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

Spring Meeting

April 7th – 9th 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

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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
- Preliminary analysis on *in-situ* radiography data from APS 2020
- Literature review on the columnar to equiaxed transition (CET) conditions for IN718 and hot cracking phenomena in IN738

Metrics

Description	% Complete	Status
1. Literature review	30%	●
2. Analysis of APS 2020 *in-situ* radiography data	20%	●
3. Initial microstructural characterization of as-built Inconel 738	10%	●
4. Ex-situ metallography and microscopy for APS samples	5%	●

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

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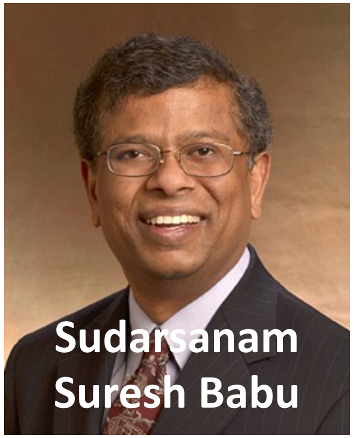

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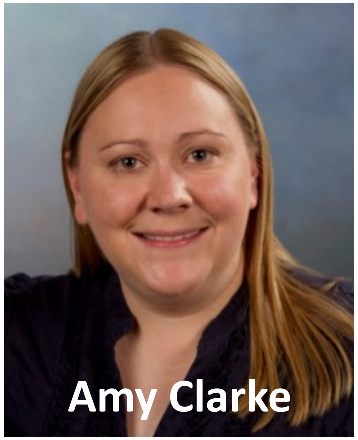

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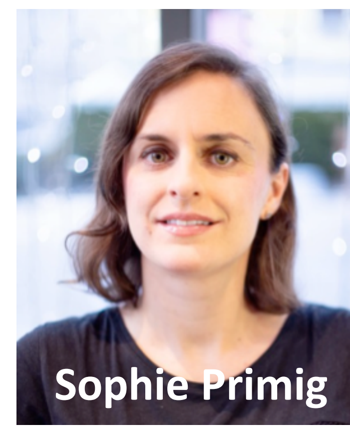
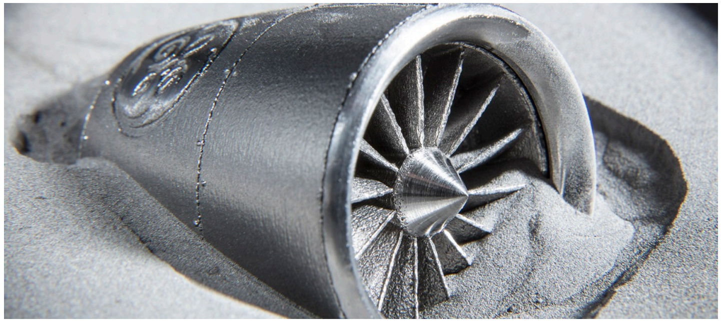


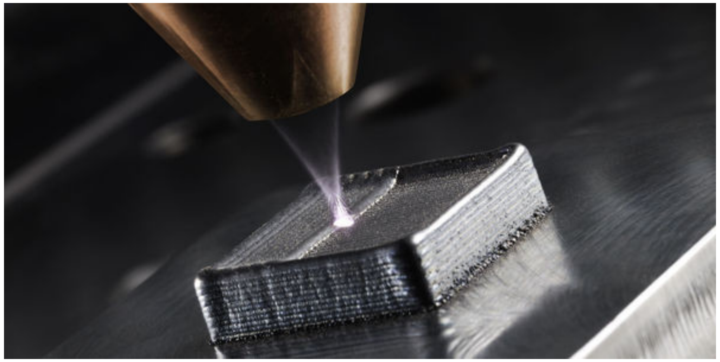
UNSW SYDNEY

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



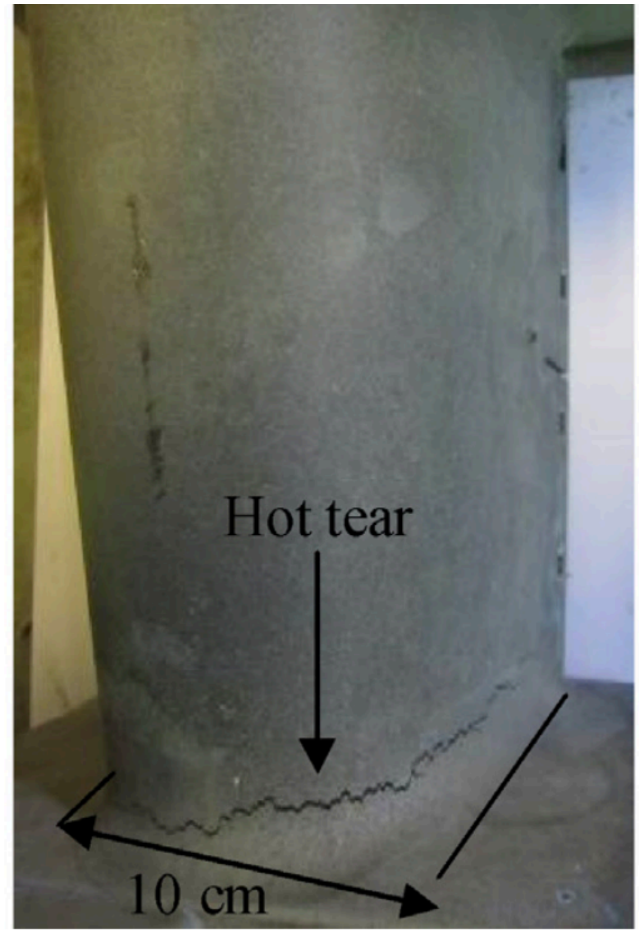
https://www.ge.com/additive/webinar/metal-additive-manufacturing-aerospace



