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Center for Advanced Non-Ferrous Structural Alloys

An Industry/University Cooperative Research Center

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

Winter 2019 Online Meeting

February 6th, 2019

Student: Alec Saville (CSM)

Faculty: Dr. Amy Clarke (CSM)

Industrial Mentors: TBD

Other Participants: Dr. Sudarsanam Suresh Babu (ORNL/UT), Dr. Sven Vogel (LANL), Dr. Pete Collins, Priyanka Agrawal, Maria Qunitana-Hernandez, Matt Kenney (ISU)

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

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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-6Al-4V/Inconel 738, and their implications for final material condition.
- Benefit: Improve performance of metallic additively manufactured parts and lay foundation for future optimization work.

Recent Progress

- Beginning characterization studies of Ti-6Al-4V samples.
- Processing data acquired from recent February-March Advanced Photon Source (APS) beam time.
- Submitted two proposals for future neutron diffraction work at Los Alamos National Laboratory (LANL).

Metrics

Description	% Complete	Status
1. Literature Review	30%	●
2. Complete neutron diffraction experiments.	40%	●
3. Process neutron diffraction data for Ti-6Al-4V.	85%	●
4. Process neutron diffraction data for IN 738.	10%	●
5. Process synchrotron experimental results.	10%	●

Industrial Relevance

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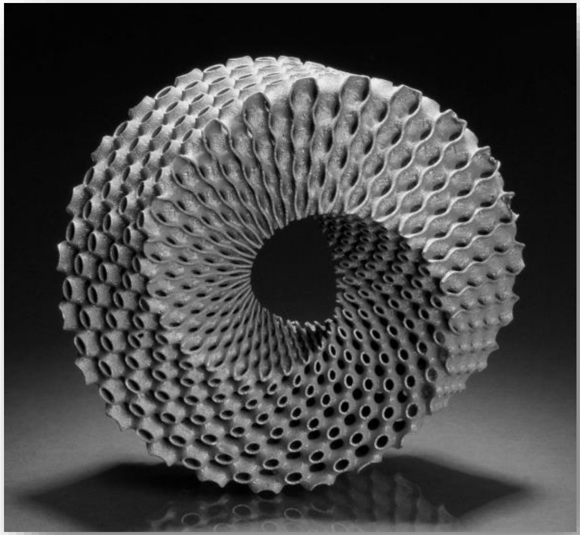
- Additive manufacturing (AM) is becoming ubiquitous
  - Freedom in engineering design
    - Aerospace
    - Rapid-repair and prototyping
- Issues in qualification and certification
- Requires fundamental understanding of microstructural evolution
- Lead to increased part performance via microstructural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

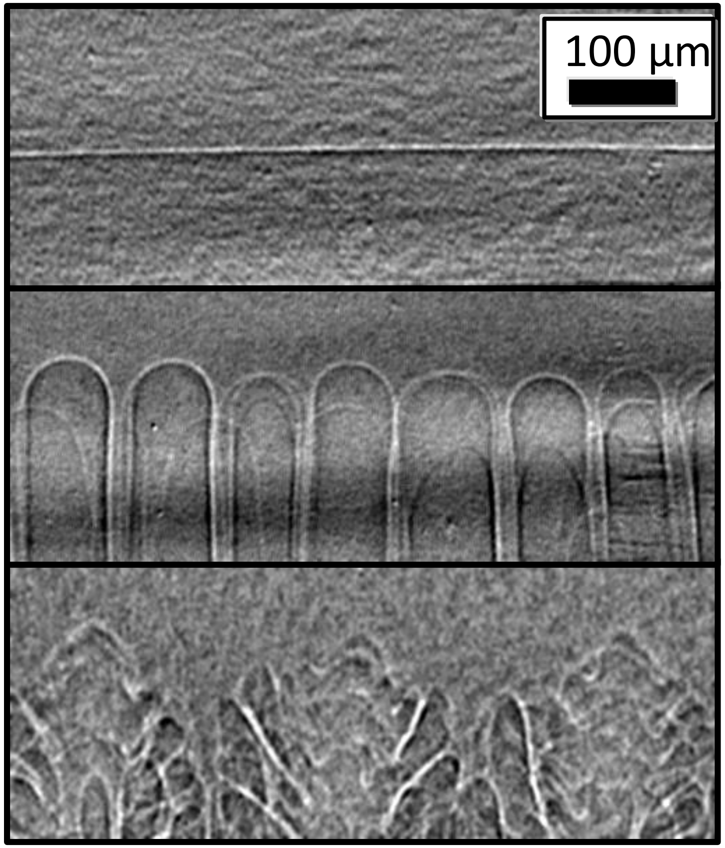


https://synergyresources.net/additive-manufacturing-next-industrial-revolution/

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
    - Heating ↔ Cooling
- Phase transformations
  - β to α' in Ti-6Al-4V
- Microstructural development
- Defect formation



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

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

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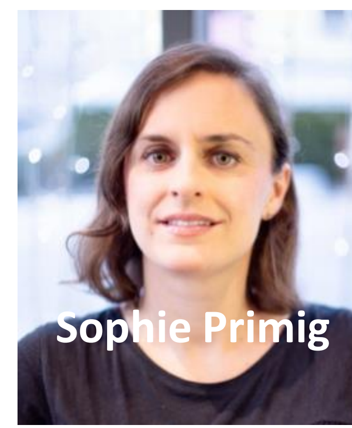
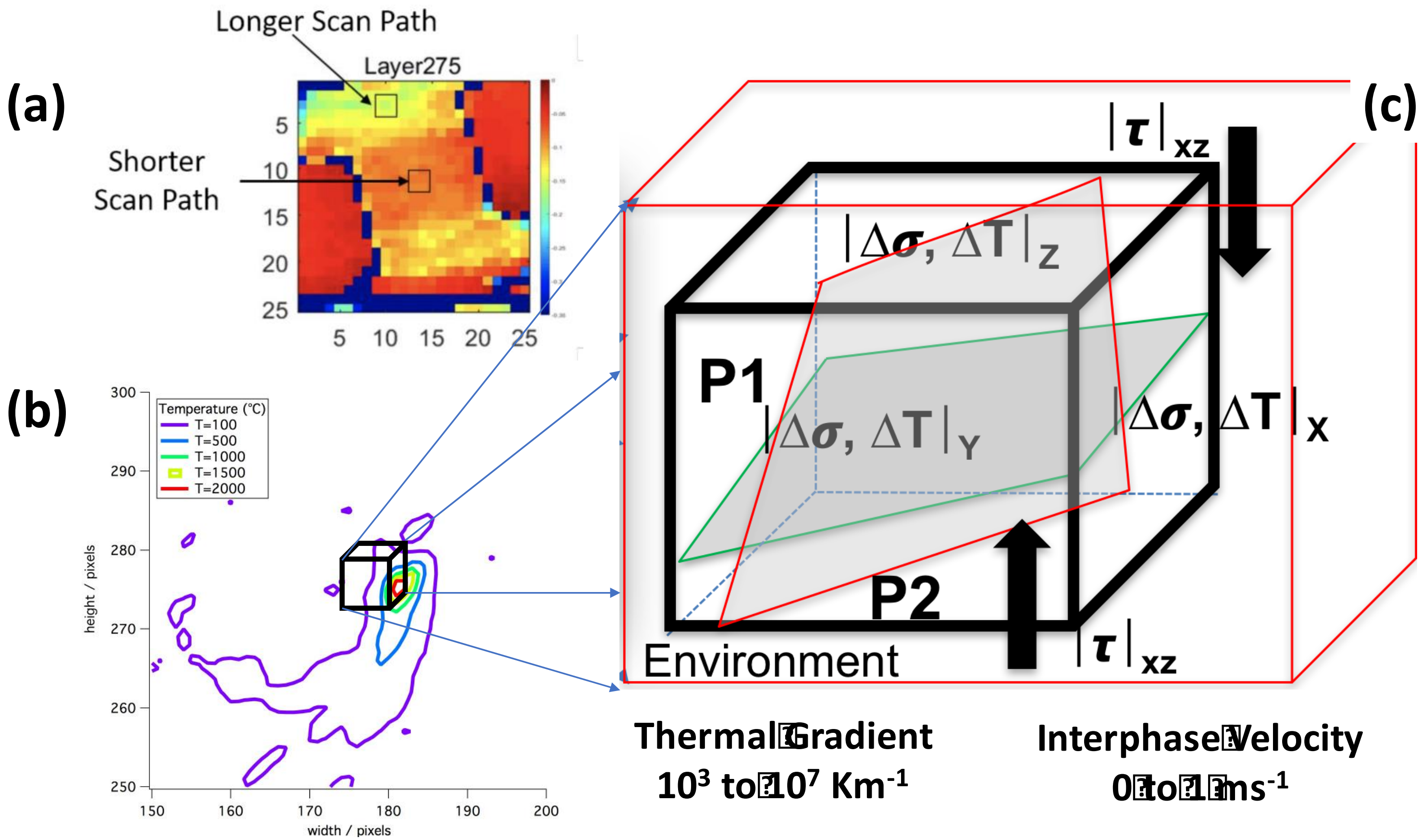
Core Research Facilities



