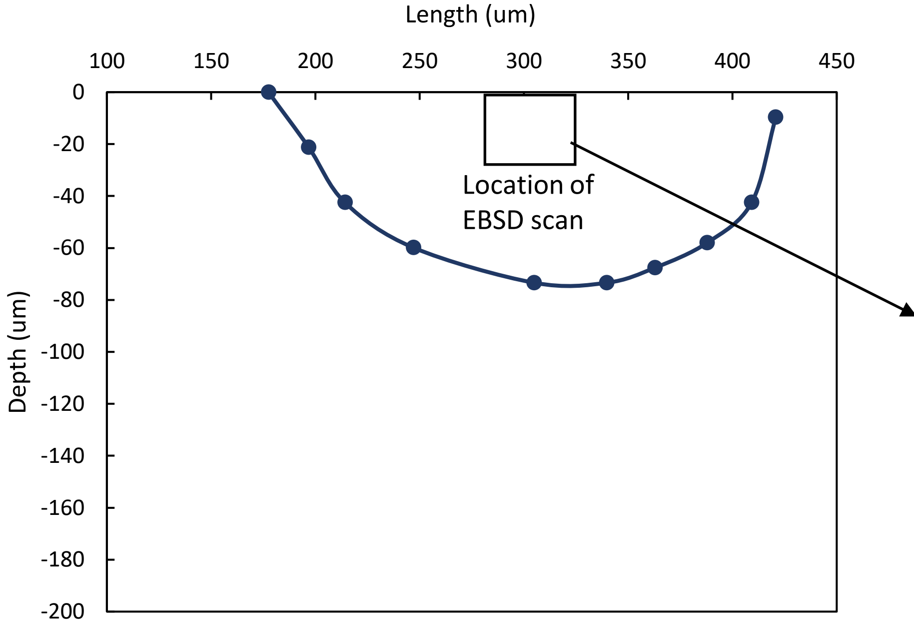

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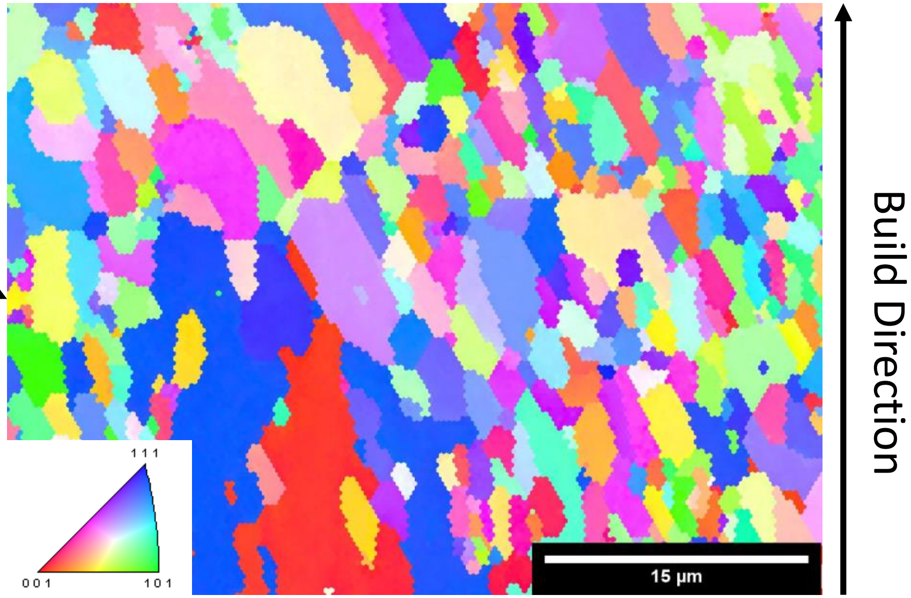

Inverse pole figure map taken from sample 1 (see above) for a 6061 wrought plate with A6061-RAM2 powder produced using in-situ experiments at APS

Changes in Grain Size with Laser Parameters (6061 wrought/ A6061-RAM2)

