CANFSA
Center for ADVANCED NON-FERROUS STRUCTURAL ALLOYS

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

Project 36-L: Rationalization of Liquid/Solid and Solid/Solid Interphase Instabilities During Thermal – Mechanical Transients of Metal Additive Manufacturing

Fall 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
October 2-4, 2018

Student: Alec Saville (Mines)

Faculty: Dr. Amy Clarke (Mines)

Industrial Mentor: TBD

Other Participant: Dr. Sudarsanam Suresh Babu (ORNL/UT), Dr. Pete Collins (Iowa State University)

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COLORADO SCHOOL OF MINES
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IOWA STATE UNIVERSITY

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- Student: Alec Saville (Mines)
- Advisor(s): Amy Clarke (Mines)

Project Duration
PhD: 2018-2022

- Problem: Instabilities during solidification lead to detrimental material properties during additive manufacturing solidification. A greater understanding of how to prevent this is required.
- Objective: Rationalize interfacial instabilities during additive manufacturing of Ti-6-4/Inconel 718, and their implications for final material conditions.
- Benefit: Improve performance of metallic additively manufactured parts and lay foundation for future optimization work.

Recent Progress

- Gathered preliminary neutron diffraction data from Los Alamos National Laboratory
- Rietveld refinement ongoing
- Beginning laser surface analysis
- Surface roughness measurements with Keyence 5000

Metrics		
Description	**% Complete**	**Status**
1. Literature Review	10%	●
2. Collect neutron diffraction data for texture analysis.	25%	●
3. Complete first round of Rietveld refinement.	15%	●
4. Surface roughness and relief analysis	10%	●
5. Characterize microstructure of different rastering modes.	0%	●

Industrial Relevance

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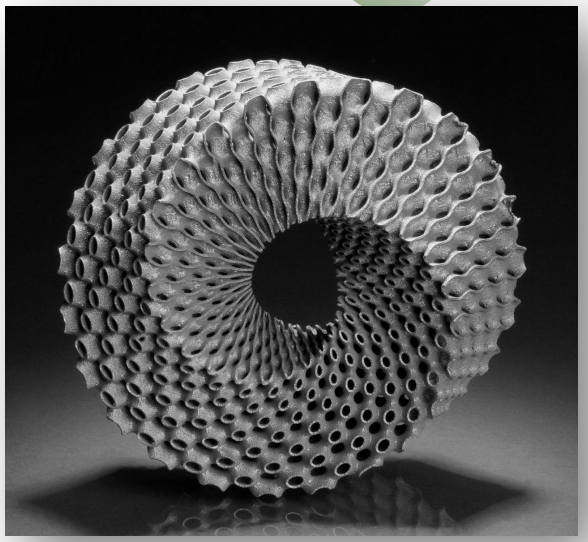
- Additive manufacturing (AM) is becoming ubiquitous
  - Freedom in engineering design
    - Aerospace
    - Rapid-repair and prototyping
- Qualification and certification of produced parts is lacking
- Requires fundamental understanding of solidification and microstructural evolution during AM
- Lead to increased part performance via microstructural and defect control
  - Higher throughput
  - Reduce waste
  - Limit defect formation

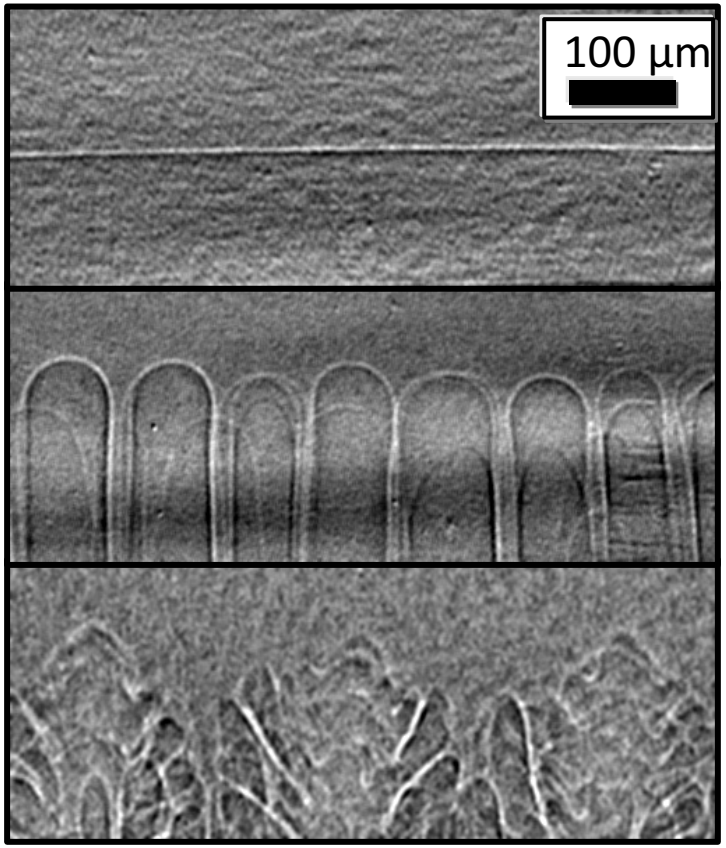


https://synergyresources.net/additive-manufacturing-next-industrial-revolution/

http://aviationweek.com/blog/meet-boeings-latest-next-gen-fighter-concept

Project Focus

- Fundamental look into interfacial instabilities during AM
  - Solid-liquid, solid-solid
- Large thermal gradients and sudden reversals
  - $10^7 \frac{K}{m}$
  - Greater than 10 Hz frequency
- Phase transformations
  - α to α’ in Ti-6Al-4V
- Microstructural development
- Defect formation



A.J. Clarke et al., Acta Materialia, 2017, 129:203-216

Multidiscipinary University Research Inititiative (MURI)