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

Background

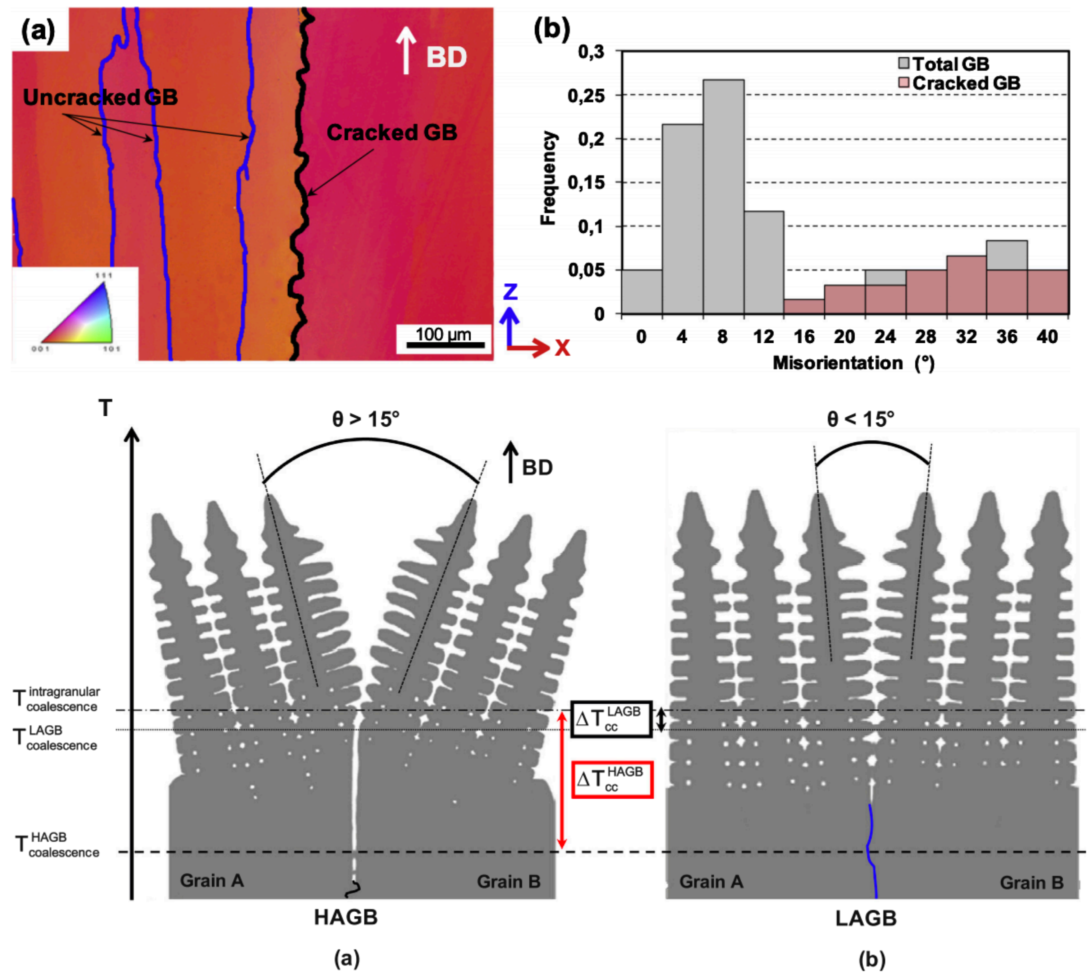
- Both IN718 and IN738 are precipitation strengthened alloys[1]
  - Commonly used for aerospace applications at high temperatures
- IN738 is susceptible to hot cracking upon rapid solidification
  - Excessive thermal stresses occur when growth of dendrites restricts liquid flow to the interdendritic regions during solidification[2]
  - High concentration of Al and Ti (~6.7wt%) leads to segregation at GBs[3]
  - Zr content leads to an increase in the solidification temperature range[4]