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…

Courtesy of S.S. Babu, University of Tennessee

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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

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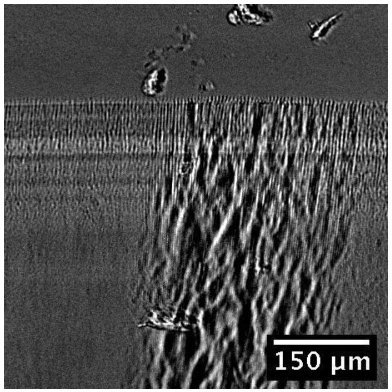
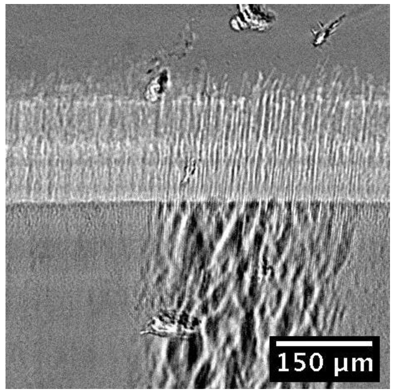
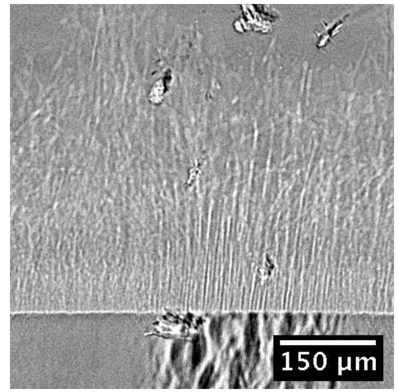
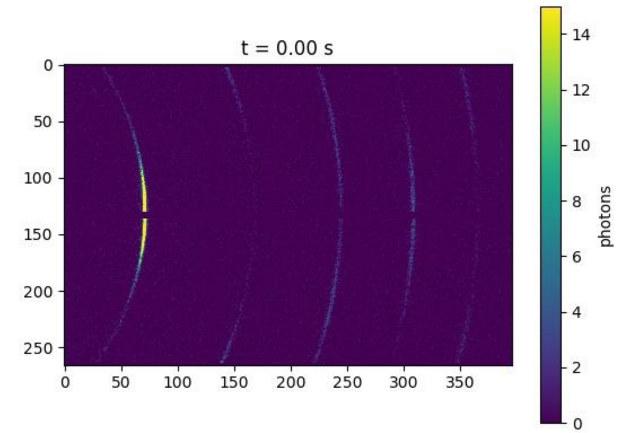
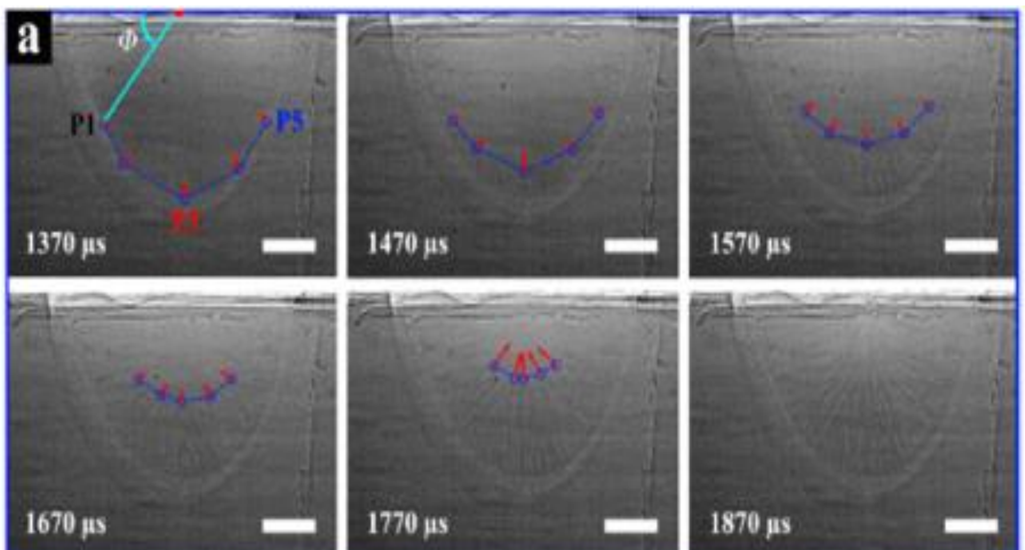








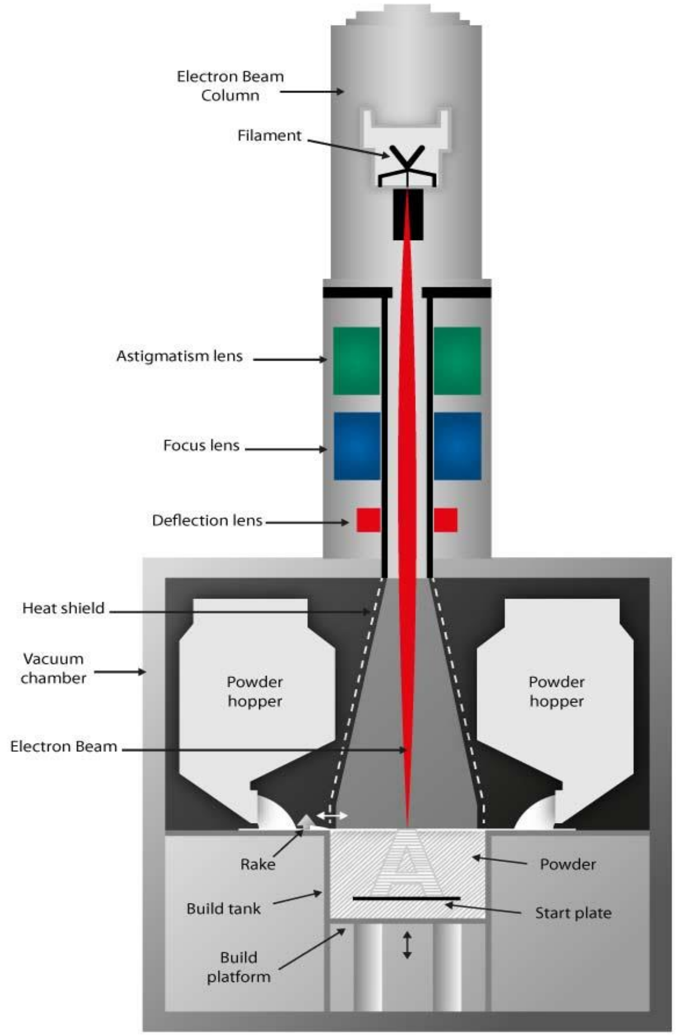
In-situ imaging/diffraction at national user facilities



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

Electron Beam Melting (EBM)

