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

Project 36D-L: Characterizing Additively Manufactured Inconel 718 & 738

Fall 2020 Videoconference

October 13th – October 15th 2020

Student: Jeremy Shin (Mines)

Faculty: Dr. Amy Clarke (Mines)

Industrial Mentors: John Carpenter (LANL), Matt Krug (AFRL)

Other Participants: UT/ORNL, ISU, OSU, Virginia Tech., UCSB, Univ. of Sydney, UNSW

Project 36D-L: Characterizing Additively Manufactured Inconel 718 & 738

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- Student: Jeremy Shin (Mines)
- Advisor: Amy Clarke (Mines)

Project Duration
PhD: September 2019 to May 2023

- Problem: The links between AM processing conditions, processing history, and the consequent microstructural evolution are not well-understood.
- Objective: Clarify the role of processing on microstructural evolution by in-situ imaging of solidification dynamics and characterization of as-built microstructures and mechanical anisotropy.
- Benefit: Fundamental understanding of microstructural evolution during AM will result in improved parts with controlled properties.

Recent Progress

- Post-mortem imaging of top melt pool surfaces for IN738 samples from APS 2020 run.
- Proposal for neutron diffraction experiments at LANL with new build geometries from ORNL.

Metrics

Description	% Complete	Status
1. Literature review	20%	●
2. Ex-situ metallography and microscopy for APS samples (738 – spot, raster)	25%	●
3. Analysis of APS 2020 *in-situ* radiography data	20%	●
4. Initial microstructural characterization of as-built Inconel 738	10%	●

Multidisciplinary University Research Initiative (MURI), Office of Naval Research

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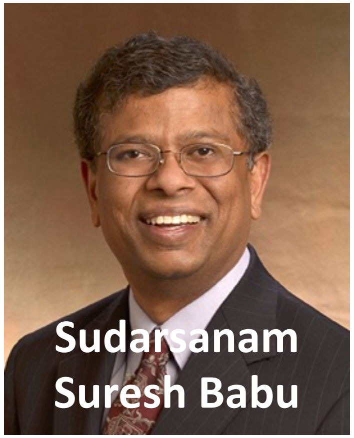

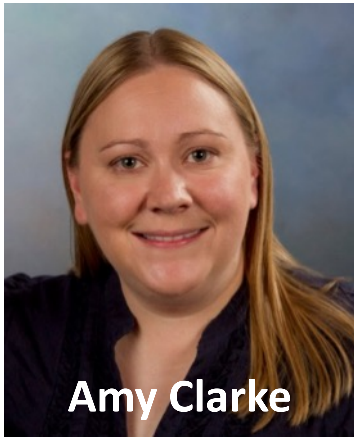

Office of Naval Research ONR Science & Technology

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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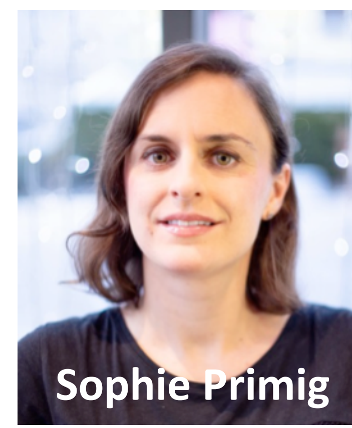


VIRGINIA TECH.

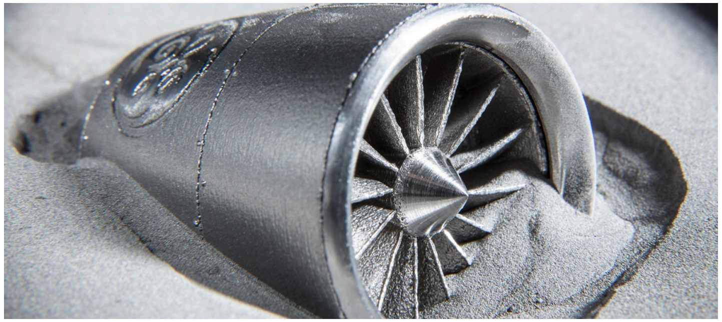
UC SANTA BARBARA MATERIALS

THE UNIVERSITY OF SYDNEY
Core Research Facilities

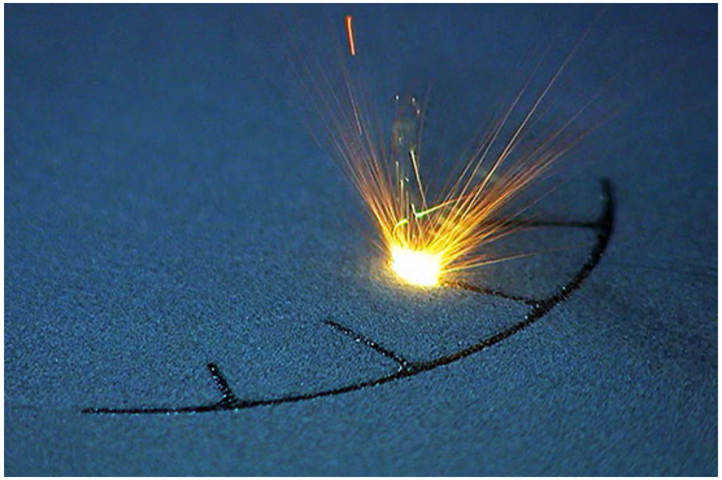
UNSW SYDNEY

Industrial Relevance

- AM allows complex geometries and near-net shapes
- Eliminate additional processing steps and save material costs
- AM results in unique processing conditions, microstructures, and material properties:
  - Large thermal gradients
  - Thermal cycling
  - Lack of fusion defects
  - Anisotropic mechanical properties



https://www.ge.com/additive/webinar/metal-additive-manufacturing-aerospace



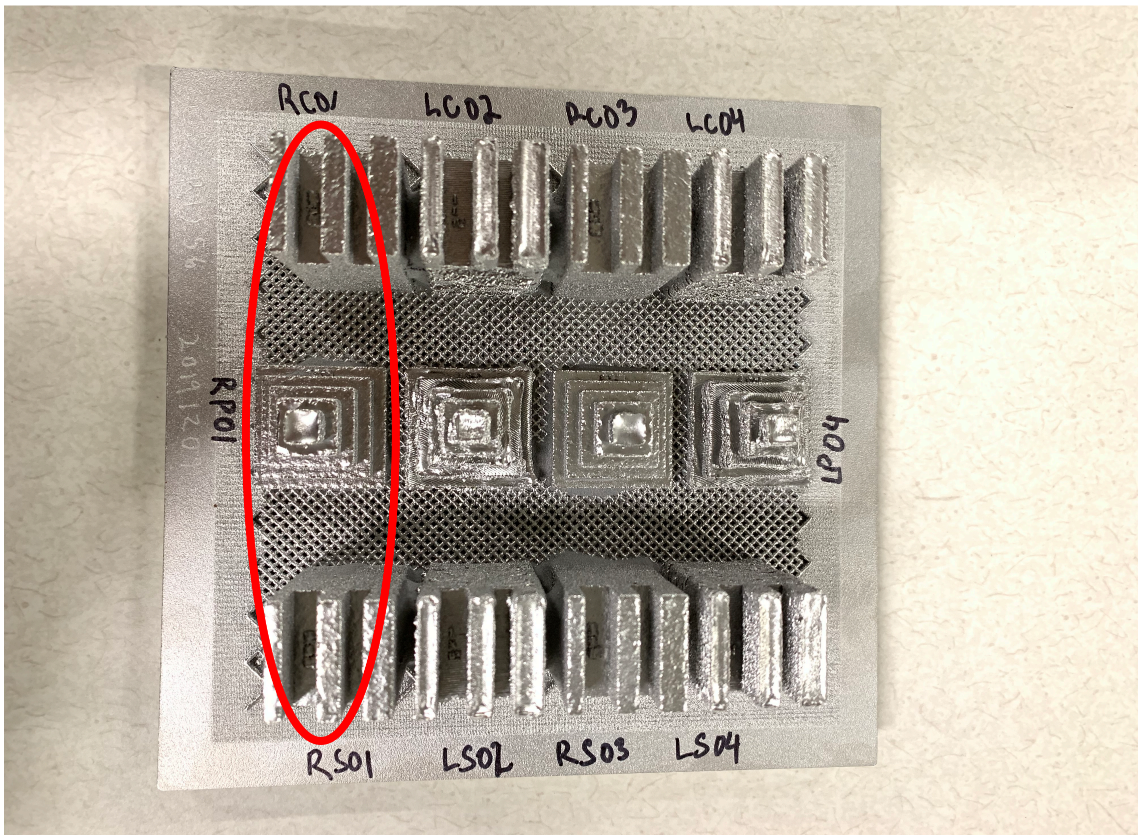
https://www.irepa-laser.com/en/applications-en/additive-manufacturing/slm-process

