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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

Fall 2019 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
October 9 - 11, 2019

Student: Alec Saville (Mines)
Faculty: Amy Clarke (Mines)
Industrial Mentors: TBD
Other Participants: Sven Vogel (LANL), Adam Creuziger (NIST)

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COLORADO SCHOOL OF MINES
IOWA STATE UNIVERSITY

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: Control of material properties in metallic additive manufacturing (AM) is difficult due to a lack of background knowledge on material evolution within AM production methods.
- Objective: Evaluate differences in material properties of Ti-6Al-4V as a function of scan strategy in additive manufacturing processes.
- Benefit: Greater understanding of material evolution in AM will inform predictive capabilities and improve performance of AM parts.

Recent Progress

- Finished processing of neutron diffraction data.
- Completed initial quantification of texture components.
- Evaluated proper specimen symmetry for experimental results.
- Began development of standardized processing routine for neutron diffraction data.

Metrics

Description	% Complete	Status
1. Literature review.	75%	●
2. Process neutron diffraction data.	100%	●
3. Quantification of texture components.	50%	●
4. Supporting material characterization.	25%	●
5. Development of instructional material to standardize neutron diffraction data processing.	15%	●

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

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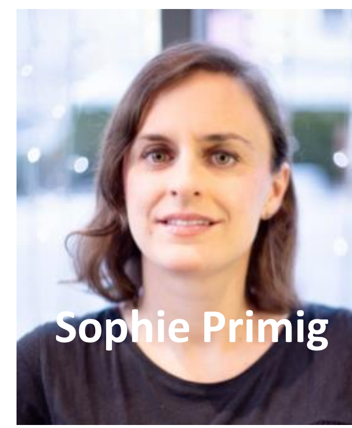


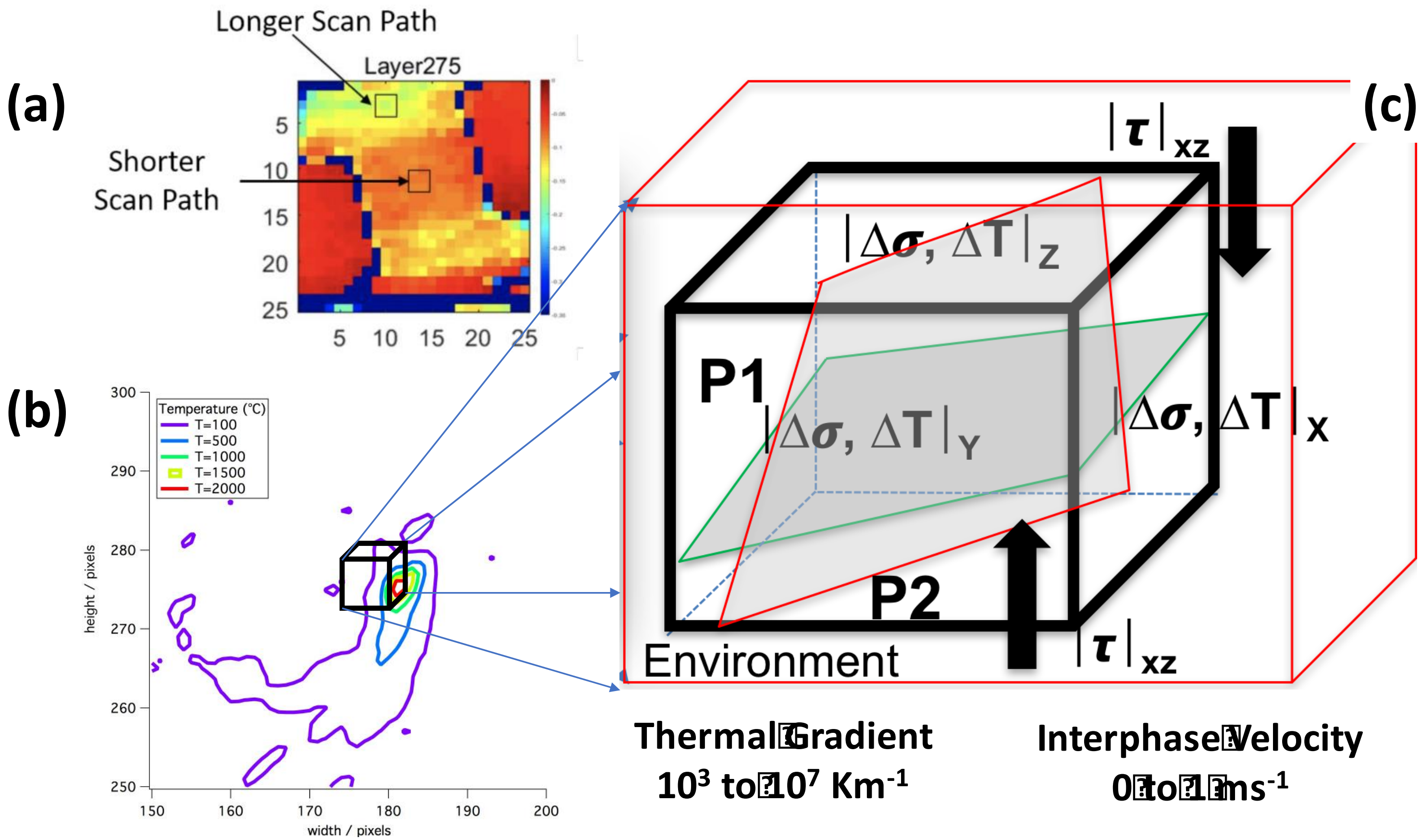
VIRGINIA TECH.

UC SANTA BARBARA MATERIALS

THE UNIVERSITY OF SYDNEY
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

Project Recap

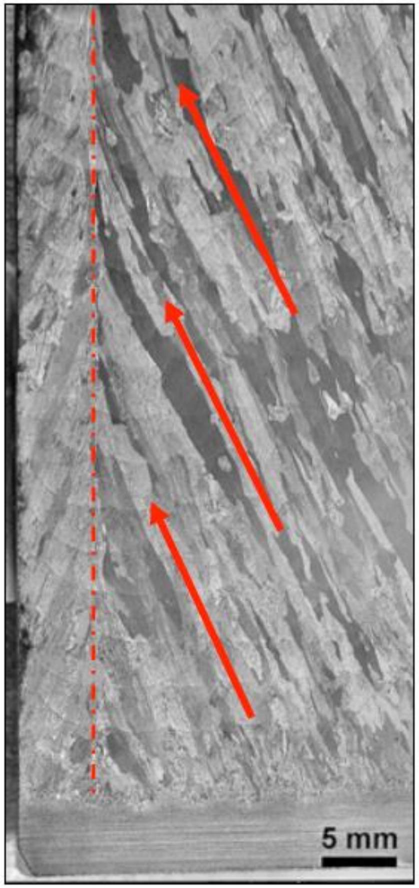
Objective: Quantify differences in crystallographic texture as a function of scan strategy and build height of additively manufactured (AM) Ti-6Al-4V.

Motivation:

- AM produced metals exhibit large degrees of anisotropy
  - *Prevents metallic AM from being used for high performance parts*
- Greater understanding of how anisotropic behavior forms is required to inform predictive capabilities and material performance
  - *Crystallographic texture major contributor to anisotropy*

Texture in AM Ti-6Al-4V

- Thermal gradients form columnar β-Ti grains
  - Strong {001} orientation for β-Ti
- α-Ti normally exhibits relatively random texture
  - Changes with AM process
- Function of build parameters
  - **Scan strategy**
- Altering scan strategy alters local thermal history
  - Potentially give rise to changes in preferred orientations

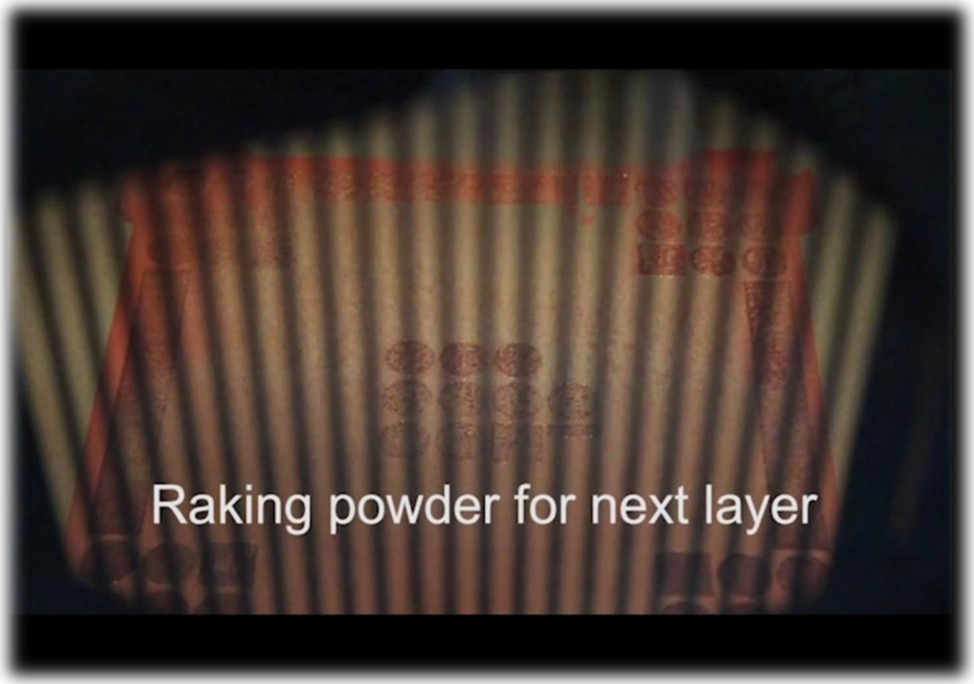


Ti-6Al-4V produced via wire-based EBF^3.
(C.A. Brice, W.A. Tayon, A.L. Pilchak, Texture Development in Titanium Components Made by Additive Manufacturing, San Diego. (2014)

Past Work

Sample Production

- Rectangular Ti-6Al-4V prisms
  - 15 mm x 15 mm x 25 mm
- Built using an ARCAM A2X
  - Electron beam melting (EBM)
  - ARCAM-provided Ti-6Al-4V powder
  - Chamber preheat of 470°C
- Three different scan strategies to vary local thermal history
  - Random (Spot)
  - Dehoff (Spot)
  - Raster



Example EBM build process employing a Raster scan strategy.
Credit: Arcam AB
https://vimeo.com/227802177

Spot Scan Strategies

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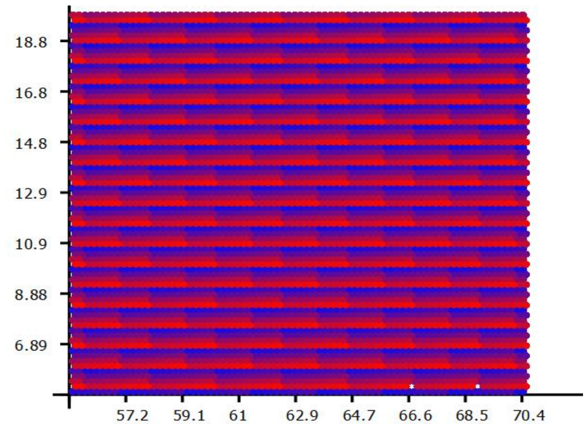
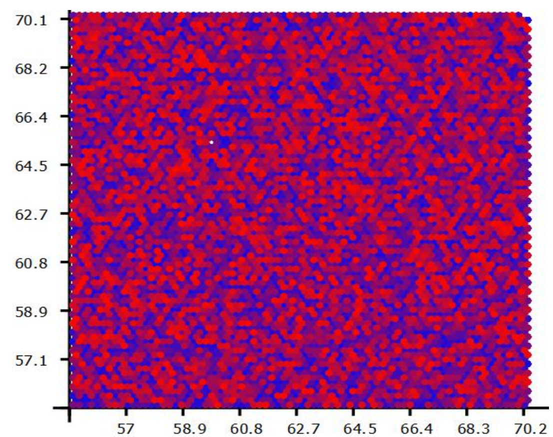
= First to melt = Last to melt