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

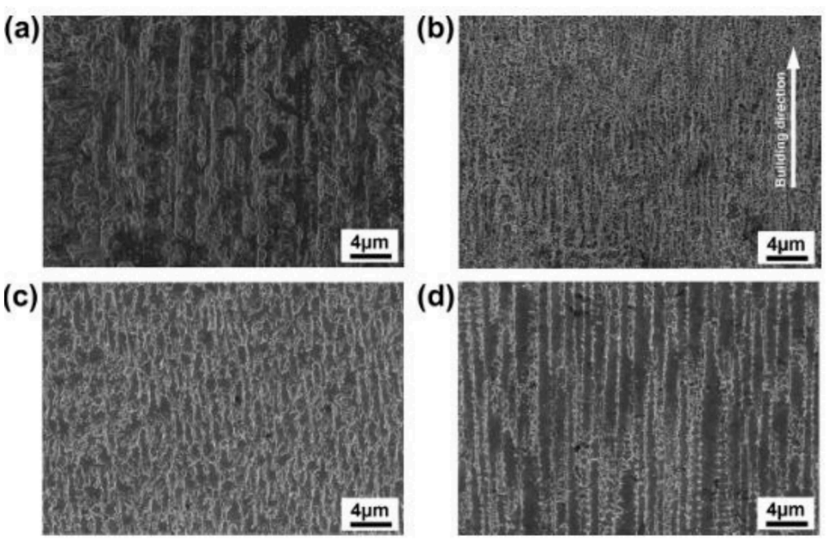
- The cracked regions of IN738 occur along high-angle grain boundaries (HAGB)
- The large misorientation accounts for the trapped liquid in the interdendritic regions

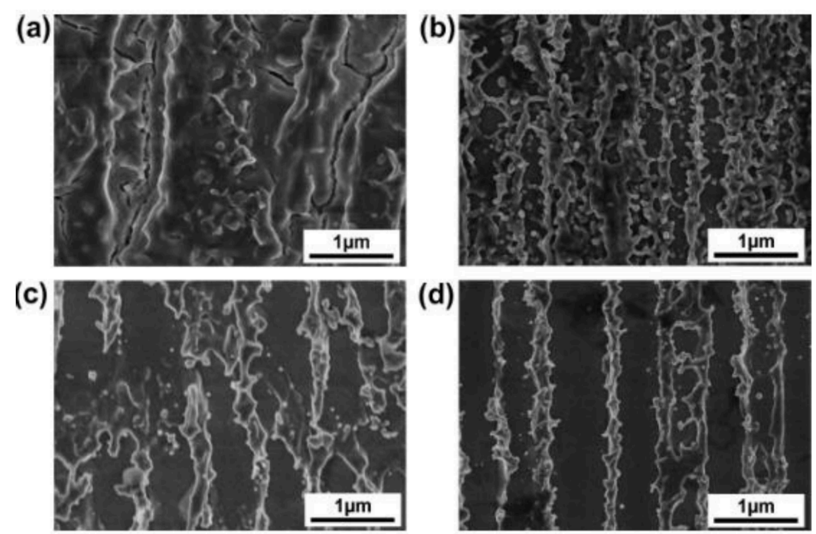


E. Chauvet, P. Kontis, E.A. Jägle, B. Gault, D. Raabe, C. Tassin, J.J. Blandin, R. Dendievel, B. Vayre, S. Abed, G. Martin, Hot cracking mechanism affecting a non-weldable Ni-based superalloy produced by selective electron Beam Melting, Acta Mater. 142 (2018) 82–94.

Background

- Laser power and velocity (P-V) control solidification behavior
- Some studies show:
  - Decreasing power density leads to finer microstructure[5]
  - Environmental chamber at elevated temperatures increases ductility[6]

