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

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

Summer 2020 Videoconference

June 29 – July 1, July 8 – 10 2020

Student: Jeremy Shin (Mines)

Faculty: Dr. Amy Clarke (Mines)

Industrial Mentors: TBD

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

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

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

- 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

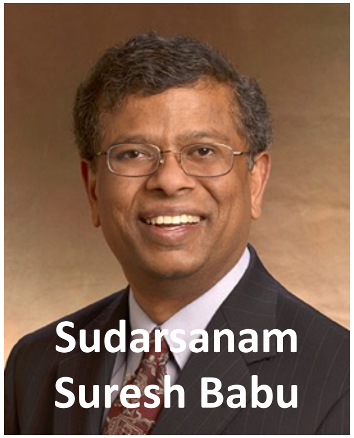
- Advanced Photon Source (APS) experiments on IN718 and IN738
- Post-mortem imaging of melt pool areas for IN738
- Solid-liquid (S/L) interface measurements on *in-situ* radiography data from APS 2020

Metrics

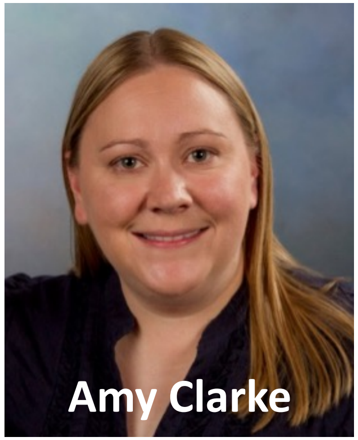
Description	% Complete	Status
1. Literature review	35%	●
2. Analysis of APS 2020 *in-situ* radiography data	20%	●
3. Ex-situ metallography and microscopy for APS samples	15%	●
4. Initial microstructural characterization of as-built Inconel 738	10%	●

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

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS



THE UNIVERSITY OF TENNESSEE KNOXVILLE



COLORADO SCHOOL OF MINES

I STATE

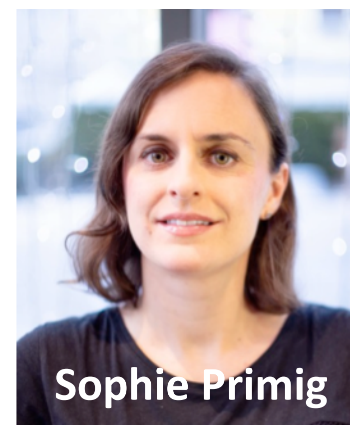
THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Office of Naval Research ONR Science & Technology

VIRGINIA TECH.

UC SANTA BARBARA MATERIALS

THE UNIVERSITY OF SYDNEY
Core Research Facilities

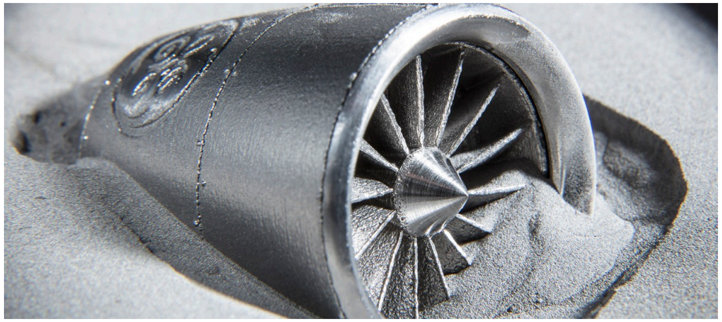


UNSW SYDNEY

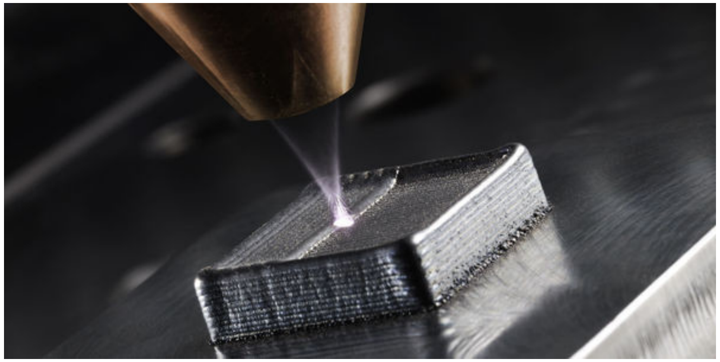
Center Proprietary – Terms of CANFSA Membership Agreement Apply

Industrial Relevance

- AM allows complex geometries and near-net shapes
- Eliminate additional processing steps and save material costs
- Understanding the microstructure is key:
  - Large thermal gradients
  - Thermal cycling
  - Lack of fusion defects
  - Anisotropy along build direction



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



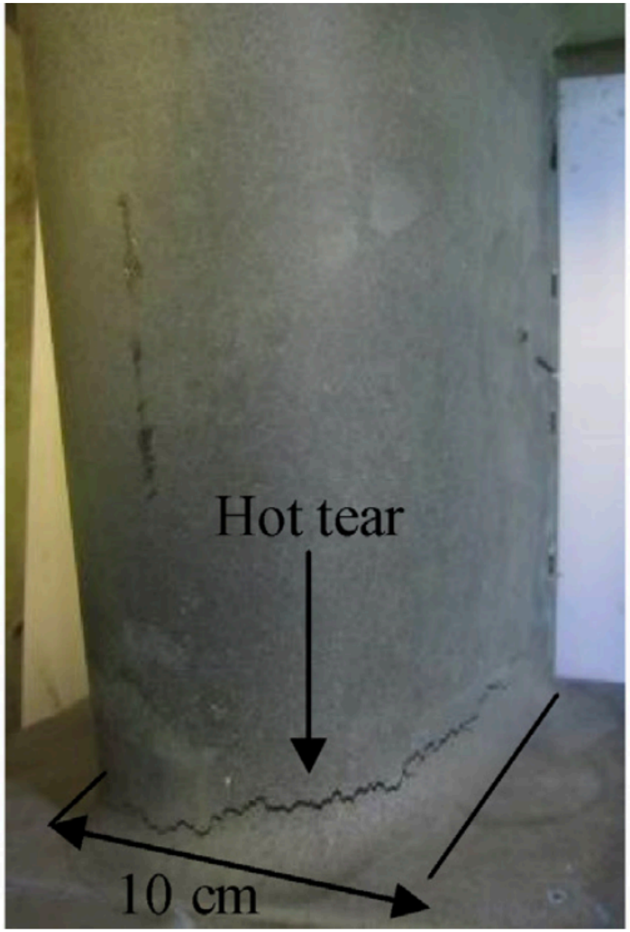
https://www.etmm-online.com/german-italian-laser-companies-ally-to-develop-metal-additive-manufacturing-a-452137/