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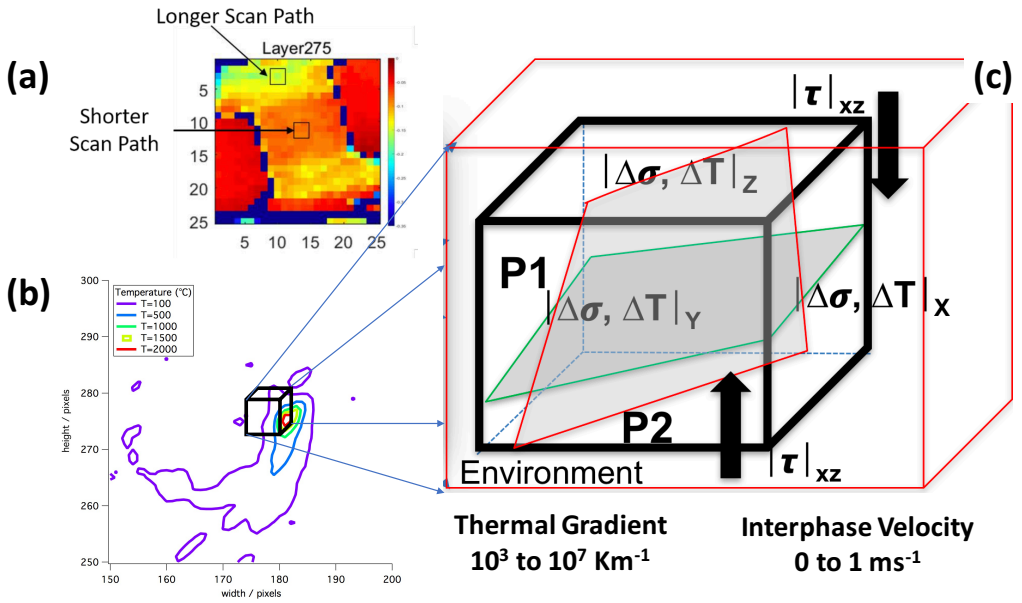
- Sudarsanam Suresh Babu, University of Tennessee & ORNL
- Amy Clarke, Colorado School of Mines
- Pete Collins, Iowa State University
- Joerg Jinschek, The Ohio State University
- Tresa Pollock, University of California Santa Barbara
- James Kong, Virginia Tech
- Simon Ringer, University of Sydney and collaborators at UNSW Sydney

Spatial and temporal transients during AM - temperature gradients (Ti-6Al-4V) and temperature contours (Inconel 718)



Spatial-temporal thermomechanical boundary conditions may trigger complex interface stabilities and defect generations…

Colorado School of Mines – Multi-Scale, In-situ/Ex-situ Characterization of Solid-Liquid/Solid-Solid Phase Transitions

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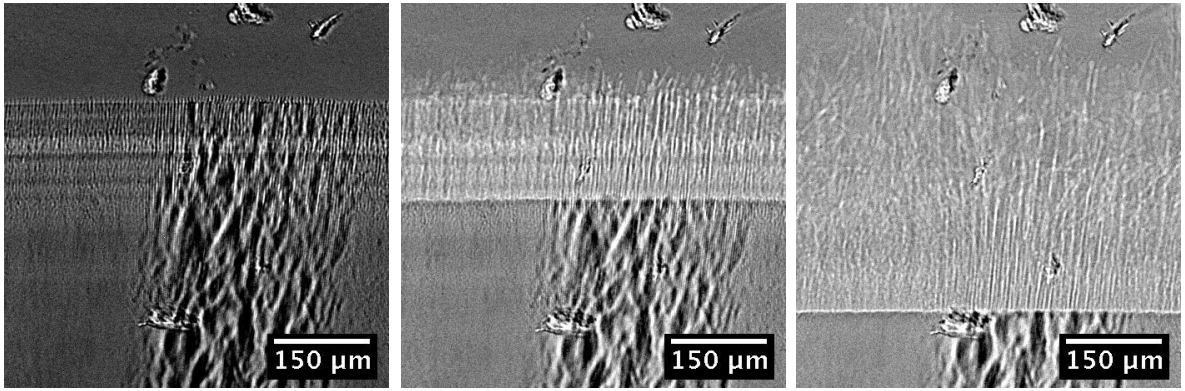
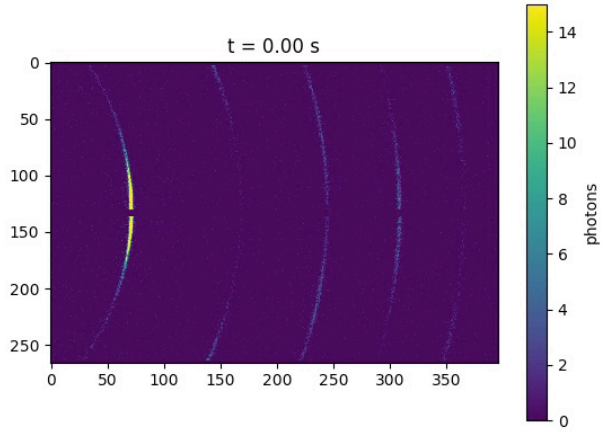
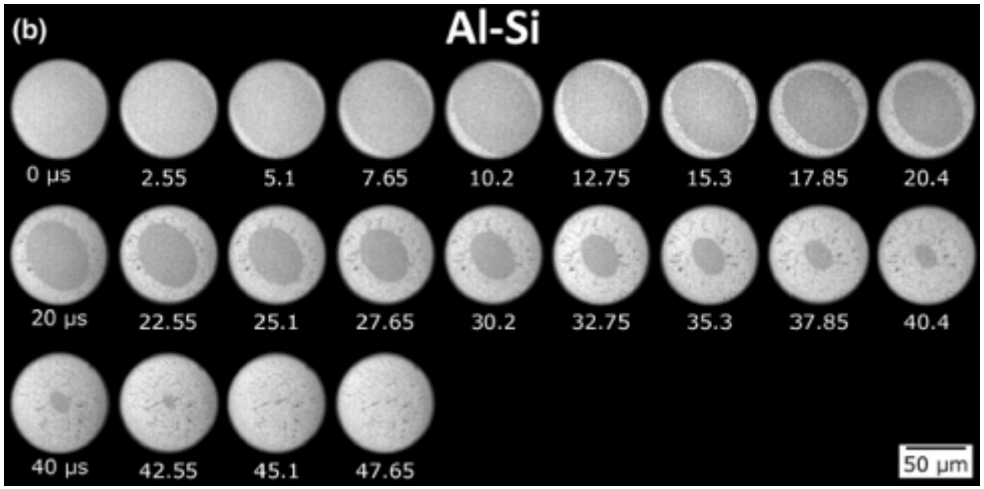