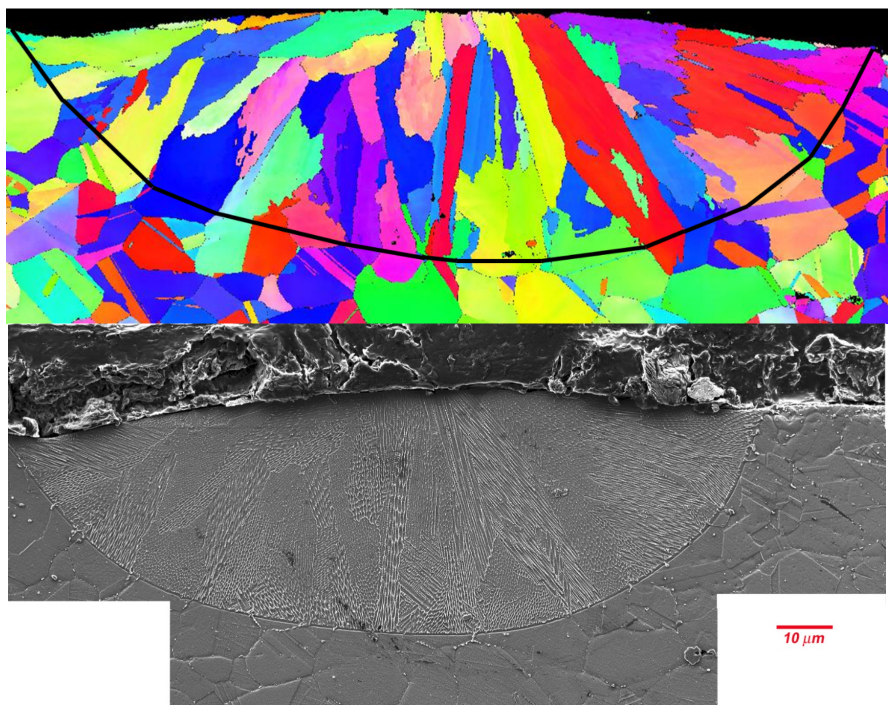




C. J. B. L. N. M. S. T. Vilaro, "Microstructure and Mechanical approaches of the selective laser melting of the selective laser melting process applied to a nickel-base superalloy," Material Science and Engineering A, vol. 534, pp. 446-451, 2012.

Background

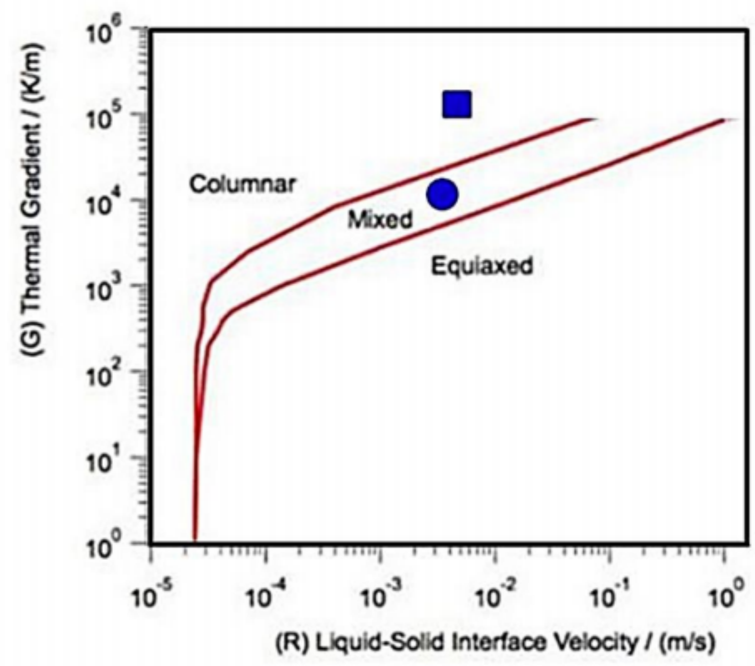
- Ni-based alloys have a preferred solidification behavior with columnar dendritic growth with a <100> fiber texture[7]
- The microstructure is different along the build direction
  - Bottom of the melt pool: columnar grains (higher G and lower V)
  - Top of the melt pool: equiaxed grains (lower G and higher V)



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

Background

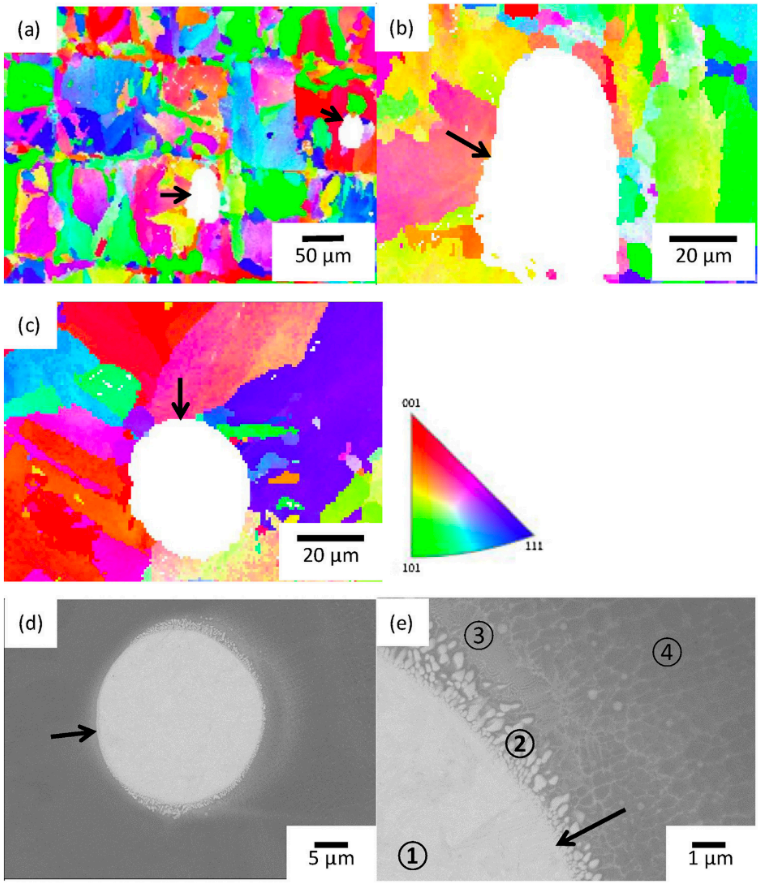
- The columnar to equiaxed transition (CET) is when dendritic growth changes to finer, equiaxed grains
  - Depends on the thermal gradient and solidification velocity (G-V)[8]
  - Typical values[9] for IN718 made by SLM process show a range of 20-100 K*s/mm²



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.