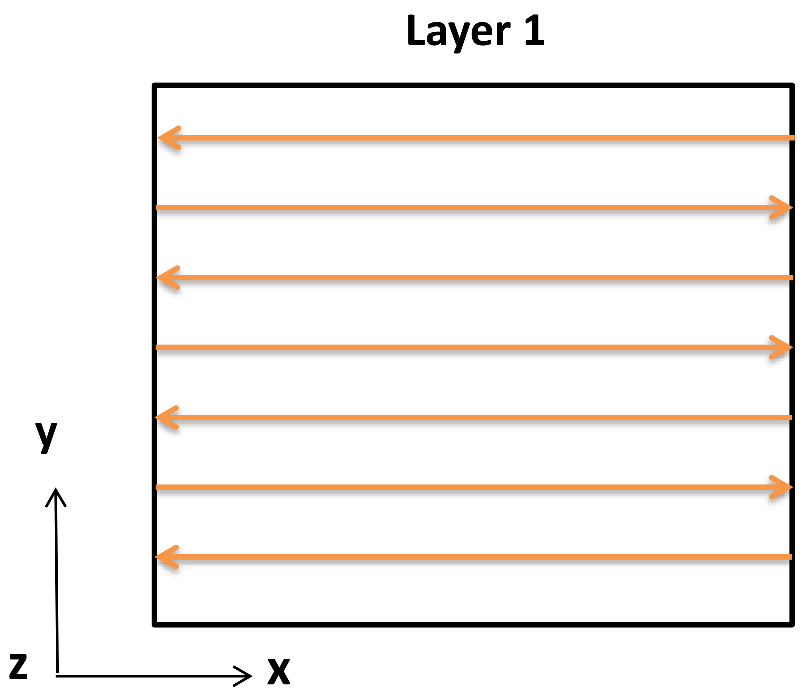
Dehoff



Random



Raster Scan Strategy



Raster Scan Strategy

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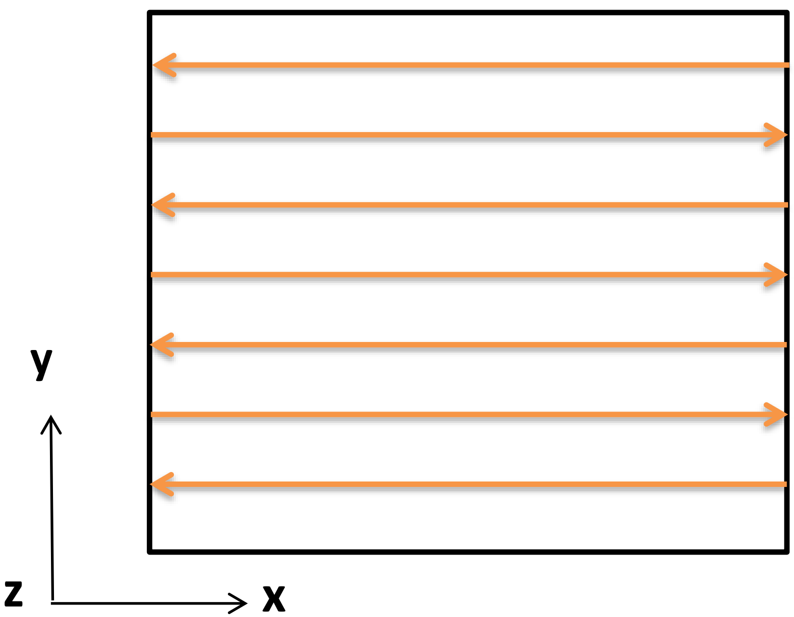
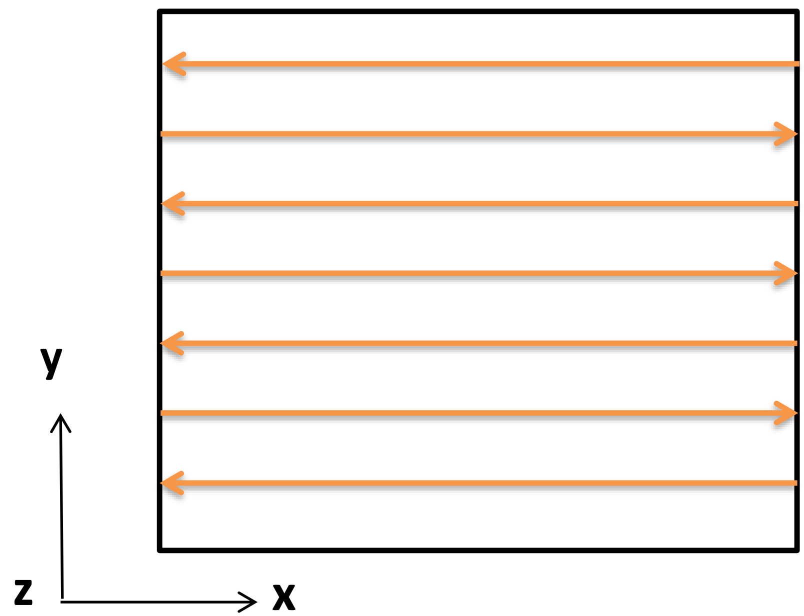
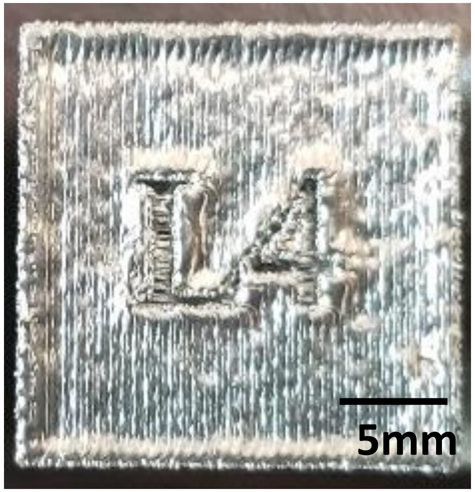
Layer 1



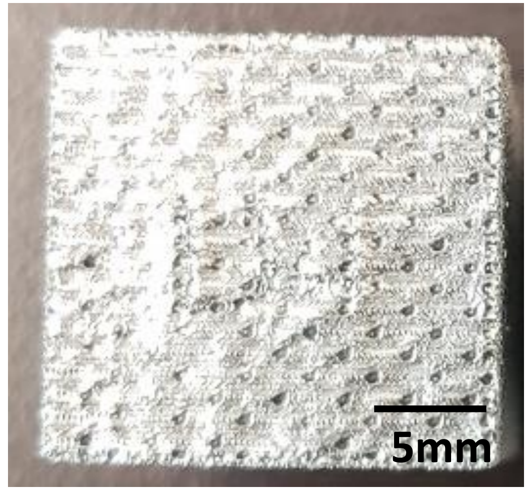
Layer 2



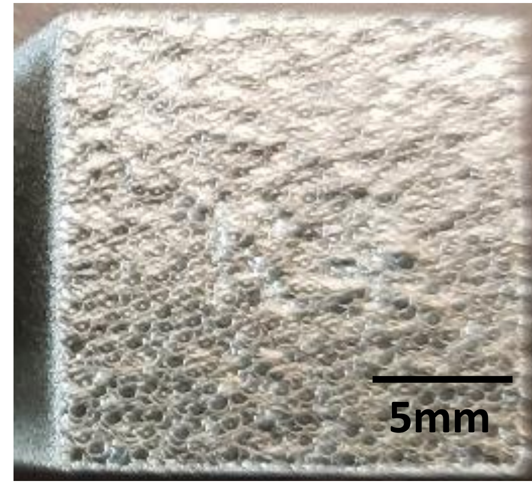
Finished Specimens



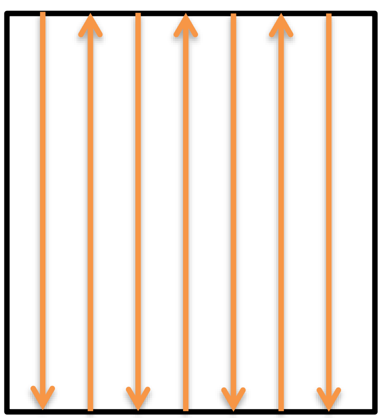
Raster

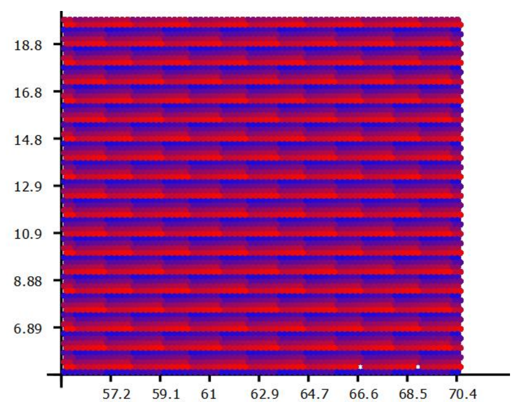


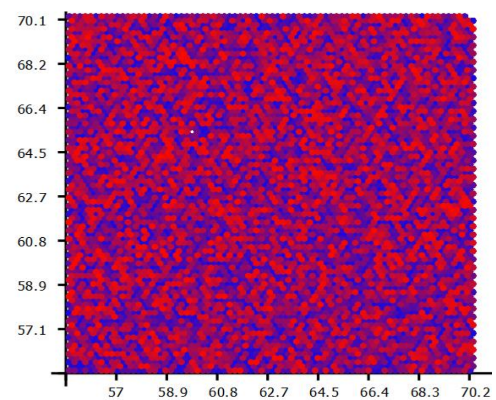
Dehoff



Random

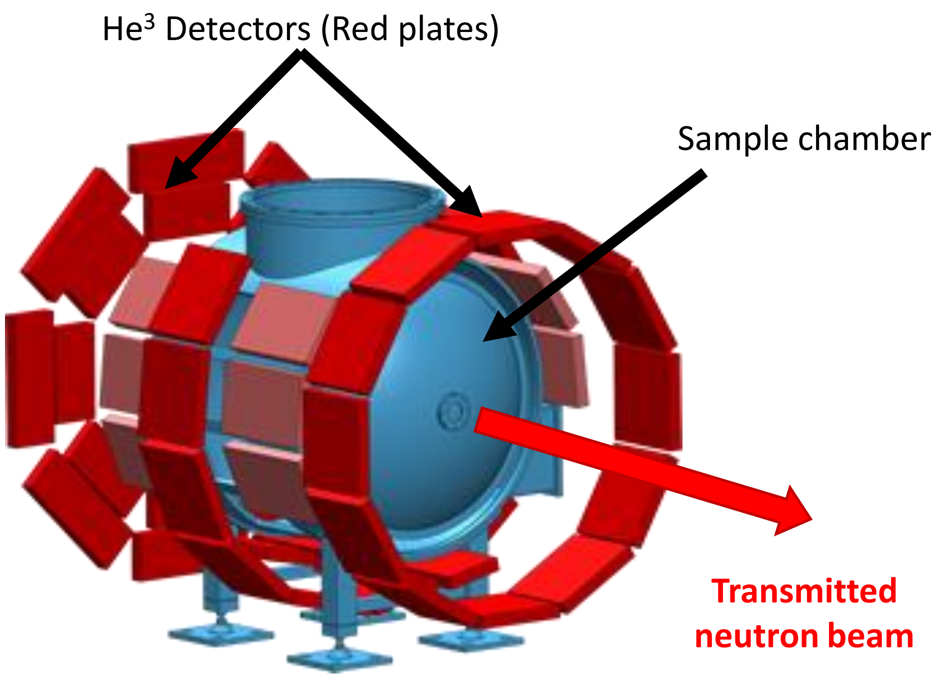






Determining Crystallographic Texture

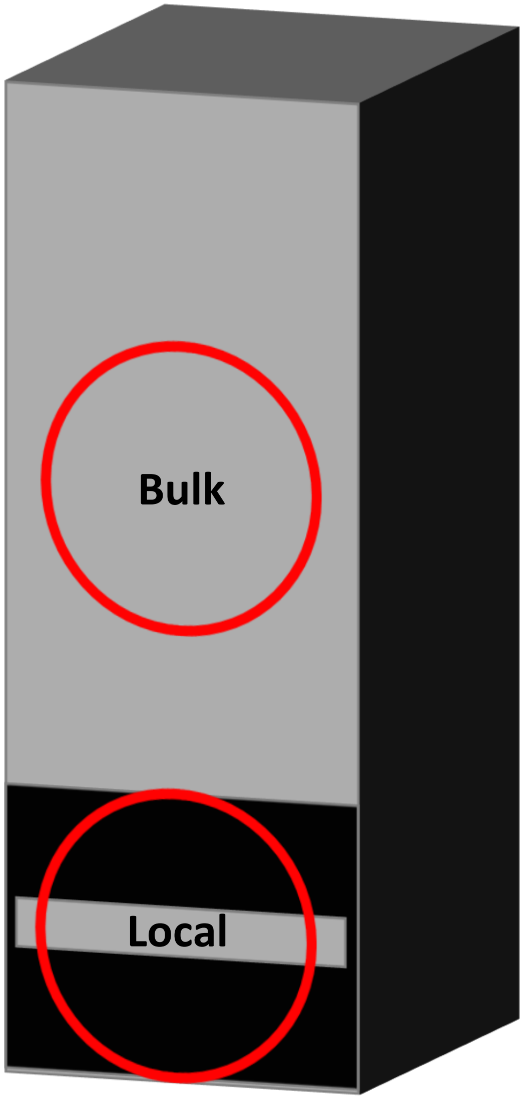
- High-Pressure-Preferred-Orientation (HIPPO) neutron diffraction beamline
  - Los Alamos National Laboratory (LANL)
- Detects diffraction events via He^3 detectors
  - Create texture profiles
- Time-of-flight detection (TOF)
- Capable of variable scan times
- 10 mm nominal diameter neutron beam



