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Center for ADVANCED NON-FERROUS STRUCTURAL ALLOYS

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

Project 14: Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings

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

Student: Connor Campbell (Mines)

Faculty: Terry Lowe (Mines), Kester Clarke (Mines)

Industrial Mentor: Tony Yao (Weber Metals), Adam Pilchak (AFRL)

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IOWA STATE UNIVERSITY

Project 14: Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings

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- Student: Connor Campbell (Mines)
- Advisor(s): Terry Lowe and Kester Clarke (Mines)

Project Duration
MS: January 2016 to May 2019

- Problem: Microtextured regions (MTRs) in forgings of Ti-6Al-4V limit ultrasonic inspectability and can be deleterious to mechanical properties of forgings.
- Objectives: Extend understanding of how microstructural heterogeneity evolves during forging; characterize and quantify deformed samples, correlate to ultrasonic scattering.
- Benefit: Observations of heterogeneity in initial and final stages of processing may provide insight into how to optimize processes for homogeneity.

Recent Progress

- Sample preparation and characterization of deformed Gleeble samples
- Electron Backscatter Diffraction (EBSD) and Taylor factor analysis of deformed microstructures
- Receipt of new material containing flaws detected via ultrasonic inspection

Metrics

Description	% Complete	Status
1. Survey of current knowledge	90%	●
2. Uniaxial compression of Gleeble Samples	100%	●
3. Sample preparation and characterization of deformed microstructures	50%	●
4. Extraction of regions of low ultrasonic quality	0%	●
5. Analysis of microstructural heterogeneity in regions of low ultrasonic quality	0%	●

Industrial Relevance

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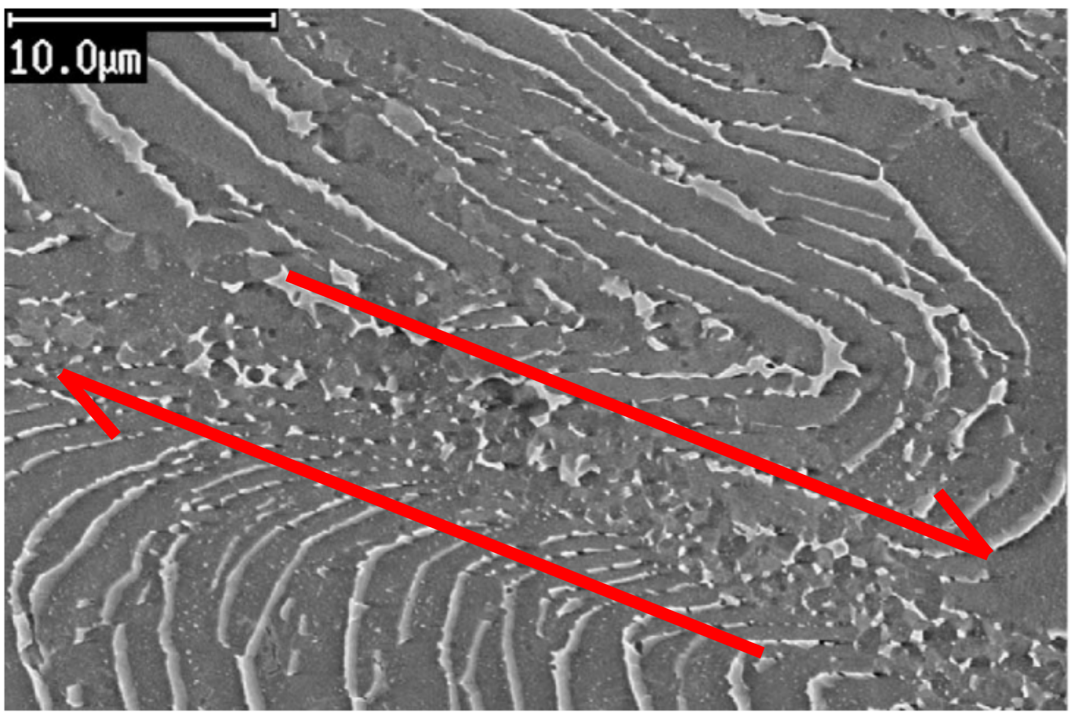
- Ti-6Al-4V is widely used in many industries
- Properties of (α+ß) Ti-alloys can vary greatly
  - Dependent on α morphology and orientation
  - Necessitates rigorous inspection
- Prone to heterogeneous deformation and localized texture during thermomechanical processing (TMP)
  - Negatively impacts fatigue properties
  - Scatter ultrasonic signals used for inspection
    - Can cause false negatives ($$$$$)
  - Hard to predict!

Industrial Relevance Continued

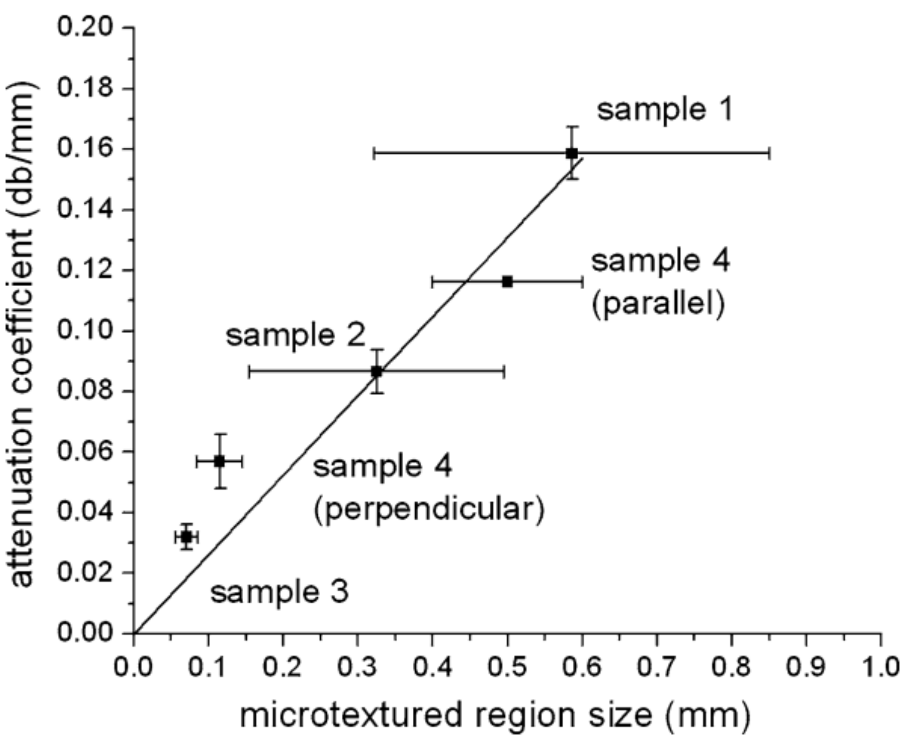
- "Understanding microstructural evolution from an *average standpoint* is useful, but the description of *non-uniformity* is more important with respect to evolution of defects that control service properties!"
  -S. L. Semiatin, 26 March 2018
  AFRL/Industry Ti-Forging Workshop