In-situ imaging/diffraction at national user facilities



Dynamic Transmission Electron Microscopy (DTEM) of phase transition dynamics

CSM Early Characterization of AM Builds

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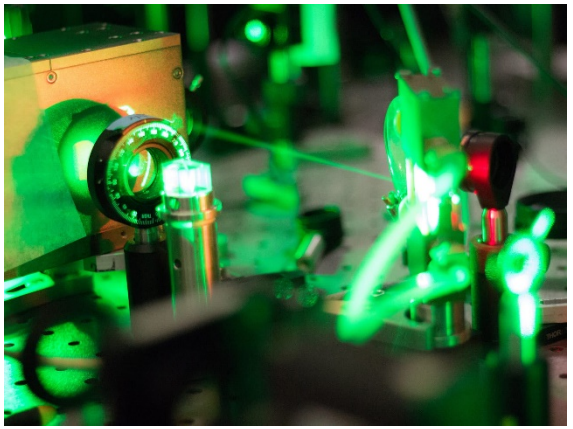
- Ti-6Al-4V samples received
  - Probing for defects and evidence of instabilities
  - Manufactured via electron beam melting
- Surface roughness
  - Keyence 5000
  - High resolution laser analysis
- Bulk and slit neutron diffraction
  - LANL
- X-ray radiography and tomography
  - *Ex-situ* at CSM (*in-situ* to follow)
- Follow-up with Inconel 718



https://mines.edu/physics

https://www.keyence.com/landing/microscope/lp_vhx5000_measurement_capabilities.jsp

Electron Beam Melting (EBM)

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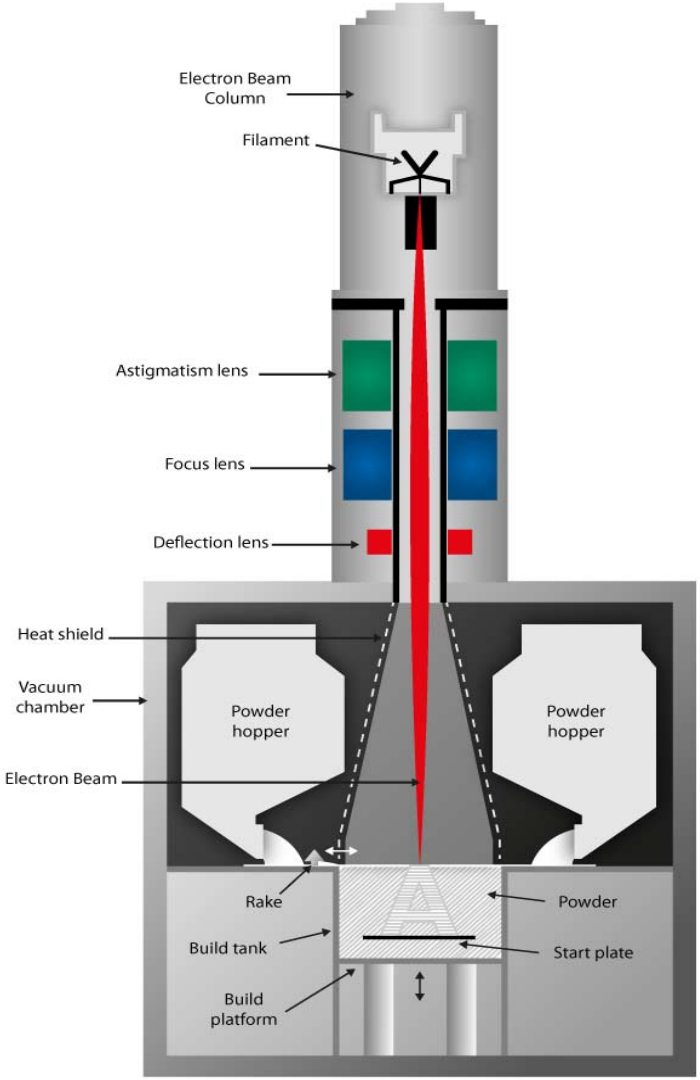
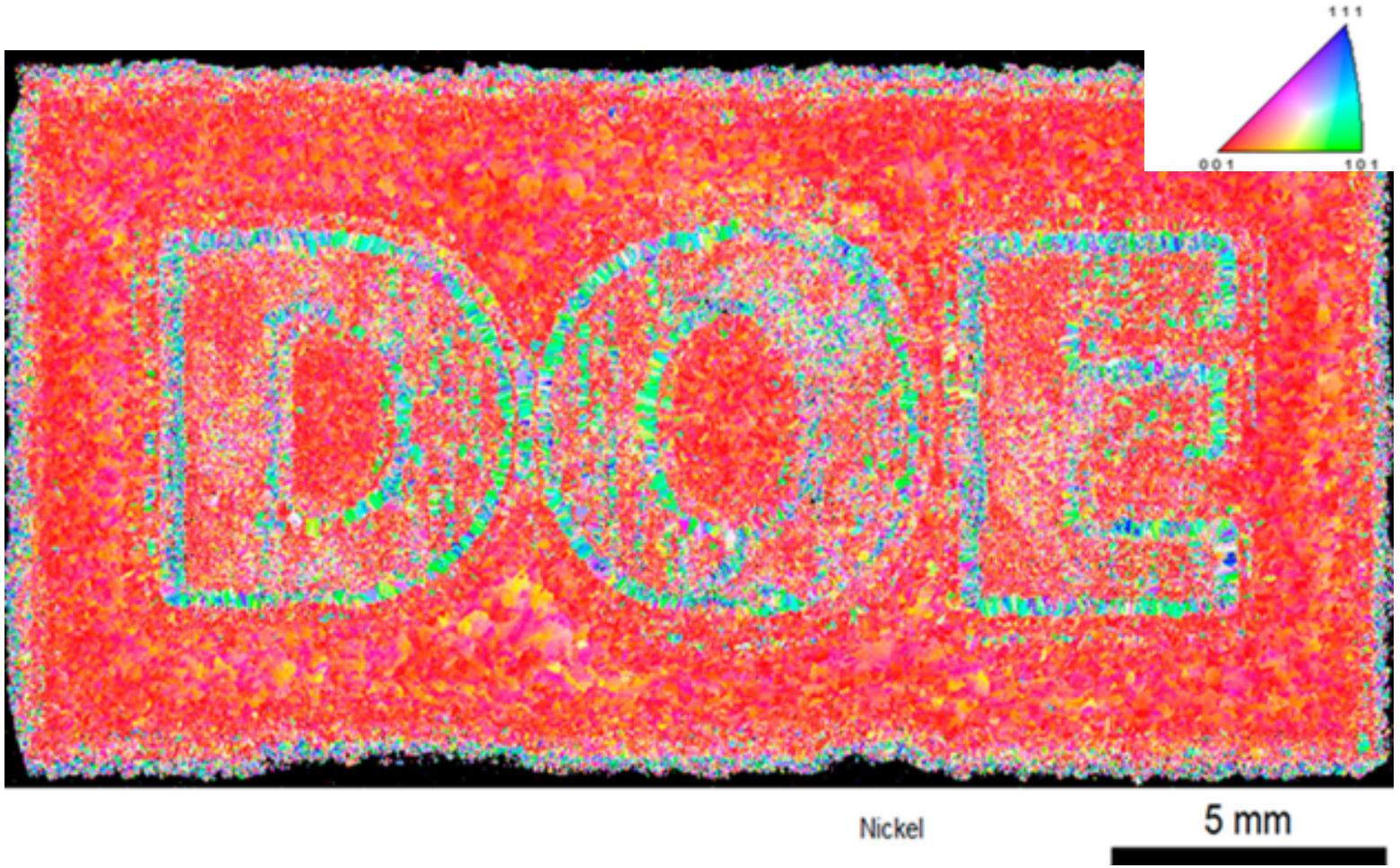
- Powder bed melting method
- Electron beam heat source
- Large powder size
- More capable ability to control microstructure
  - Equiaxed vs. columnar
- Completed at Oak Ridge National Laboratory - Manufacturing Demonstration Facility