- Ti-6Al-4V and Inconel 738
- Powder bed melting method
- Electron beam heat source
- Large powder size
  - 100 μm average diameter
- Chamber heated to ~ 600°C
- Completed at Oak Ridge National Laboratory Manufacturing Demonstration Facility



http://www.arcam.com/technology/electron-beam-melting/hardware/

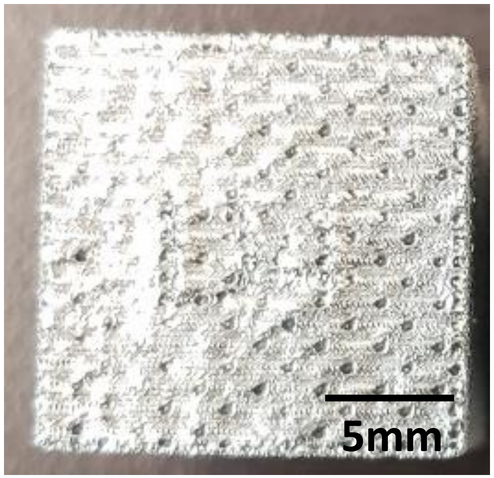
Sample Production

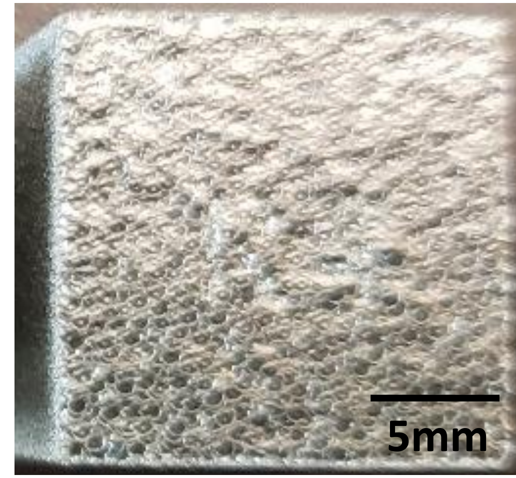
- Varying build strategies
  - Alter local thermal history
- 15 mm x 15 mm x 25 mm

Dehoff build pattern

Random build pattern

Finished Product

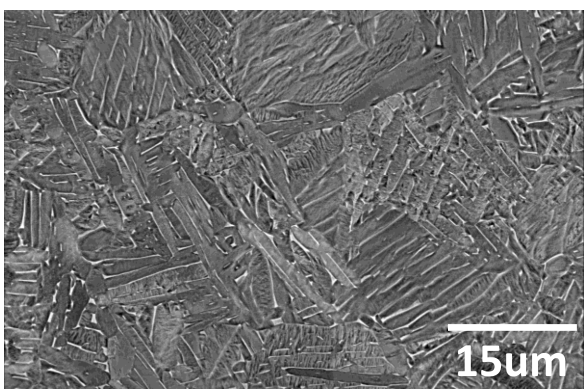


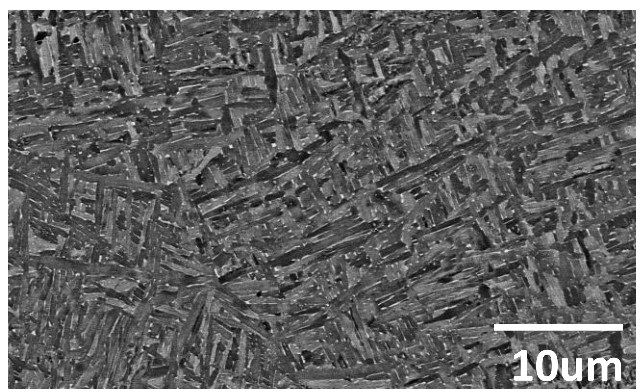


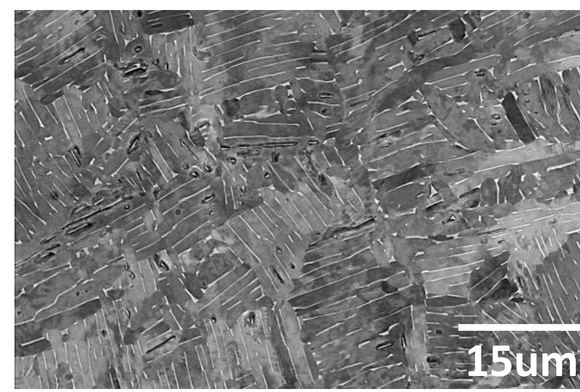
Dehoff

Raster

Random



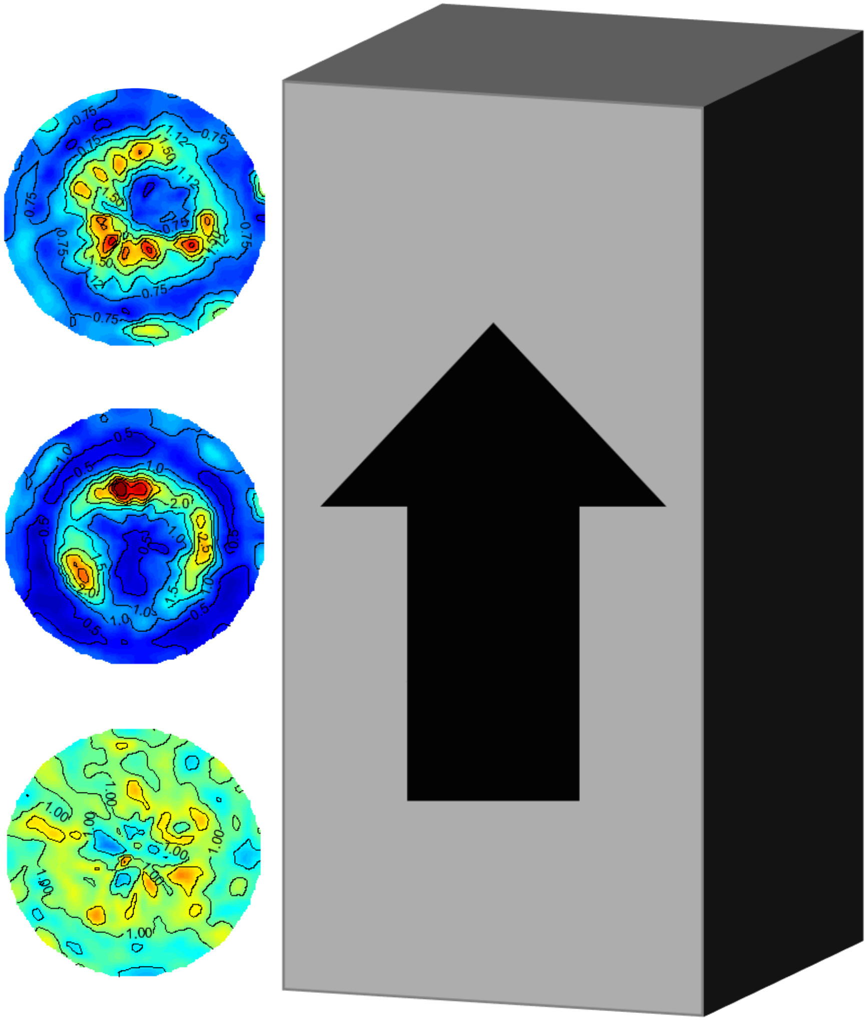




P. Collins, et. al, ISU

Recent Work

- Texture experiments completed on Ti-6Al-4V
  - Bulk texture
  - Local texture
    - Variation with build height
- Ongoing analysis of neutron diffraction data
  - Explain textures
  - Develop understanding for variations seen between samples
- Processing x-ray radiography data and samples from the Advanced Photon Source