Pictured: Shear band in a severely bent α colony, permitting deformation to flow around hard-oriented regions

T. Bieler, S.L. Semiatin: Int. J. of Plasticity, 2002, vol. 18, pp. 1165-1189.

Microtextured Regions (MTRs) Impede Ultrasonic Inspection

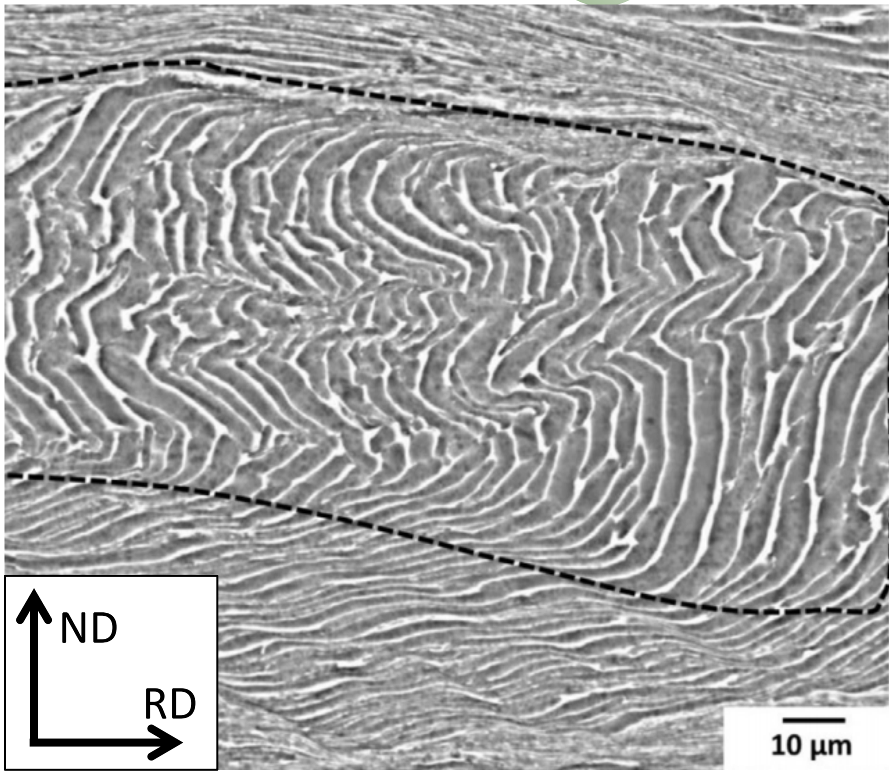


- MTRs have been correlated to prior α colony size, and breakdown thereof
  - Larger colonies, less breakdown = larger MTRs
- Previous work has correlated MTR size with ultrasonic inspectability
  - Larger MTRs = more noise
- Improving inspectability requires elimination of microtextured regions

A. Bhattacharjee, A.L. Pilchak, J.W. Foltz, et al.:
Metall. Mater. Trans. A, 2011, vol. 42A, pp. 2358–72.

Project Goal

- Extend understanding of how microstructural heterogeneity develops and persists throughout TMP
  - Performed experiments to investigate α colony interactions during sub-transus compression
- Correlate localized microstructural features and heterogeneous deformation to ultrasonic scattering
  - Material with regions of higher ultrasonic noise donated by Weber Metals



Pictured: A hard-oriented α colony bends and kinks in a sample subjected to sub-transus rolling

S. Roy, S. Suwas: Acta Materialia, 2017, vol 134, pp. 283-301

Project Methodology

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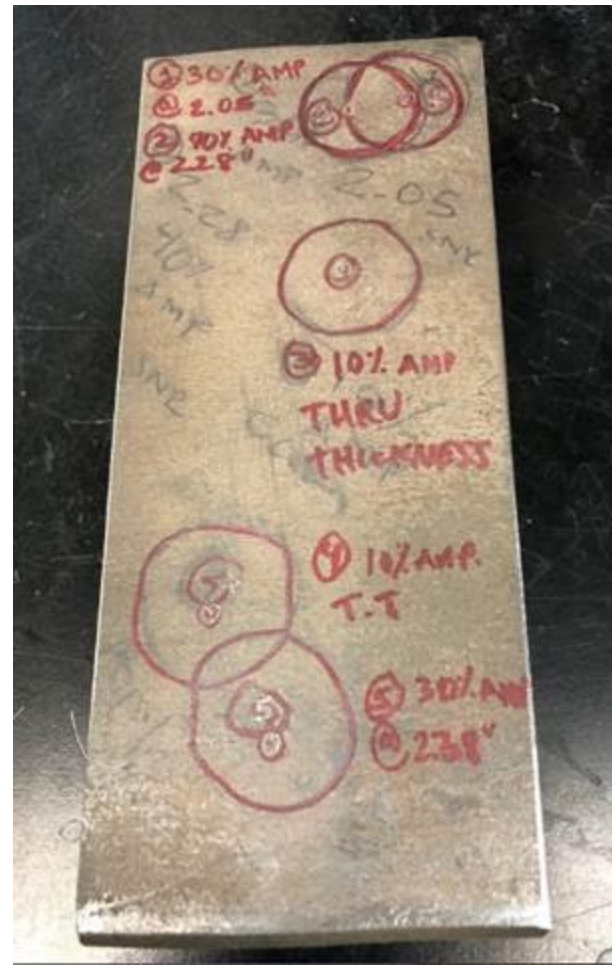
- Compress Ti64 samples in the (α+ß) field to varying degrees
  - Material donated by Weber Metals with large, coarse α colonies
- Characterize deformed microstructures via electron backscatter diffraction (EBSD)
  - Gain insight into origins of persistent microstructural heterogeneity
- Examine new material supplied by Weber (pictured on right)
  - Real data linking ultrasonic noise to microstructural heterogeneity
  - Material has been ß annealed, (α+ß) forged, but not heat treated