Objectives

- Identify a hot cracking regime in G-V space for IN738
  - AM process for spot and raster melts with and without a powder layer
  - Track the solid/liquid interface of the melt pool during solidification
  - Relate ex-situ electron microscopy to in-situ radiography data
- Analyze texture/microstructure as a function of local conditions for as-built IN738

Background

- Both IN718 and IN738 are precipitation strengthened alloys[1]
  - Commonly used for aerospace applications at high temperatures
- IN738 is susceptible to hot cracking upon rapid solidification
  - Excessive thermal stresses occur when growth of dendrites restricts liquid flow to the interdendritic regions during solidification[2]
  - High concentration of Al and Ti (~6.7wt%) leads to segregation at GBs[3]
- Some studies show:
  - Decreasing power density leads to finer microstructure[4]
  - Environmental chamber at elevated temperatures increases ductility[5]

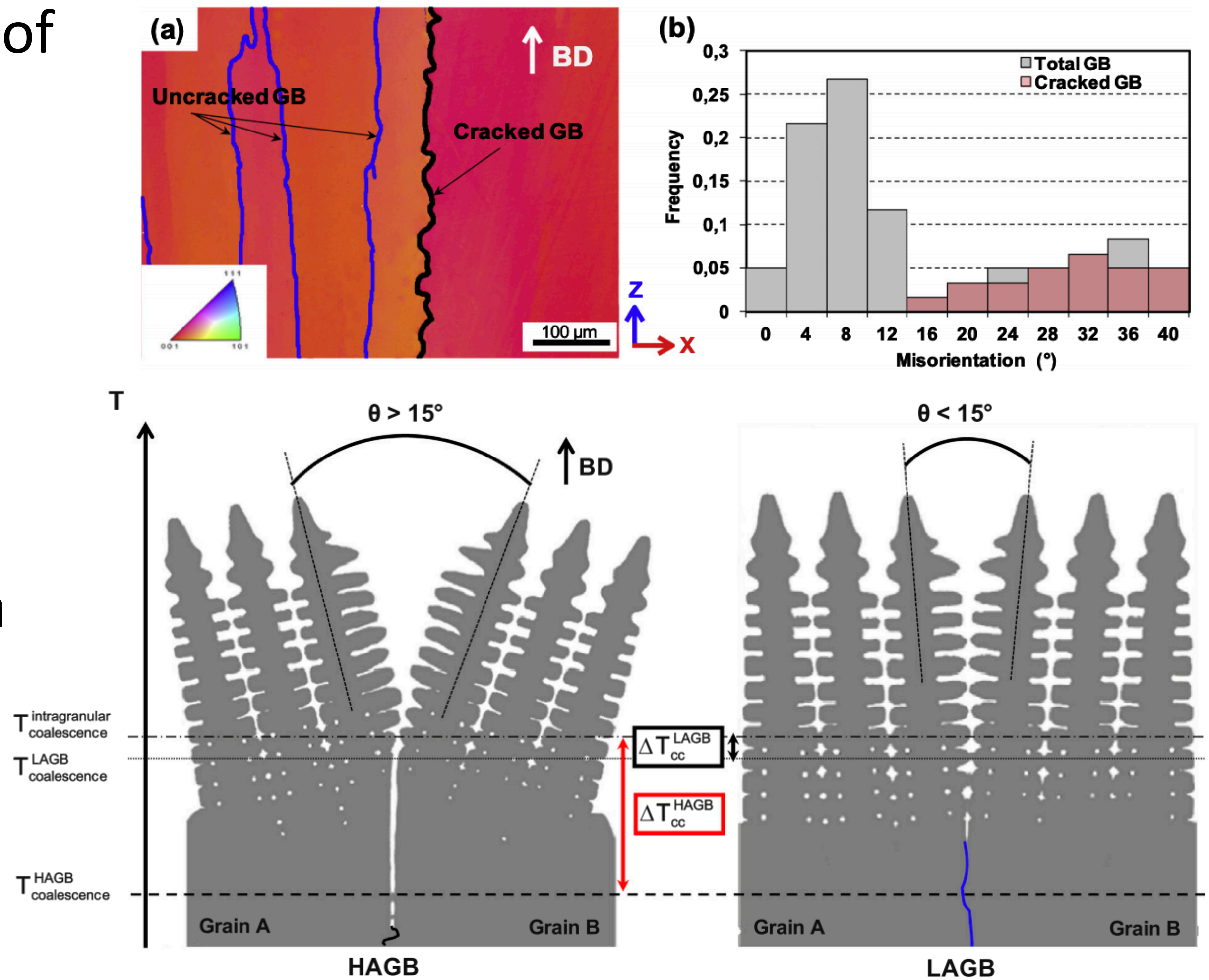


D. Heydari, A.S. Fard, A. Bakhshi, J.M. Drezet, Hot tearing in polycrystalline Ni-based IN738LC superalloy: Influence of Zr content, J. Mater. Process. Technol. 214 (2014) 681–687.