R.R. Dehoff et al., Site specific control of crystallographic grain orientation through electron beam additive manufacturing, Materials Science and Technology, 2015, 31:8, 931-938

Sample Production

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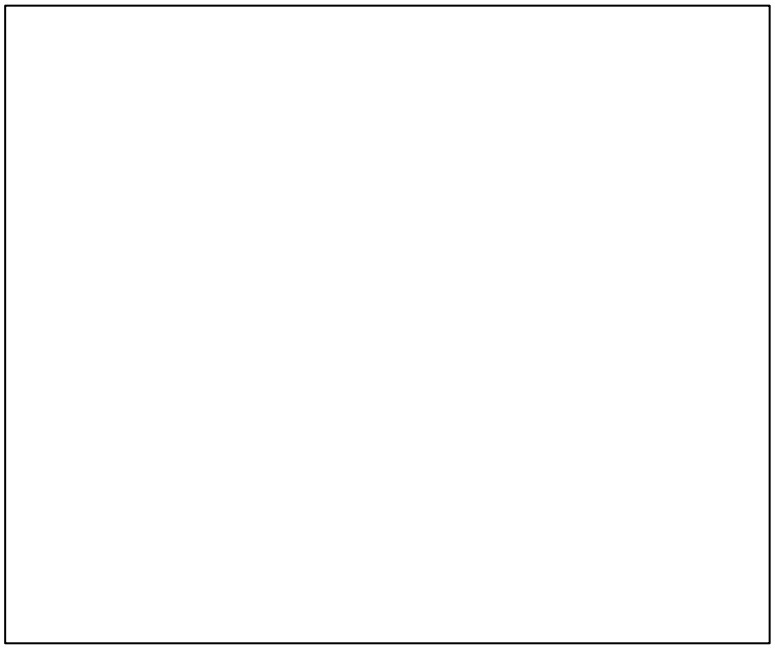
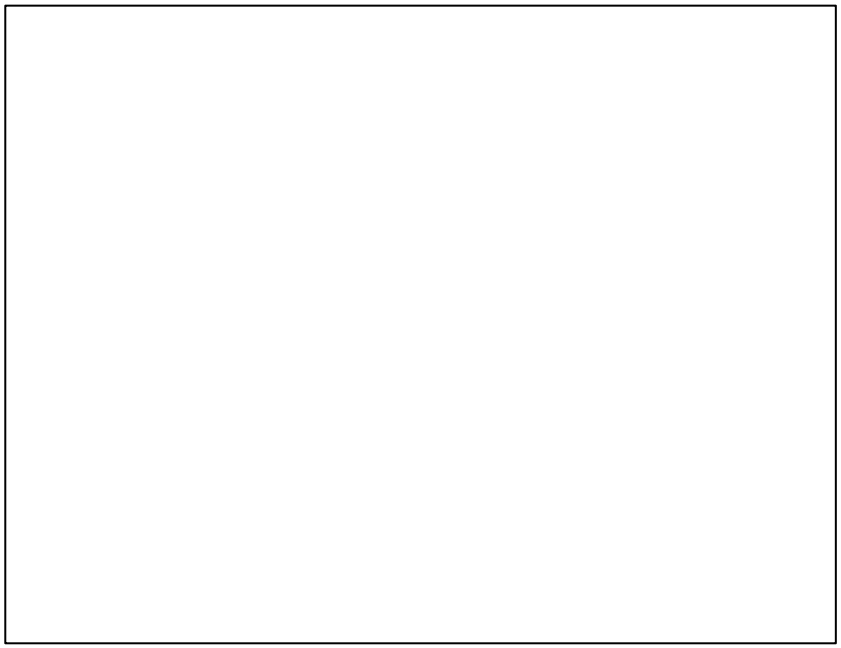
- Varying rastering modes
  - Alter local thermal history
- 15 mm x 15 mm x 25 mm