Neutron Diffraction

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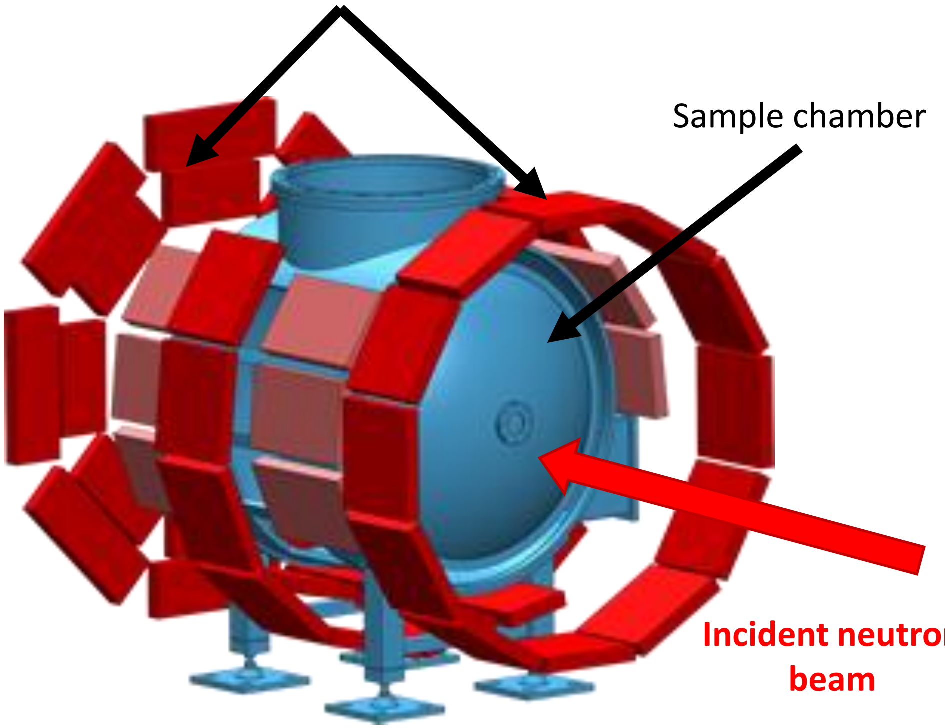
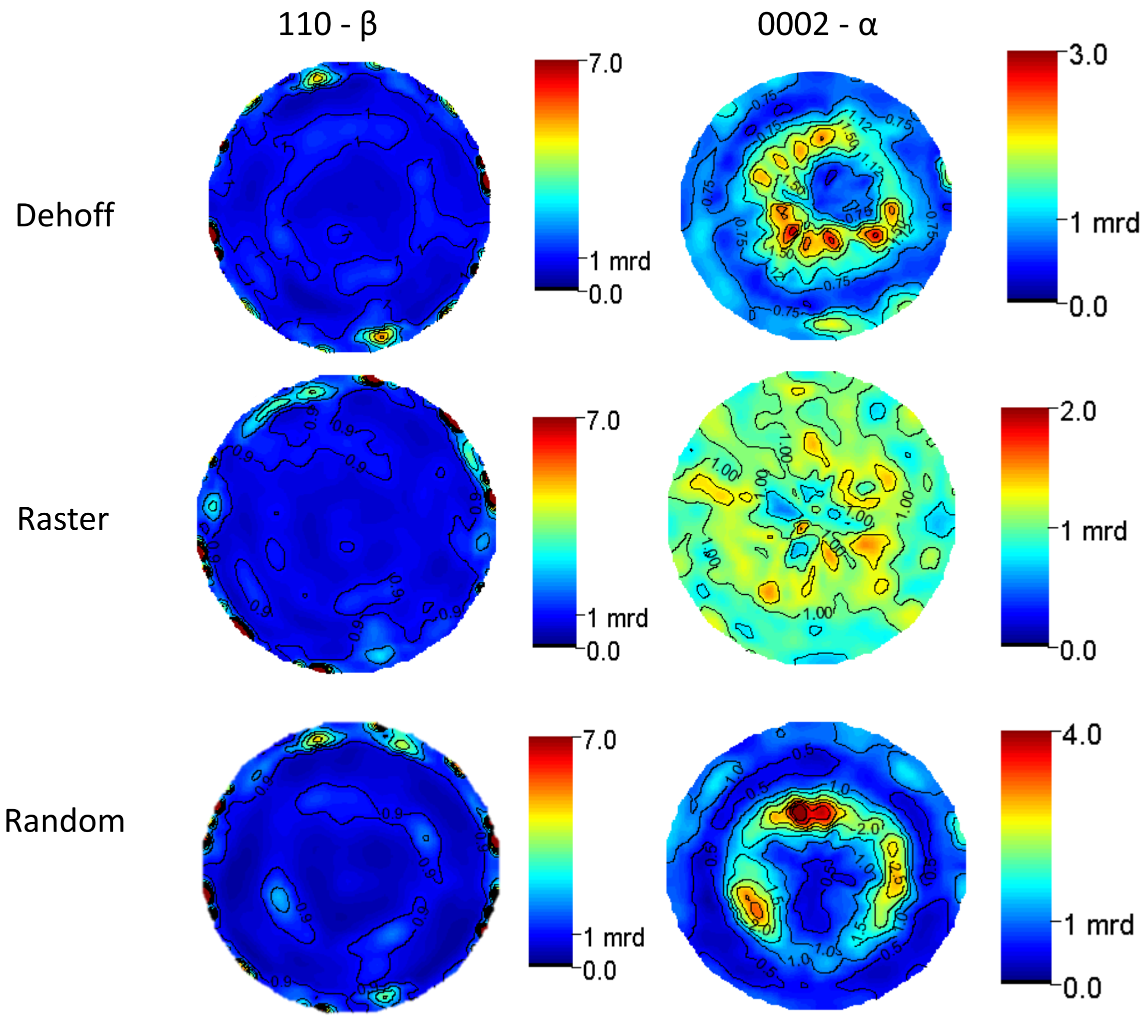
- Uses neutrons to penetrate larger volumes of material
  - $1000\ mm^3$
  - High energy, low distance neutrons
- Scattering events produce crystallography data
  - Preferred orientations
  - Crystal structure
- Bulk and slit experiments
  - Full specimen texture
  - Localized texture profile



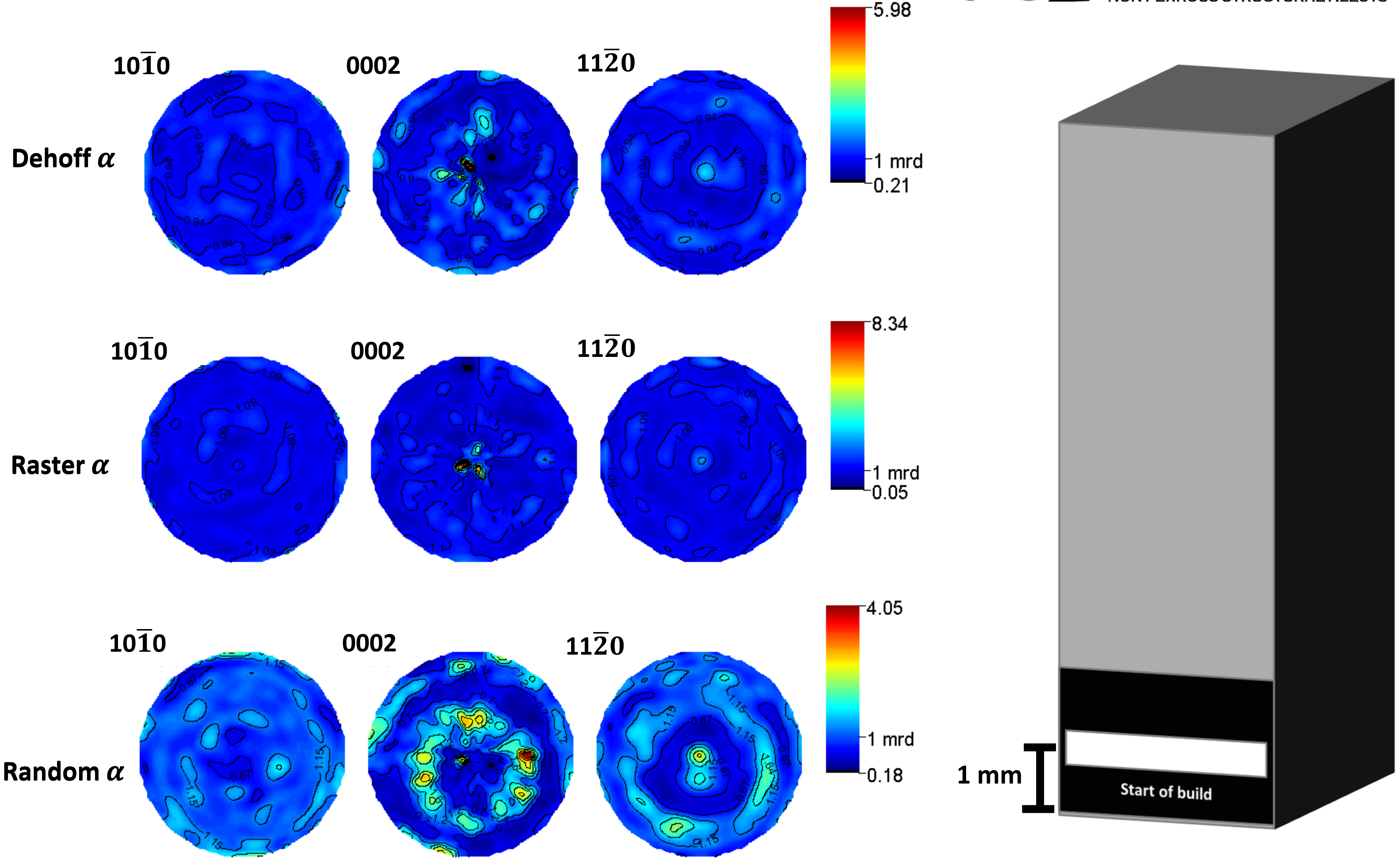
HIPPO (High Pressure Preferred Orientation) beamline at LANL