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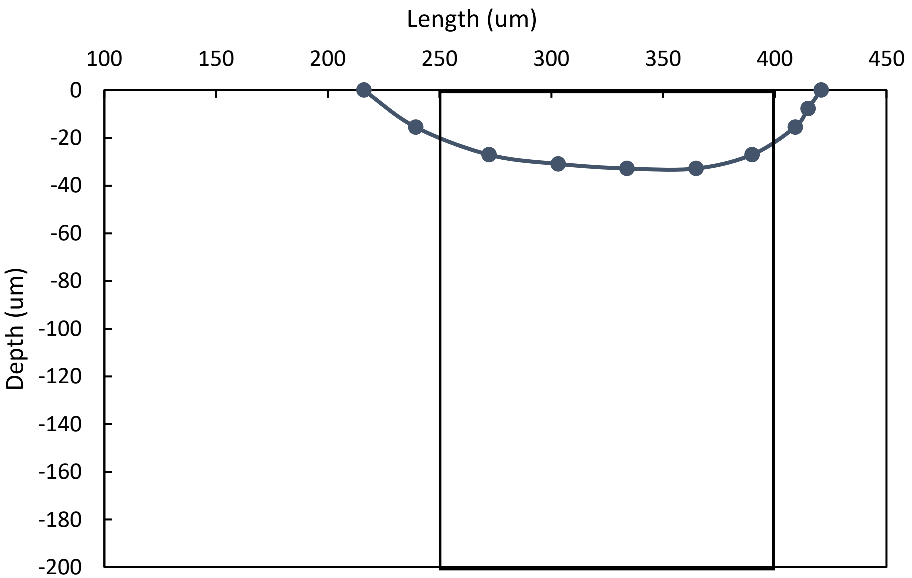
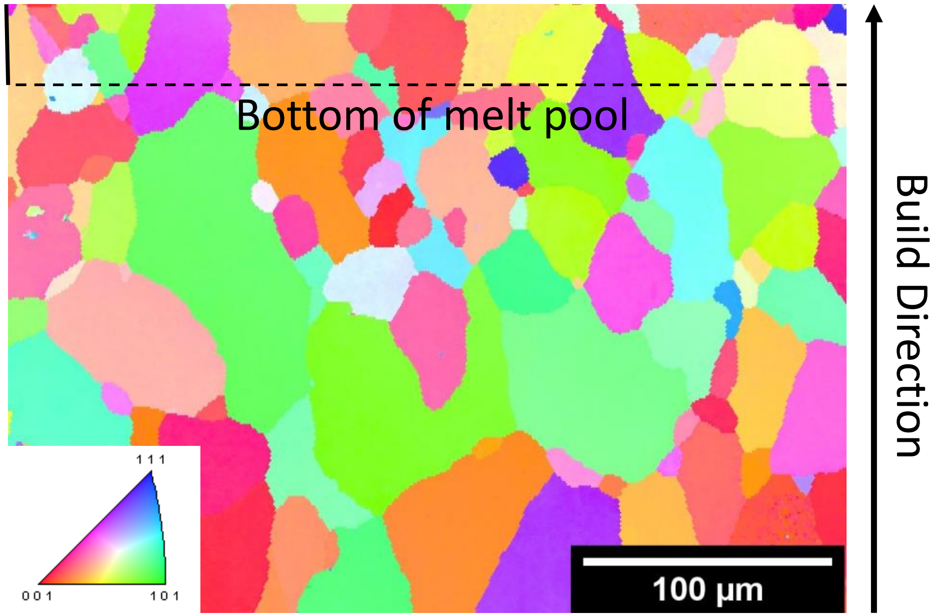


Location of EBSD scan relative to melt pool depth for sample 3; the scan was taken in the middle section of the raster.



Inverse pole figure map taken from sample 3 (see above) for a 6061 wrought plate with A6061-RAM2 powder produced using in-situ experiments at APS

Some Hypotheses…

- Less initial reactant particles (based on rough calculations from melt pool and powder dimensions ~1.3-1.4 vol. % RAM)
- Seems to lead to more dependence on solidification conditions, namely this process could now be affected by
    1. Relative flow or turbulence at different laser conditions
    2. Changes in thermal gradient/cooling rate due to linear energy density
    3. Longer/varying diffusion times in the liquid for different solidification rates