Background

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

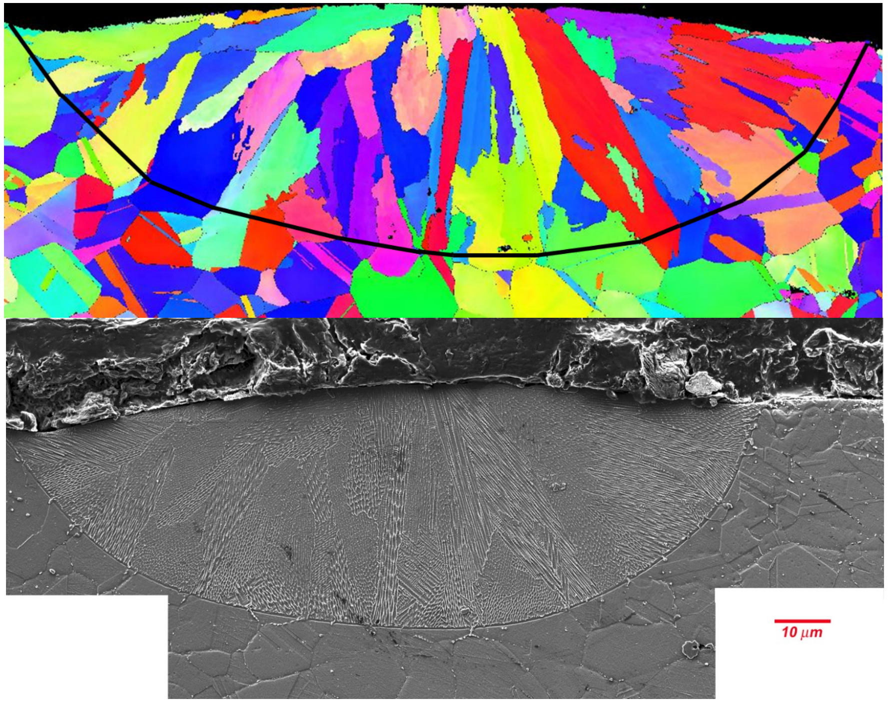
- The cracked regions of IN738 occur along high-angle grain boundaries (HAGB)
- The large misorientation accounts for the trapped liquid in the interdendritic region



E. Chauvet, P. Kontis, E.A. Jägle, B. Gault, D. Raabe, C. Tassin, J.J. Blandin, R. Dendievel, B. Vayre, S. Abed, G. Martin, Hot cracking mechanism affecting a non-weldable Ni-based superalloy produced by selective electron Beam Melting, Acta Mater. 142 (2018) 82–94.

Background

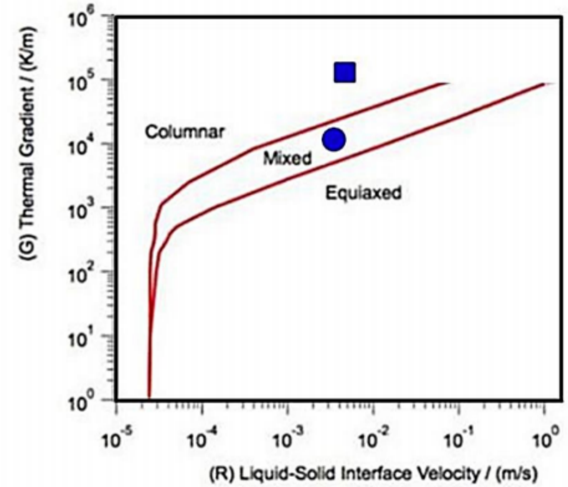
- Laser power and velocity (P-V) control solidification behavior
- Ni-based alloys have a preferred solidification behavior with columnar dendritic growth with a <100> fiber texture[6]
- The microstructure is different along the build direction
  - Bottom of the melt pool: columnar grains (higher G and lower V)
  - Top of the melt pool: equiaxed grains (lower G and higher V)



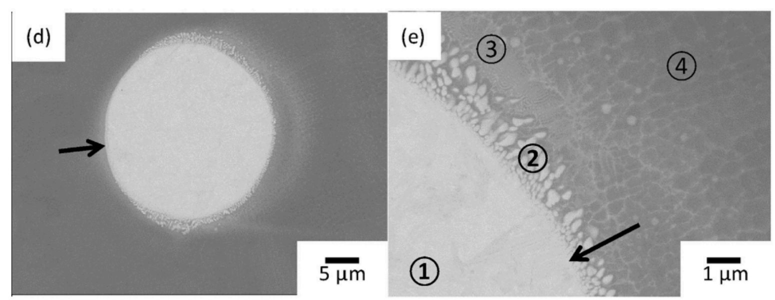
https://www.nist.gov/ambench/amb2018-02-description

Background

- The columnar to equiaxed transition (CET) is when dendritic growth changes to finer, equiaxed grains
  - Depends on the thermal gradient and solidification velocity (G-V)[7]
  - Typical values[8] for IN718 made by SLM process show a range of 20-100 K*s/mm^2
- Addition of inoculants can change microstructure
  - Heterogeneous nucleation will occur ahead of the solidification front[9]
  - The CET condition is easily initiated
  - More uniform microstructure



H.L. Wei, T. Mukherjee, T. DebRoy, Grain Growth Modeling for Additive, Proc. 6th Int. Conf. Recryst. Grain Growth, ReX GG 2016. (2016) 265–269.



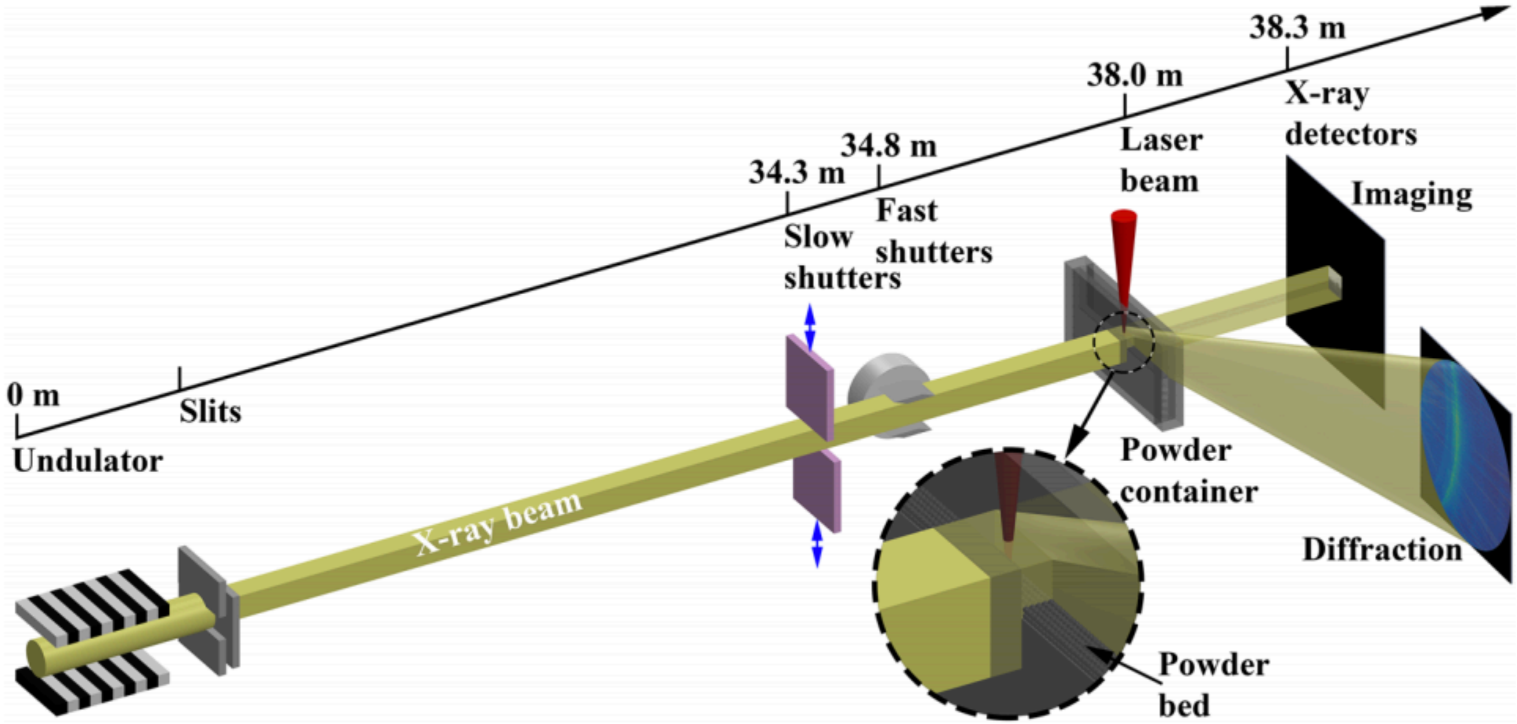
The arrows indicate the inoculants.