Bulk Texture Results

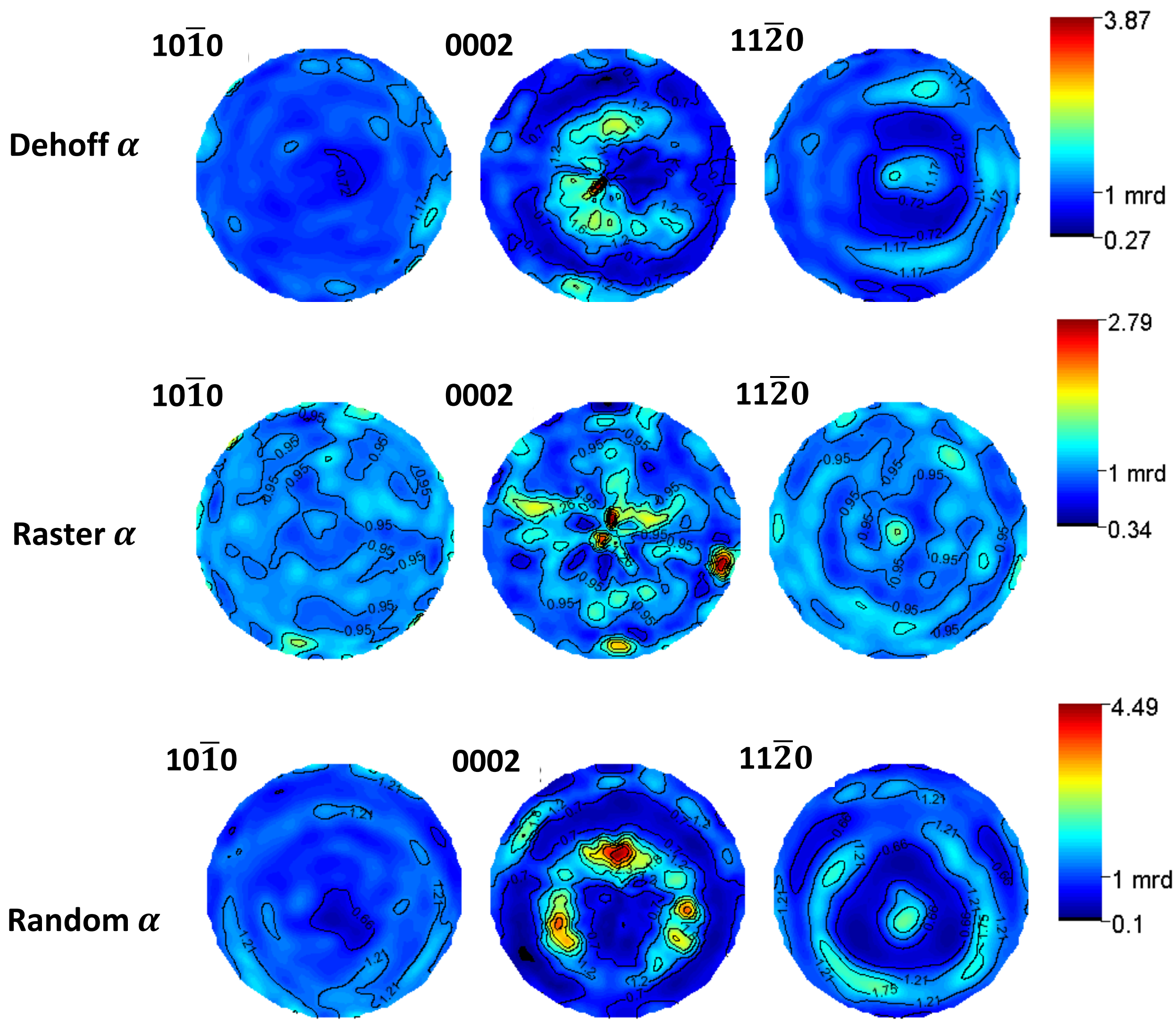
- Raster exhibited lowest texture intensity
- Random and Dehoff exhibited higher texture intensity
- Evidence of Burger's orientation relationship
  - Ring pattern
- Indications of variant selection