Schematic of the HIPPO beamline at LANL

Advantages of HIPPO

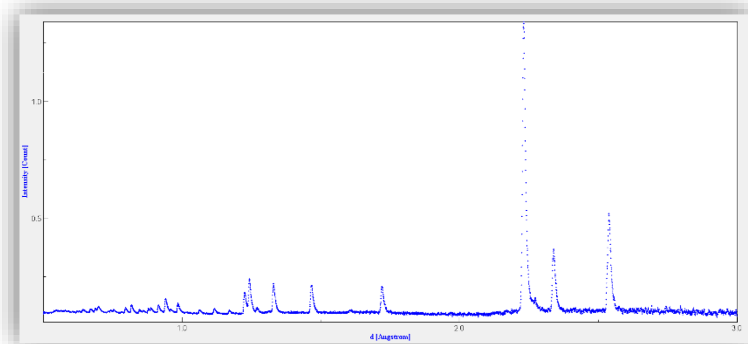
- Neutrons allow for analyzing larger volumes
  - 1000 mm^3
- Environmental control
  - In-situ heating/cooling
- Capable of bulk and local scans
  - Bulk texture (~ 600 mm^3)
  - Local texture (~ 150 mm^3)



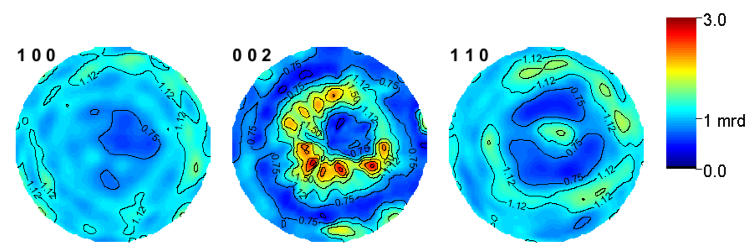
Data Processing

- Rietveld refinement using MAUD software package
  - Generates texture file
- Large number of parameters
  - Phase fraction
  - Lattice parameters
  - Differential calibration value
  - Debye-Waller factor
- Large amount of variability in processing
- Requires iterative process
  - Identify suitable parameter values for consistent analysis

Diffraction Data



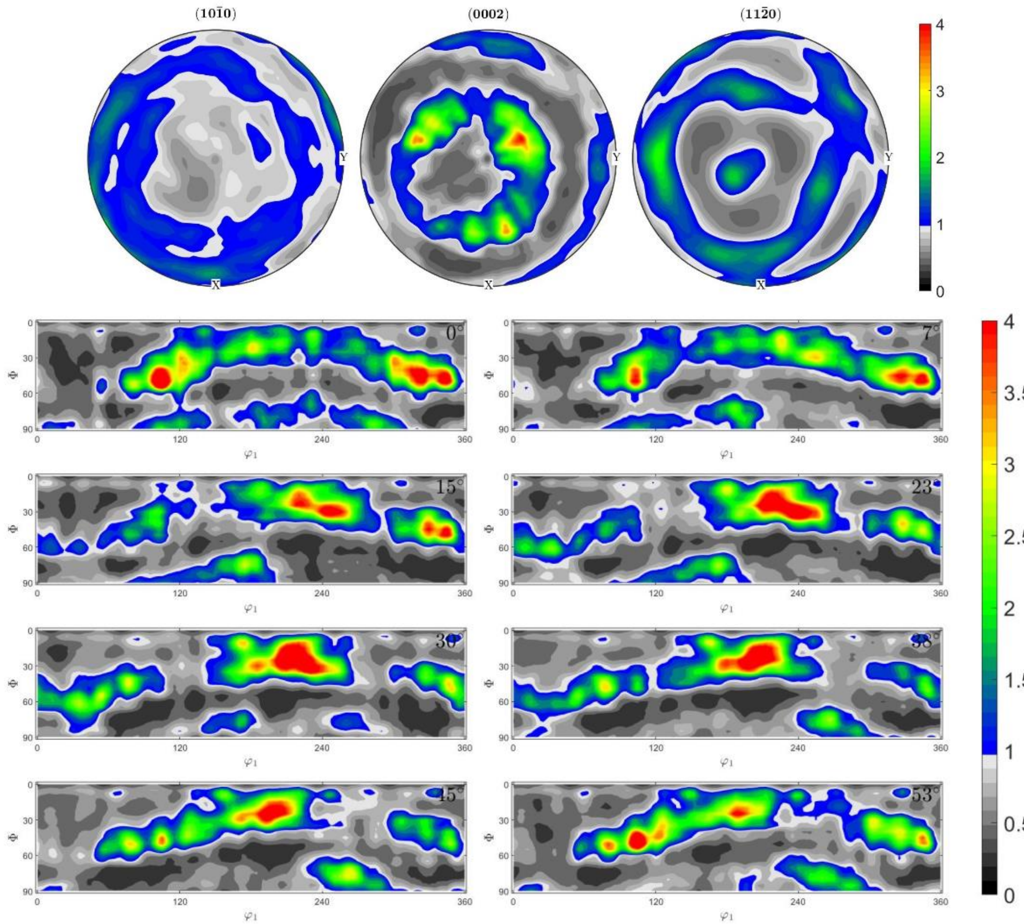
Texture information



Quantifying Texture

- MAUD file imported into MATLAB MTEX plugin
- Enables manipulation and quantification of texture information

1. Updated pole figures
   - Qualitative texture assessment
     - General trends in texture
2. Orientation distribution functions (ODF)
   - Quantitative operations



Example updated pole figures (top) and ODF (bottom) generated using MTEX.

Recent Work

Recent Work

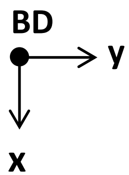
1. Finished processing data using MAUD
   - Observed texture changes with scan strategy but not build height
2. Developing instructional documentation for standard operating procedure in MAUD
   - Need for standardization demonstrated
3. Analysis of ODF's and updated pole figures
   - Initial quantification of texture components
     - Findings inconsistent with literature
       - Specimen symmetry
   - Fiber texture observed in all diffraction experiments

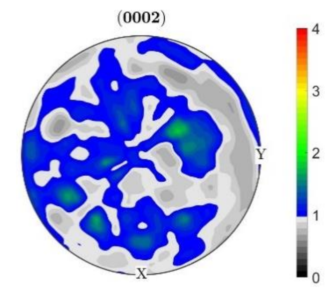
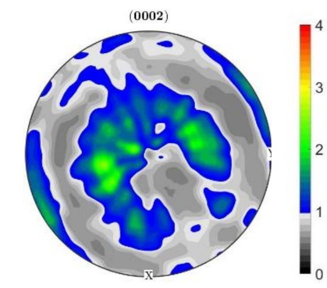
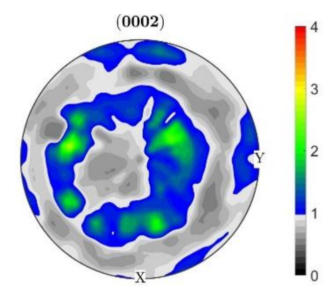
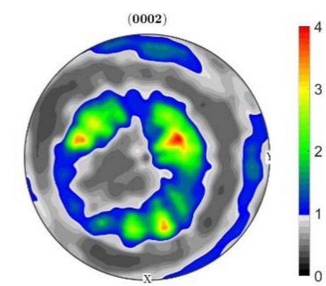
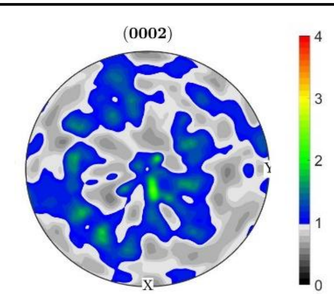
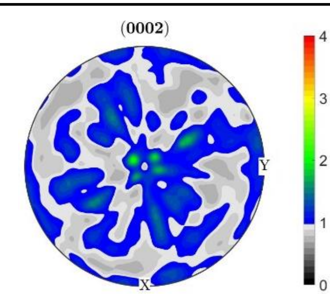
Crystallographic Texture Trends

1. α-Ti texture changes with scan strategy
2. α-Ti texture does not change considerably with build height

Analysis Details:

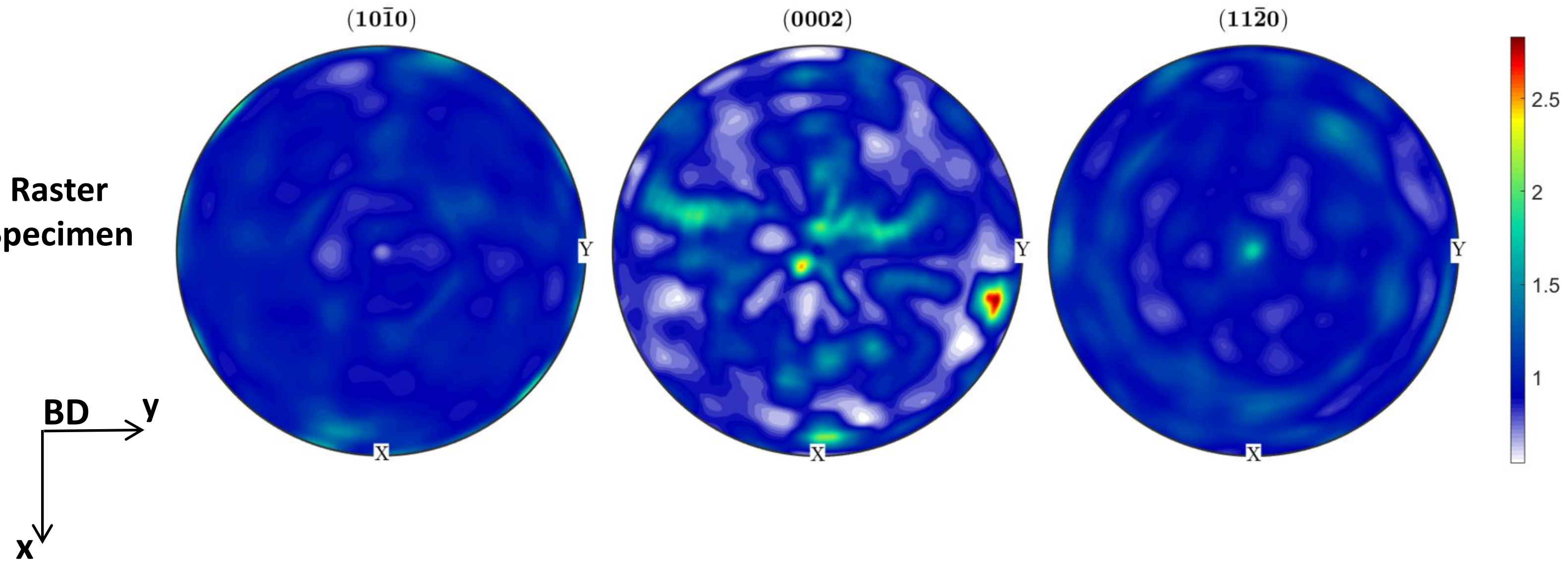
- Only analyzing α-Ti textures
  - β-Ti phase fraction ~ 1-4%
  - Insufficient for confident texture analysis (>5%)
- Build direction (BD)=Into screen



Scan Strategy	1 mm Build Height	23 mm Build Height
Dehoff α-Ti		
Random α-Ti		
Raster α-Ti		