Background

- Addition of inoculants can change microstructure
  - Heterogeneous nucleation will occur ahead of the solidification front[10]
  - The CET condition is easily initiated
  - More uniform microstructure



The arrows indicate the inoculants.

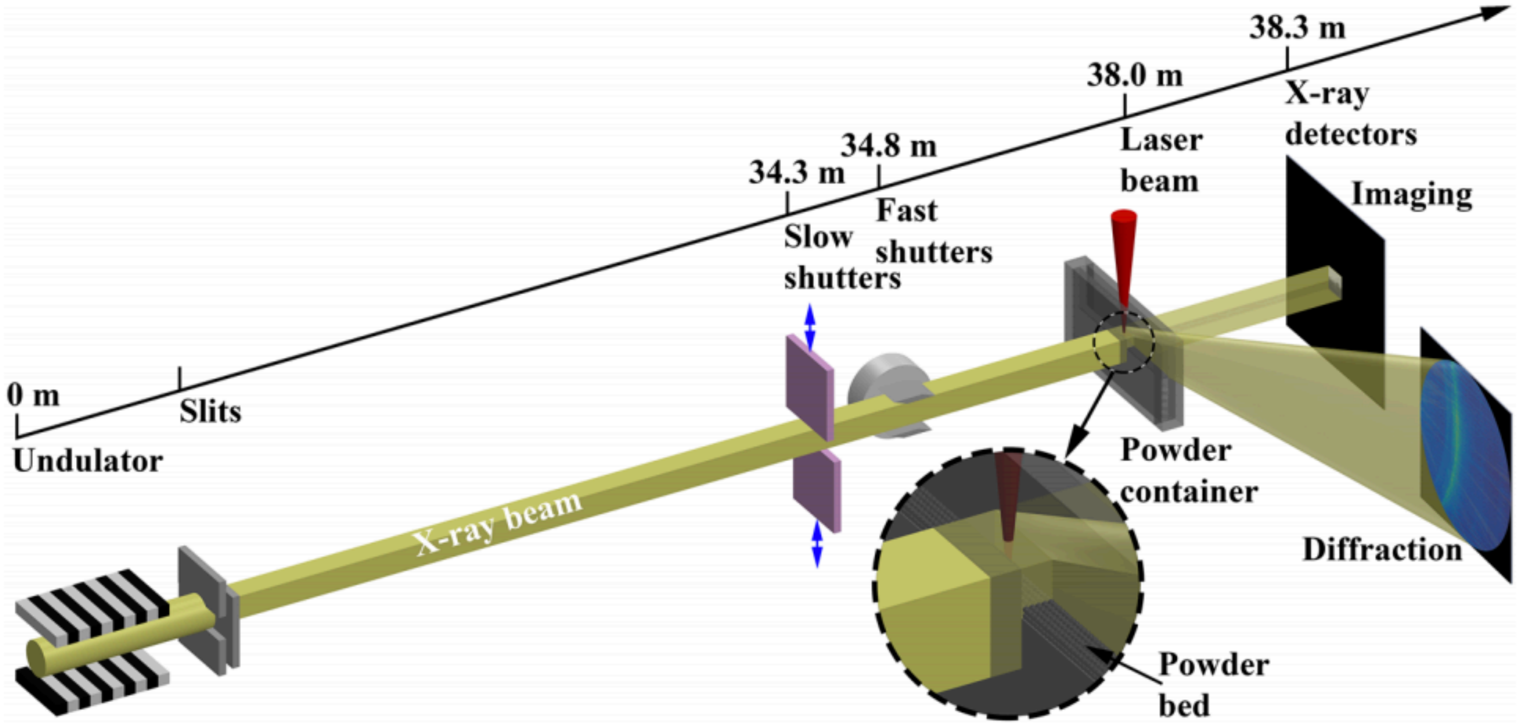
I.T. Ho, Y.T. Chen, A.C. Yeh, C.P. Chen, K.K. Jen, Microstructure evolution induced by inoculants during the selective laser melting of IN718, Addit. Manuf. 21 (2018) 465–471.