I.T. Ho, Y.T. Chen, A.C. Yeh, C.P. Chen, K.K. Jen, Microstructure evolution induced by inoculants during the selective laser melting of IN718, Addit. Manuf. 21 (2018) 465–471.

APS 2020

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

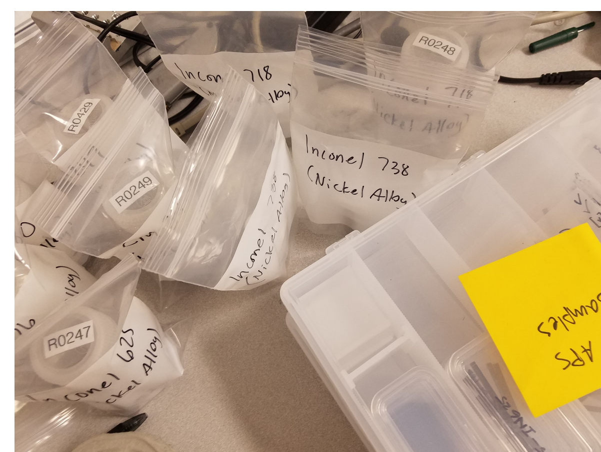
- Sector 32-ID: Argonne National Laboratory



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

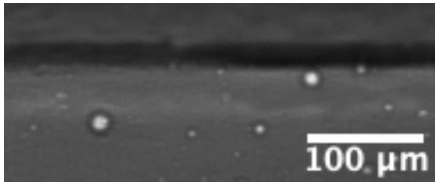
- Experiments were performed at low, medium and high laser powers to sample a large portion of G-V space
  - Equiaxed grain IN718 samples (UCSB) were tested with and without a powder layer
  - Inoculated IN718 samples (Elementum3D) were test with an inoculated powder layer
  - IN738 samples were tested 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



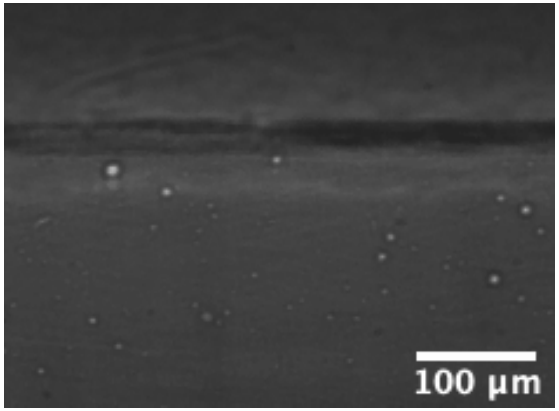
In-situ radiography (spot)

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

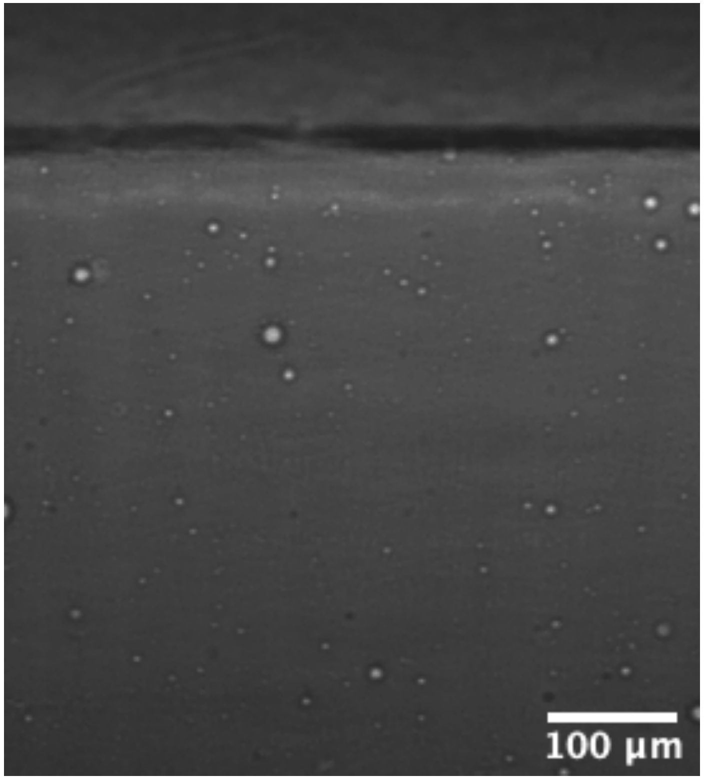
Low (20% - 82.19W)



Medium (30% - 139.42W)