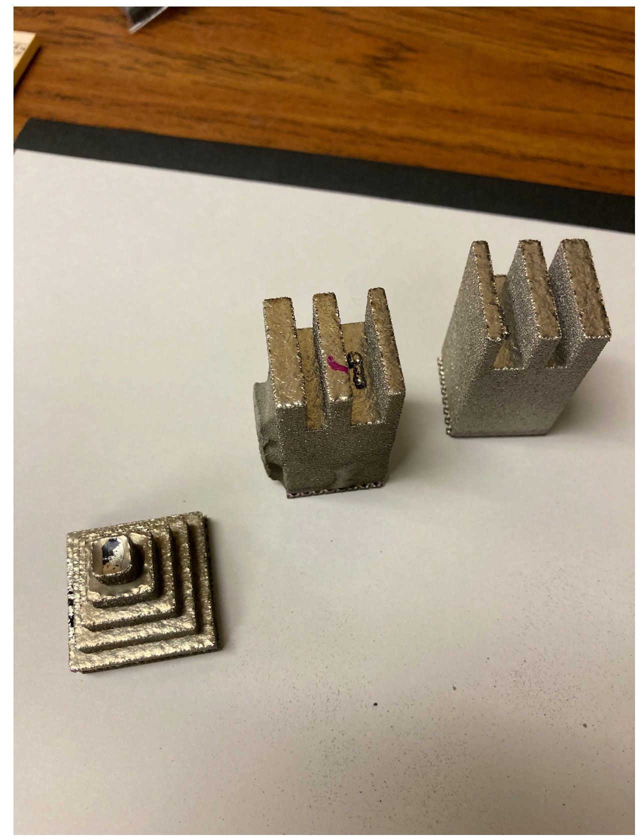
Objectives

- Understand the origins of mechanical anisotropy in IN718
  - Evaluate anisotropy using neutron diffraction to measure and probe for contributions from texture and microstructural defects
  - Compare inoculated vs. regular builds
- Identify a hot cracking regime in G-V space for IN738
  - Find thermal gradients using FLOW-3D simulation software
  - Calculate velocities from solid/liquid interface of the melt pool
  - Relate ex-situ electron microscopy to in-situ radiography data
- Analyze texture/microstructure as a function of local processing conditions for as-built AM structures: IN718, IN738, Haynes282
  - Bulk measurements along the build direction to correlate different local microstructures relative to processing conditions
  - Rectangular samples of IN718 and IN738
  - Various experimental geometries of Haynes282

New geometries from ORNL (Haynes282)

- All new sample geometries use a raster scan strategy





Build geometries of Haynes282

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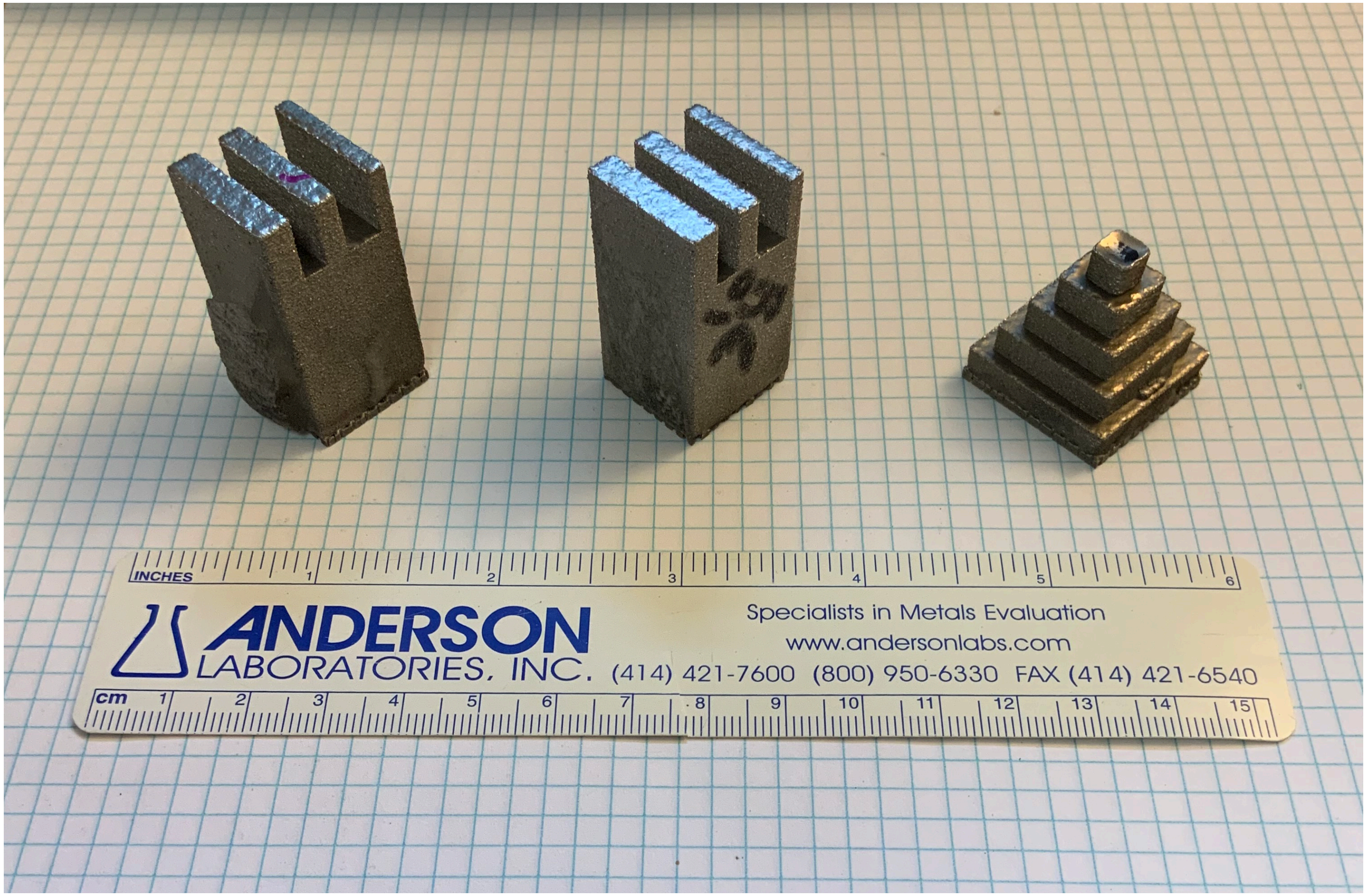
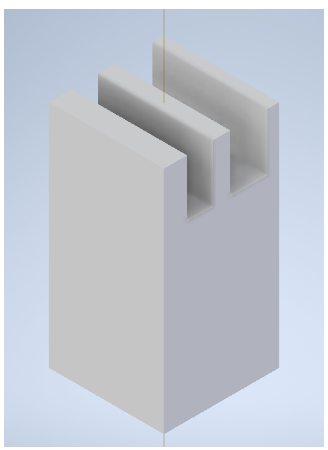
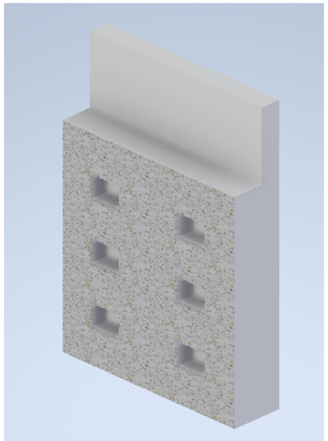
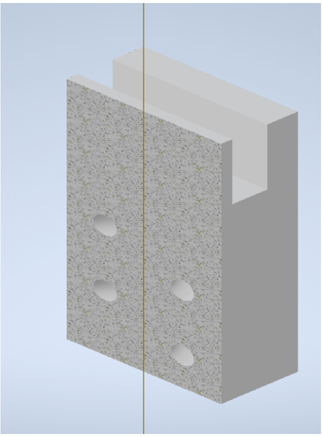


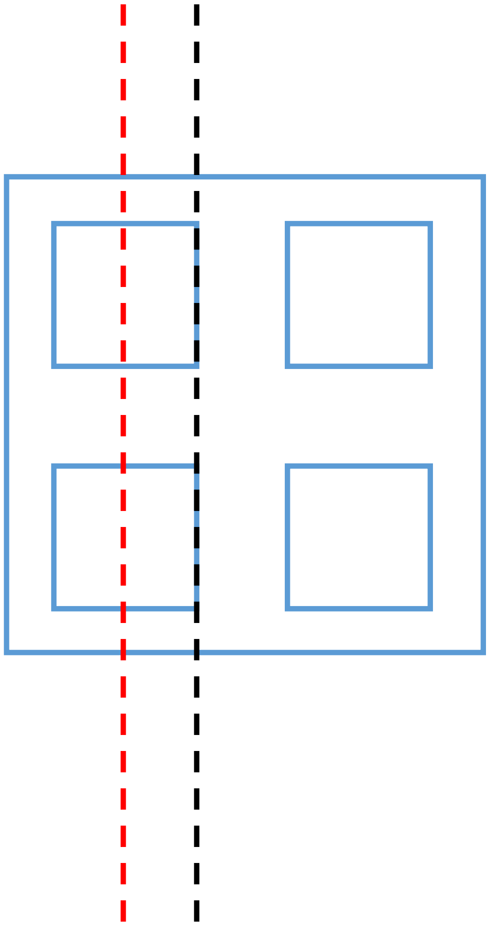
Build geometries of Haynes282 (neutron diffraction plans)