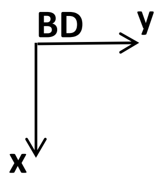
Processing Variability

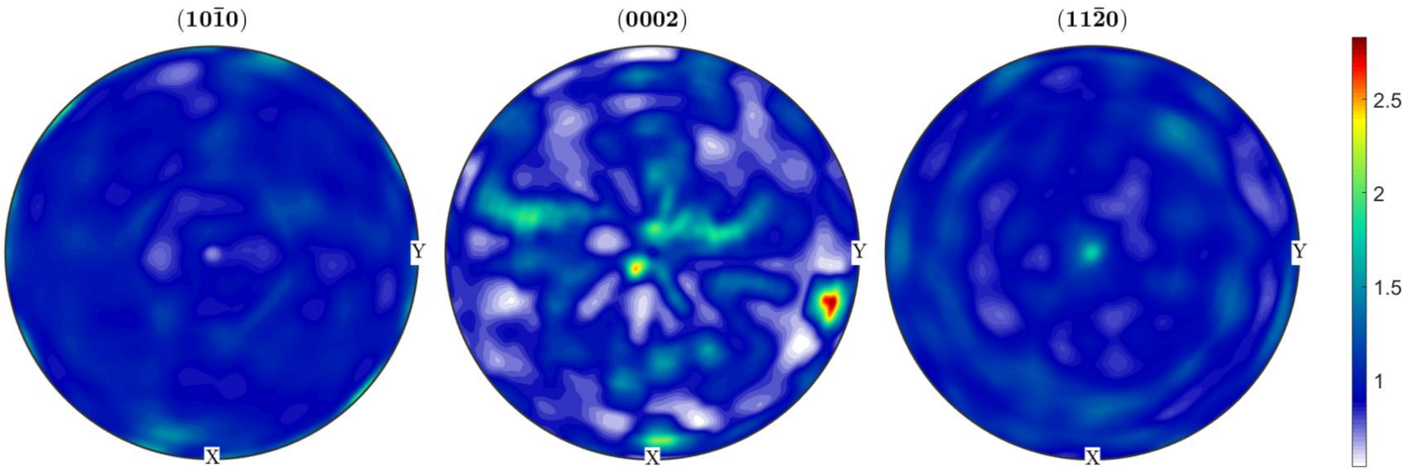
Raster Specimen



Processing Variability

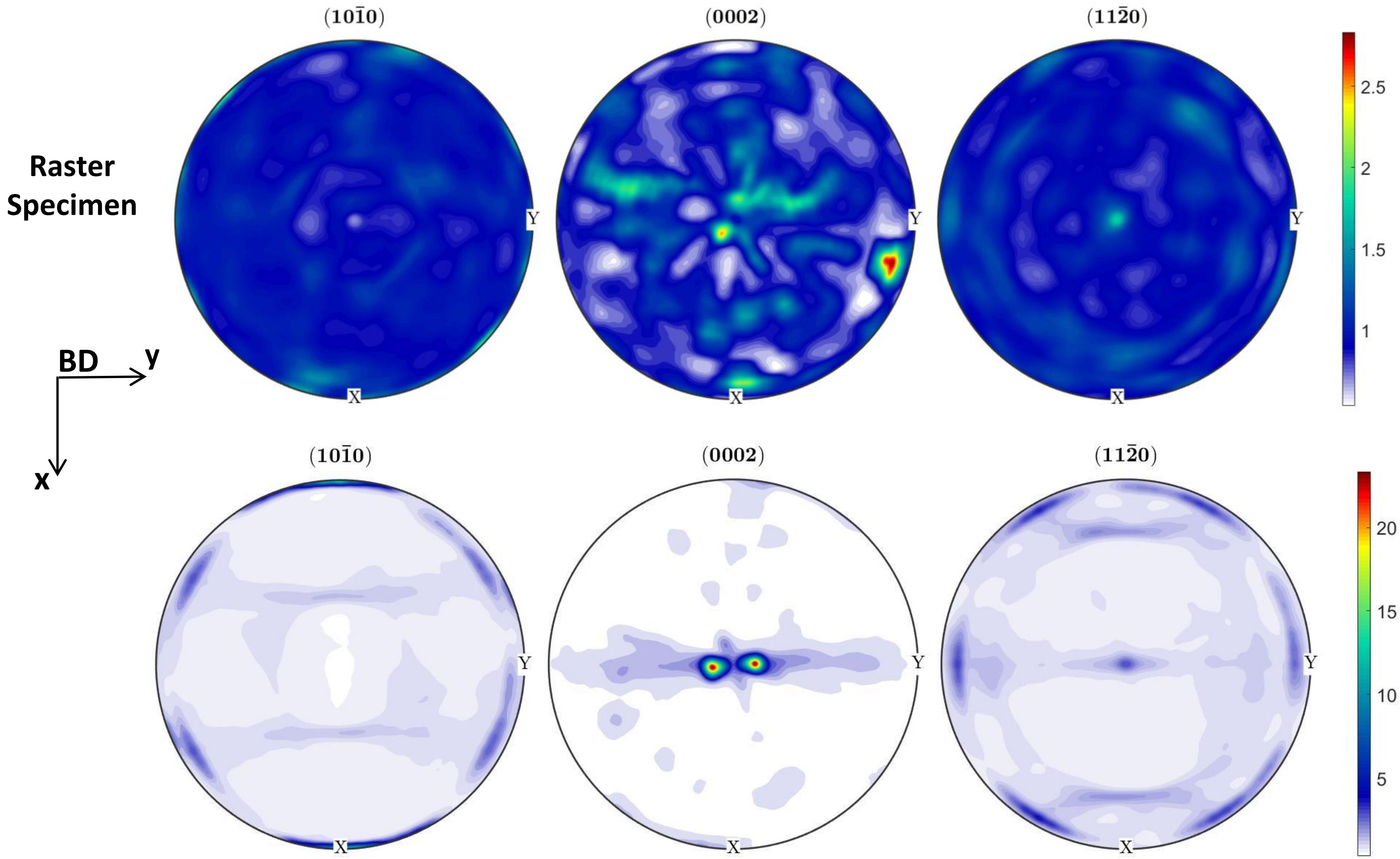
Raster Specimen





If we **change parameter values and states** with another 2-3 refinement iterations…

Processing Variability



Gives motive to create unifying process documentation for calculating texture.

Processing Variability

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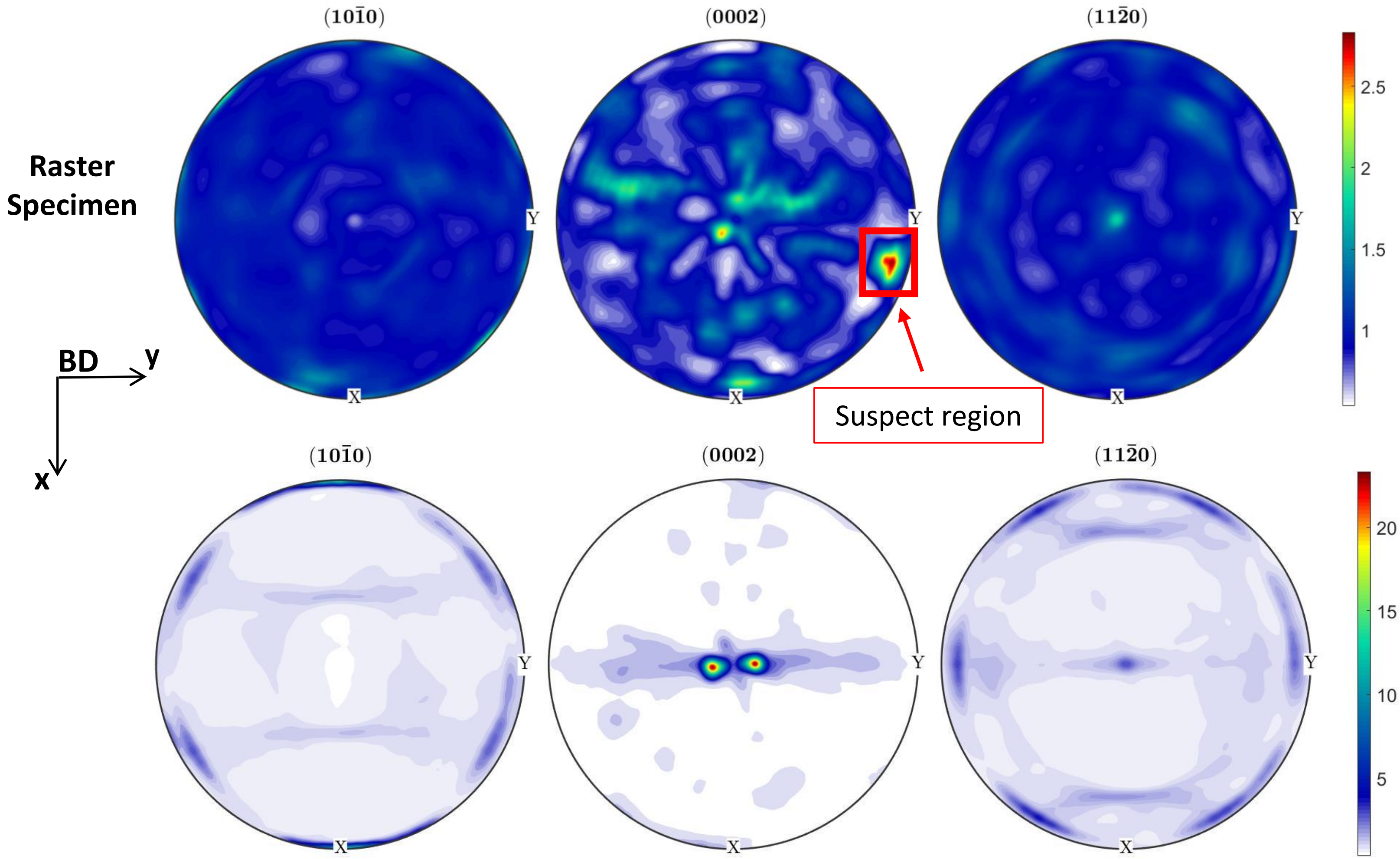
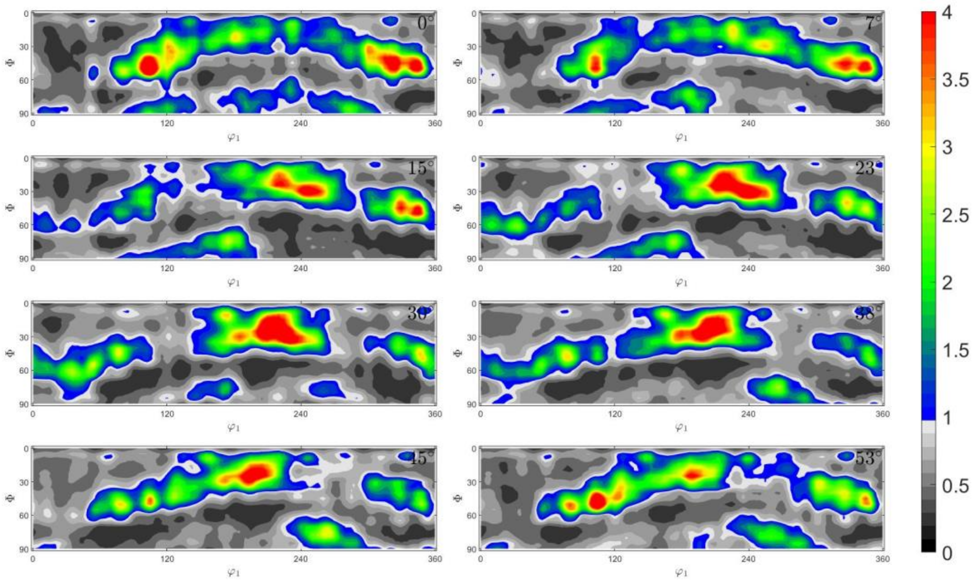


Gives motive to create unifying process documentation for calculating texture.

Quantifying Texture

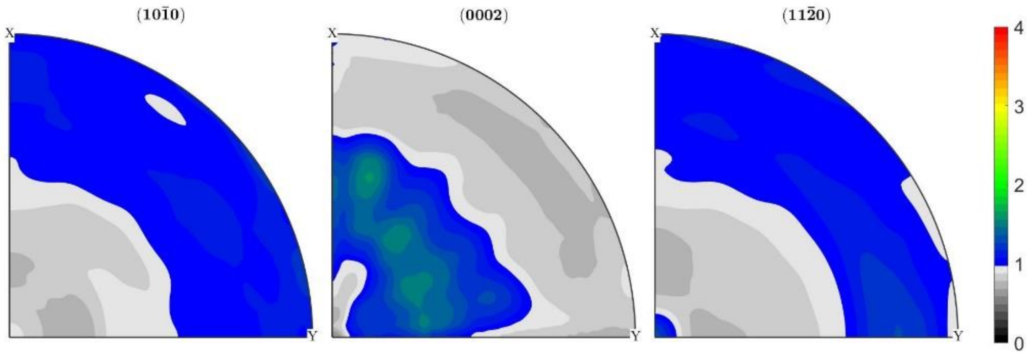
- Primary texture components differed from those reported in literature
- Underlying assumption on specimen symmetry varied
  - Orthotropic vs. triclinic specimen symmetries
- Changes quantification results considerably
  - Further evaluation required

Triclinic?



Orthotropic?