Objectives

- Identify a hot cracking regime in G-V space for IN738
- Quantify the effects of inoculant particles on the degree of anisotropy in IN718
- Compare results of AM process for spot and raster melts with and without a powder layer
- Track the solid/liquid interface of the melt pool during solidification

APS 2020

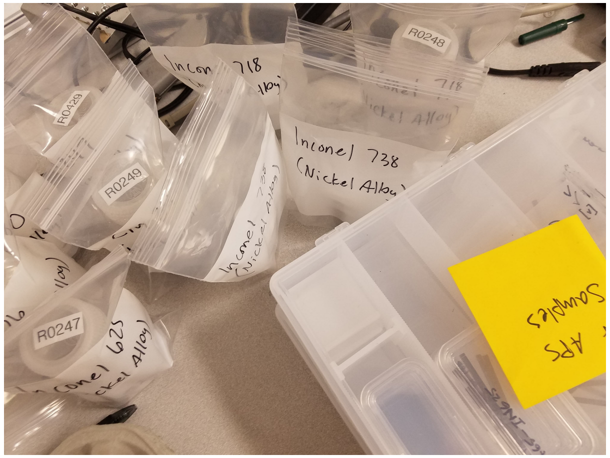
- Sector 32-ID: Argonne National Laboratory



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

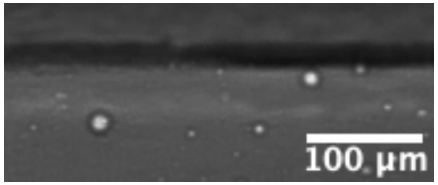
- Experiments were performed at low, medium and high laser powers to sample a large portion of G-V space
  - Equiaxed grain IN718 samples (UCSB) were tested with and without a powder layer
  - Inoculated IN718 samples (Elementum3D) were test with an inoculated powder layer
  - IN738 samples were tested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



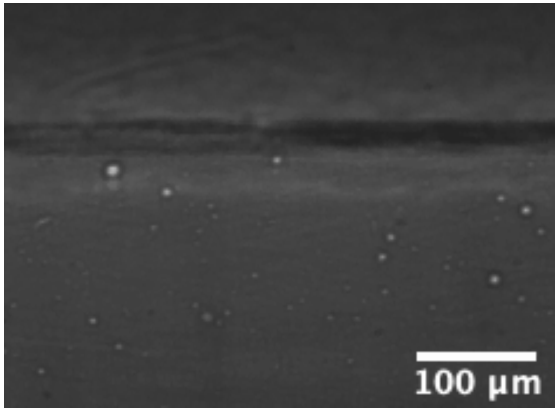
Preliminary Results

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

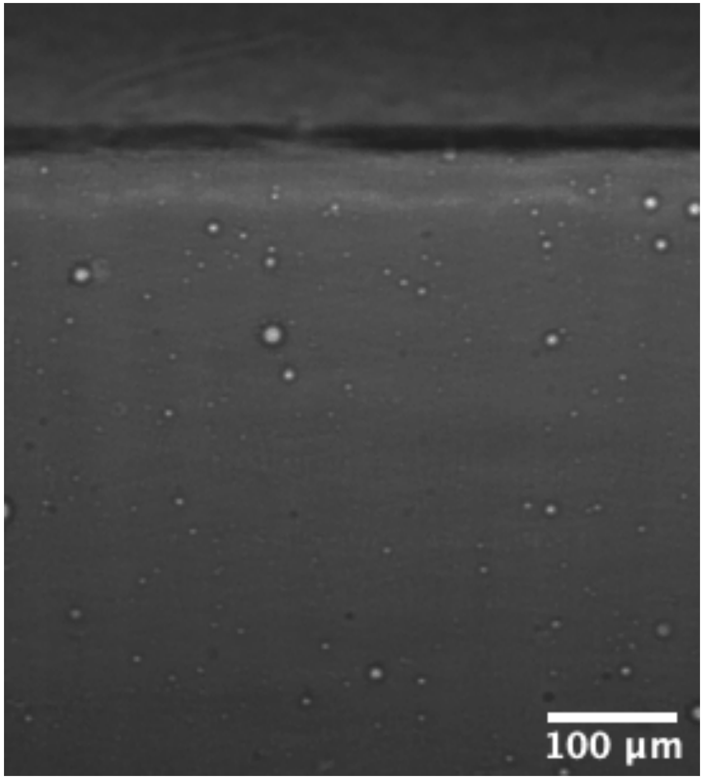
Low (20%)



Medium (30%)



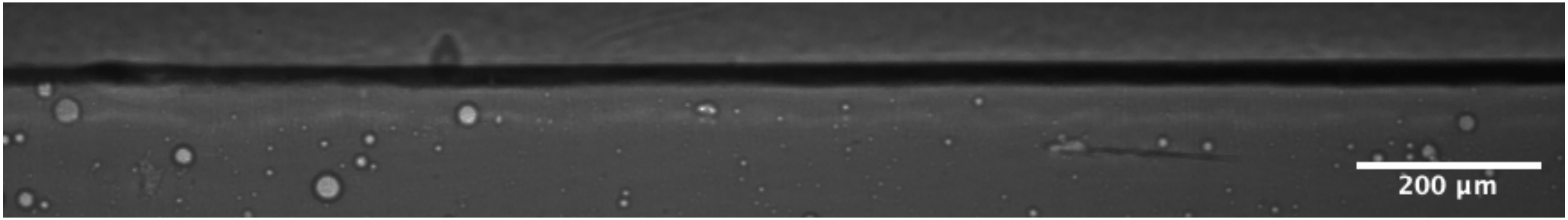
High (50%)