- 20 x 20 x 30 mm body
  - 2/3/4 mm struts
  - 3 x 3 mm cubes
  - 3 mm diameter



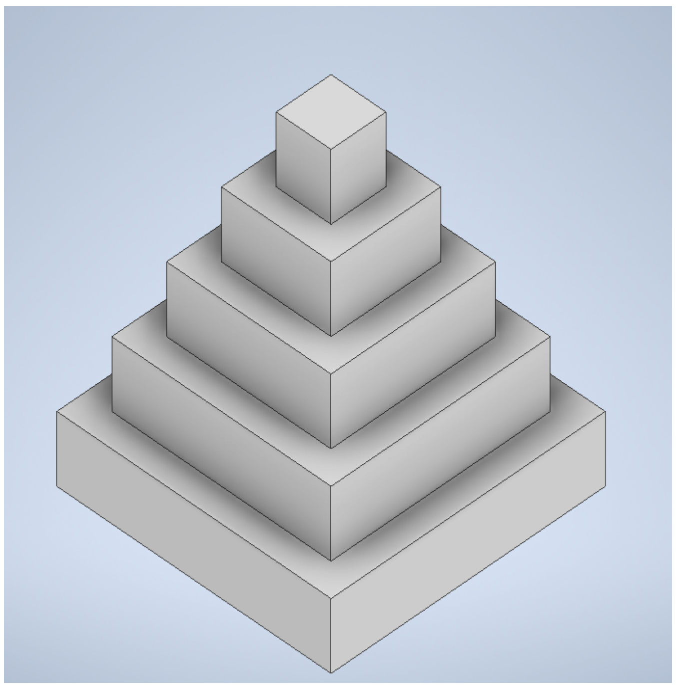


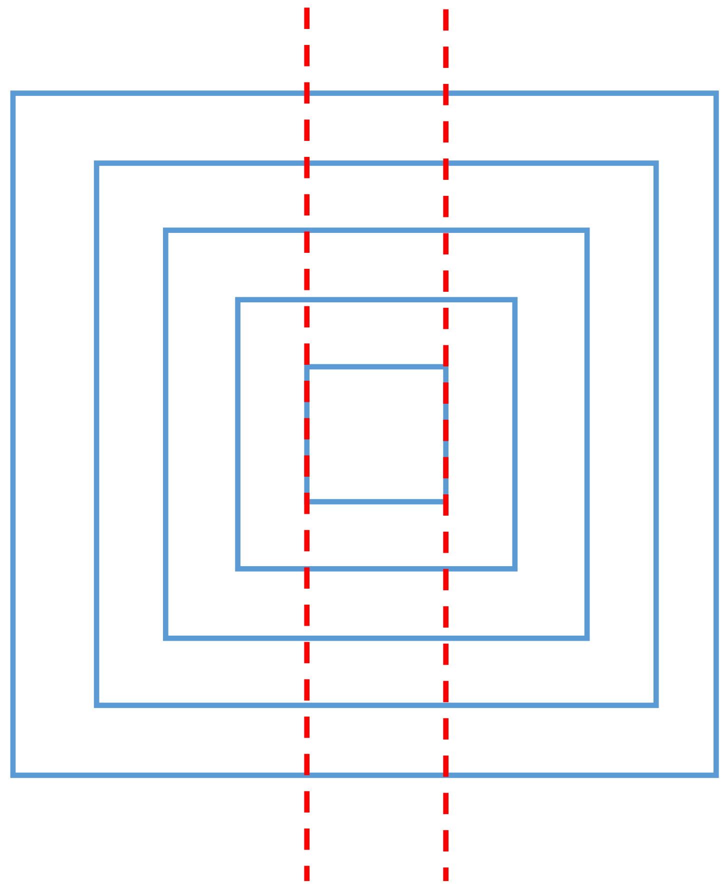




Build geometries of Haynes282 (neutron diffraction plans)

- 25 x 25 mm base
  - with 5 x 5 mm step size





IN738
(neutron diffraction plans)

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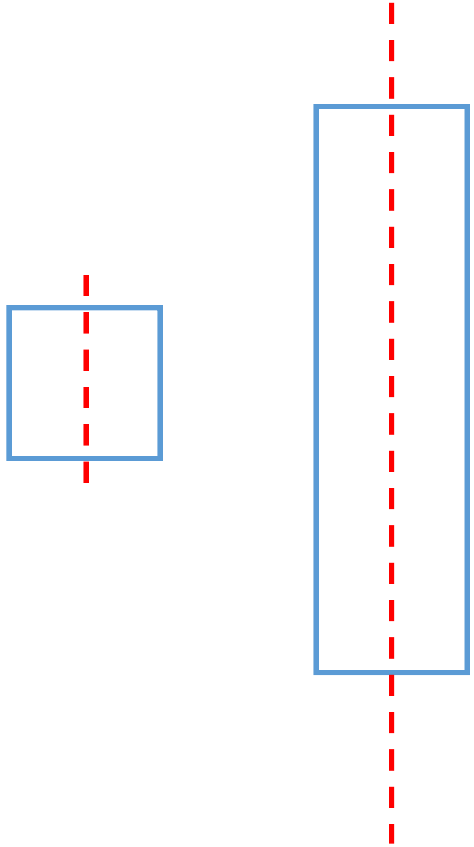
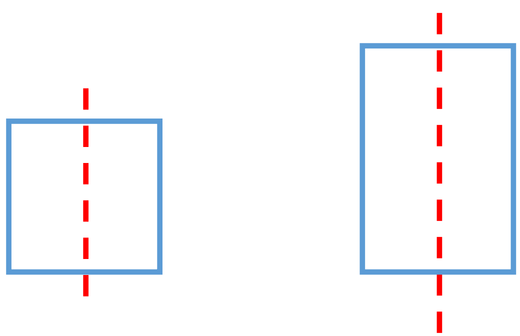
- 75mm x 15mm x 15mm



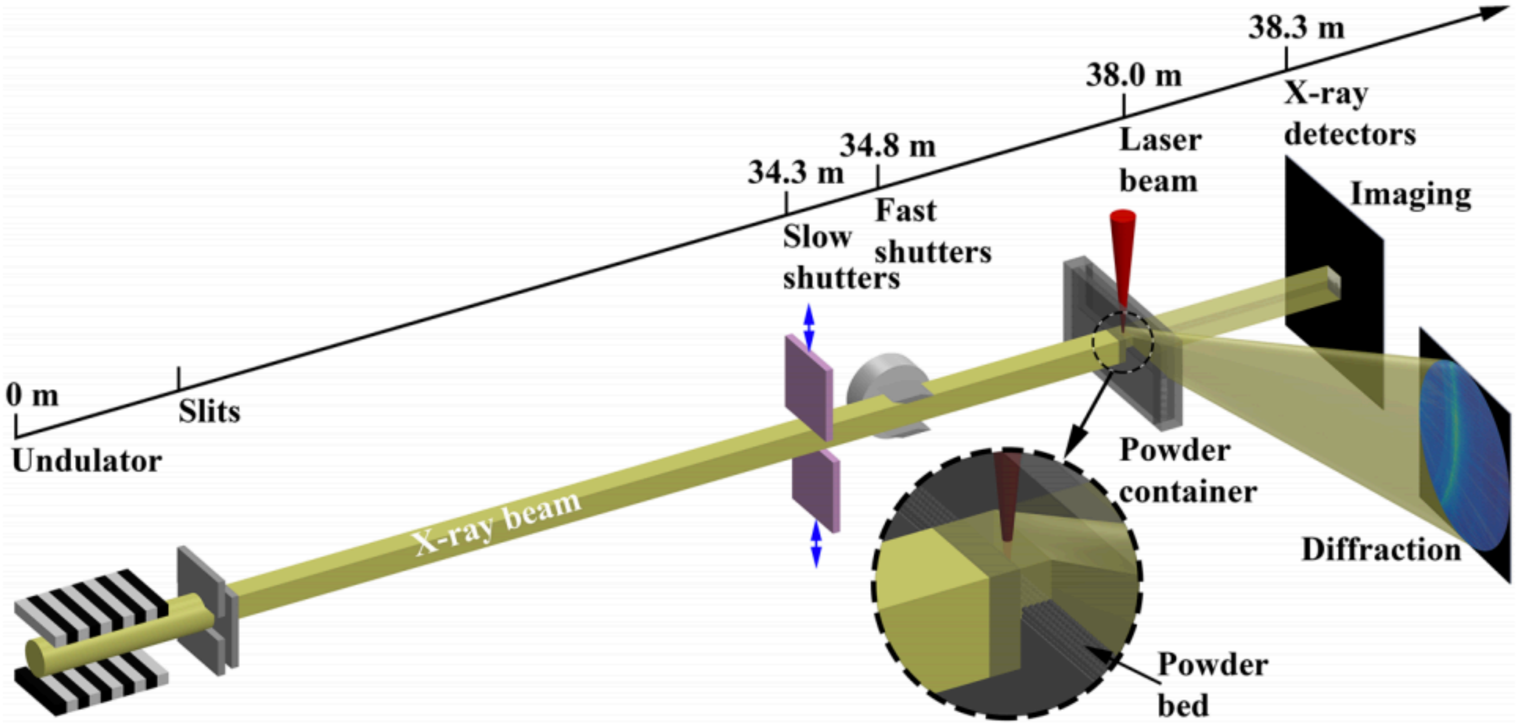
Random IN738
(neutron diffraction plans)

- Random build strategy
- 22mm x 15mm x 15mm



APS 2020

- Sector 32-ID: Argonne National Laboratory



C. Zhao, K. Fezzaa, R.W. Cunningham, H. Wen, F. De Carlo, L. Chen, A.D. Rollett, T. Sun, Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction, Sci. Rep. 7 (2017) 1–11.