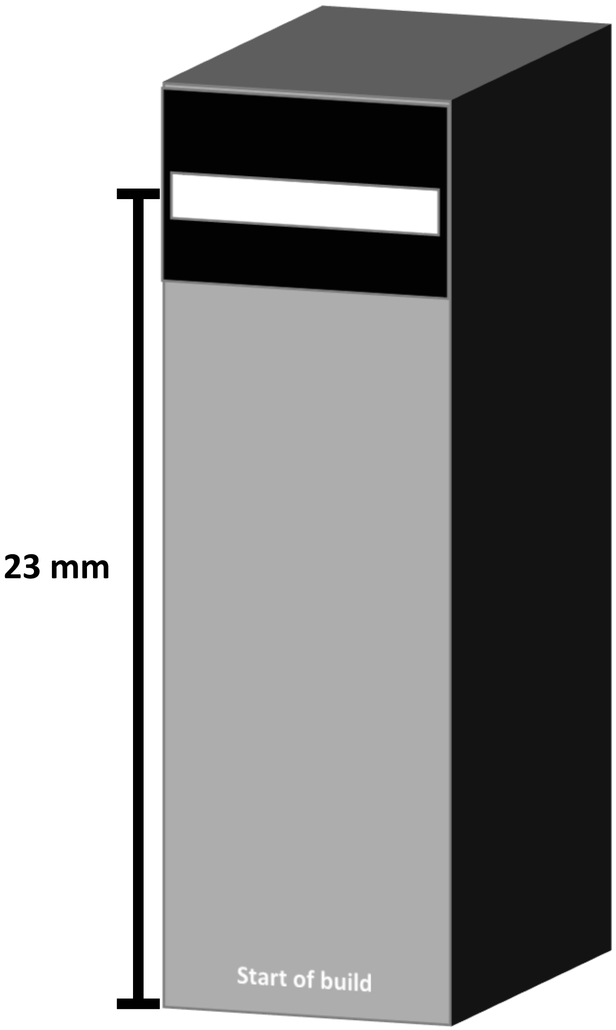


Local α Texture Near Build Start



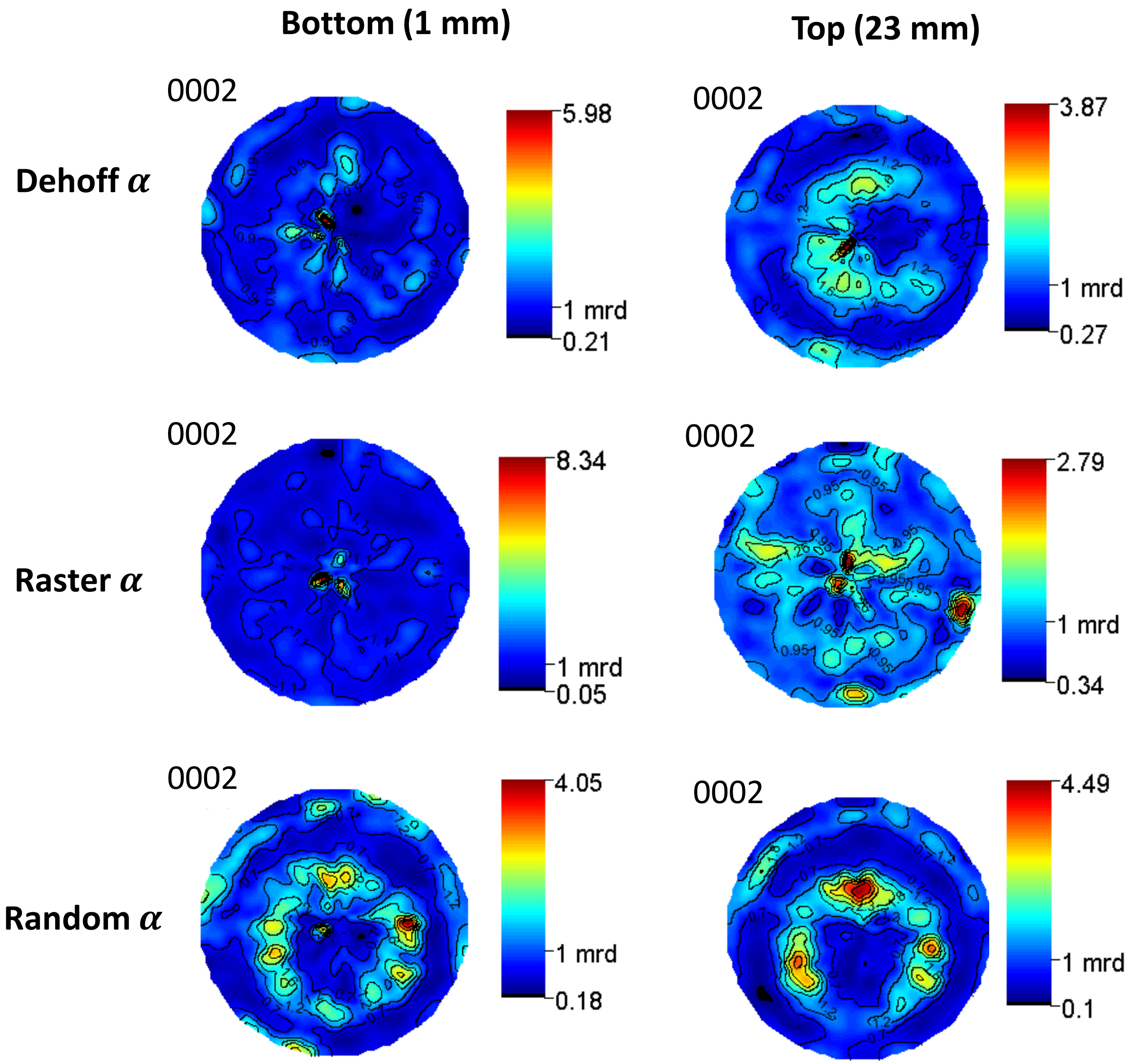
Local α Texture at Build End





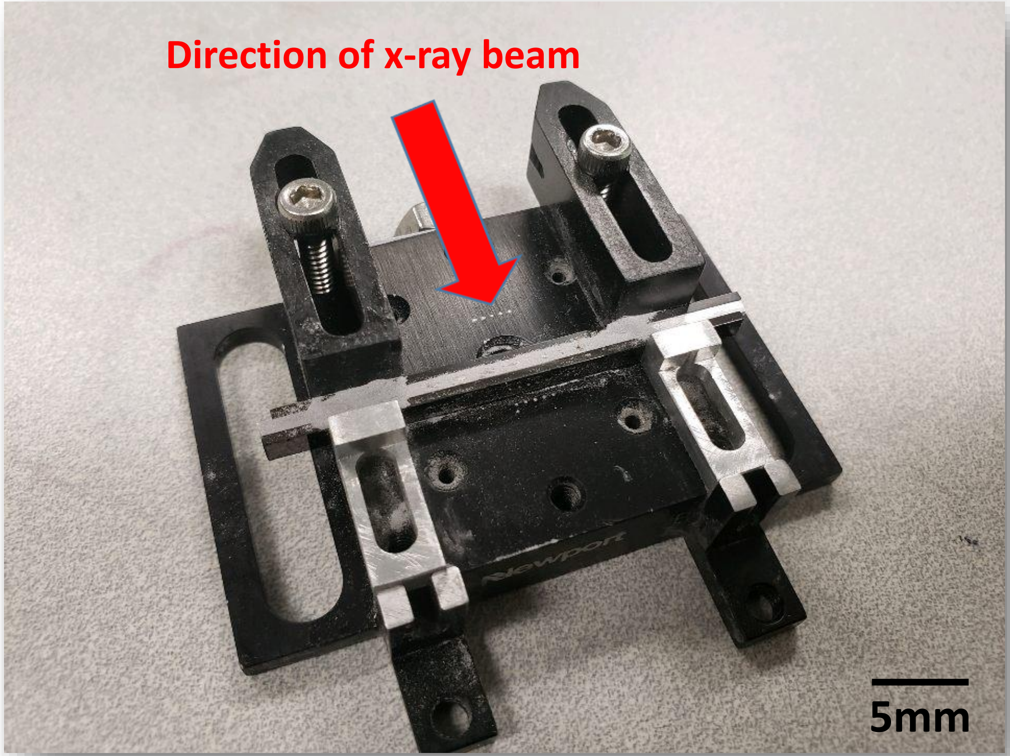
Local α Texture Results Summary

- Texture variation present throughout build height
  - Raster → Largest
  - DeHoff → Moderate
  - Random → Minimal
- β data still inconclusive
  - Very low phase fraction
- Varying thermal history seen to alter texture considerably
  - Directly supports MURI effort



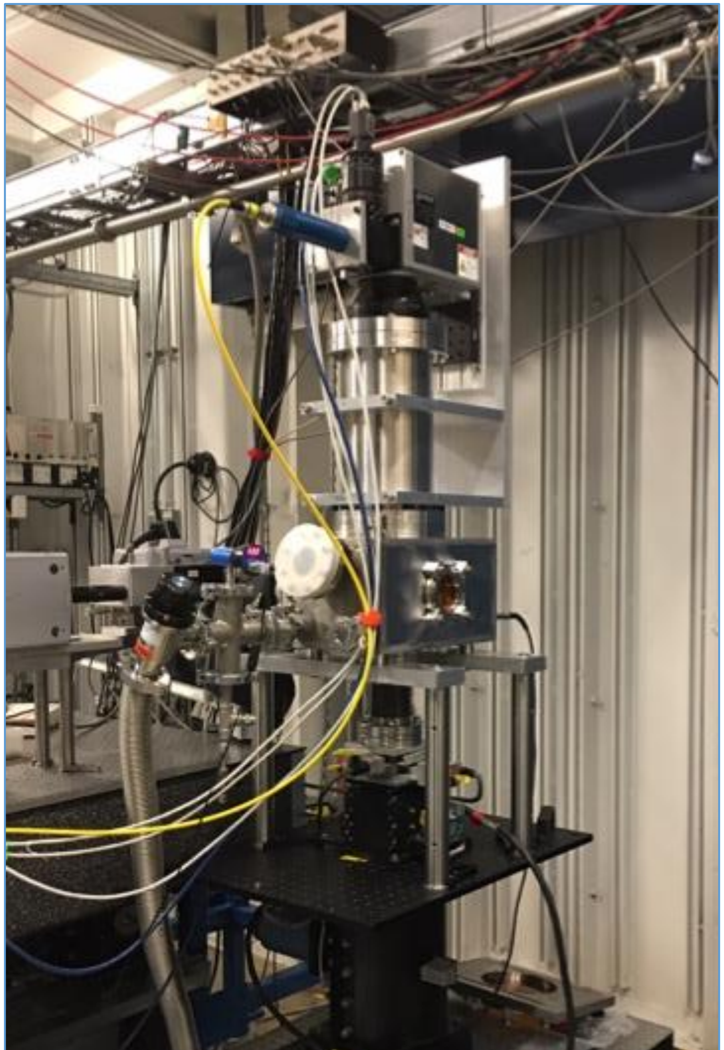
APS Experiments

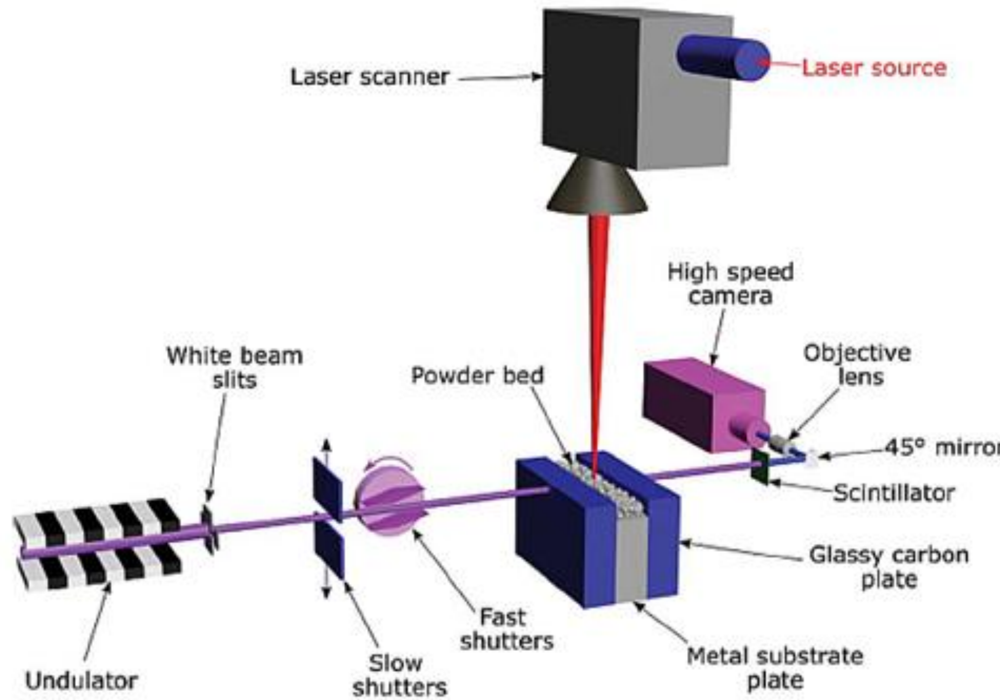
- Observe real-time AM solidification phenomena
  - Diffraction
  - Radiography
- Examined various Ni alloys and powders
  - Inconel 718, Inconel 738
  - Ni-Al-Mo single crystals (Pollock, UCSB)
- Completed both raster and spot experiments



Example specimen and mounting assembly.