3.625 inches

Previous Work: Gleeble Compression

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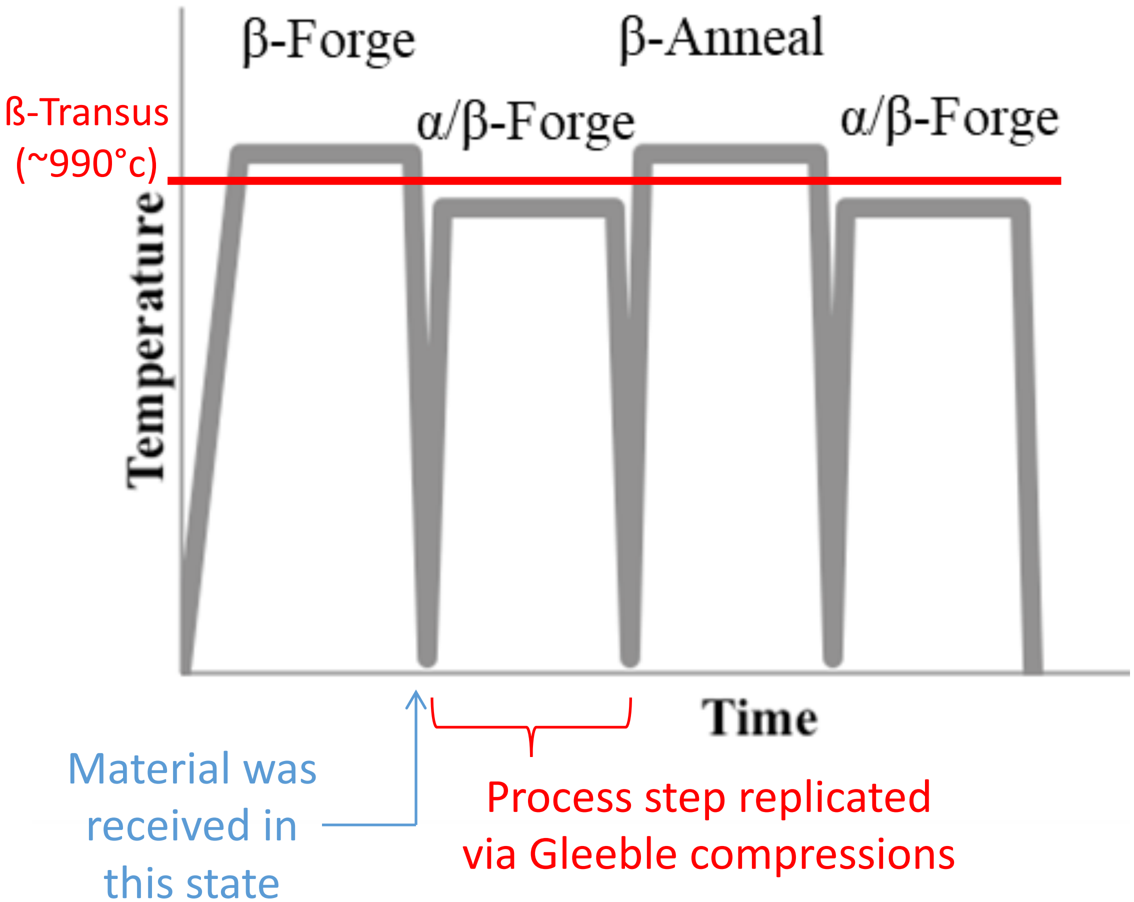

1. ß-forging homogenizes as-cast microstructure
2. α+ß forging introduces hot work that drives ß recrystallization
3. ß anneal generates finer ß grains, rapid cooling produces fine α colonies that are easily broken up
4. Final α+ß work to net-shape creates equiaxed, fine grained α in a matrix of transformed ß

Previous Work: Gleeble Experimental Matrix

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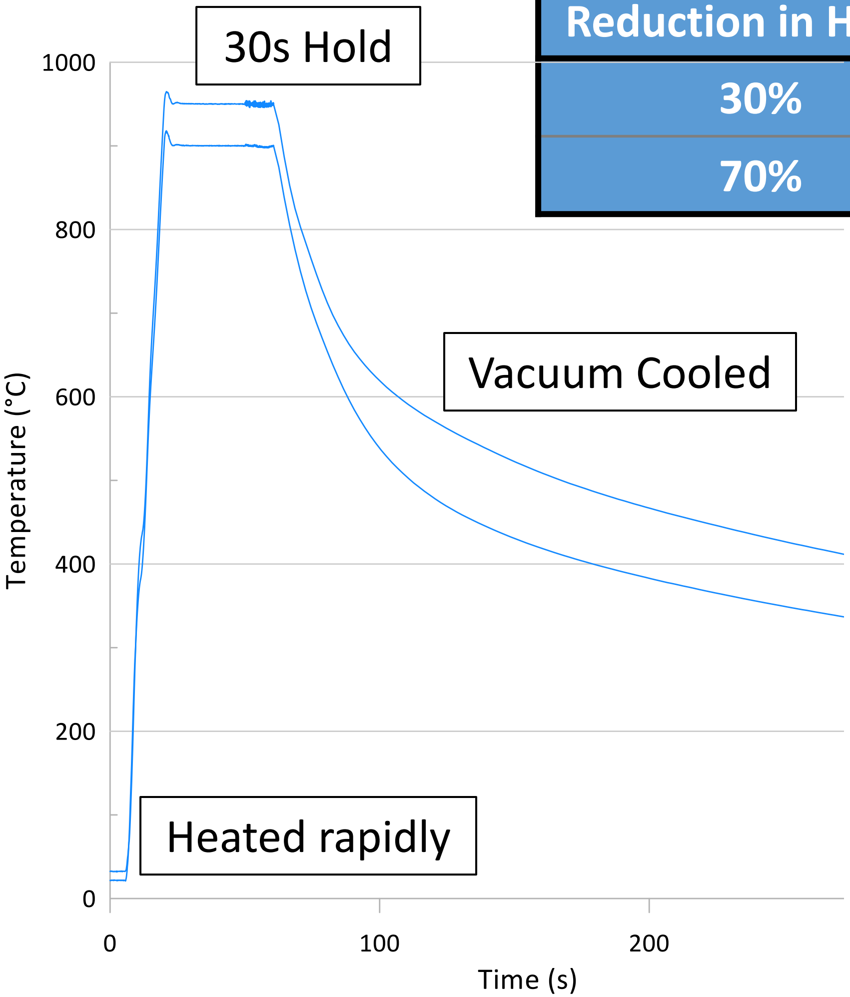
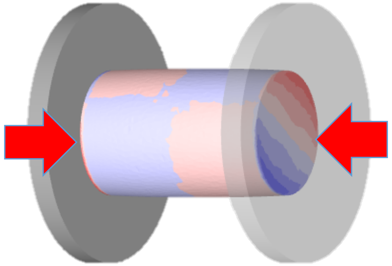
Reduction in Height	1650 °F (900°C)	1700°F (925°C)	1750°F (950°C)
30%	1 sample	1 sample	1 sample
70%	2 samples	2 samples	2 samples



- Cylindrical samples with large α colony microstructures compressed at varying temperatures, then vacuum cooled
- Some deformed more uniformly than others; strain varies with position

T = 925°C

T = 950°C



Non-Uniform Deformation

Sample machined from edge of billet, uniaxially compressed to 30% height reduction at 925°C and macroetched

- Strain rate = $0.01 s^{-1}$
- Temperature = 925°C
- Compressed to 30% height reduction (light deformation)
- Heterogeneous deformation complicates quantifying strain