AM simulator

- Experiments were performed at low, medium and high laser powers to sample a large portion of G-V space
  - Equiaxed grain IN718 samples (UCSB) were tested with and without a powder layer
  - Inoculated IN718 samples (Elementum3D) were test with an inoculated powder layer
  - IN738 samples were tested with and without a powder layer
  - All above sample were tested with spot and raster melt conditions
- Other inoculated Ni-alloys (Elementum3D) were also tested
  - IN625
  - Hastelloy 276
  - Rene 80
  - CM 247LC

Table of IN738 experiments

spot (1ms)

Material	Laser %	Power (W)
IN738	10	25
IN738	20	82
IN738	30	139
IN738	40	197
IN738	50	254
IN738	60	311
IN738	70	368
IN738 w/powder	10	25
IN738 w/powder	20	82
IN738 w/powder	30	139
IN738 w/powder	40	197
IN738 w/powder	50	254
IN738 w/powder	60	311
IN738 w/powder	20	82

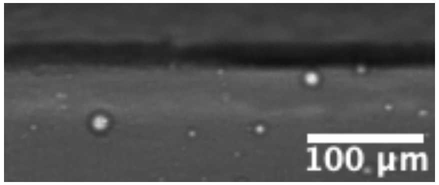
raster

Material	Laser %	Power (W)	Laser Speed (m/s)
IN738	40	197	0.5
IN738	30	139	0.5
IN738	35	168	0.5
IN738	20	82	0.25
IN738	90	483	2
IN738 w/powder	35	168	0.5
IN738 w/powder	40	197	0.5
IN738 w/powder	20	82	0.25
IN738 w/powder	90	483	2
IN738 w/powder	90	483	1.5

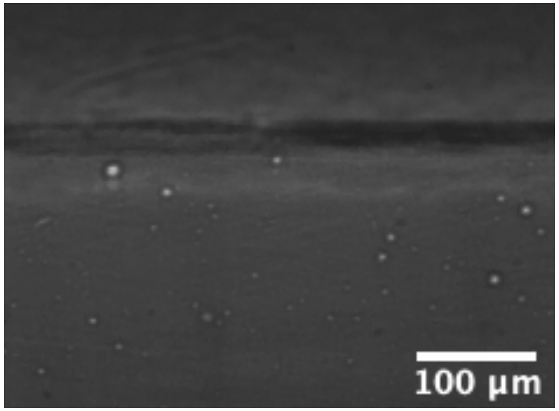
In-situ radiography (spot)

- Spot scans of IN738 at dwell time of 1ms (no powder)

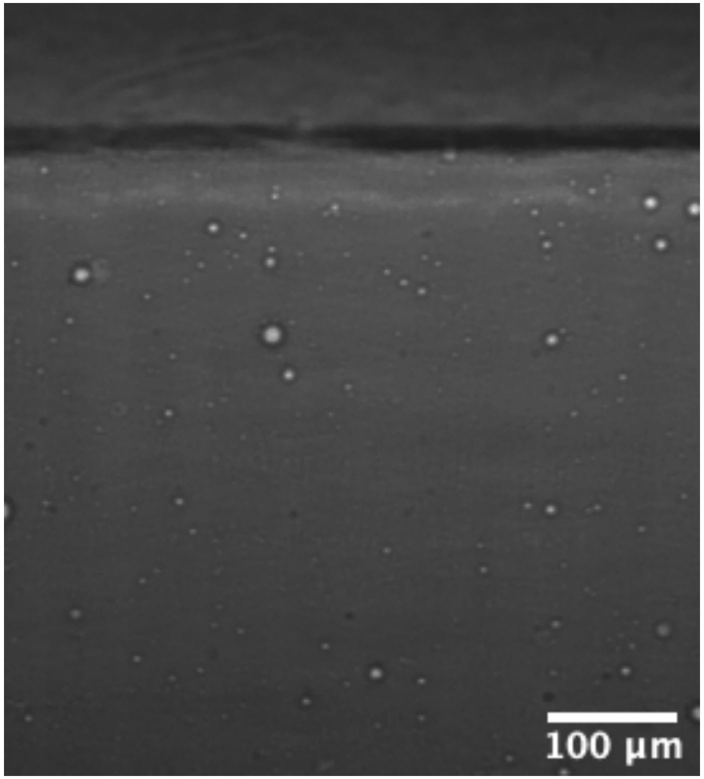
Low (20% - 82W)



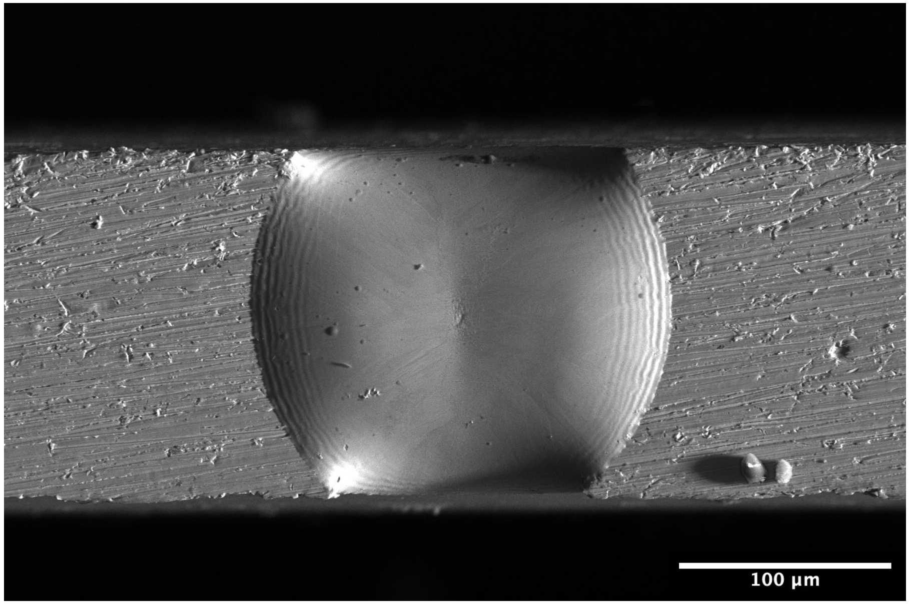
Medium (30% - 139W)

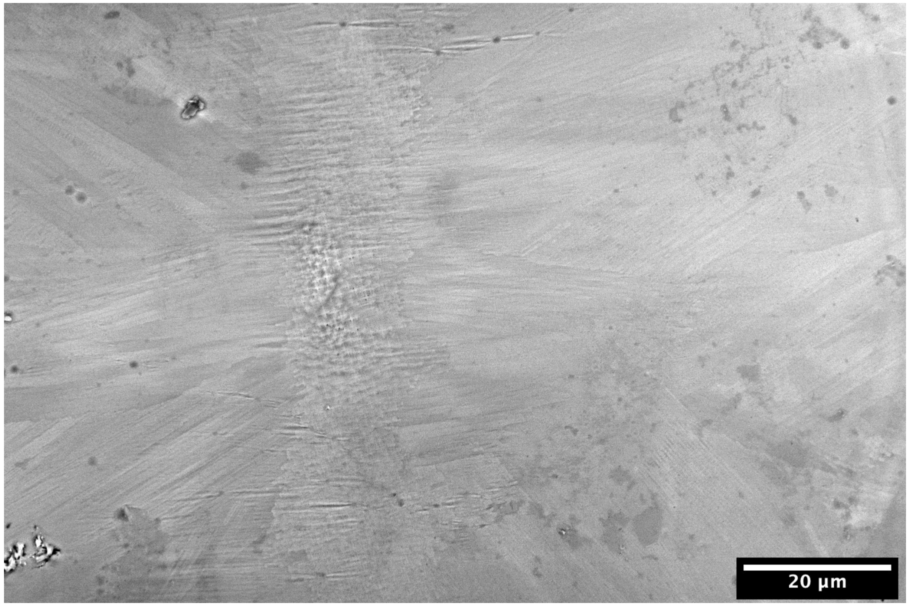


High (50% - 254W)



Spot melts – 82W (20%)





Spot melts – 139W (30%)

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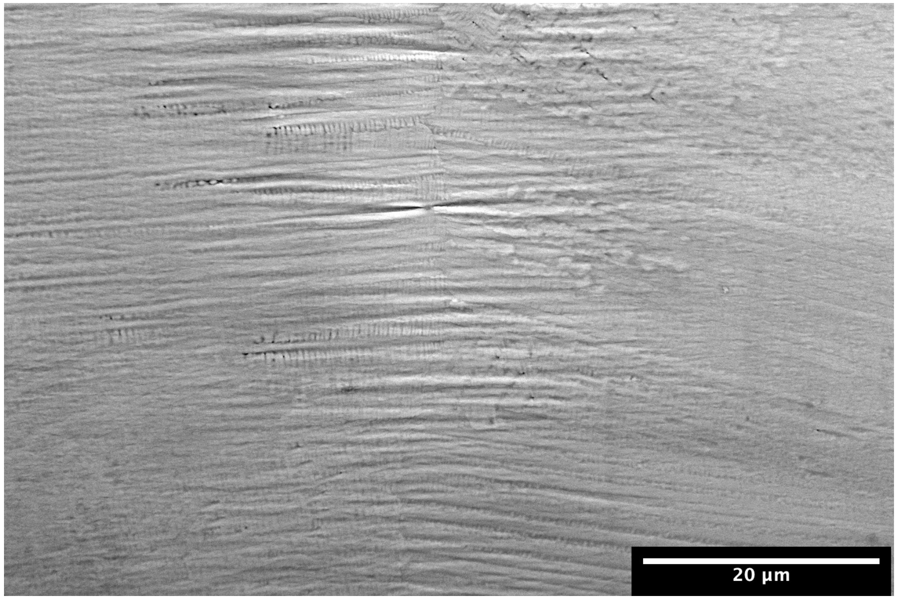