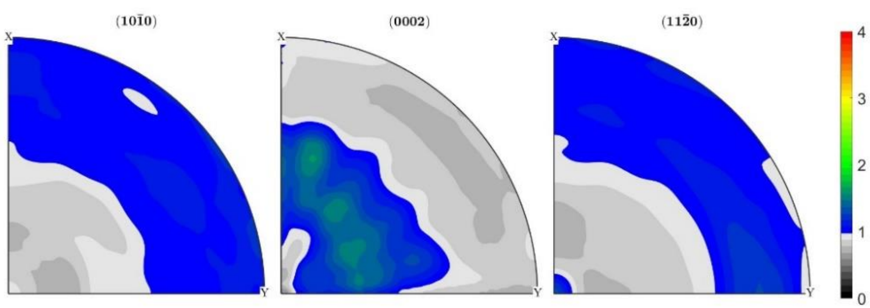
Orthotropic vs Triclinic

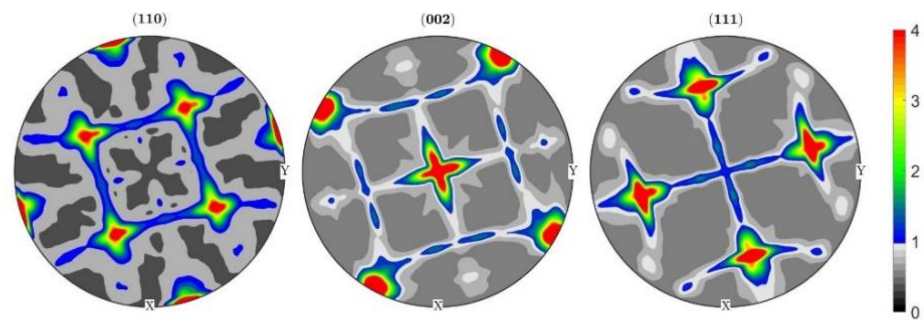


Orthotropic Specimen Symmetry
(Implies symmetry in processing operations - eg: rolling)

Orthotropic vs Triclinic

Random Scan Strategy Specimen





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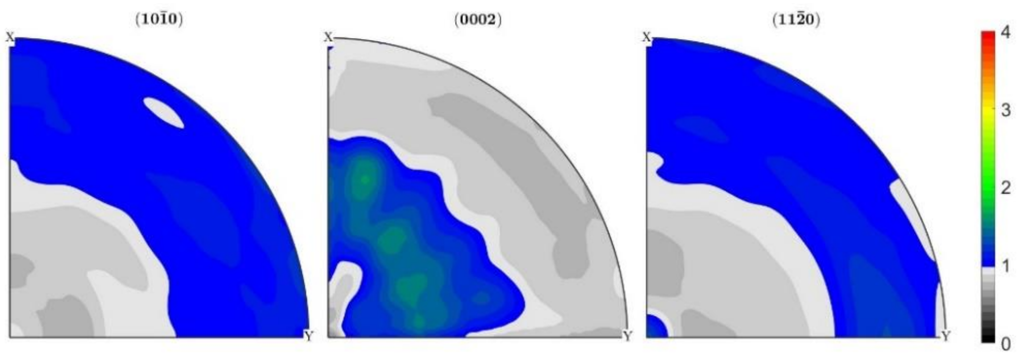
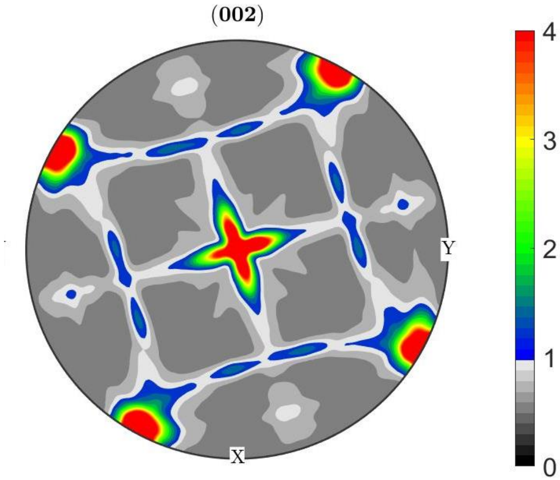


Orthotropic Specimen Symmetry
(Implies symmetry in processing operations - eg: rolling)



Orthotropic vs Triclinic

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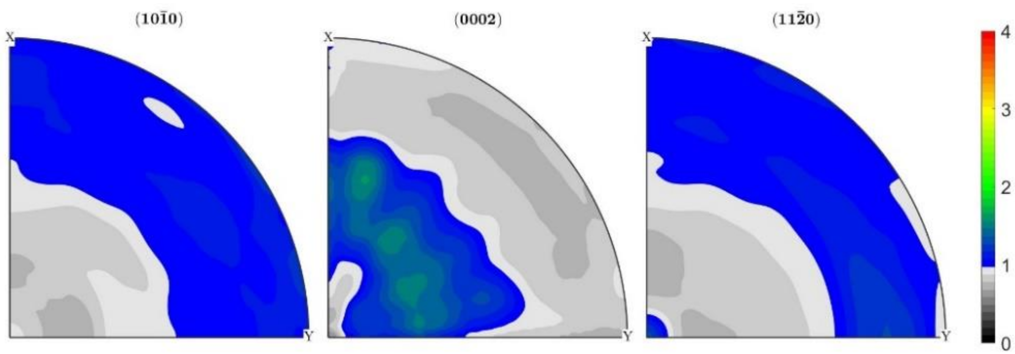
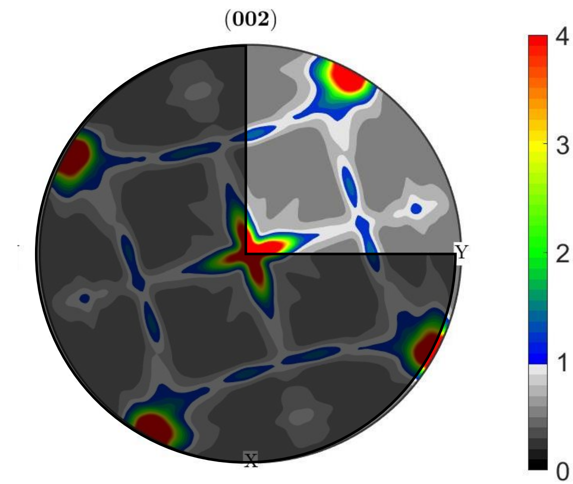
Random Scan Strategy Specimen



Orthotropic Specimen Symmetry
(Implies symmetry in processing operations - eg: rolling)



Orthotropic vs Triclinic

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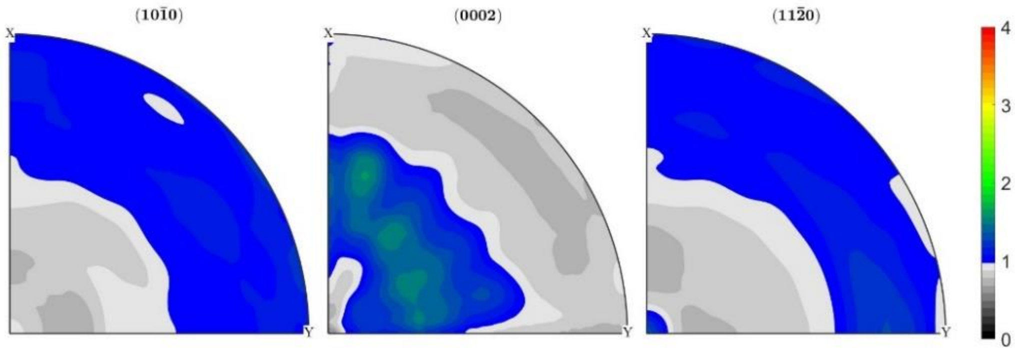
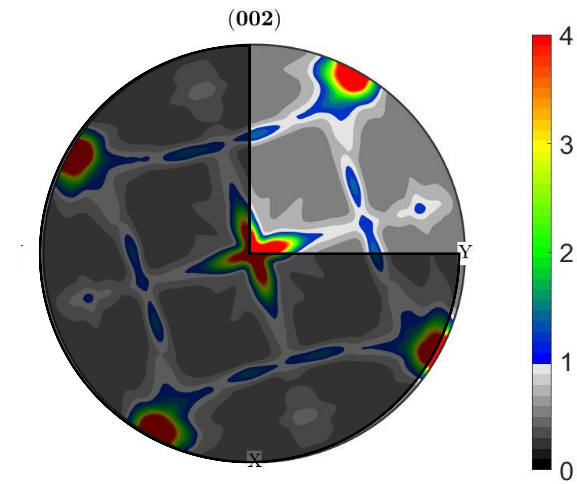
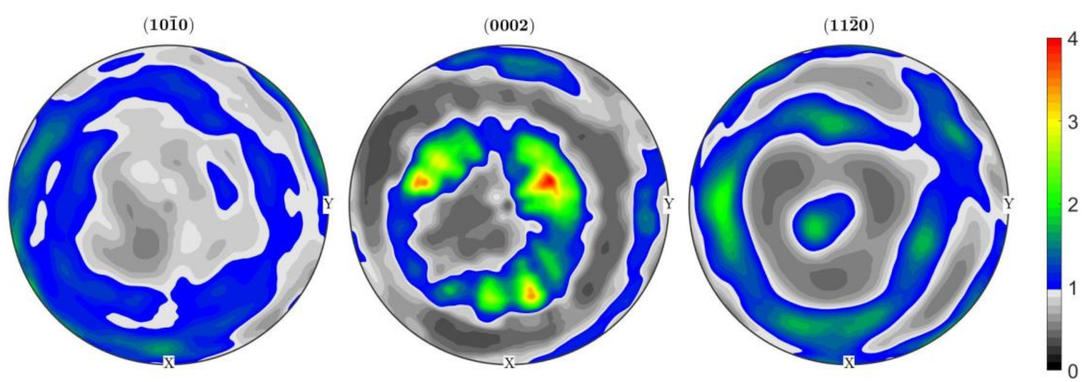
Random Scan Strategy Specimen





Orthotropic Specimen Symmetry
(Implies symmetry in processing operations - eg: rolling)



Triclinic Specimen Symmetry
(Implies no symmetry in processing operations)

Orthotropic vs Triclinic

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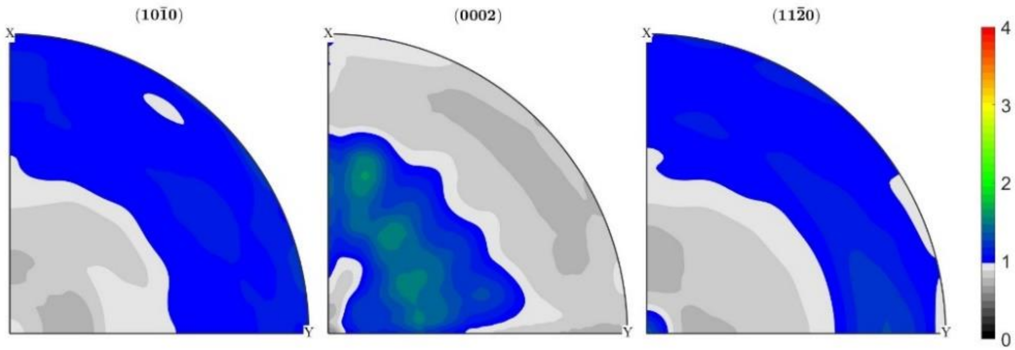
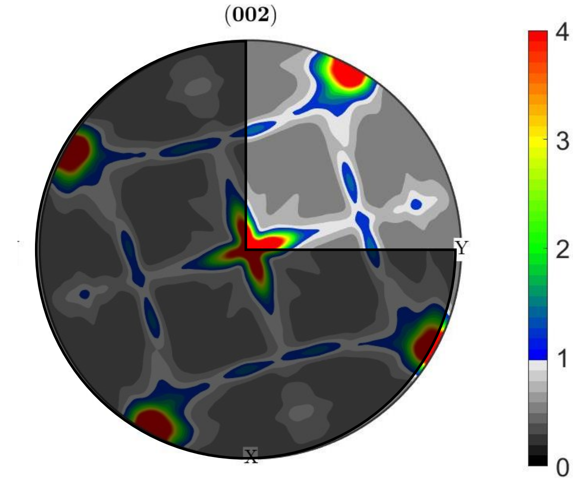
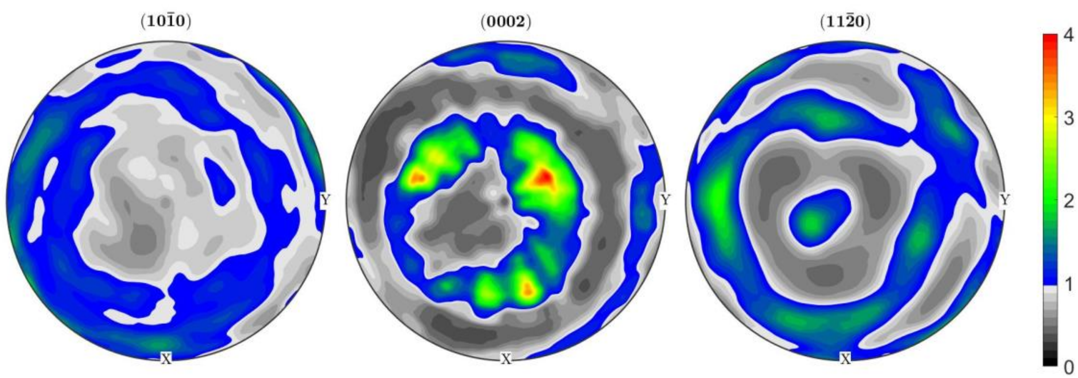
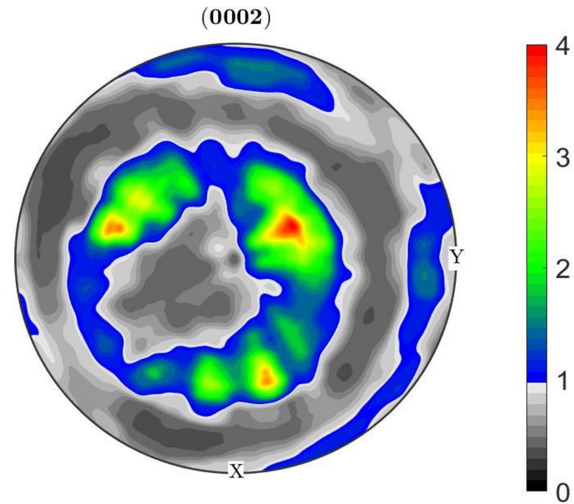
Random Scan Strategy Specimen