As-Received Material for macrostructure comparison

Non-uniform deformation in 70% height reduction sample

EBSD Characterization of “Heavily” Deformed Microstructures

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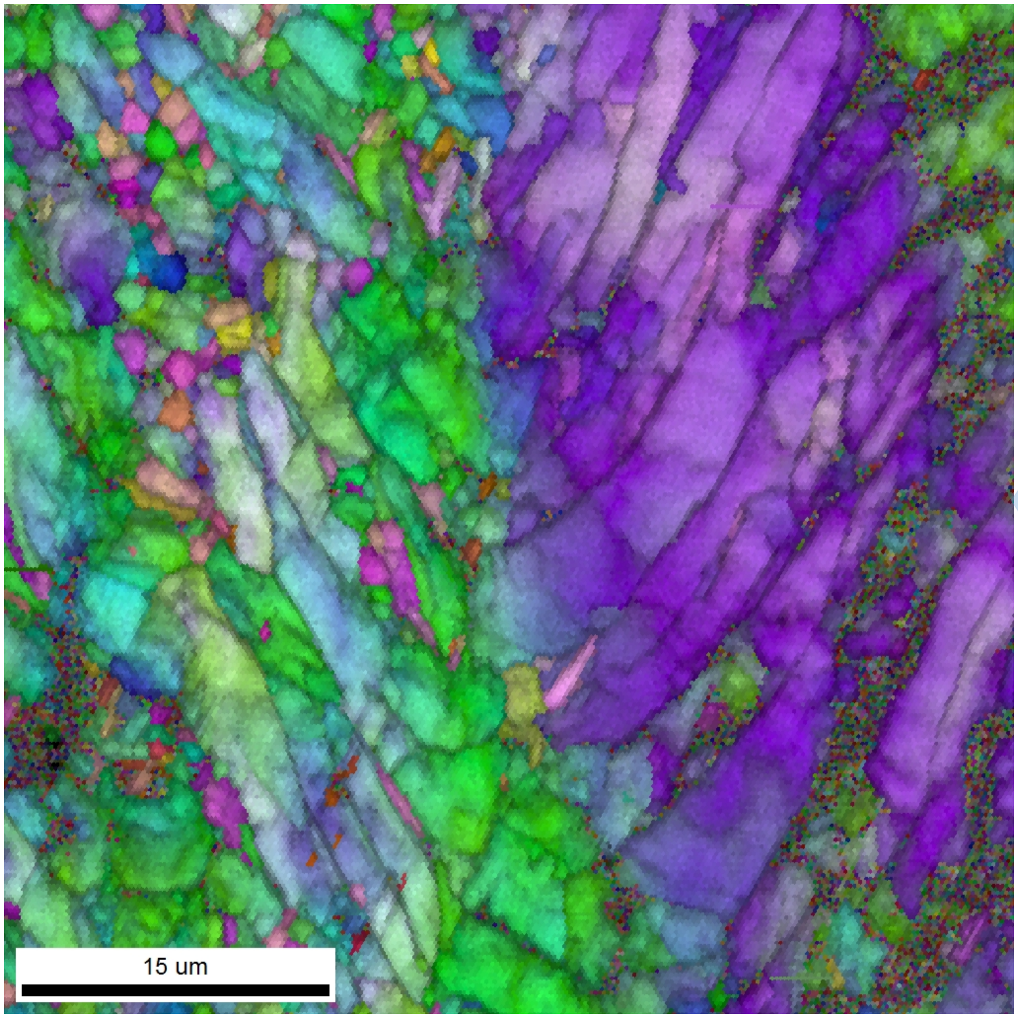
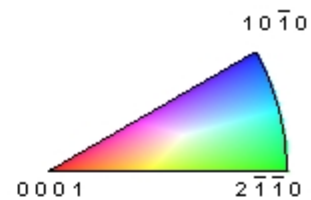


70% avg. height reduction, T = 925°C

- When severely bent, α lamellae break into regions of weaker texture and equiaxed grain size
- Colony remnants (purple) are ideally eliminated during ß-anneal and subsequent processing



EBSD Characterization of “Lightly” Deformed Microstructures

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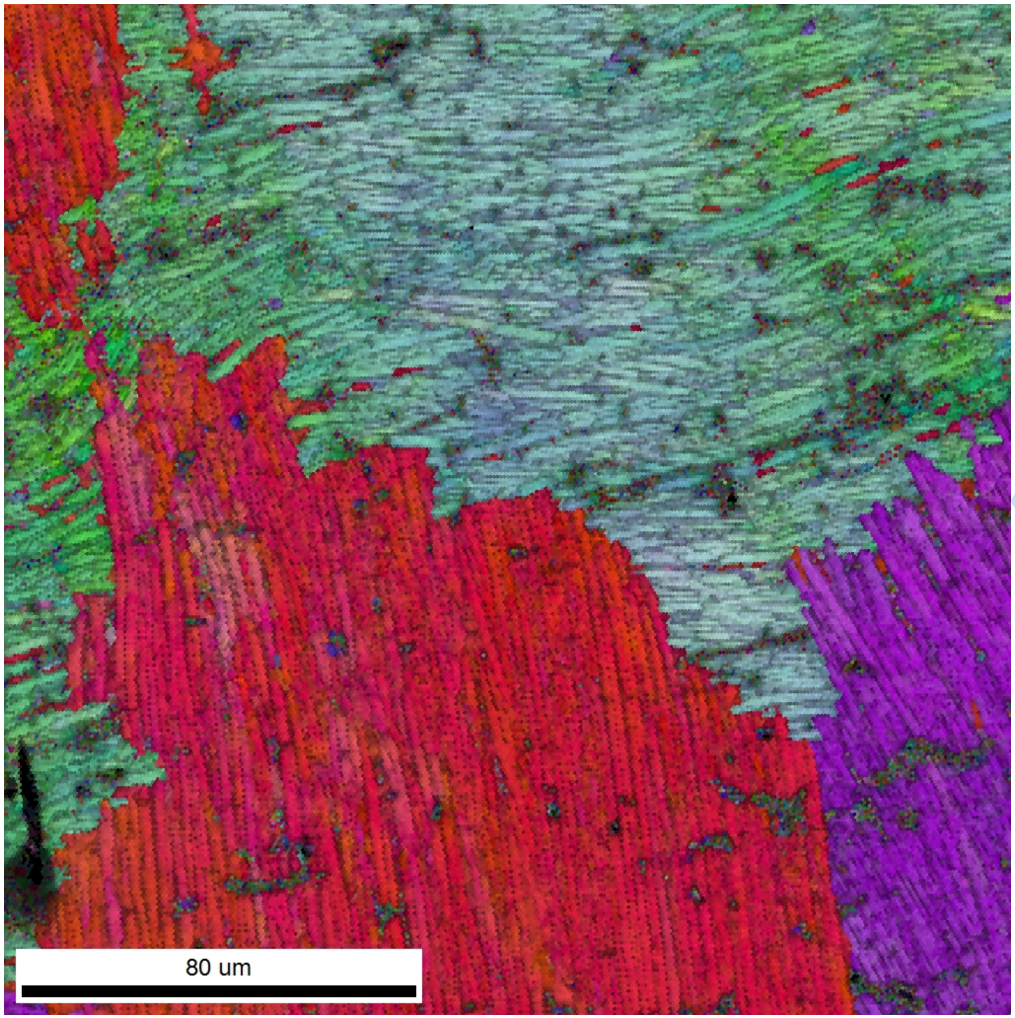
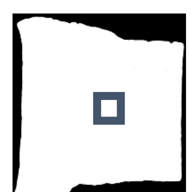
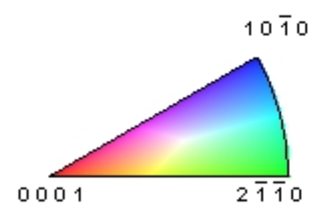