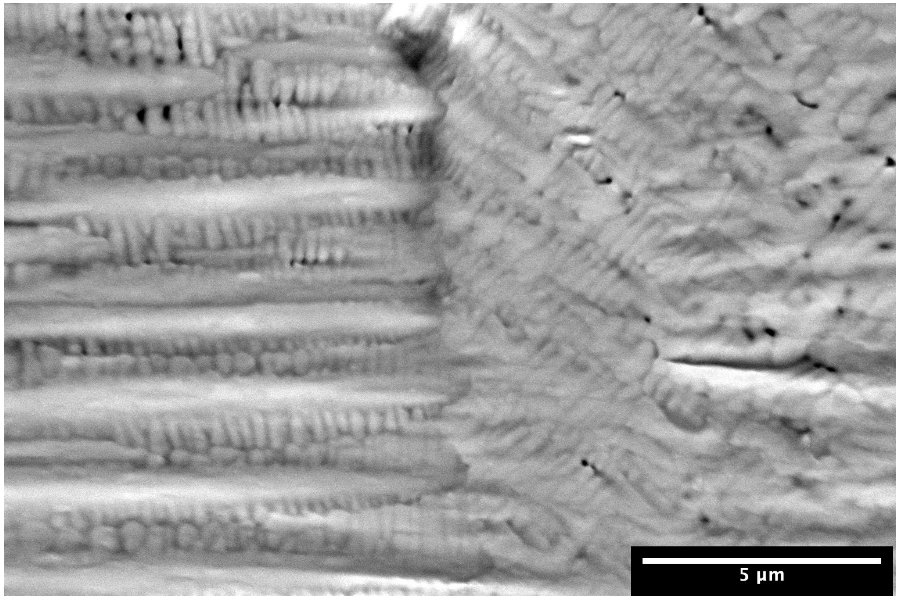

Spot melts – 254W (50%)

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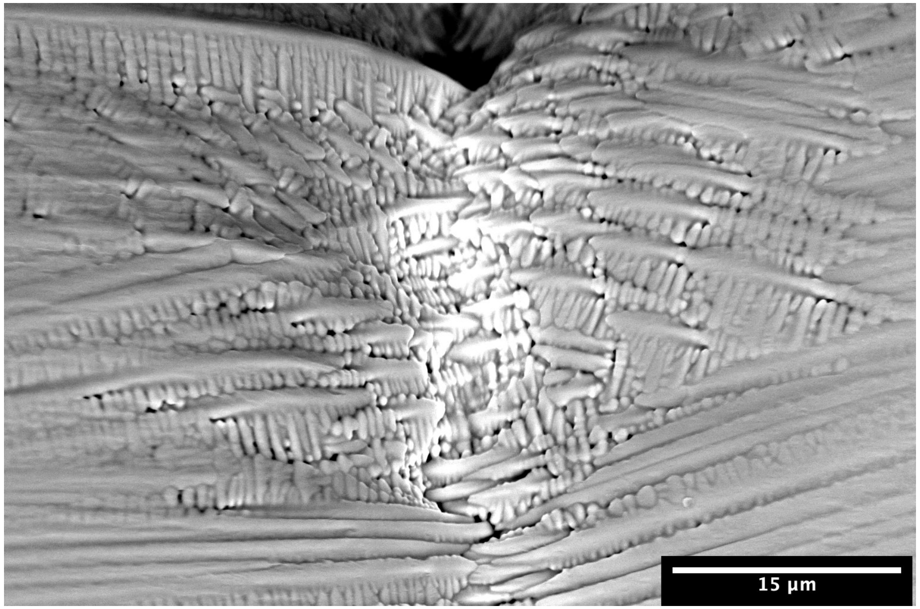
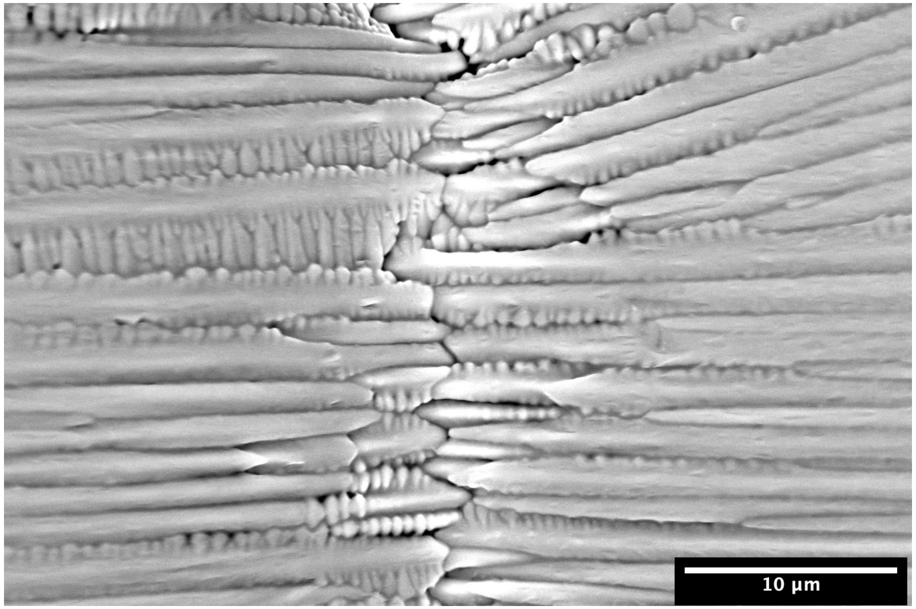
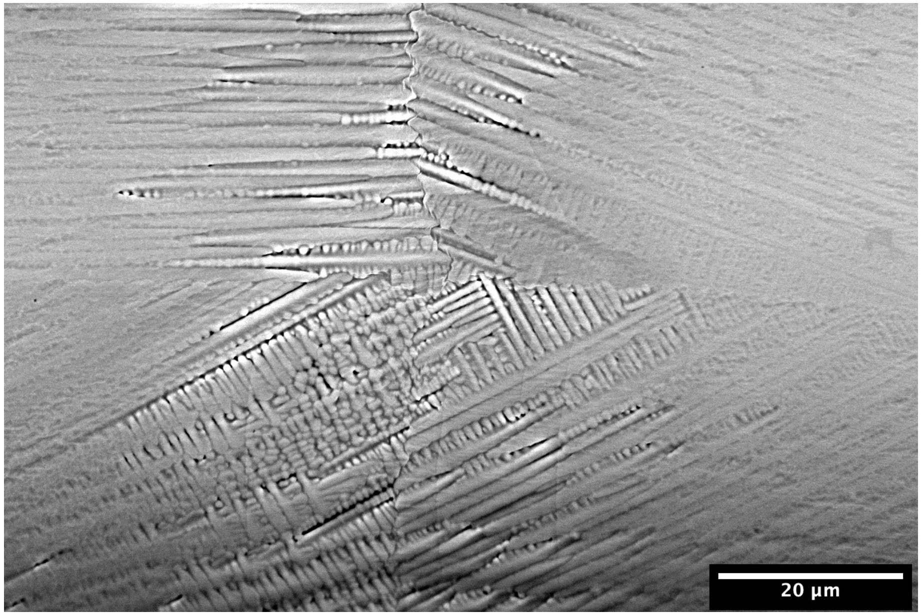
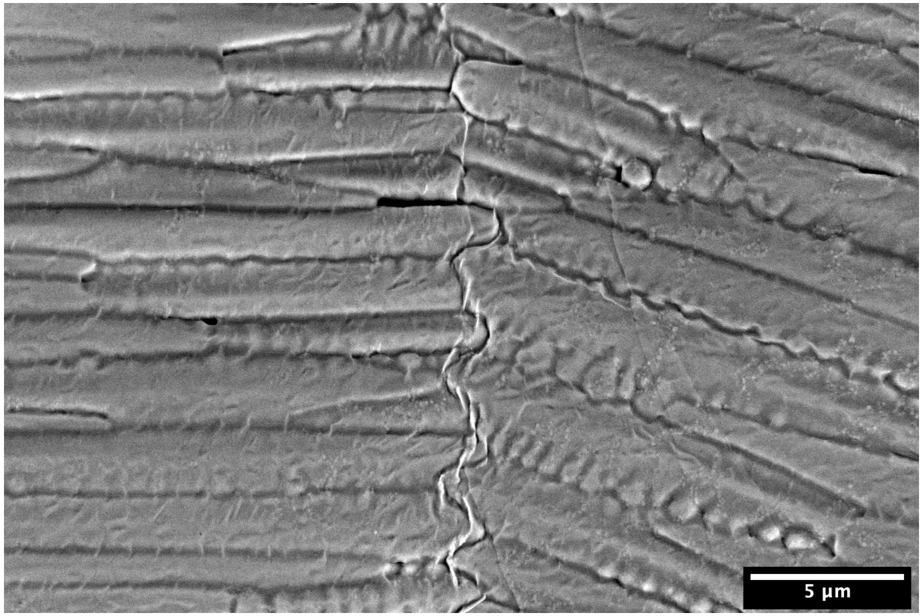