Laser Powder Bed Fusion (LPBF) AM Simulator



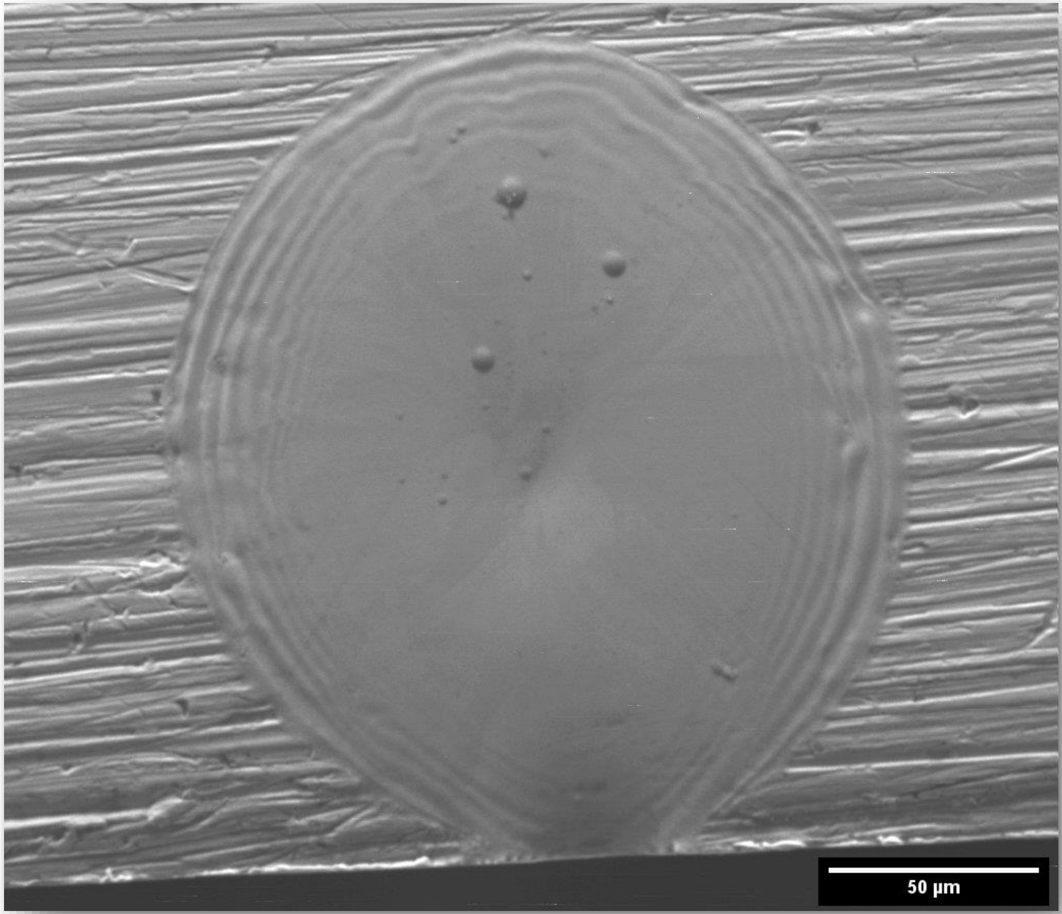


N. Parab et al., J. Synchrotron Rad. 2018, 25:1467-1477

Ni-Al-Mo Single Crystal Experiments

APS Results

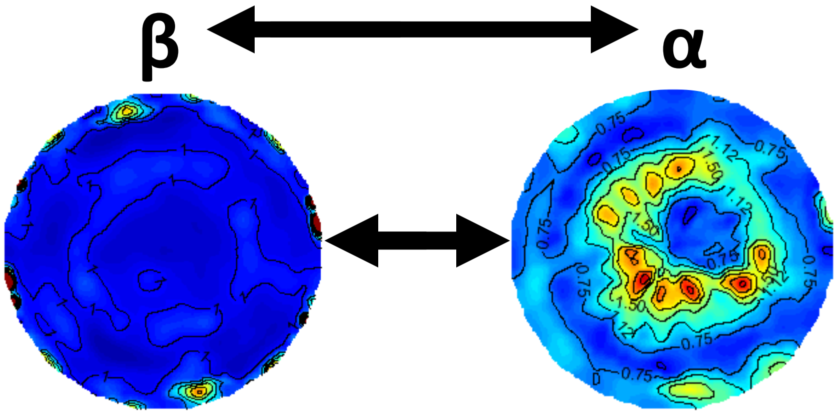
- Adjusted number of parameters
  - Dwell time
  - Laser power
  - Raster speed
- Clear evidence of solid-liquid interface
- Solidification structure visible in scanning electron microscopy