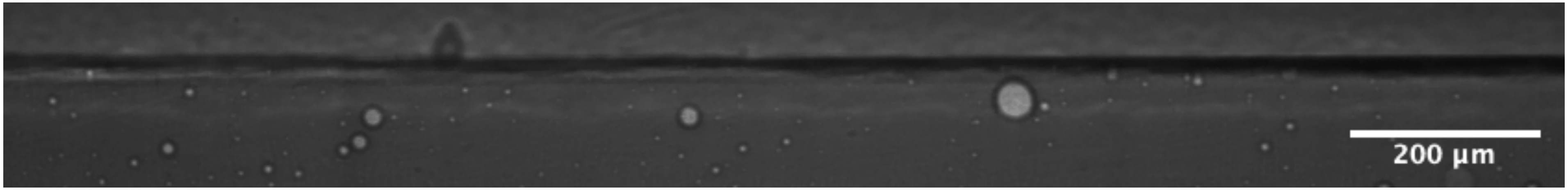
Preliminary Results

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

30%



35%

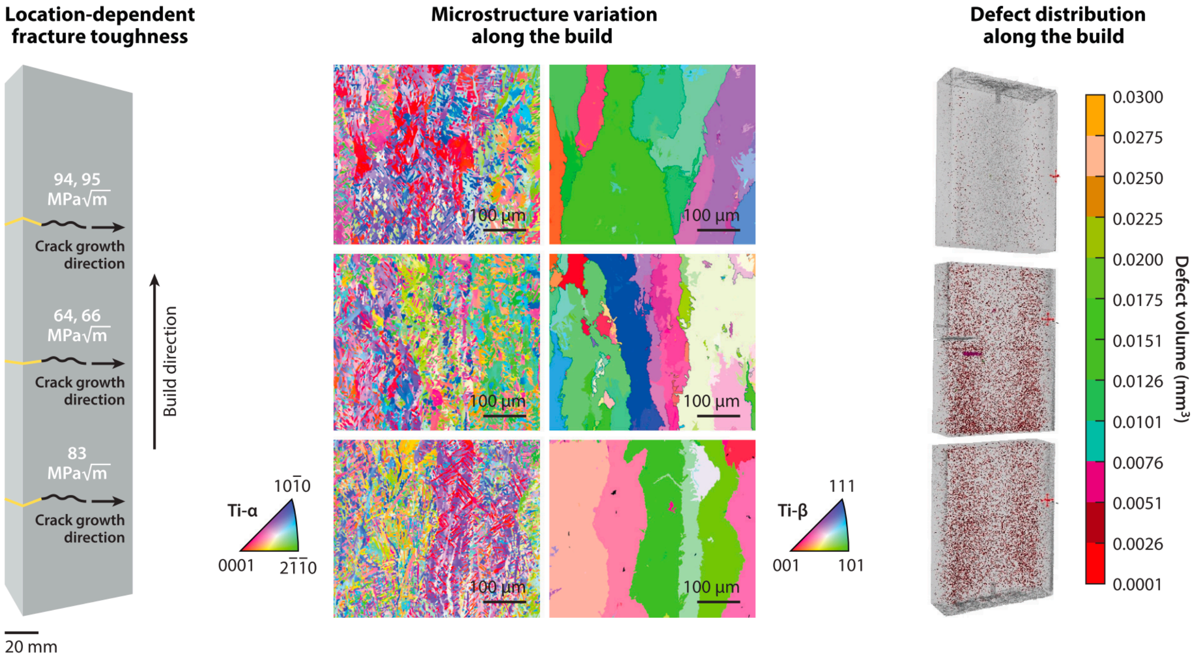


Future Work

- Determination of solid/liquid interface velocities from synchrotron x-ray radiography
- Post-mortem analysis using metallography and electron microscopy
- Define a hot cracking regime for IN738
- Neutron diffraction experiments to analyze texture and residual stress as a function of build height and scan strategy
- Compare mechanical properties along the build direction for IN718 with and without inoculants