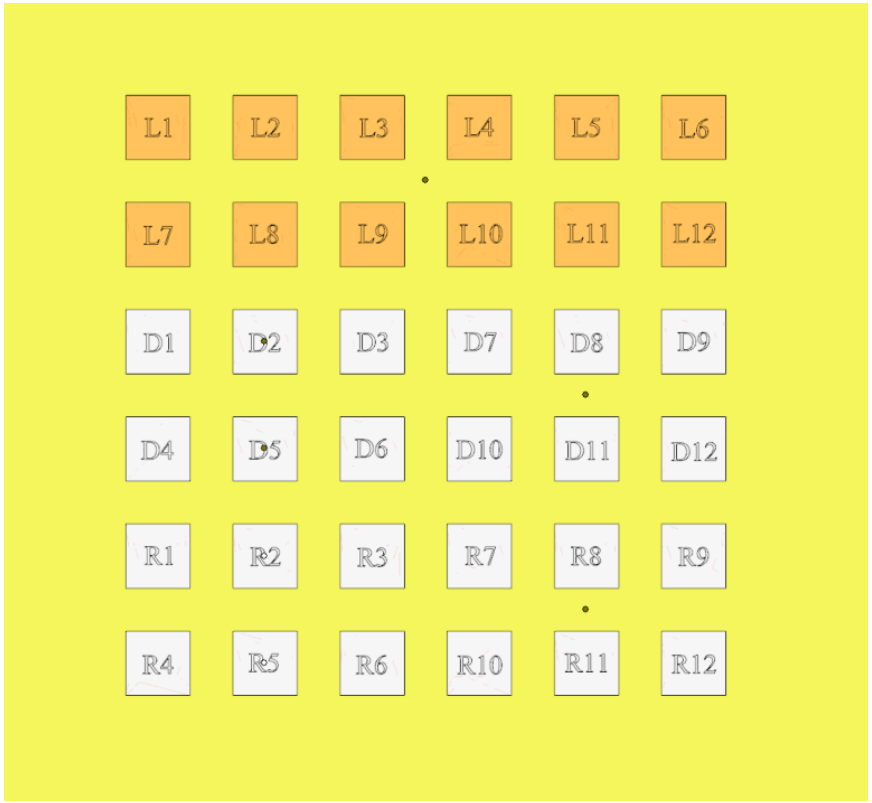


Dehoff build pattern



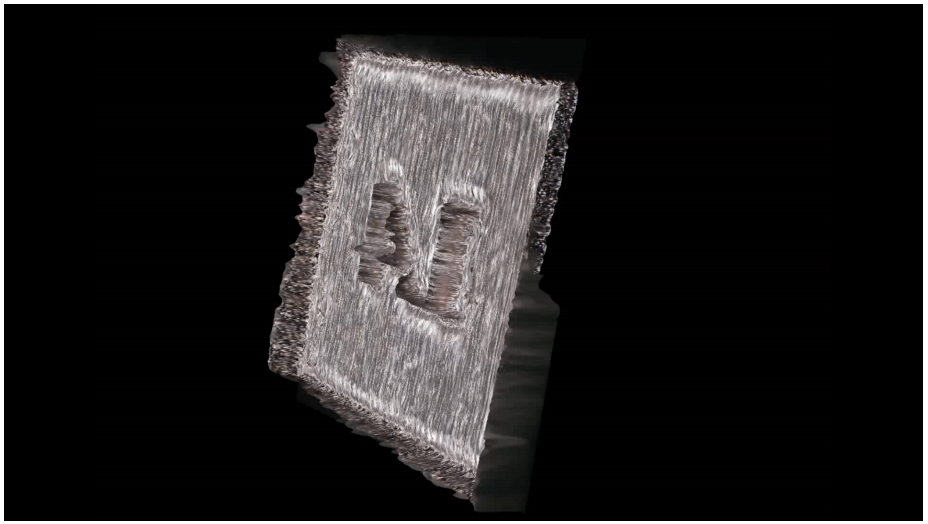
Random build pattern

Finished Product



Printing process

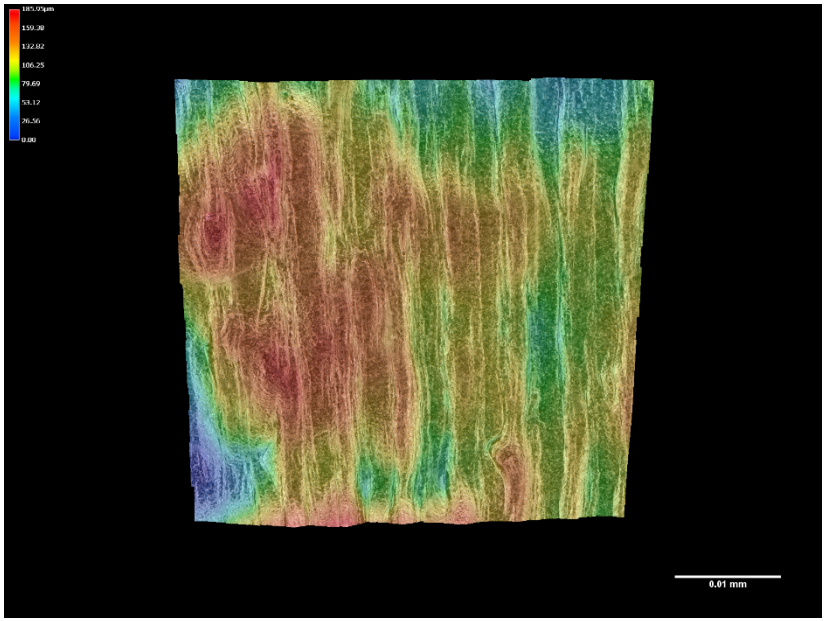
S. Kumar, et al. 2018



Dehoff Basketweave Raster Random

Keyence 5000

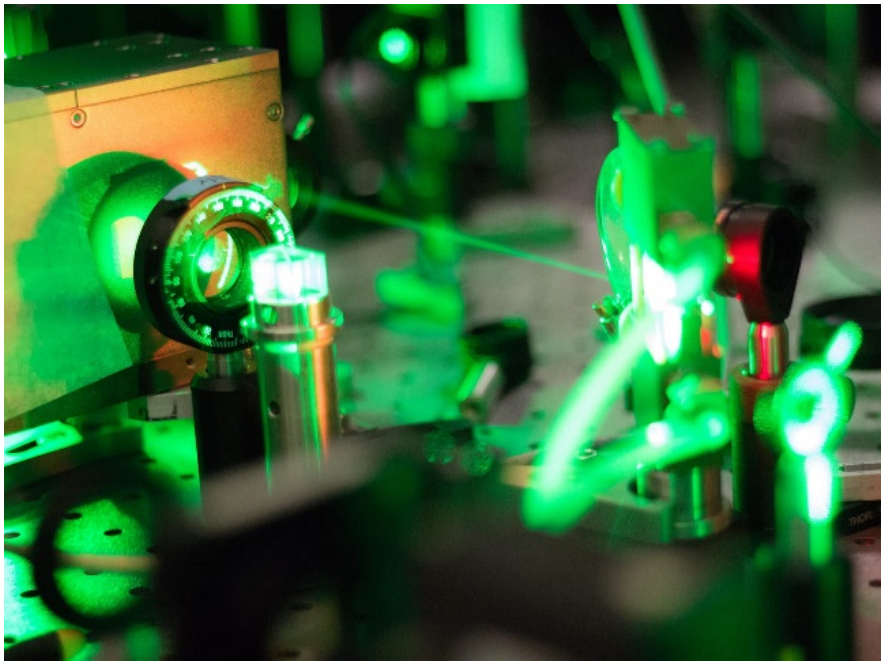
- Light optical microscope
- Flexible lens holder
  - Angled/free form analysis
- Variable-Z capability
  - Surface depth
  - Surface roughness