Orthotropic Specimen Symmetry
(Implies symmetry in processing operations - eg: rolling)





Triclinic Specimen Symmetry
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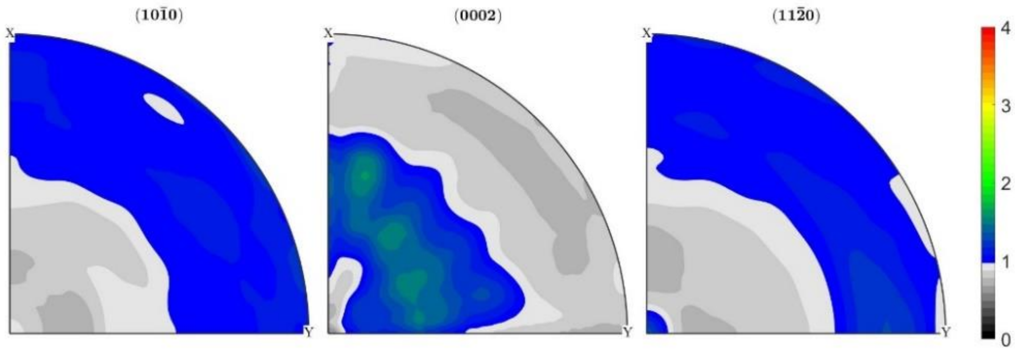
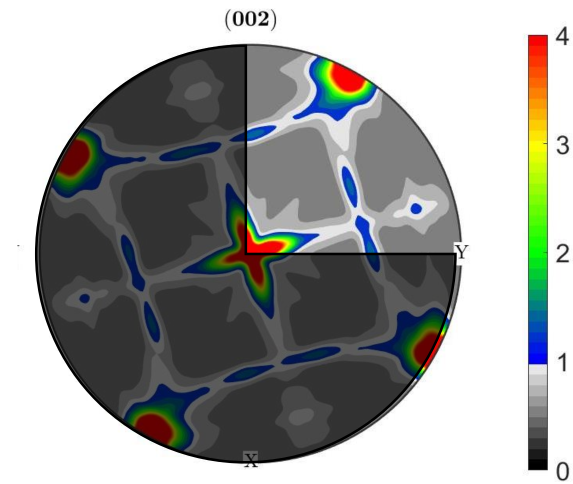
Orthotropic vs Triclinic

Random Scan Strategy Specimen





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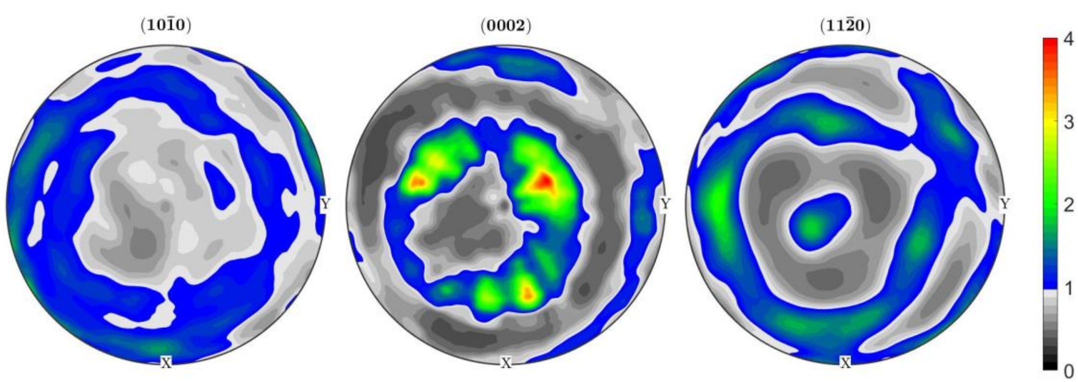
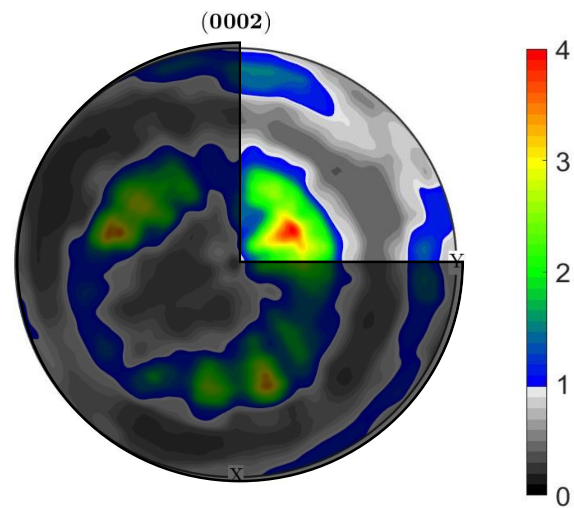
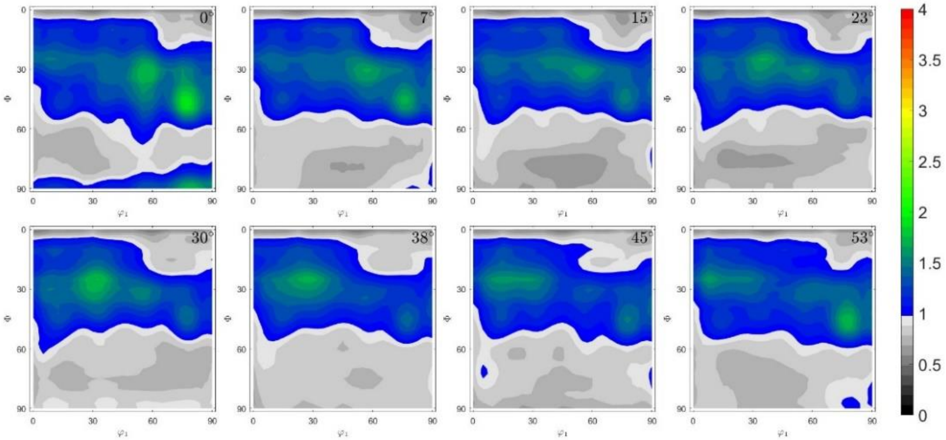




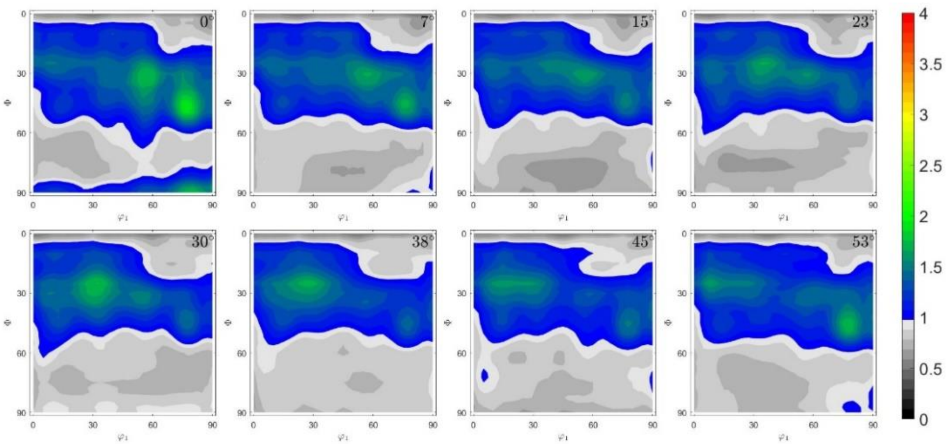
Triclinic Specimen Symmetry
(Implies no symmetry in processing operations)