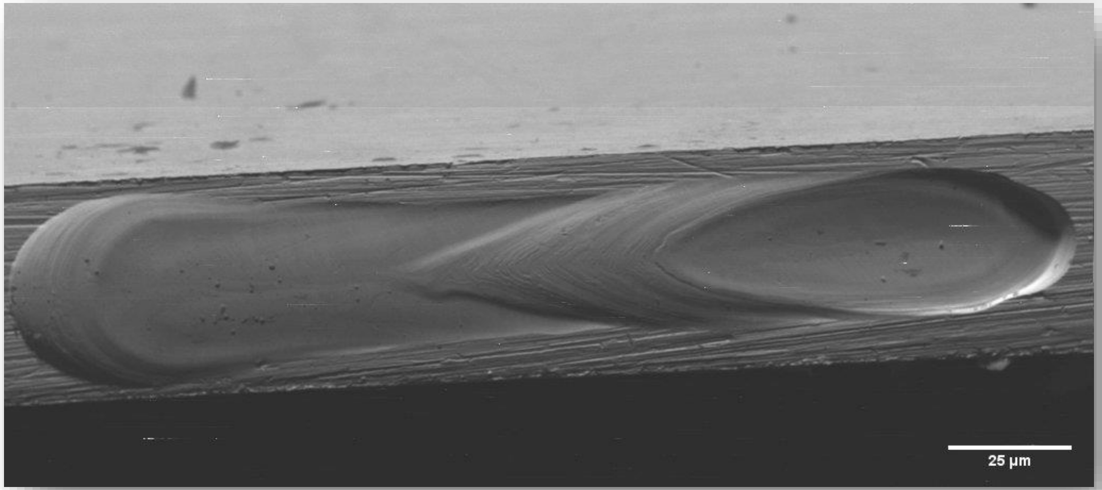


Spot melt pool of a Ni-Al-Mo single crystal at 20% laser power

Future Work

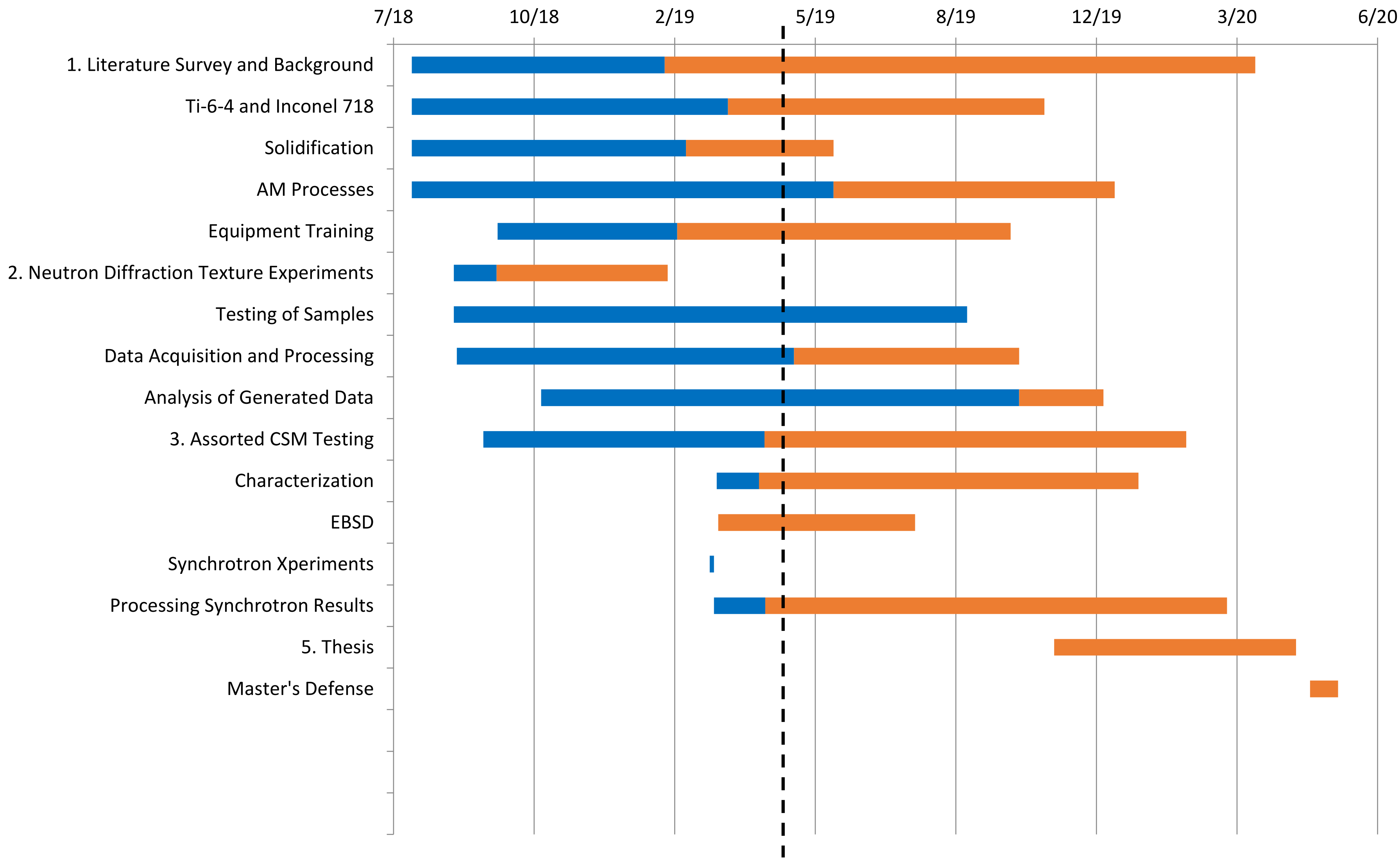
- *In-situ* experiments with HIPPO at LANL
  - Heating-cooling for Ti-6Al-4V β↔α transformations
  - Texture evolution of Inconel 738
- Microstructural characterization of Ti-6Al-4V samples
  - EBSD
  - SEM microscopy
- Devise method to analyze β texture evolution
- Finish processing APS experimental data





Raster melt pool of a Ni-Al-Mo single crystal.

Progress



7/18
10/18
2/19
5/19
8/19
12/19
3/20
6/20
1. Literature Survey and Background
Ti-6-4 and Inconel 718
Solidification
AM Processes
Equipment Training
2. Neutron Diffraction Texture Experiments
Testing of Samples
Data Acquisition and Processing
Analysis of Generated Data
3. Assorted CSM Testing
Characterization
EBSD
Synchrotron Xperiments
Processing Synchrotron Results
5. Thesis
Master's Defense

Thank you for listening!

Any questions, comments, or concerns?

Alec Saville

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303-990-0939

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Student: *Alec Saville*

Faculty: *Amy Clarke*

Other Partcipants: *ORNL (Sudarsanam Suresh Babu)*

Project Duration: *August 2018 – May 2022*

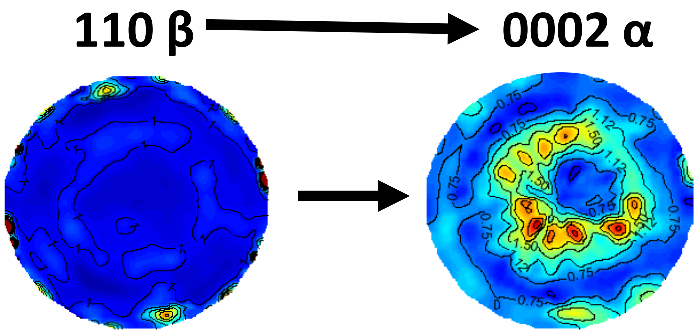
http://aviationweek.com/blog/meet-boeings-latest-next-gen-fighter-concept

Achievement

- Fundamental rationalization of instabilities during additive manufacturing of metallic systems and their effects on material performance in Ti-6Al-4V and Inconel 738

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.



Pole figures depicting a $\beta \rightarrow \alpha$ transformation in a Dehoff scan strategy in Ti-6Al-4V.

Research Details

- Analyzing effects of scan strategy/thermal gradients on texture evolution and material microstructure in EBM produced Ti-6Al-4V.

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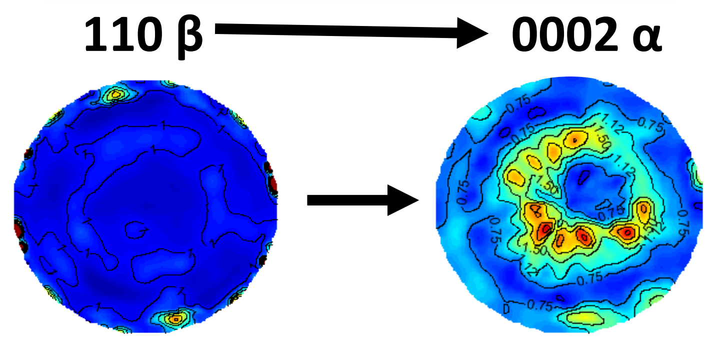

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Program Goal

- Rationalize how instabilities in additive manufacturing of Ti-6Al-4V and Inconel 738 impact resultant microstructure and material performance

Approach

- Use *in-situ* synchrotron beam line experiments, neutron diffraction texture experiments, and characterization techniques to analyze interfacial evolution during AM processing

Benefits

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

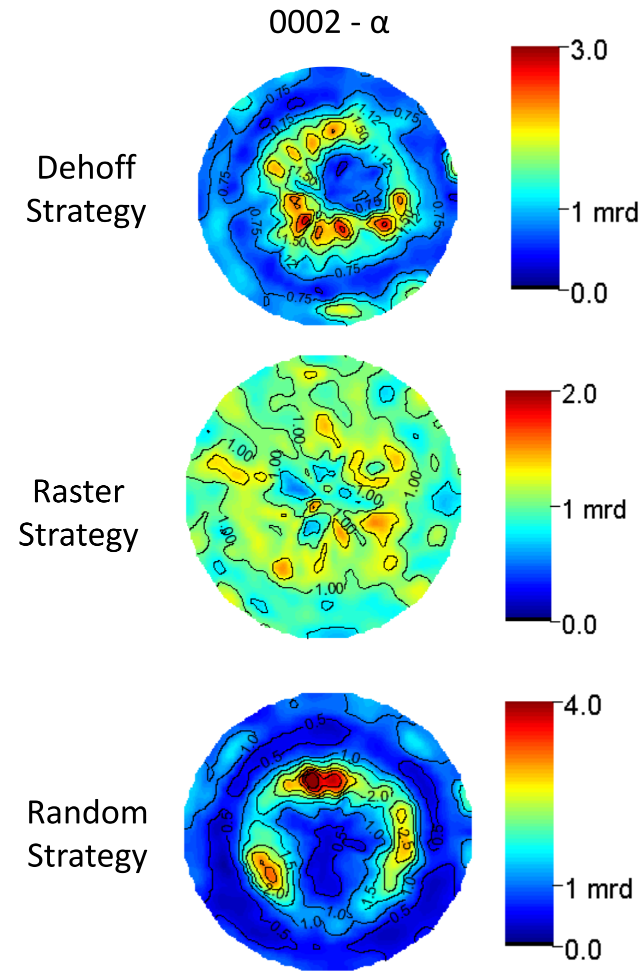

Figure: Pole figures depicting α Ti texture for various scan strategies in Ti-6Al-4V.