Consideration of Melt Pool Geometry & Laser Settings

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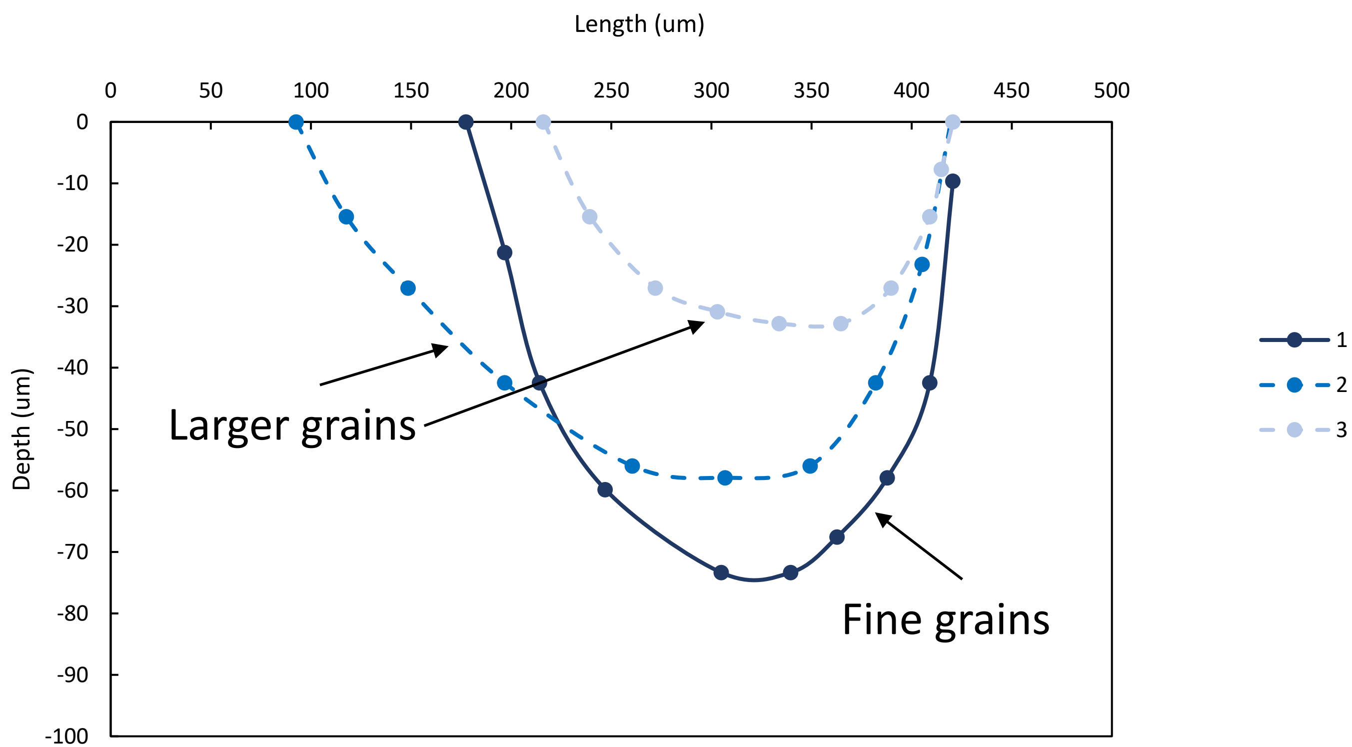
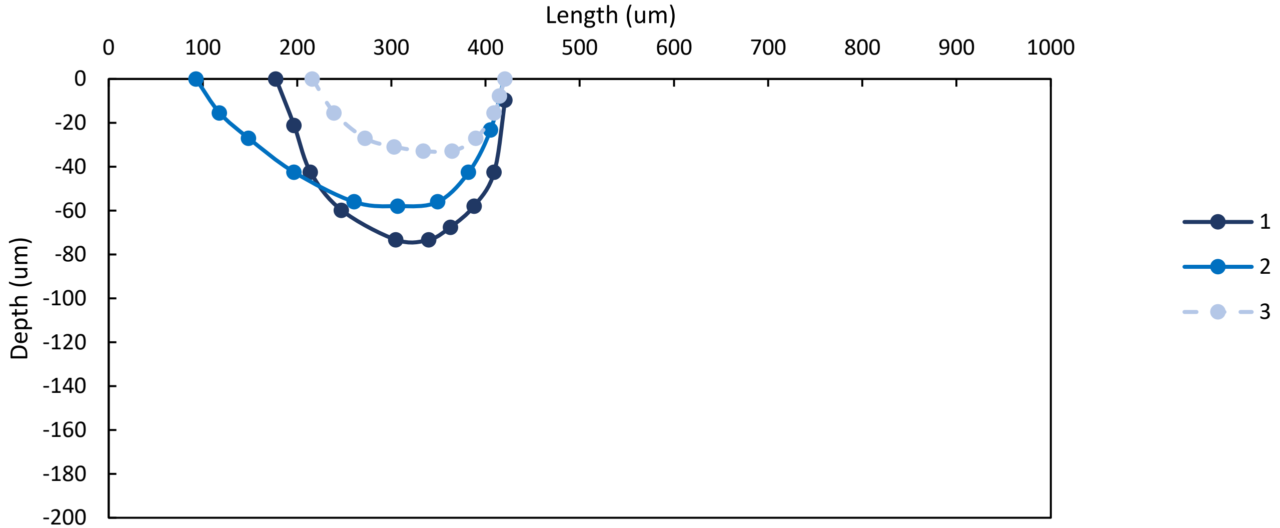
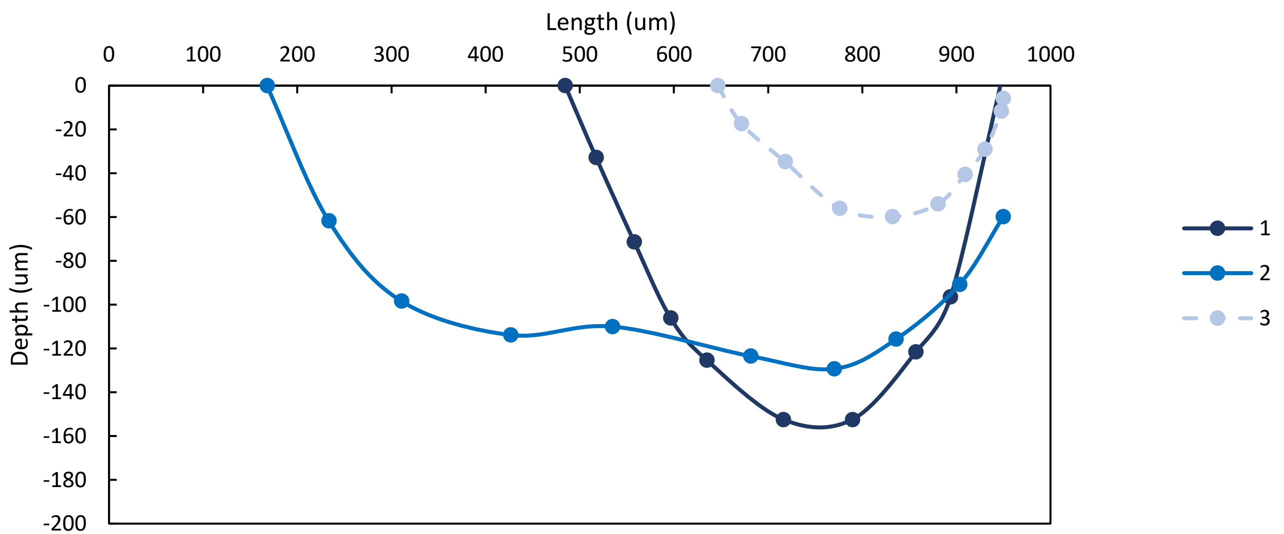