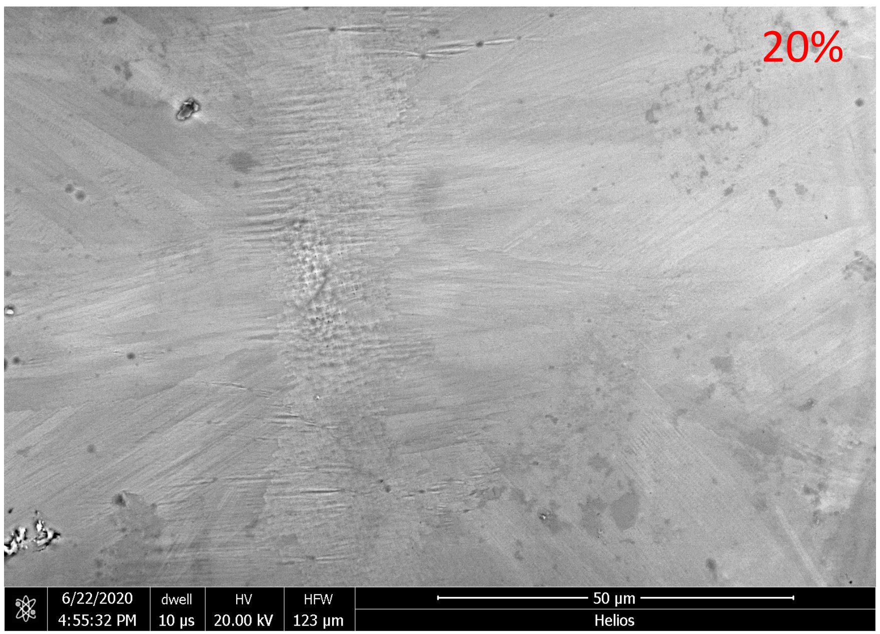


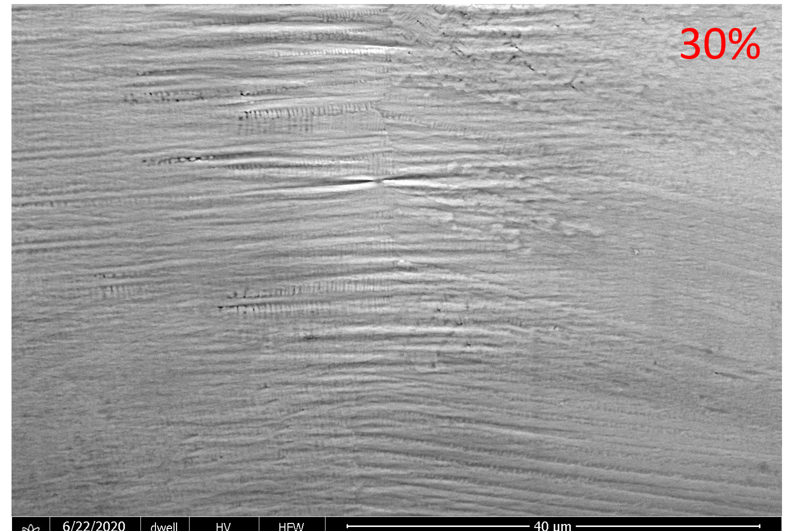
High (50% - 253.89W)