30% avg. height reduction, T = 925°C

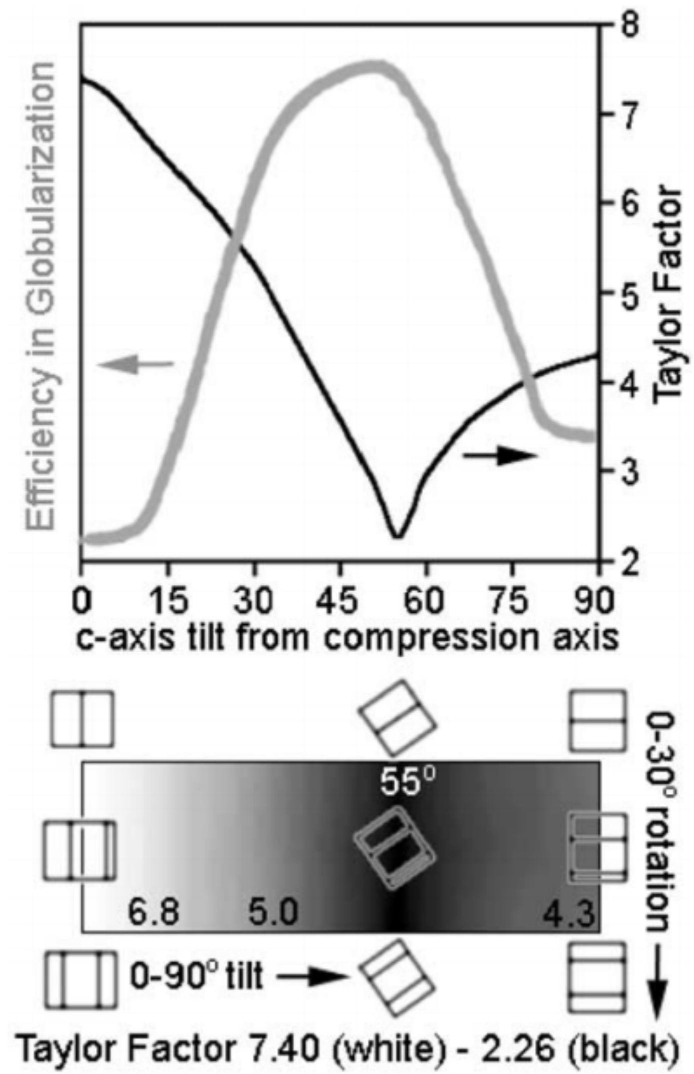
- Colonies that are “hard-oriented” w.r.t. applied load (i.e. no basal or prismatic slip) bend and kink in early stages of deformation
- Taylor factor is a good starting point for identifying these hard-oriented regions
  - Easy to calculate using orientation imaging microscopy software!





Taylor Factor is Inversely Proportional to Globularization Efficiency

- Assuming a critical resolved shear stress ratio of 0.7 : 1 : 3 (prismatic<a>:basal<a>:pyramidal<c+a>)
- Regions with high Taylor factor will be difficult to break up, resulting in non-uniform microstructure
- Provides a more rigorous test than simply identifying bent colonies
- Readily calculated with assumed deformation gradients using OIM software, therefore highly convenient!



T. Bieler, S.L. Semiatin: Int. J. of Plasticity, 2002, vol. 18, pp. 1165-1189.

Example: Using Taylor Factors to Identify Hard-Oriented α Colonies

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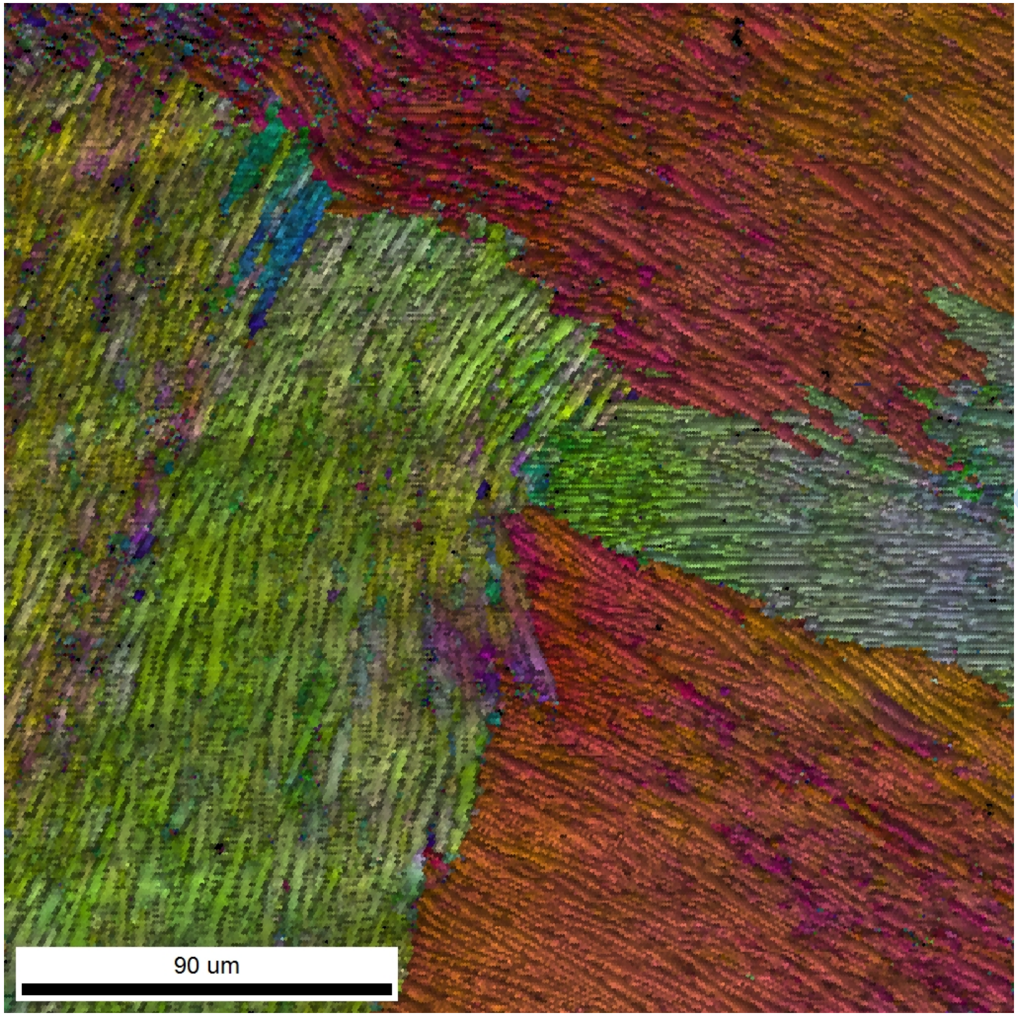
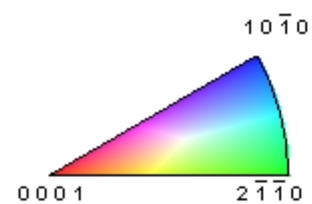