- Computerized profile analyzer
  - 2D and 3D
- Higher resolution imaging than standard LOM
  - 5-10 micron resolution

https://www.keyence.com/landing/microscope/lp_vhx5000_measurement_capabilities.jsp

Optical Laser Analysis



https://mines.edu/physics

- Femtosecond laser system
- High resolution surface analysis
  - 500 nm
- Collaborate with data from Keyence 5000
- Observe solidification phenomenon *ex-situ*
  - Phase transformations
    - Surface relief

Neutron Diffraction

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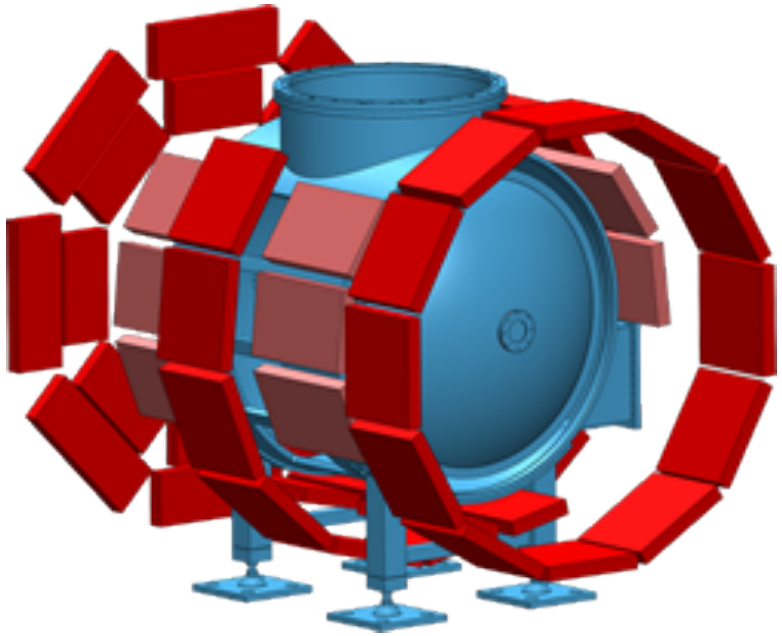
- Uses neutrons to penetrate larger volumes of material
  - Centimeter – millimeter
  - High energy, low distance neutrons
- Scattering events produce crystallography data
  - Texture evolution
  - Crystal structure
- Bulk and slit experiments
  - Full specimen texture
  - Localized texture profile



HIPPO line at LANSCE-LANL

Current Work

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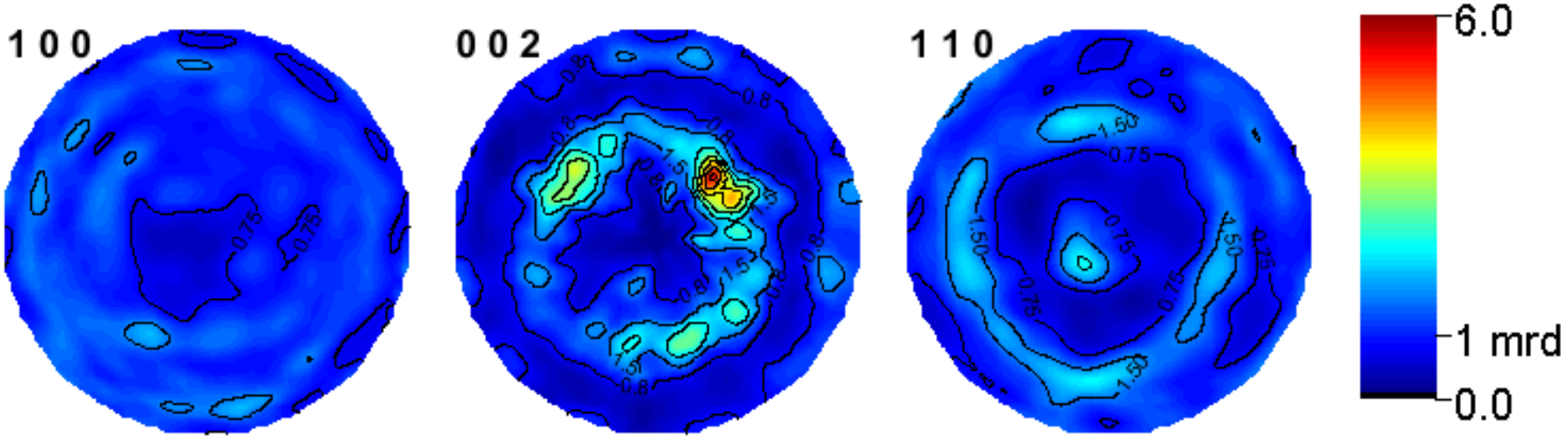
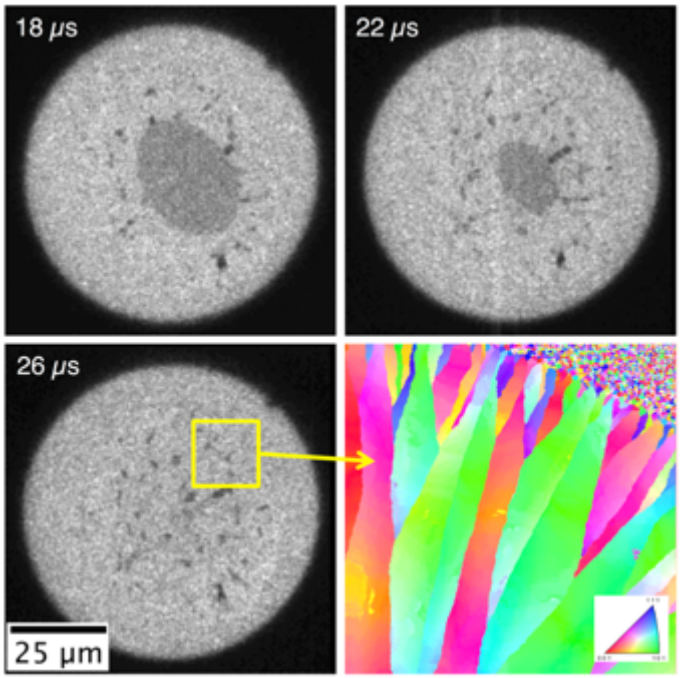
- Continue initial microstructural characterization
- Surface analysis of Ti-6-4 with laser and optical imaging
- Ongoing Rietveld refinement and ODF processing of preliminary bulk neutron texture measurements