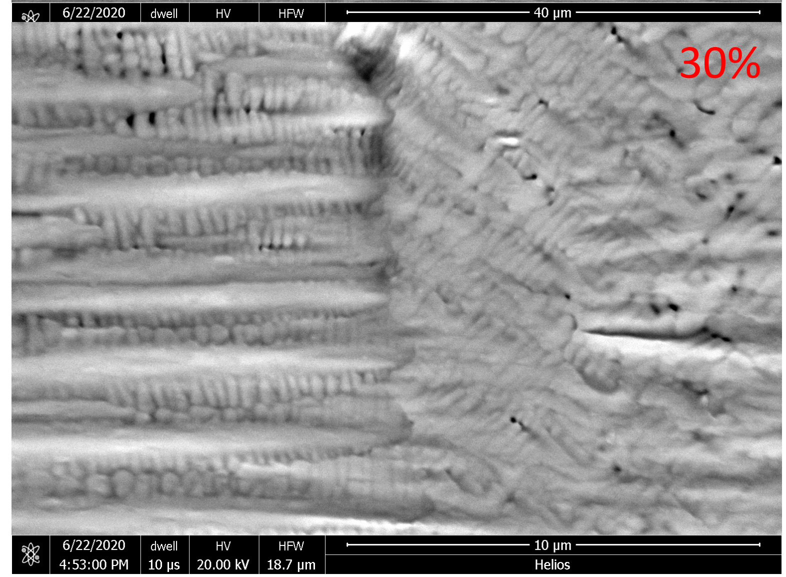


Top-down images of IN738

CANFSA
CENTER FOR ADVANCED
NON-FERROUS STRUCTURAL ALLOYS

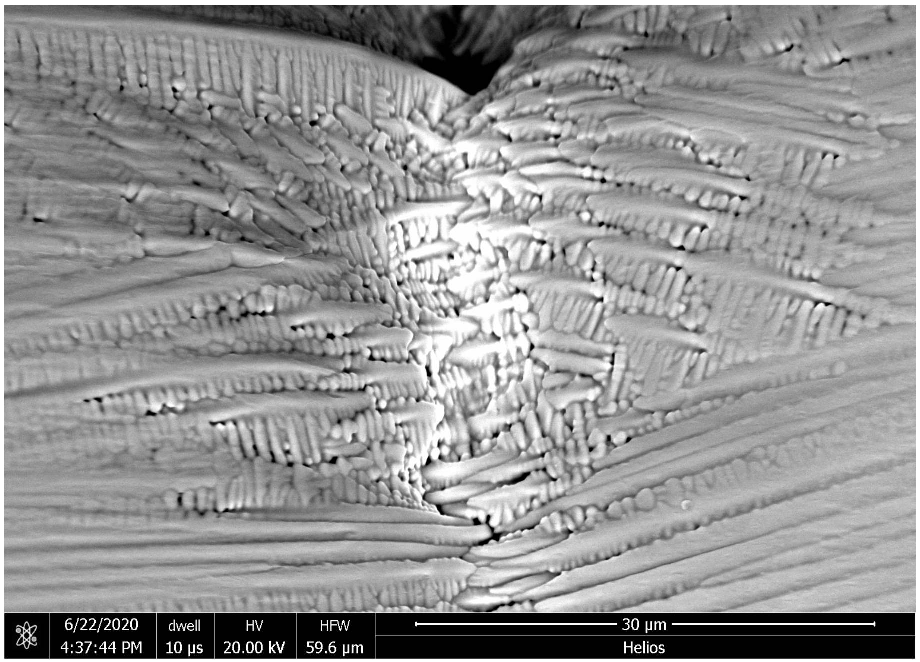


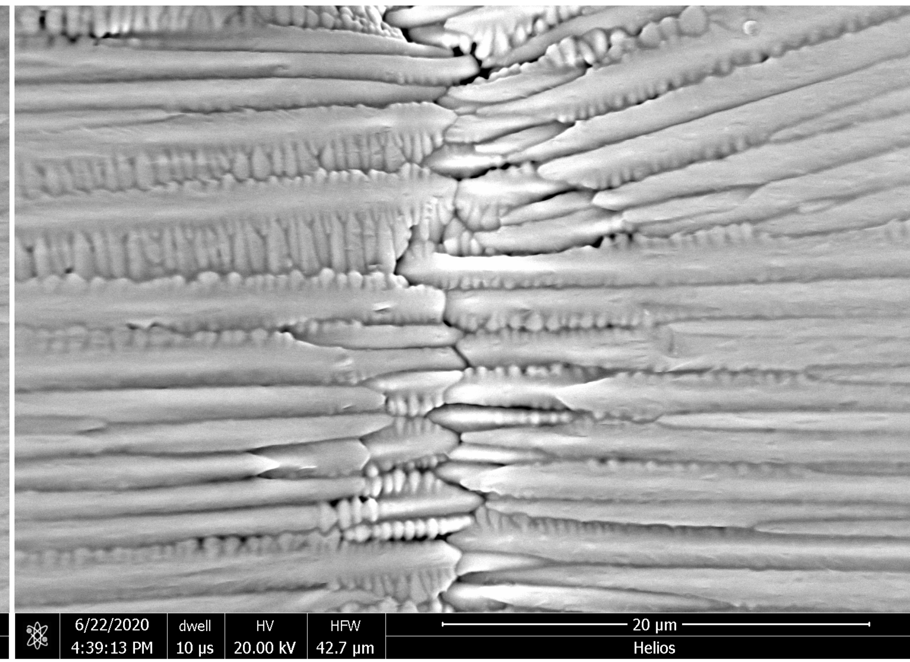




Top-down images of IN738

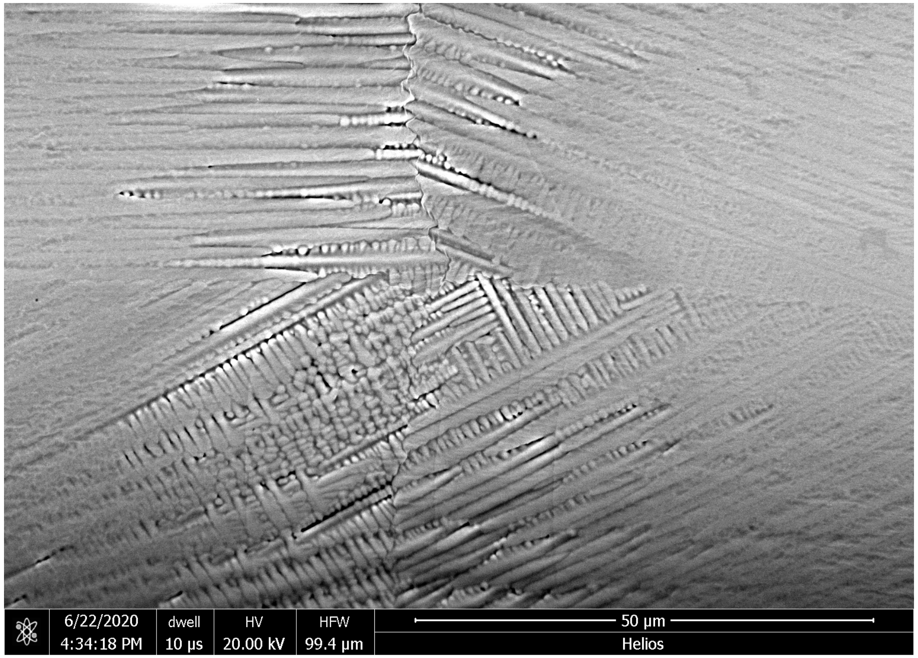
50%

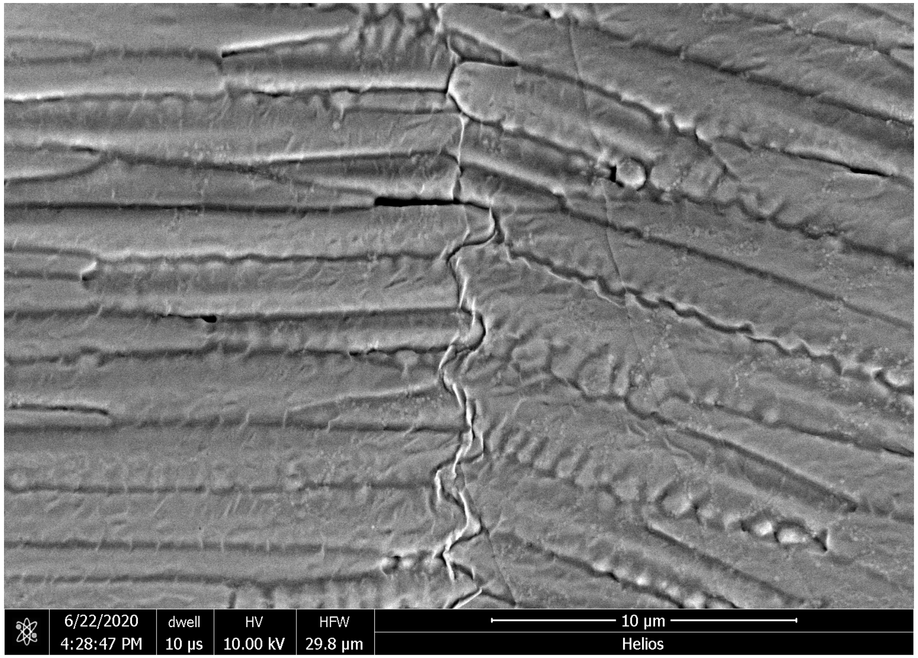




Top-down images of IN738

60%

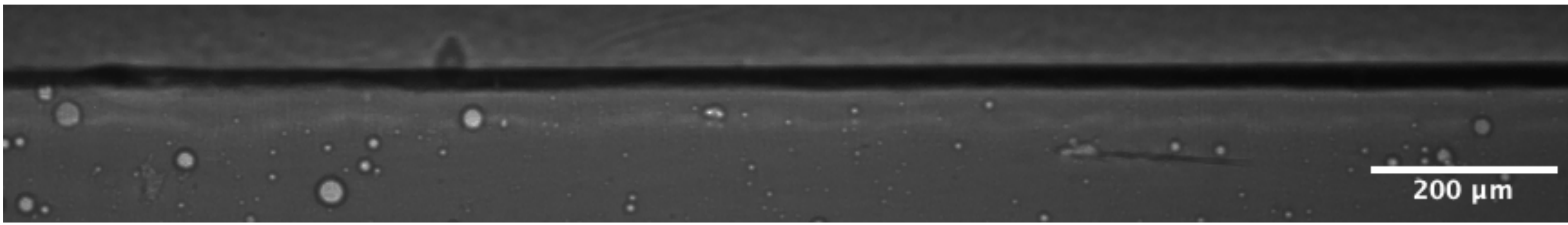




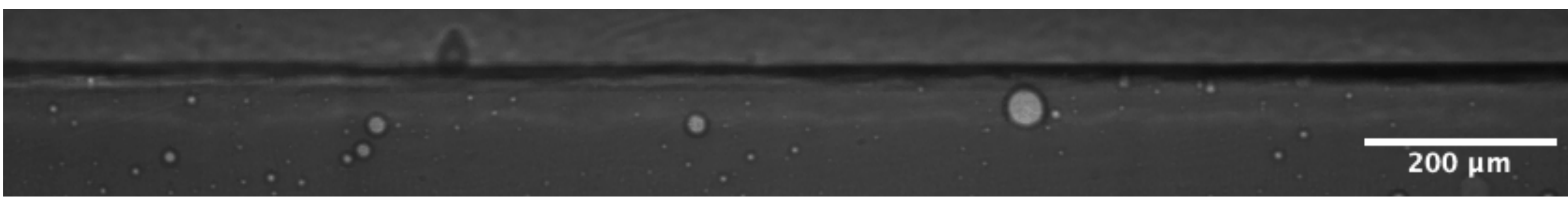
In-situ radiography (raster)