70% avg. height reduction, T = 900°C

- Region near "top" surface of sample, close to the axis of compression
- Selected because colonies with similar crystal orientation but perpendicular lamellae orientation are interacting



Example: Using Taylor Factors to Identify Hard-Oriented α Colonies

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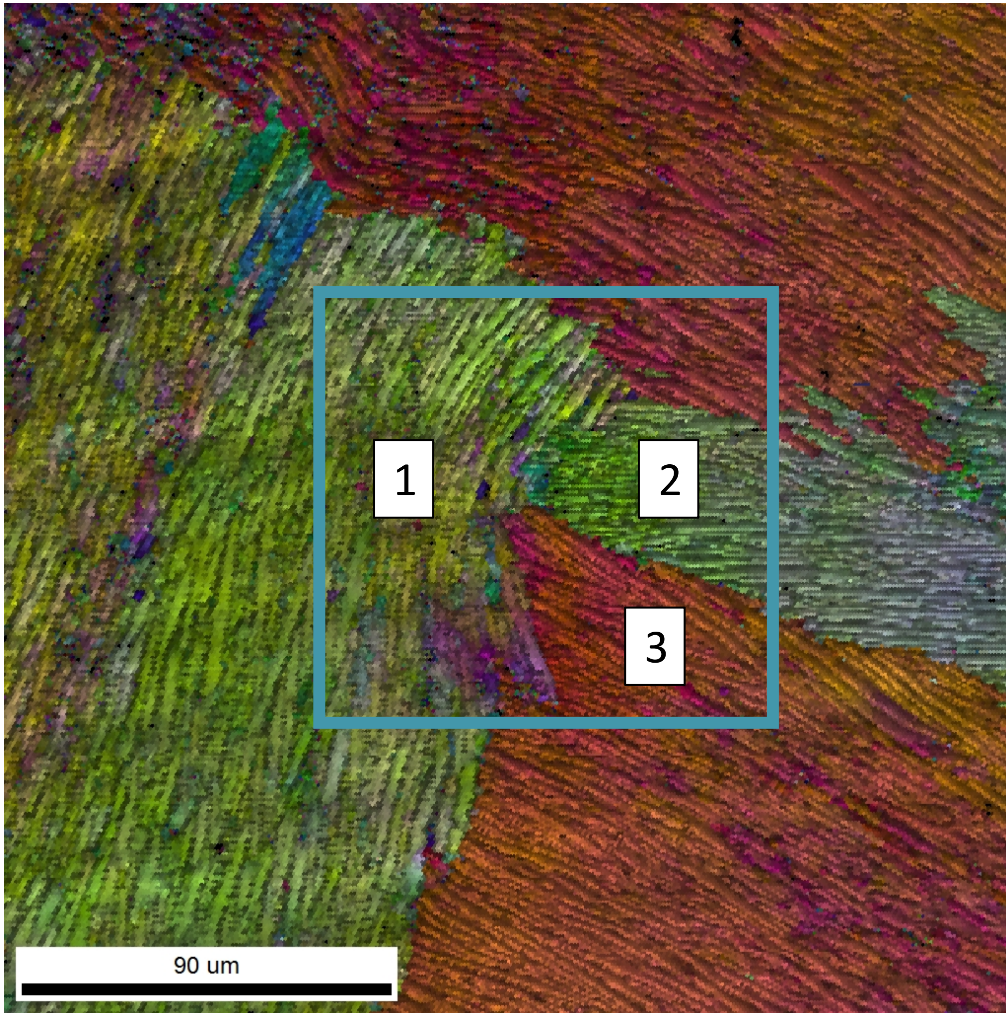

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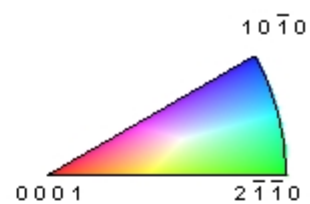