Orthotropic vs Triclinic in ODF's

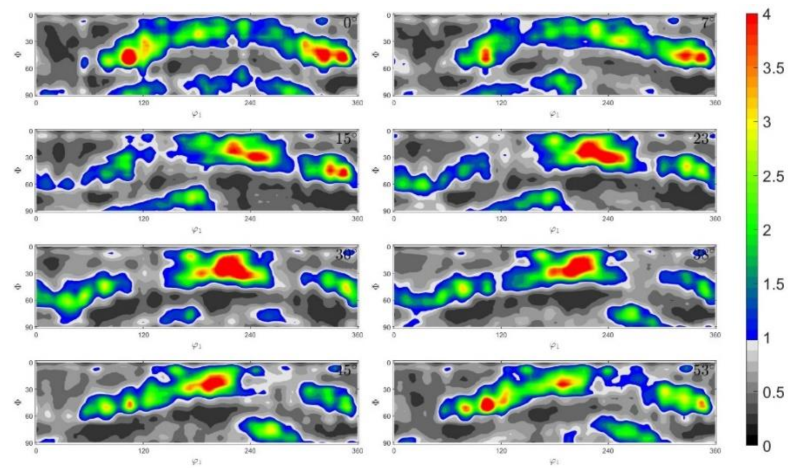


Orthotropic Specimen Symmetry

Orthotropic vs Triclinic in ODF's

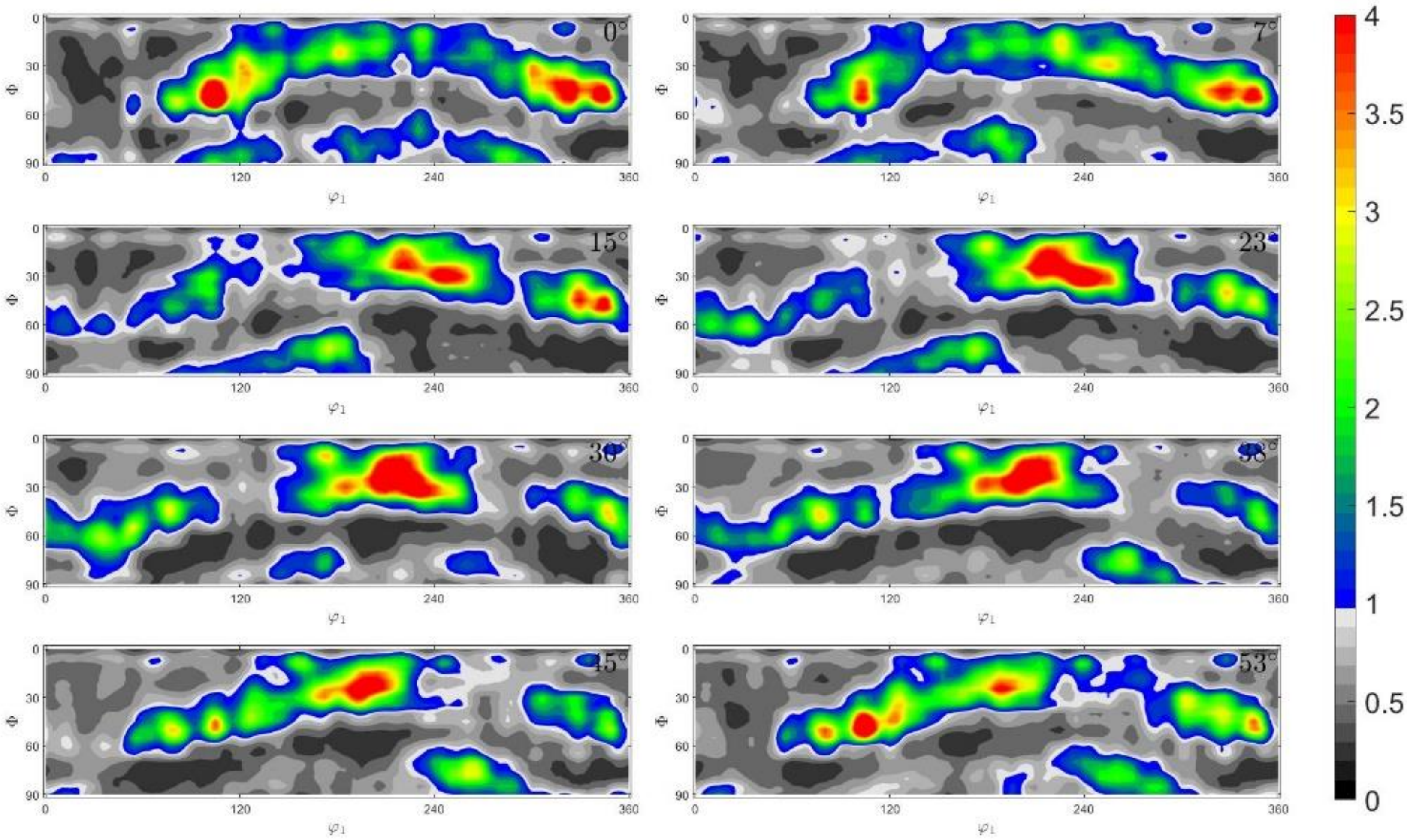


Orthotropic Specimen Symmetry

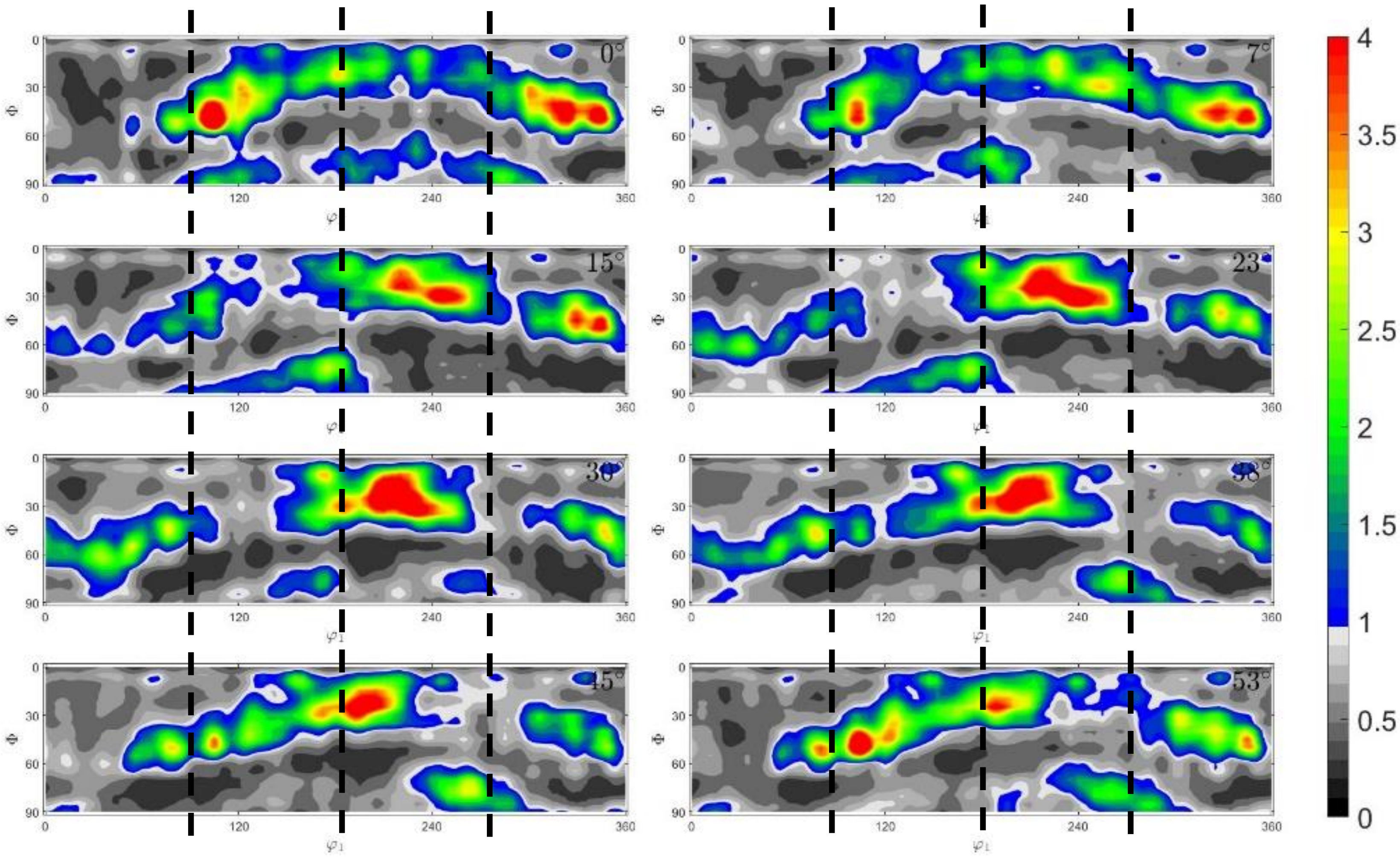


Triclinic Specimen Symmetry

Evaluating Periodicity

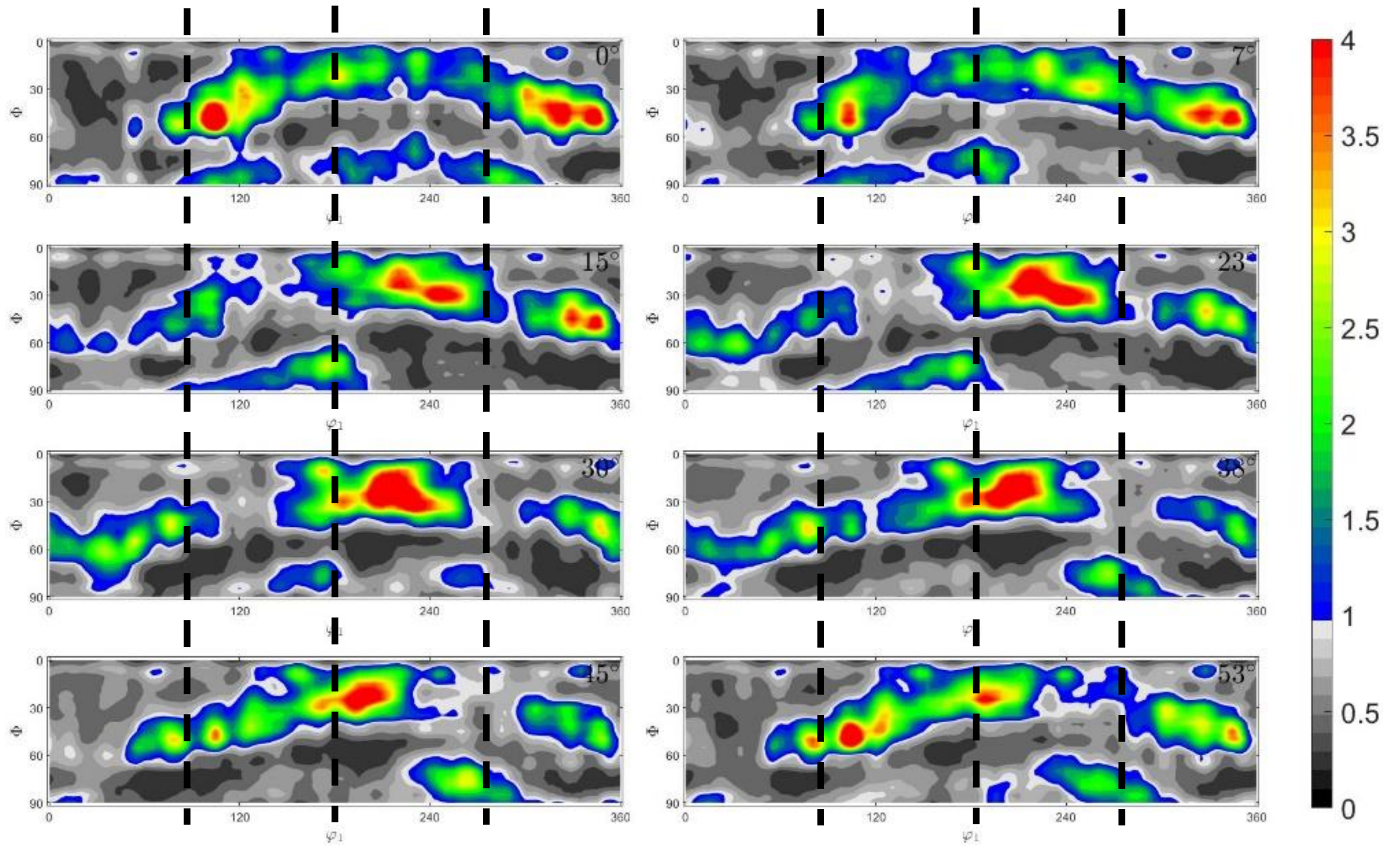


Evaluating Periodicity



Evaluating Periodicity

Is a triclinic specimen symmetry more appropriate for AM metals?

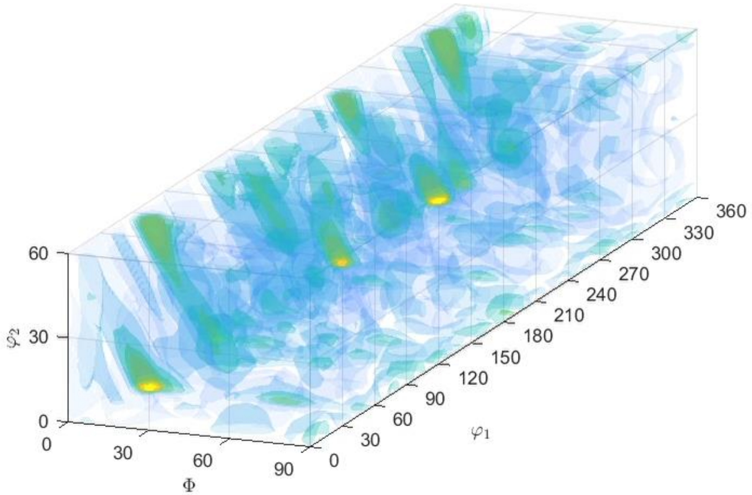


Presence of a Fiber Texture

- Fiber texture observed in all three scan strategy specimens
- Suspected to be basal fiber texture
- Orientation and intensity varies with scan strategy
  - Intensity Scale: Random > Dehoff > Raster
- Formation not completely understood
  - Indications of dynamic recrystallization during build process?
  - Evidence of orientation relationship between α-Ti and β-Ti?
    - Assumes strong {001} β-Ti solidification texture

Raster Fiber Texture

- Fiber texture along ϕ=0°
- Displays some characteristics of orthotropic specimen symmetry
- Overall weak intensity



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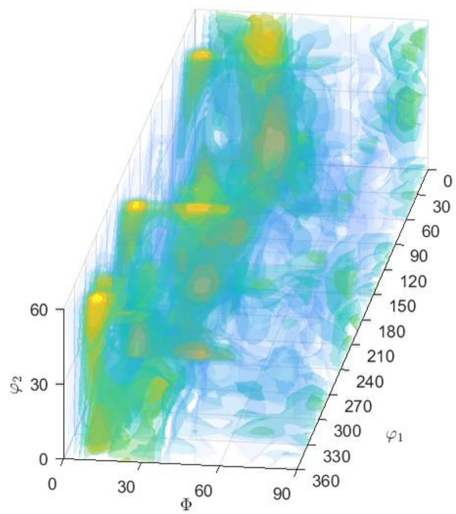
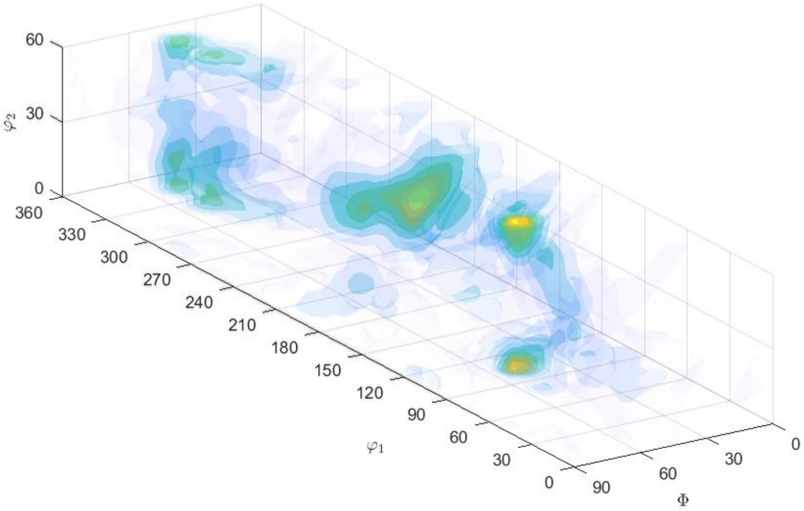
Dehoff Fiber Texture