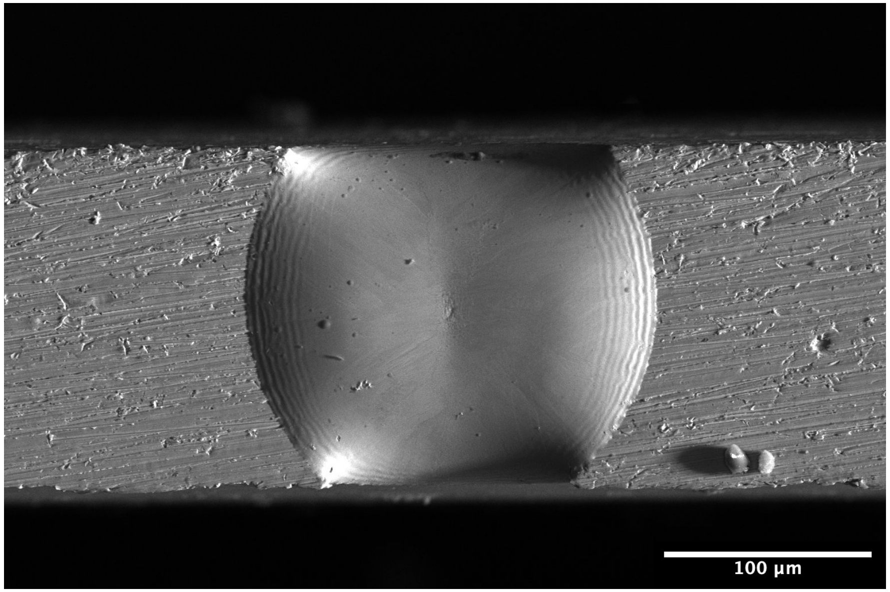


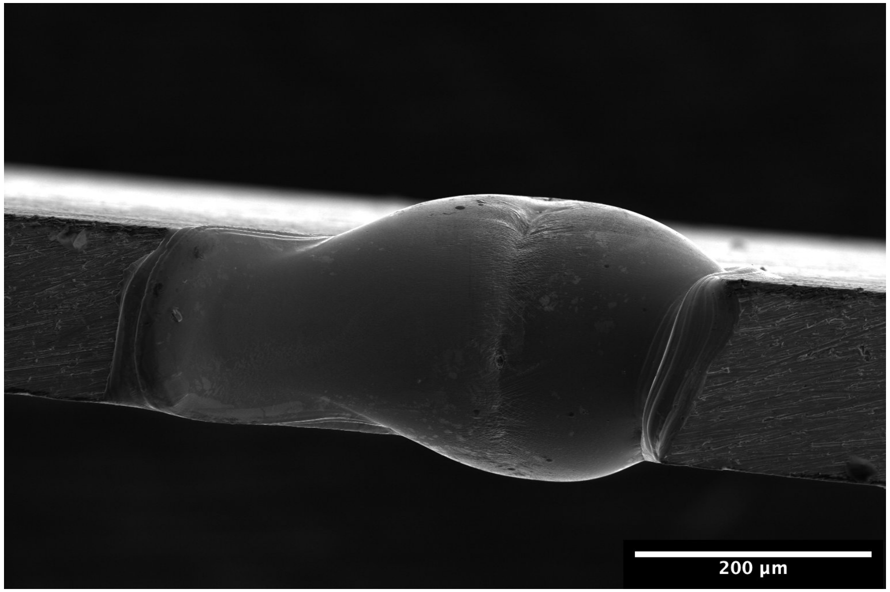
Spot melts – 311W (60%)





82W (20%) → 368W (70%)

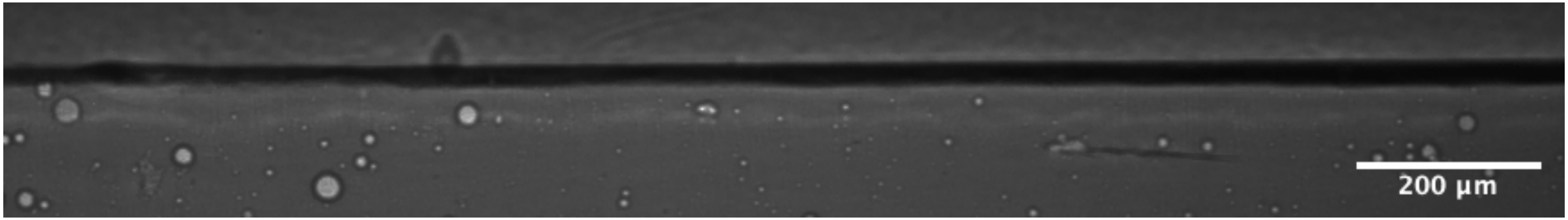




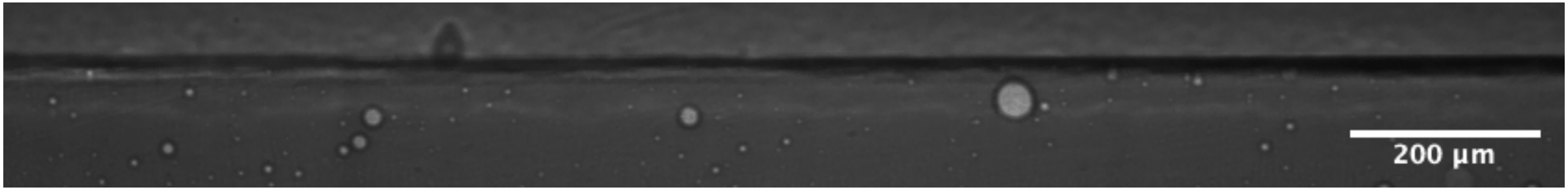
In-situ radiography (raster)

- Raster scans of IN738 at 0.5m/s (without powder)

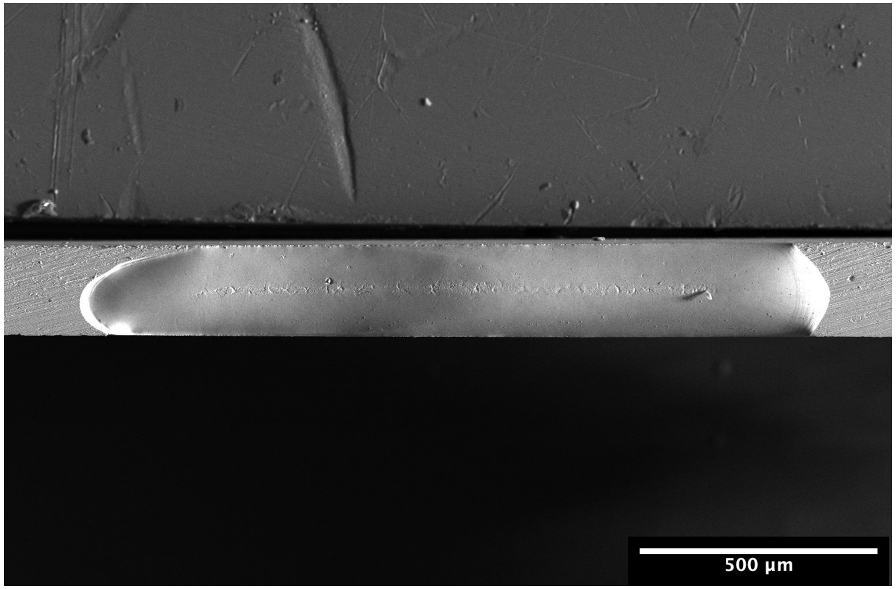
30% - 139W

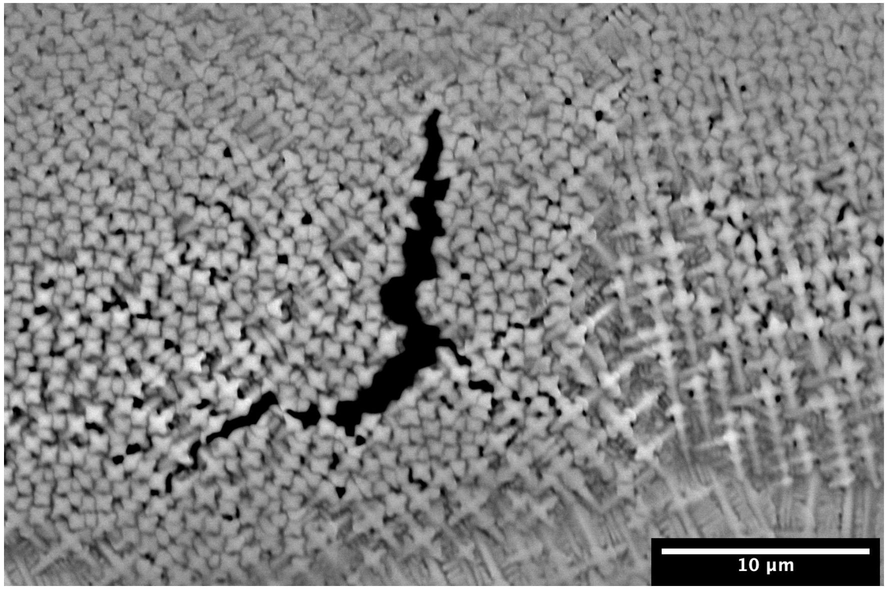


35% - 168W



Raster scans – 168W (35%) travel speed: 0.5m/s





Raster scans – 197W (40%) travel speed: 0.5m/s

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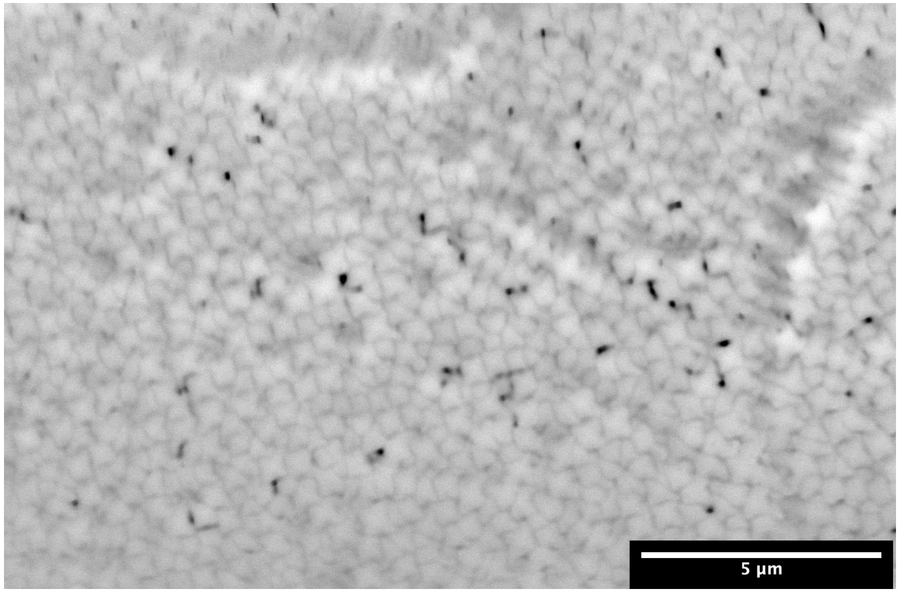