Calculated Taylor Factor map using OIM Software

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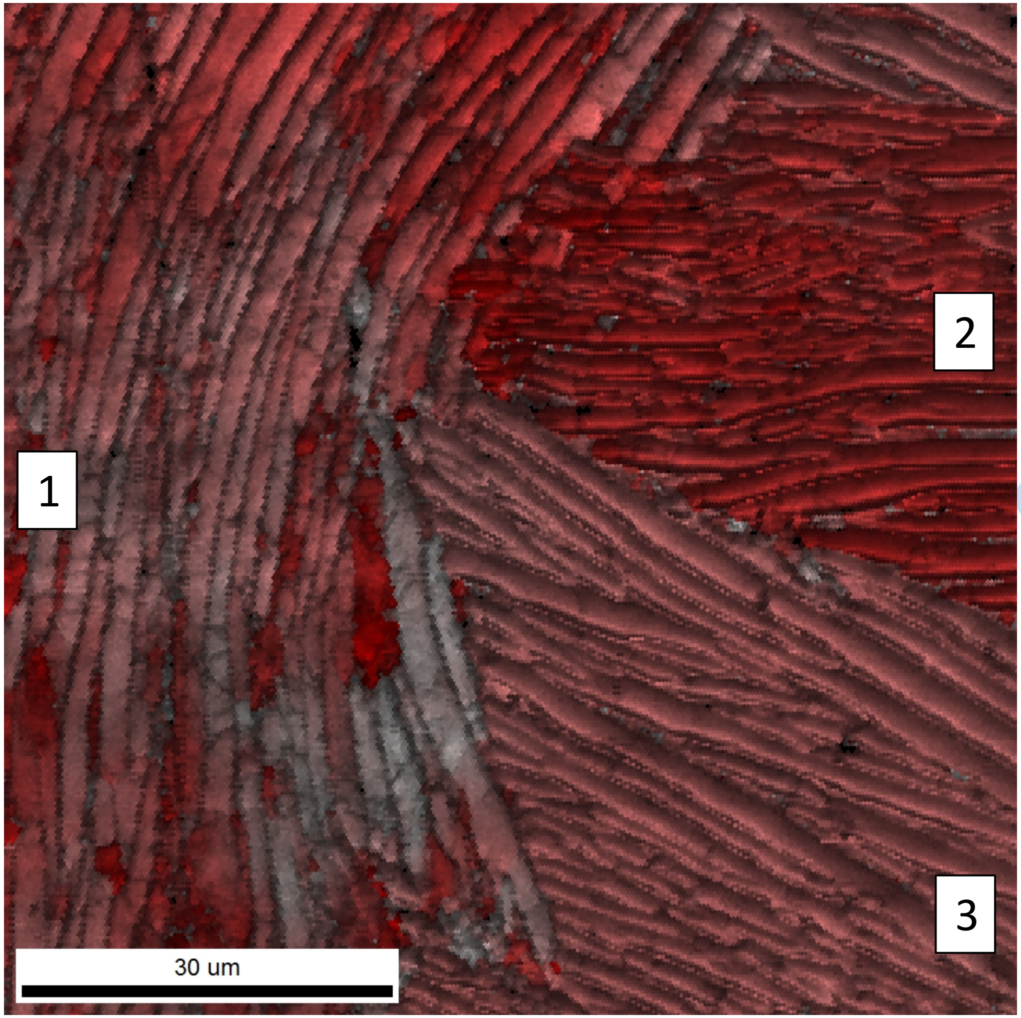

70% avg. height reduction, T = 900°C

- Deformation is assumed to be pure horizontal compression
- Red regions are harder, which is intuitive here…
- But it provides a powerful tool to identify hard-oriented remnants that may cause problems!

	Min	Max	Total Fraction	Partition Fraction
	3.23144	9.49949	0.996	0.996

Identifying Hard-Oriented Remnants using Taylor Factor

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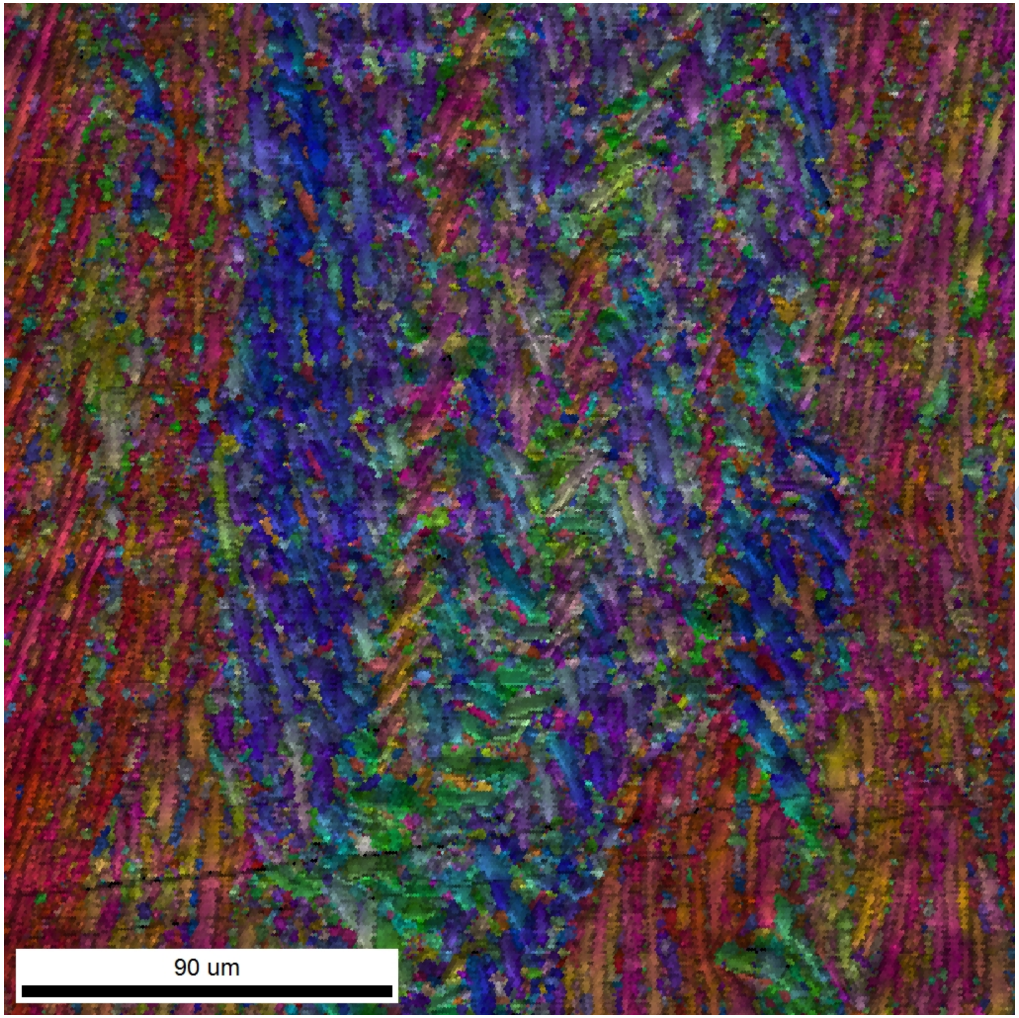
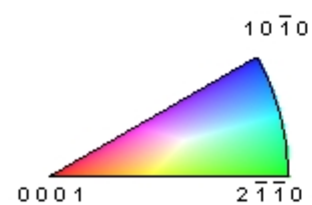


70% avg. height reduction, T = 900°C

- Region near midplane of sample, along axis of compression
- Appears to be broken up, fewer bent colonies observed