- Fiber along ϕ= 0-20°
- Moderately stronger intensity
- Shows minimal characteristics of orthotropic specimen symmetry



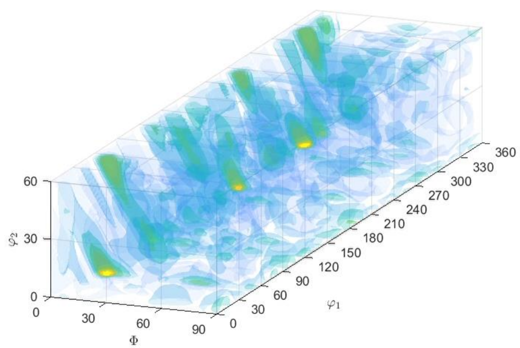
Random Fiber Texture

- Distinct fiber
  - Variable Euler coordinates
- Moderately stronger intensity
- Demonstrates no orthotropic characteristics

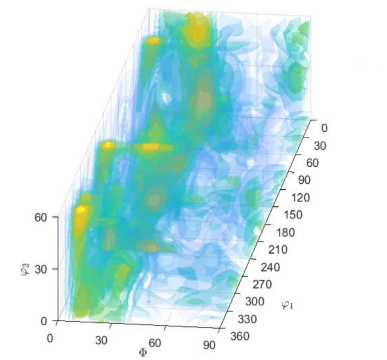


Fiber Textures

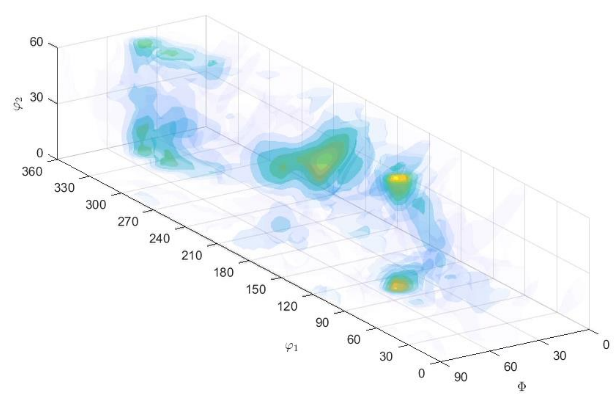
Raster (Down ϕ=0°)



Dehoff (Down ϕ=0-20°)



Random



Summary

1. Crystallographic texture changes with scan strategy
2. Texture does not vary considerably with build height
3. Triclinic specimen symmetry more appropriate for experimental results
    a. Suggests new assumption for analyzing texture in AM materials?
4. Fiber texture present in all three scan strategies
    a. Throughout build height
5. Standardization of processing texture data required

Challenges & Opportunities

- Issues in processing neutron diffraction data arose from lack of previous literature
  - Finer details of analysis
    - Outside information required
    - Troubleshooting
- Standardization of process required
- Opportunity to develop instructional dataset and documentation

Planned Work:

- Develop instructional material for greater scientific community on processing neutron diffraction data in MAUD
  - Video demonstrations
  - Publication documentation

Progress

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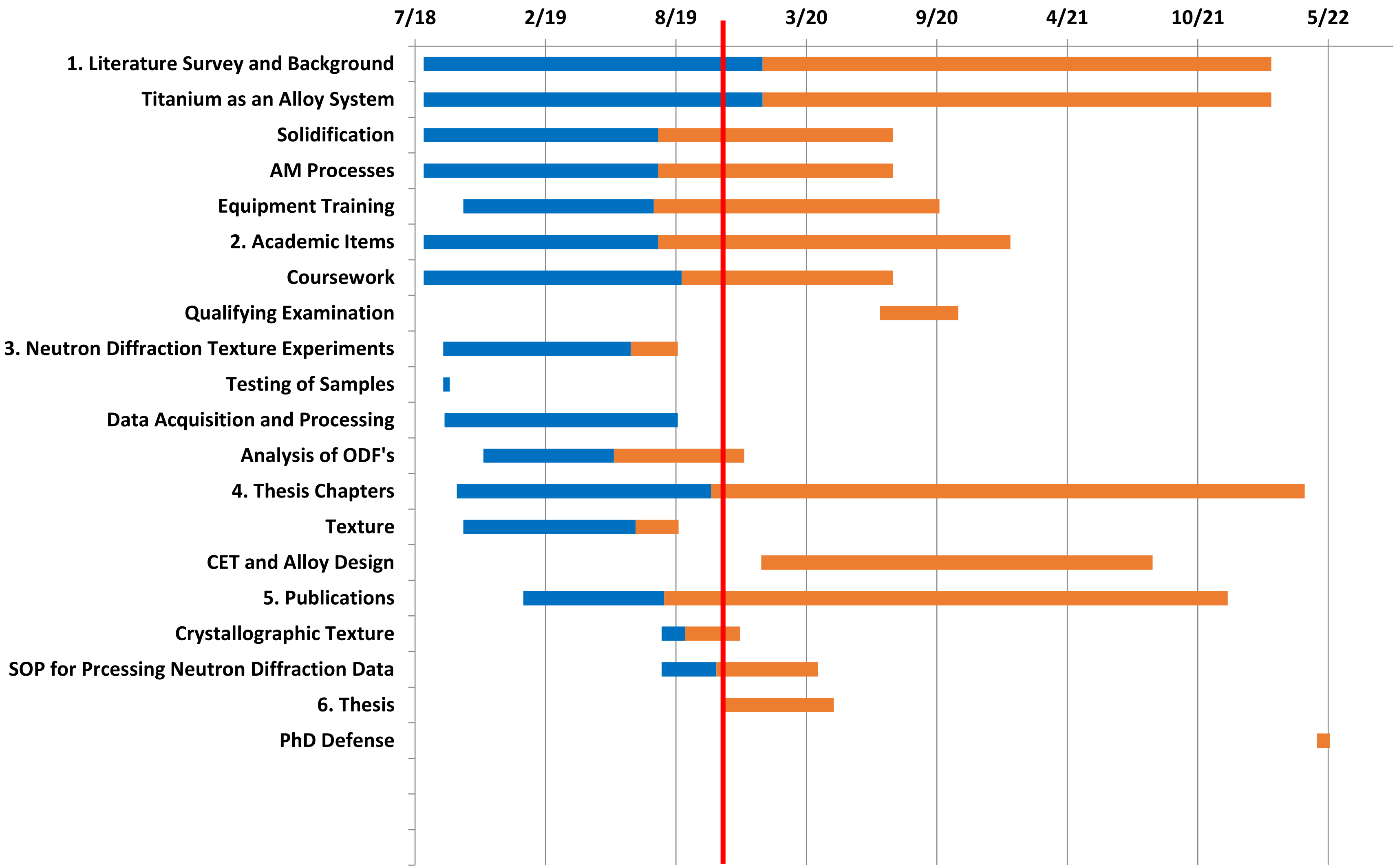


Thank you!

Any comments, questions, or feedback?

Alec Saville

asaville@mymail.mines.edu

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

Student: *Alec Saville*

Faculty: *Amy Clarke*

Industrial Partners: *TBD*

Project Duration: *August 2018 – May 2022*

Achievement

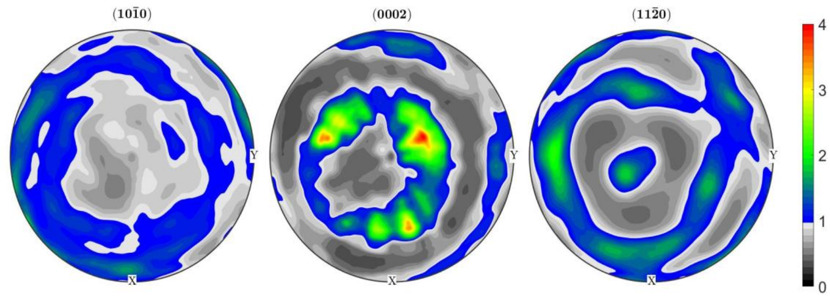
- Quantification of crystallographic texture differences in additively manufactured (AM) Ti-6Al-4V as a function of scan strategy and build height

Significance and Impact

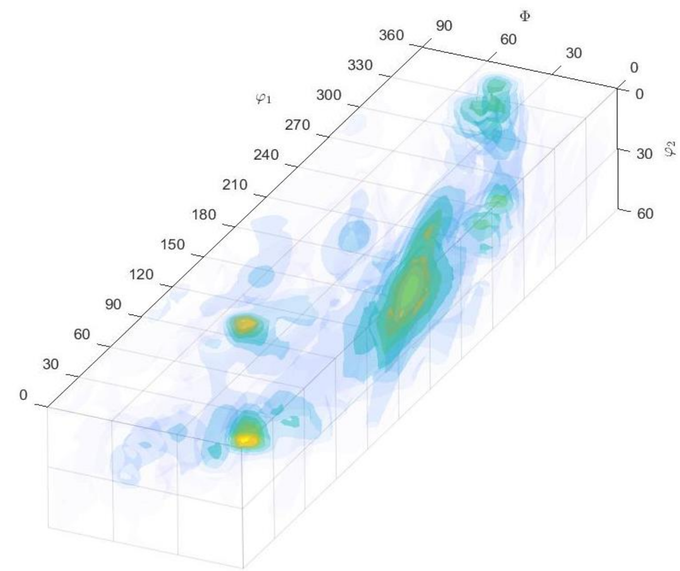
- Understanding evolution of texture enables a greater understanding of anisotropy in AM parts, informing predictive capabilities and confidence of AM part performance.

Research Details

- Finished neutron diffraction data processing and began initial quantification efforts



α-Ti Pole figures for the Random scan strategy specimen



α-Ti fiber texture observed in the Random scan strategy specimen

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

Student: *Alec Saville*

Faculty: *Amy Clarke*

Industrial Partners: *TBD*

Project Duration: *August 2018 – May 2022*

Program Goal

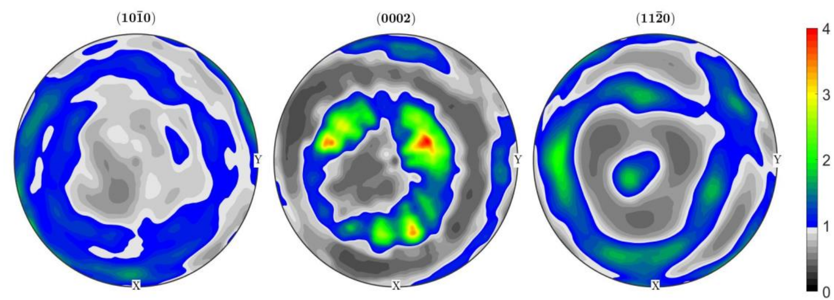
- Quantify differences in crystallographic texture as a function of scan strategy and build height of additively manufactured (AM) Ti-6Al-4V.

Approach

- Utilize neutron diffraction, Rietveld refinement using the MAUD software package, and MATLAB quantification to identify trends in crystallographic texture of AM Ti-6Al-4V.

Benefits

- Greater understanding of how anisotropic behavior forms will better inform predictive capabilities and increase confidence in metallic AM for higher end applications.



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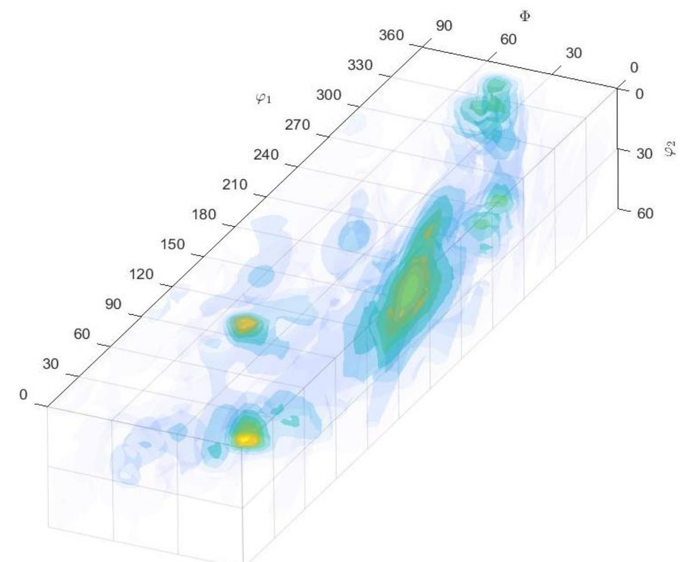

α-Ti fiber texture observed in the Random scan strategy specimen