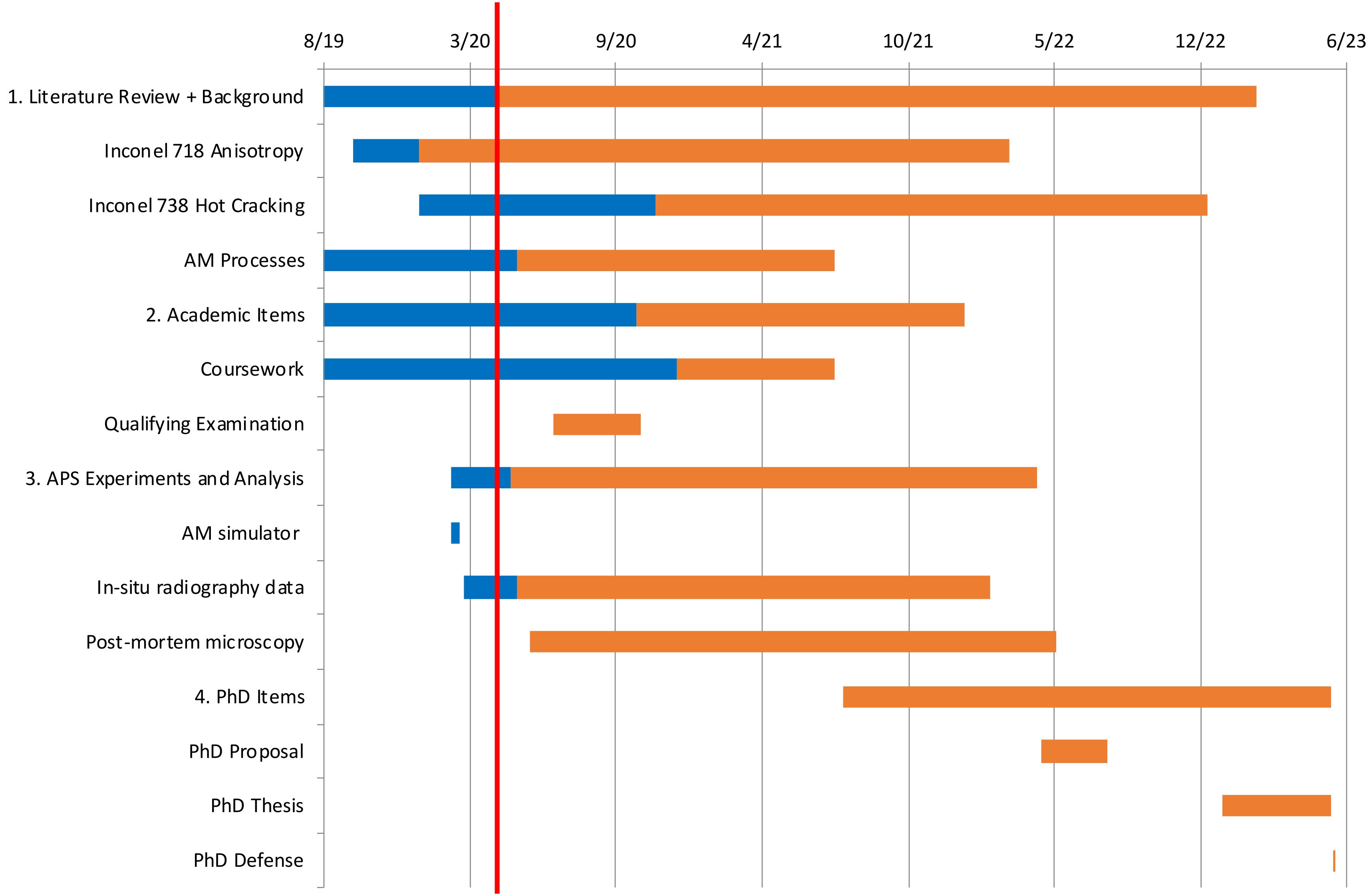
Challenges & Opportunities

- Challenges
  - In-situ radiography data more difficult to analyze with powder layer
  - Automate tracking of the solid/liquid interface velocities
- Opportunities
  - Defining AM parameters of materials kinetics to fine-tune the microstructure



J.J. Lewandowski, M. Seifi, Metal Additive Manufacturing: A Review of Mechanical Properties, Annu. Rev. Mater. Res. 46 (2016) 151–186.

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
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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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] 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.

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

[6] 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.

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

[8] 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.

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

[10] 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.

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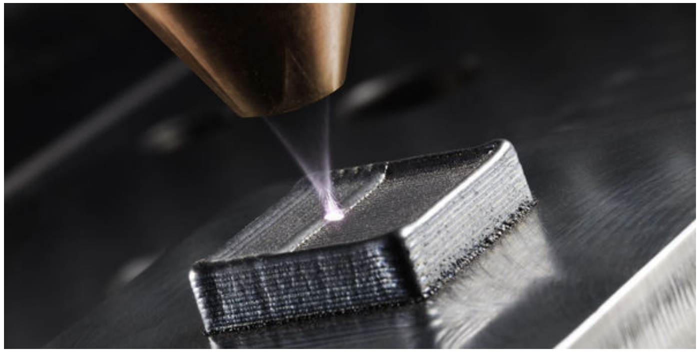
Industrial Partners: *TBD*

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



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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

Benefits

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