Relative Thermal Gradient Changes with RAM Content



Melt pool geometry for 6061 wrought base plate with A6061-RAM2 powder measured from in-situ video data

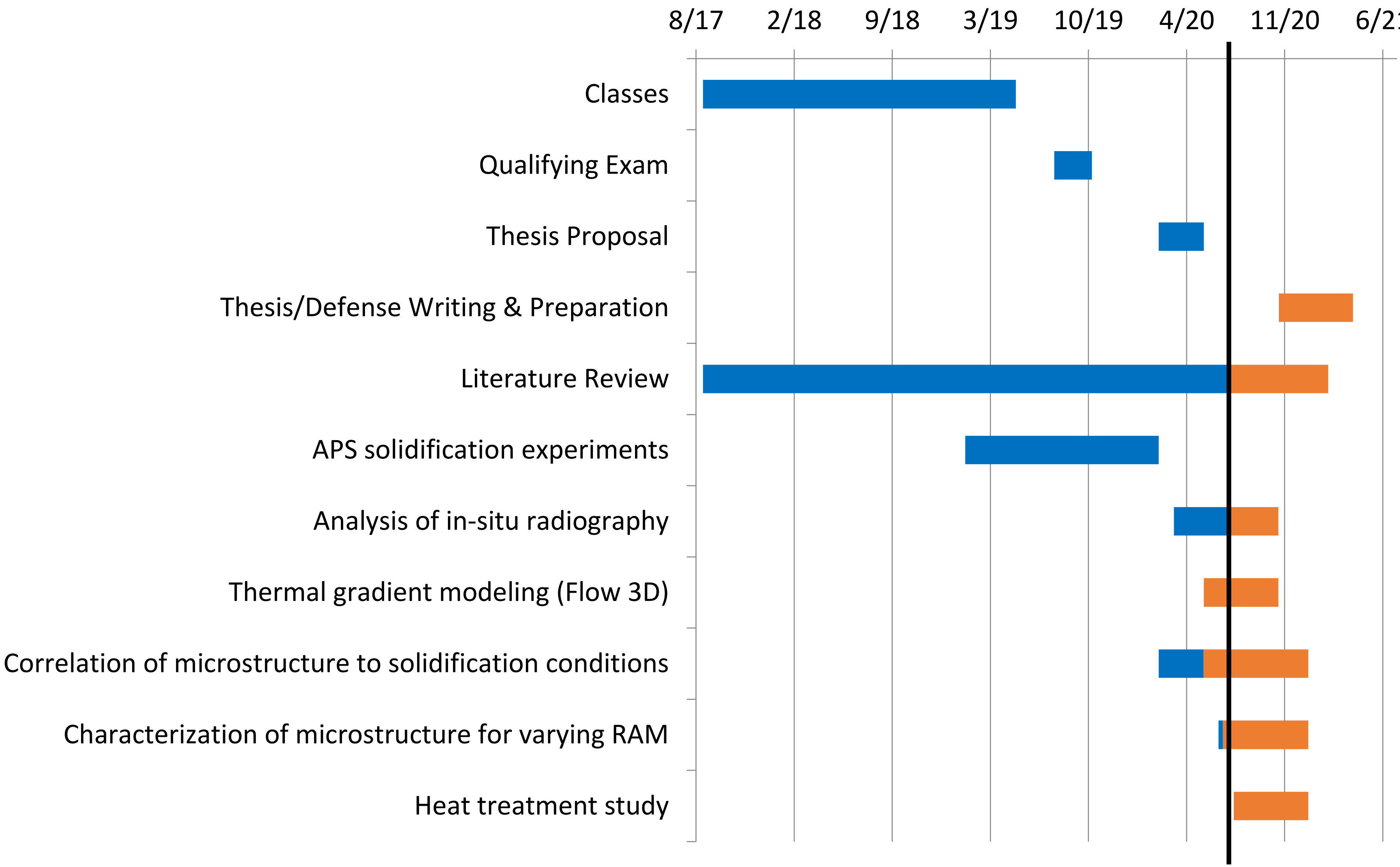


Melt pool geometry for A6061-RAM2 build with A6061-RAM2 powder measured from in-situ video data

Conclusions & Future Work

- Changes in sensitivity to process parameters & resulting solidification conditions will be investigated further via microstructural characterization of shown samples from in-situ experiments
- Further understanding of solidification conditions will be gathered via calculation of solidification velocity (in-situ data) & simulation of thermal gradient (Flow 3D)
- Builds will be performed with various RAM contents to continue to investigate the sensitivity to RAM content, as well as the direct impact of the RAM reaction on final microstructure

Progress


8/17
2/18
9/18
3/19
10/19
4/20
11/20
6/21
Classes
Qualifying Exam
Thesis Proposal
Thesis/Defense Writing & Preparation
Literature Review
APS solidification experiments
Analysis of in-situ radiography
Thermal gradient modeling (Flow 3D)
Correlation of microstructure to solidification conditions
Characterization of microstructure for varying RAM
Heat treatment study

Challenges & Opportunities

- Challenges
  - What is contributing to a transition to more refined grains in samples with lower vol. % of reactant particles?
  - Modeling RAM melt pools effectively versus traditional 6061 (Flow 3D)
- Opportunities
  - Better understanding how RAM contributes to local solidification conditions via modeling and measurement of solidification conditions and general melt pool geometry
  - Evaluation of largest contribution to grain refinement (i.e. RAM reaction vs solidification conditions) with variation of RAM content and linear energy density/solidification conditions

Thank you!

Chloe Johnson

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