Preliminary Pole Figures of α-titanium

Future Work

- *In-situ* characterization of Ti-6Al-4V and Inconel 718
  - Neutron diffraction during heating of Ti-6Al-4V
  - Synchrotron X-ray imaging and diffraction (AM Simulator at Sector 32-ID at the Advanced Photon Source at Argonne National Laboratory)
  - Dynamic transmission electron microscopy (DTEM)
    - Surrogate alloys?
  - X-ray cabinet at CSM?
- Neutron diffraction data analysis
- Complementary *ex-situ* characterization (e.g. laser and optical imaging, x-ray diffraction, micro-computed tomography, electron microscopy)



J.T. McKeown et al., JOM, 2016, 68 (3), 985-999
J.D. Roehling et al., Acta Materialia, 2017, https://doi.org/10.1016/j.actamat.2017.03.061

APS AM Simulator

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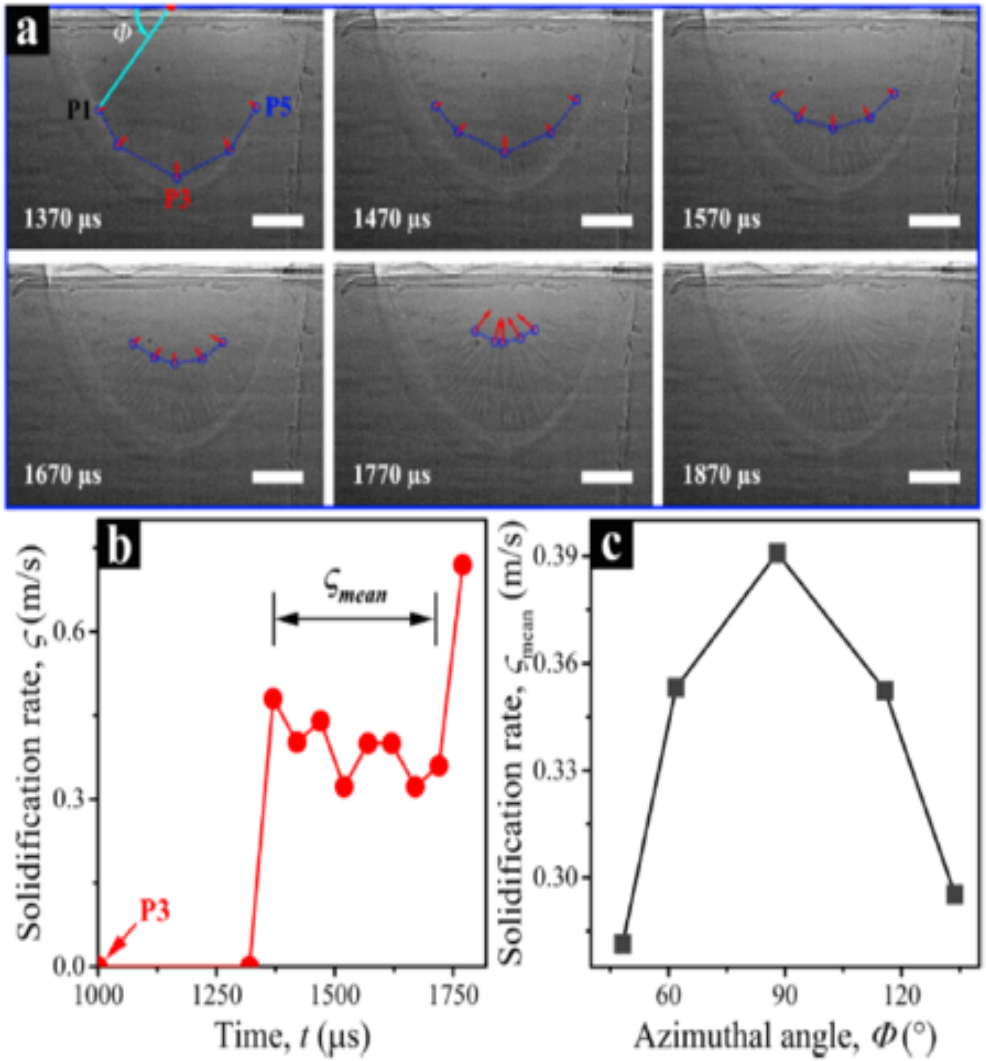