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

30%



35%

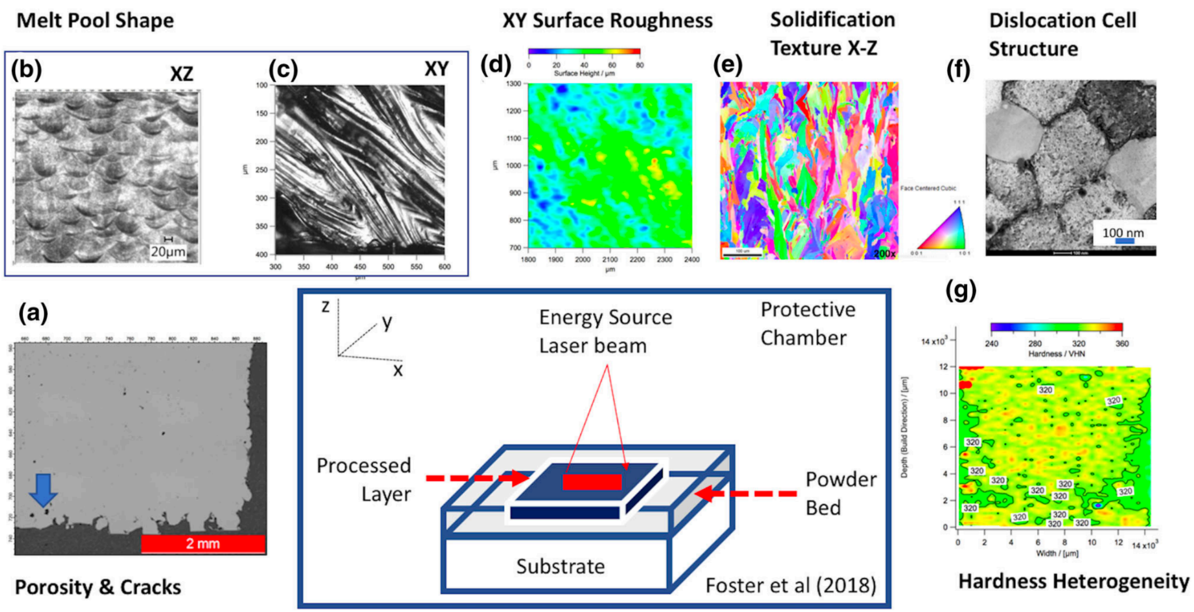


Future Work

- Determination of solid/liquid interface velocities from synchrotron x-ray radiography
- Post-mortem analysis of cross sections using metallography and electron microscopy
- Define a hot cracking regime for IN738
- Neutron diffraction experiments to analyze texture as a function of local processing conditions related to geometry and scan strategy