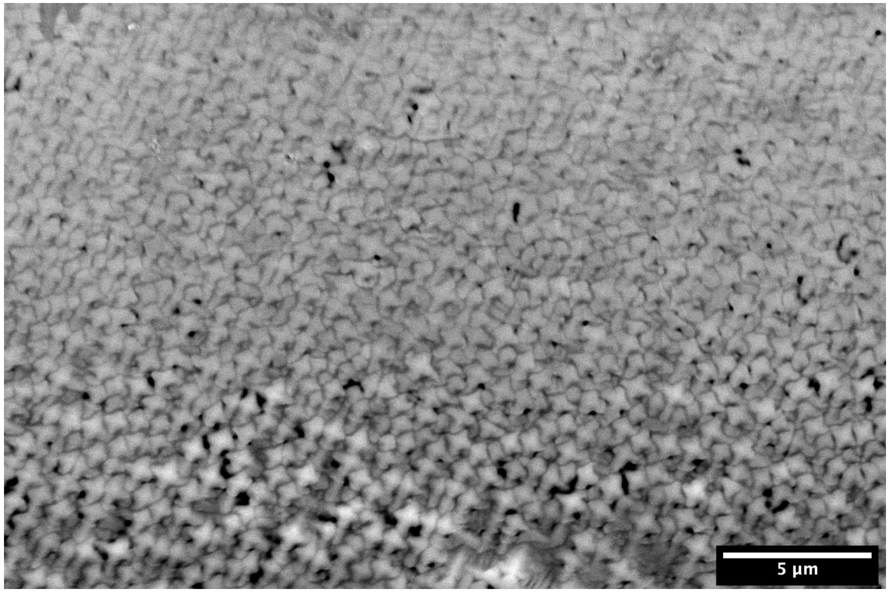

Raster scans – 82W (20%) travel speed: 0.25m/s

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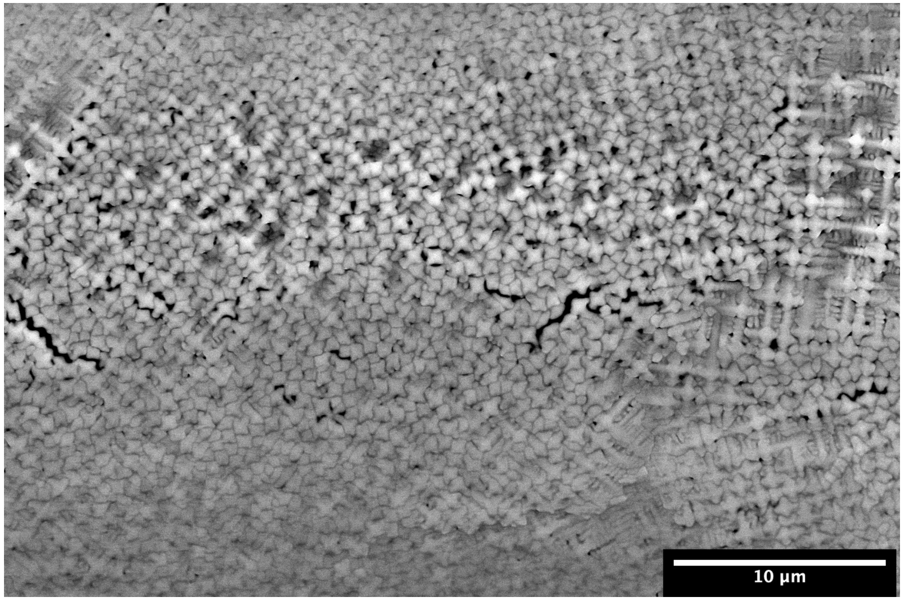

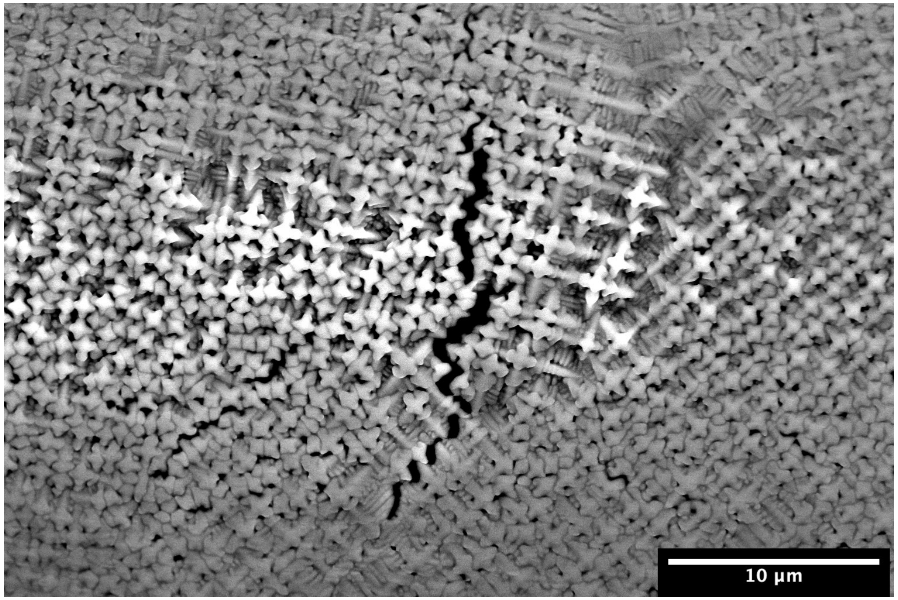

Raster scans – 483W (90%) travel speed: 2m/s

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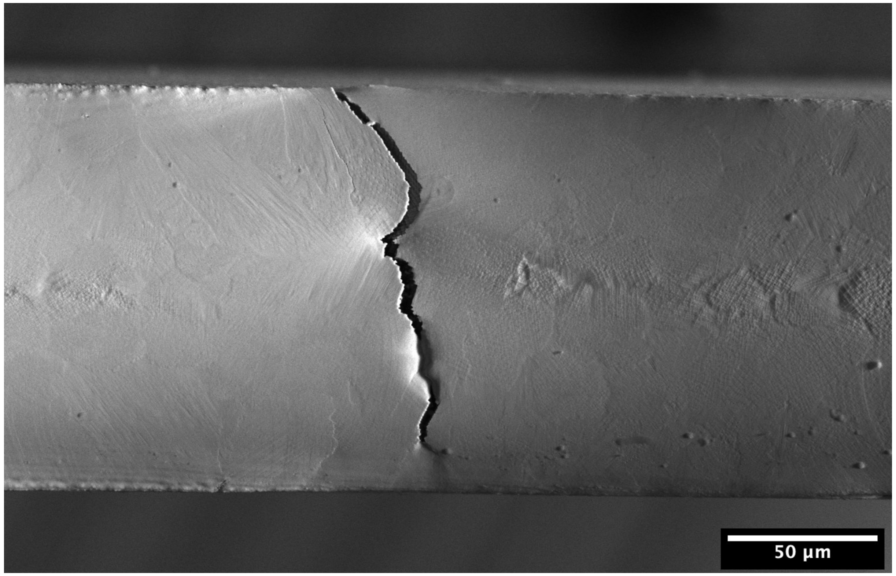

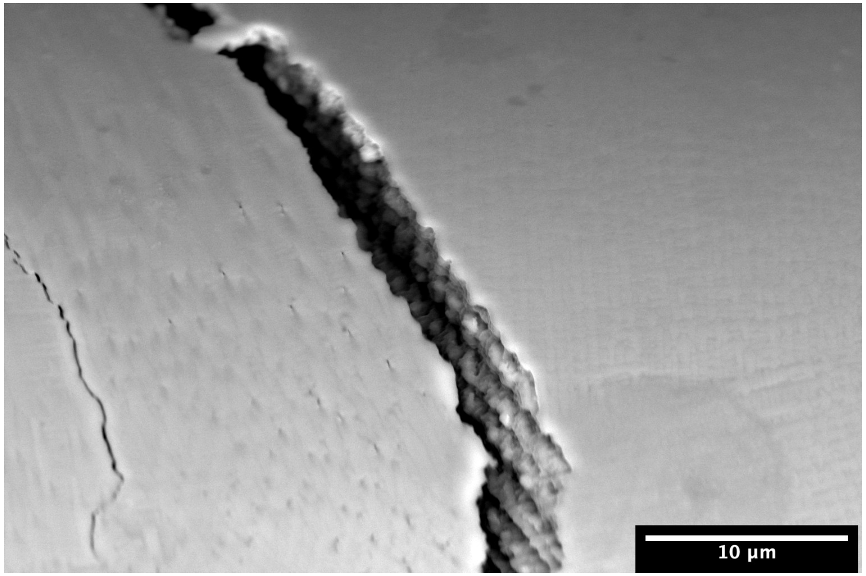

Future Work

- Calculating solid/liquid interface velocities of melt pool from synchrotron x-ray radiography
- Using FLOW-3D simulation software to find thermal gradients
- Post-mortem analysis for EBSD of cross sections using metallography and electron microscopy
- Neutron diffraction experiments to analyze texture as a function of local processing conditions related to geometry and scan strategy, trying to understand origins of anisotropic behavior in AM