Argonne NATIONAL LABORATORY

C. Zhao et al., Scientific Reports 2017, 7:3602

Progress

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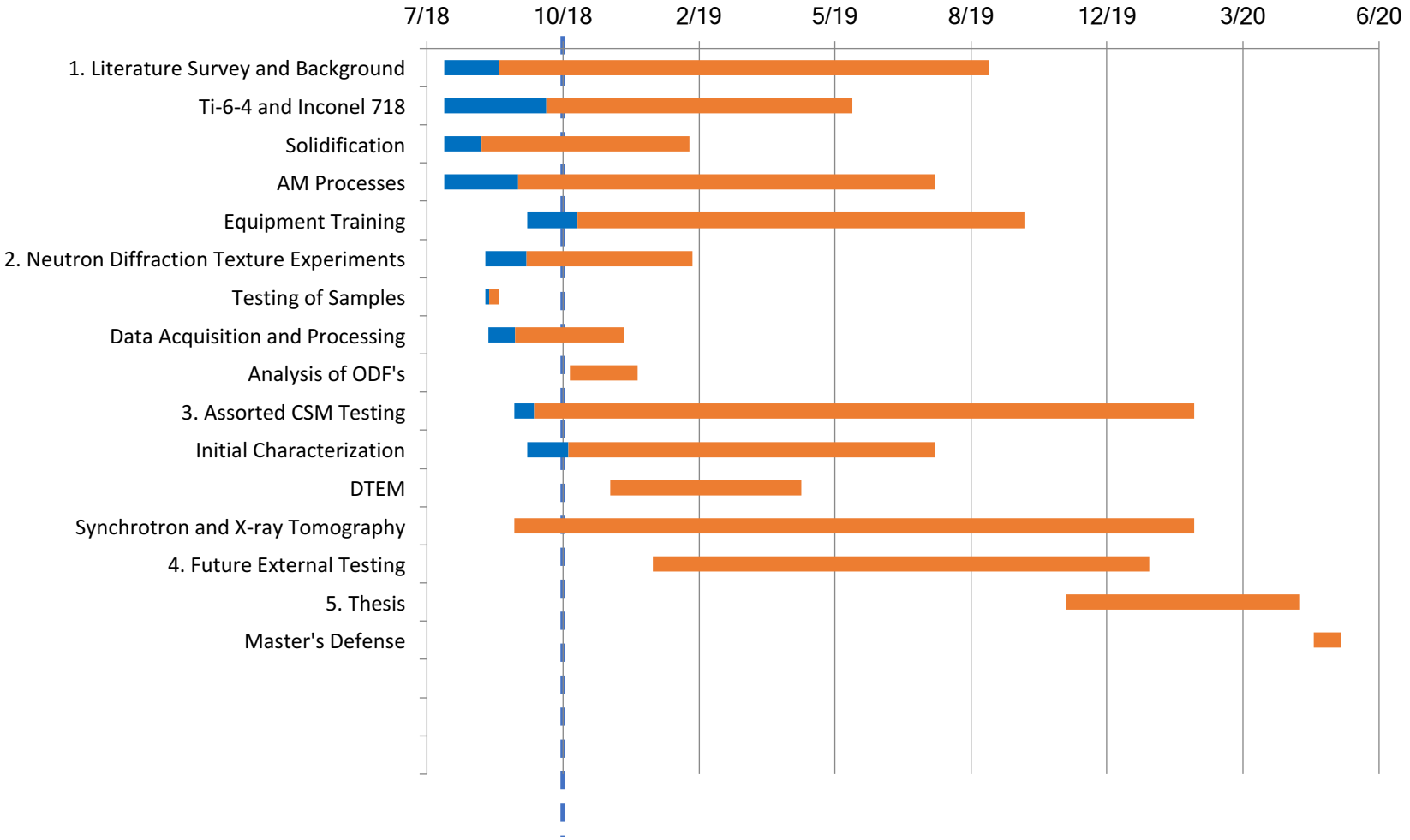

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Thank you for listening! Any quick questions?

Alec Saville

asaville@mymail.mines.edu

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Student: *Alec Saville*

Faculty: *Amy Clarke*

Other Partcipants: *ORNL/UT (S.S. Babu), ISU (P. Collins)*

Project Duration: *August 2018 – May 2022*

http://aviationweek.com/blog/meet-boeings-latest-next-gen-fighter-concept

Achievement

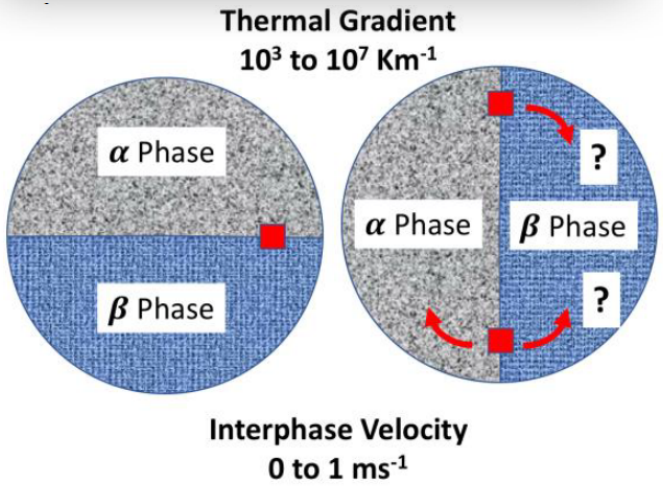
- Fundamental rationalization of instabilities during additive manufacturing of metallic systems and their effects on material performance in Ti-6-4 and Inconel 718

Significance and Impact

- Additively manufactured metals exhibit great variability in performance due to non-steady state solidification. A greater understanding of this phenomena will improve performance and assist in developing future process refinements.

Research Details

- Performing laser and light optical surface analysis, processing texturing data from neutron diffraction experiments.



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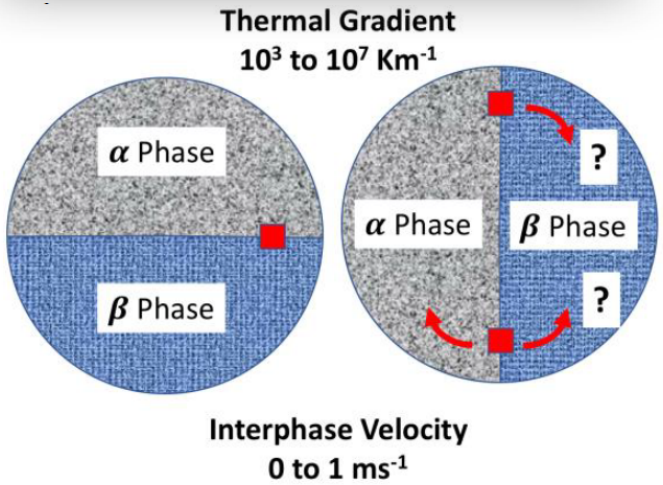

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Project Duration: *August 2018 – May 2022*

Program Goal

- Rationalize how instabilities in additive manufacturing of Ti-6-4 and Inconel 718 impact resultant microstructure and material performance

Approach

- Use *in-situ* AM beam line experiments, neutron diffraction, laser and light optical surface analysis, and X-ray tomography to rationalize interfacial evolution during AM processing

Benefits

- Improved qualification evaluations of metallic AM for production and increased scientific understanding of material evolution during AM

700X view of a Ti-6-4 sample surface