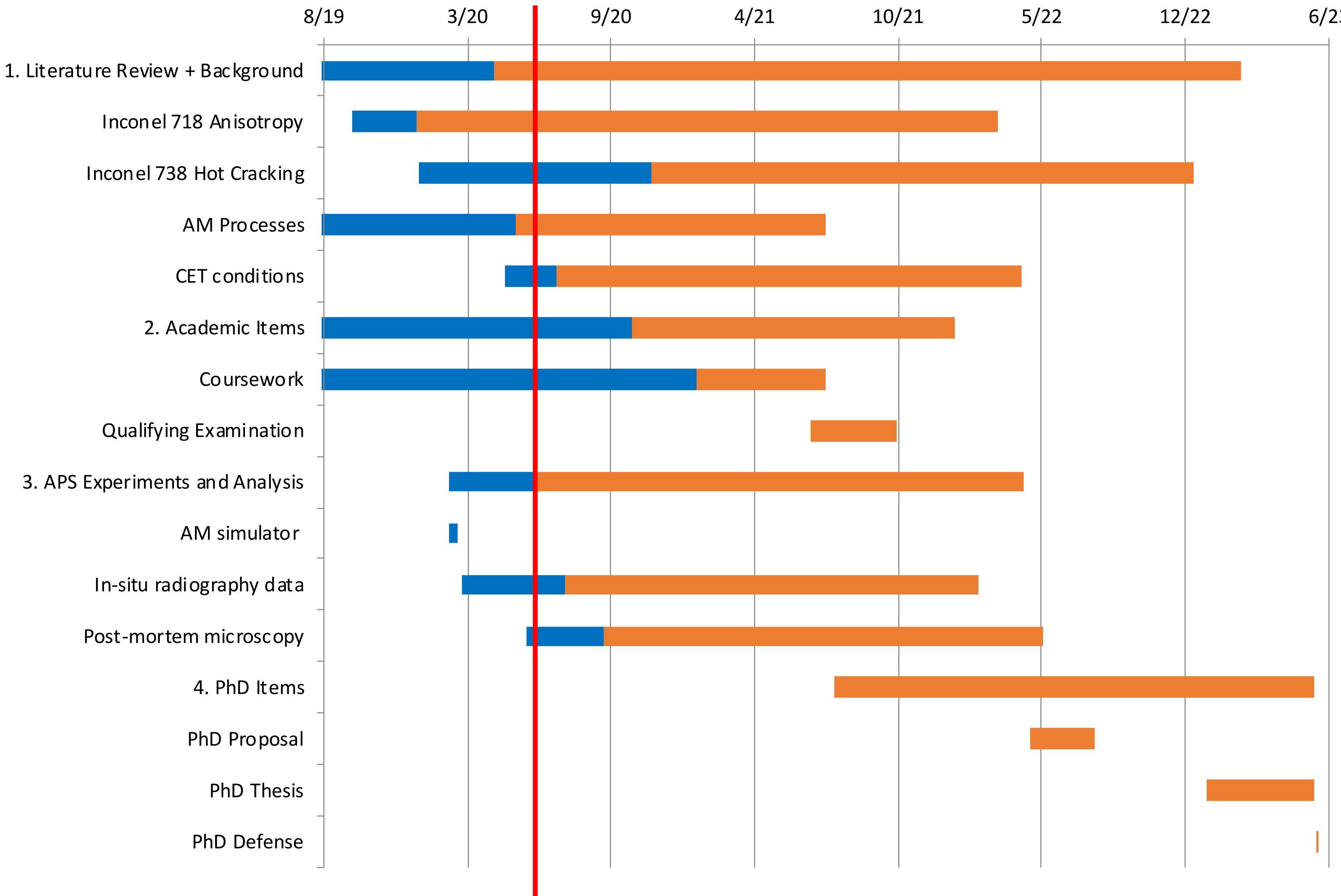
Challenges & Opportunities

- Challenges
  - In-situ radiography data more difficult to analyze with powder layer
  - Calculations for thermal gradients requires more sophisticated computational model
- Opportunities
  - Defining AM parameters of materials kinetics 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
jeremyshin@mymail.mines.edu

References

[1] M.E. Kassner, J.S. Tiley, γ/γ′ Nickel-Based Superalloys, in: Fundam. Creep Met. Alloy., 2008.

[2] E. Chauvet, P. Kontis, E.A. Jägle, B. Gault, D. Raabe, C. Tassin, J.J. Blandin, R. Dendievel, B. Vayre, S. Abed, G. Martin, Hot cracking mechanism affecting a non-weldable Ni-based superalloy produced by selective electron Beam Melting, Acta Mater. 142 (2018) 82–94.

[3] J.C. Lippold, S.D. Kiser, J.N. DuPont, Welding Metallurgy and Weldability of NickelBase Alloys, John Wiley & Sons, 2011.

[4] M. Cloots, Empirische und simulative studie über die Ver- arbeitbarkeit von IN738LC mittels SLM. ETH Zurich, 2017.

[5] J. Risse, C. Golebiewski, W. Meiners, K. Wissenbach, Ein-fluss der Prozessführung auf die Rissbildung in mittels SLM herg-estellten Bauteilen aus der Nickelbasislegierung IN738LC, Proceedings of RapidTech 2013.

[6] S. Kou, Welding metallurgy 2nd edn., John Wiley & Sons, New Jersey, 2003.

[7] H.L. Wei, T. Mukherjee, T. DebRoy, Grain Growth Modeling for Additive, Proc. 6th Int. Conf. Recryst. Grain Growth, ReX GG 2016. (2016) 265–269.

[8] H.L. Wei, J. Mazumder, T. DebRoy, Evolution of solidification texture during additive manufacturing, Sci. Rep. 5 (2015) 1–7.

[9] I.T. Ho, Y.T. Chen, A.C. Yeh, C.P. Chen, K.K. Jen, Microstructure evolution induced by inoculants during the selective laser melting of IN718, Addit. Manuf. 21 (2018) 465–471.

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

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

Student: *Jeremy Shin*

Faculty: *Amy Clarke*

Industrial Partners: *TBD*

Project Duration: *September 2019 – May 2023*

Achievement

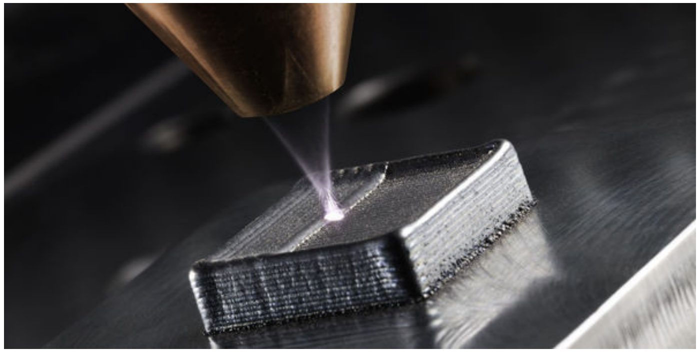
- Understanding of rapid solidification during AM and its effect on underlying microstructure and material properties

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



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

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

Student: *Jeremy Shin*

Faculty: *Amy Clarke*

Industrial Partners: *TBD*

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