Challenges & Opportunities

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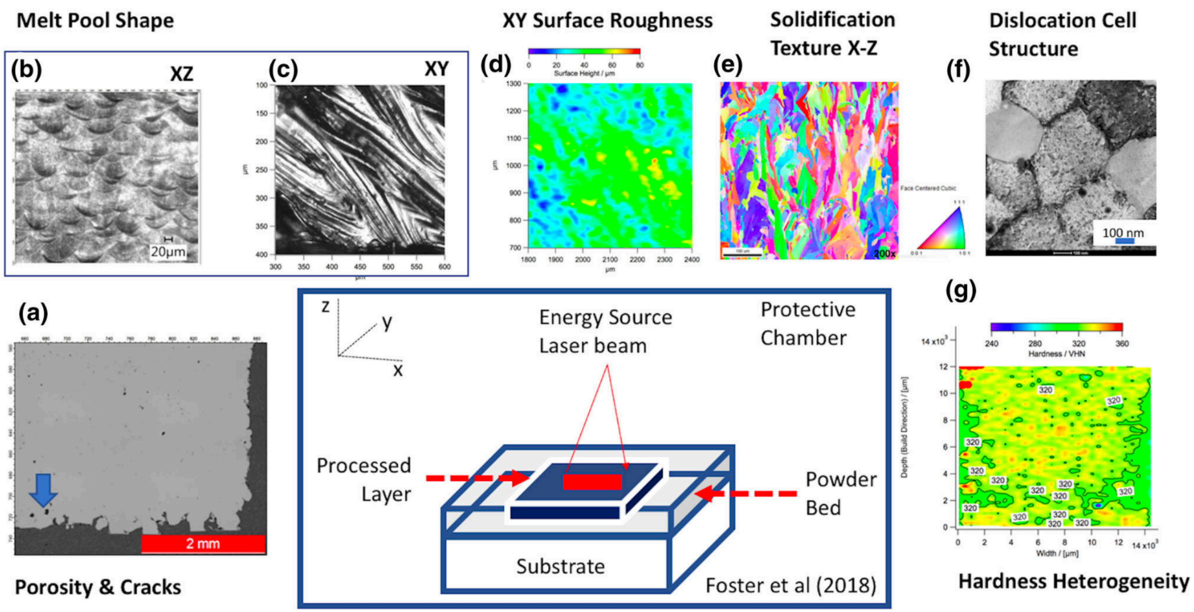
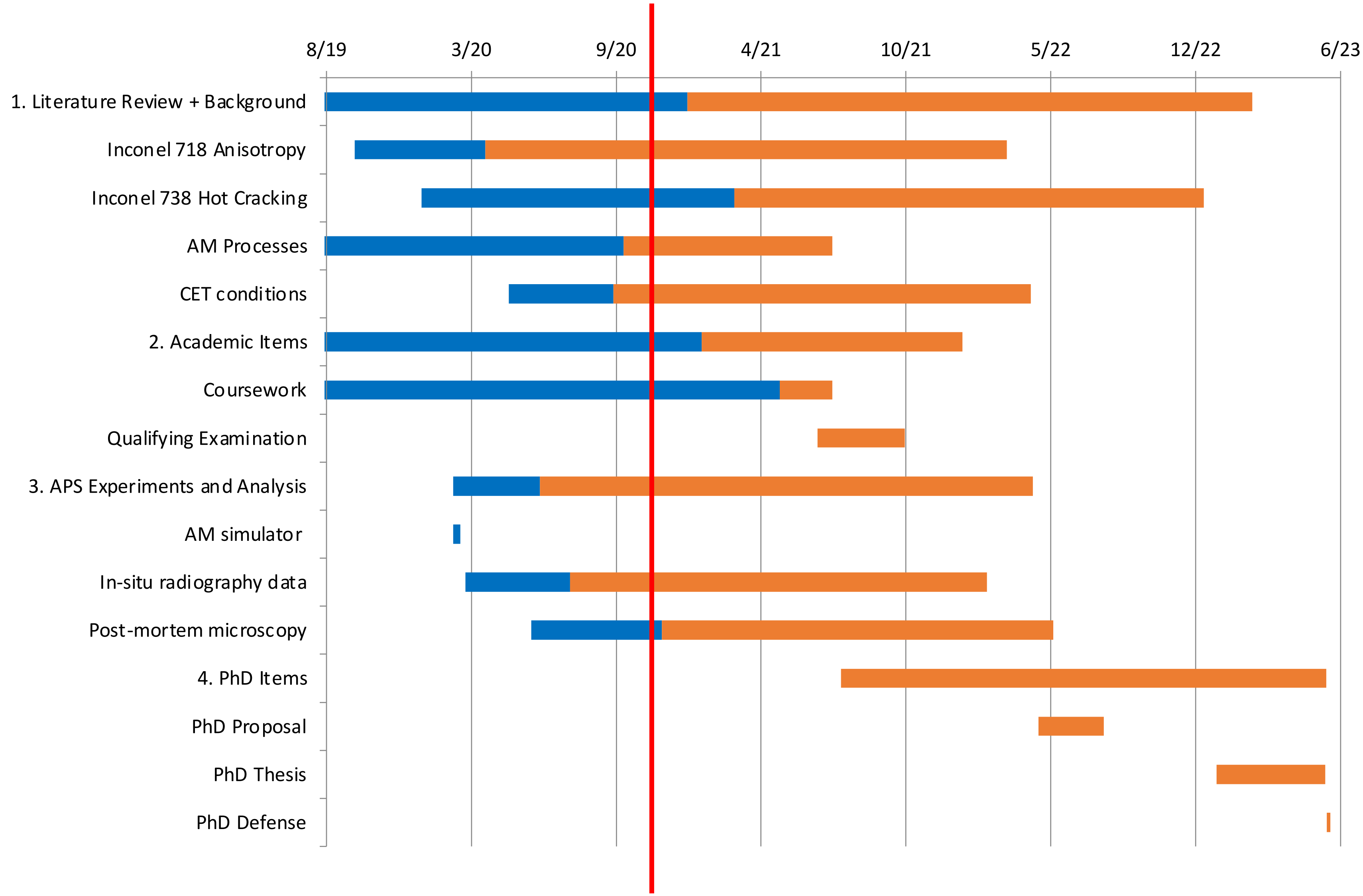
- Challenges
  - Radiography data of powder layer is difficult to analyze
  - Cracking in IN738 may be caused by more than one mechanism
  - New geometry builds from ORNL are more complicated than previous prisms
- Opportunities
  - Defining AM parameters to fine-tune the microstructure



S.S. Babu, N. Raghavan, J. Raplee, S.J. Foster, C. Frederick, M. Haines, R. Dinwiddie, M.K. Kirka, A. Plotkowski, Y. Lee, R.R. Dehoff, Additive Manufacturing of Nickel Superalloys: Opportunities for Innovation and Challenges Related to Qualification, Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 49 (2018) 3764–3780.

Progress



8/19
3/20
9/20
4/21
10/21
5/22
12/22
6/23
1. Literature Review + Background
Inconel 718 Anisotropy
Inconel 738 Hot Cracking
AM Processes
CET conditions
2. Academic Items
Coursework
Qualifying Examination
3. APS Experiments and Analysis
AM simulator
In-situ radiography data
Post-mortem microscopy
4. PhD Items
PhD Proposal
PhD Thesis
PhD Defense

Thank you!

Jeremy Shin
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Project 36D-L: Characterizing Additively Manufactured Inconel 718 & 738

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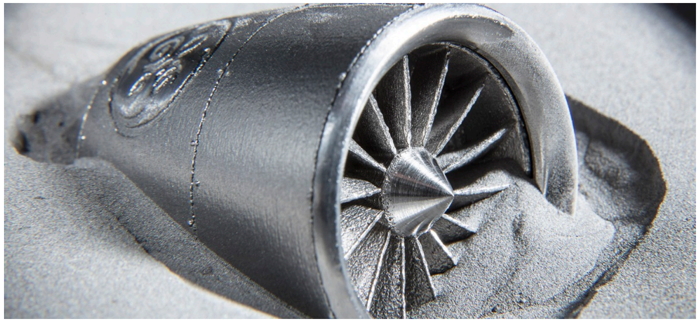
Faculty: *Amy Clarke*

Industrial Partners: *John Carpenter (LANL), Matt Krug (AFRL)*

Project Duration: *September 2019 – May 2023*



Achievement

- Understanding of rapid solidification during AM and its effect on underlying microstructure and material properties

Significance and Impact

- Determination of microstructural evolution in AM allows for a more reliable processing for product realization of engineering components

Research Details

- Analyzing in-situ radiography data of different power conditions and relating this to ex-situ electron microscopy

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Project Duration: *September 2019 – May 2023*

Program Goal

- Better understanding of underlying microstructure that occurs from AM melt phenomena in order to avoid unwanted material properties

Approach

- Utilize in-situ radiography from synchrotron source to capture real-time solidification dynamics, and compare to post-mortem microscopy

Benefits

- Provide a predictive methodology for AM processes to avoid structural defects and mechanical anisotropy