Identifying Hard-Oriented Remnants using Taylor Factor

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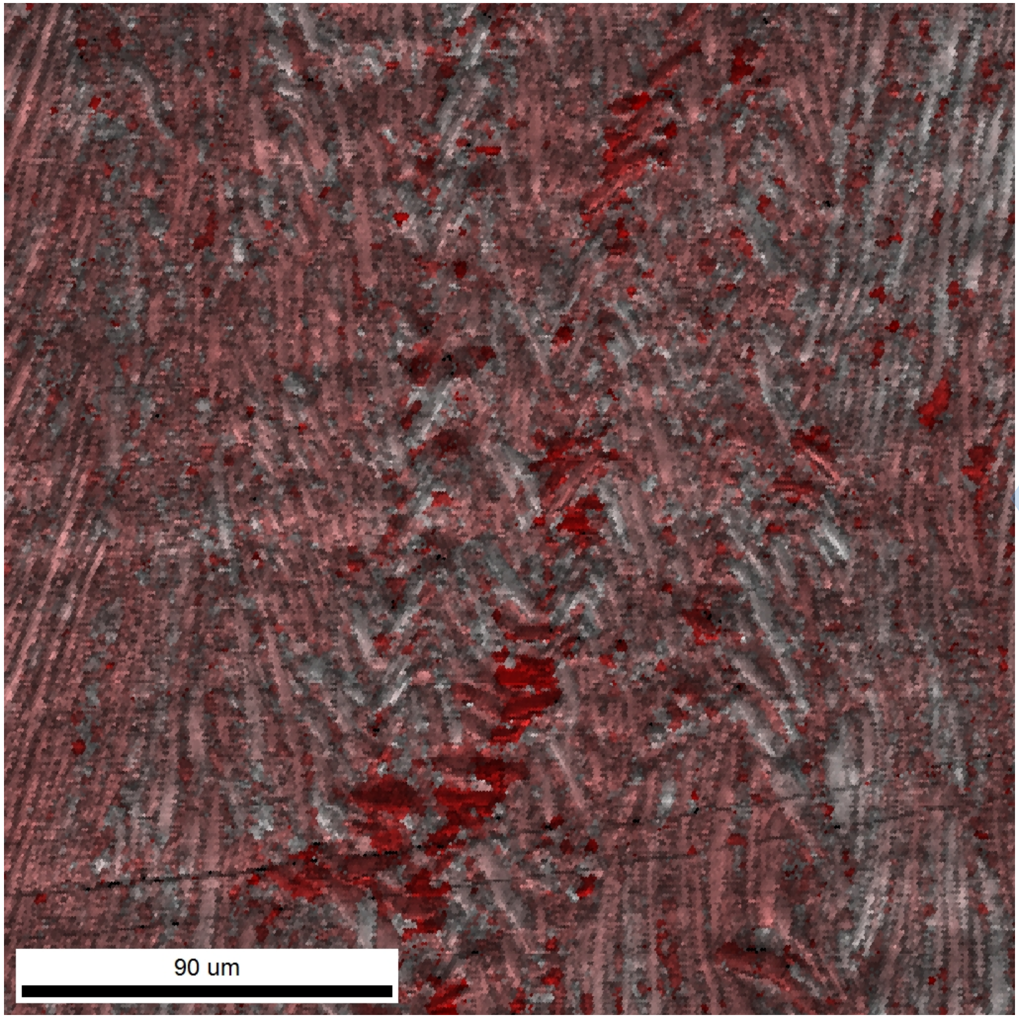

70% avg. height reduction, T = 900°C

- Hard-oriented remnants of globularized colonies are now clearly visible
  - …Assuming uniaxial compression in horizontal direction

Min	Max	Total Fraction	Partition Fraction
3.23144	9.49949	0.996	0.996

Deformation Axis can be Easily Rotated

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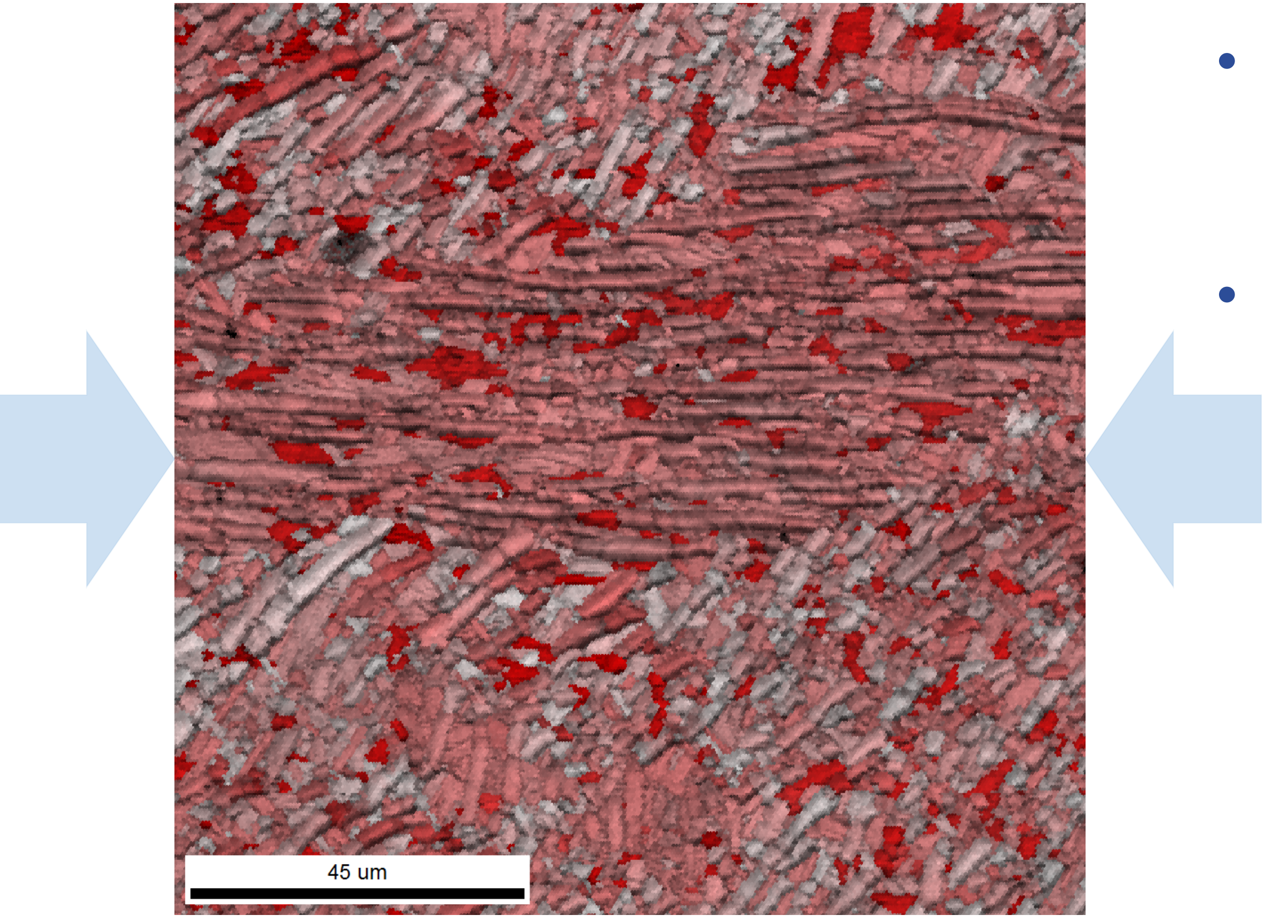

70% avg. height reduction, T = 950°C

Taylor factors calculated with pure horizontal compression

- Hard-oriented regions depend on imposed deformation
- Deformation gradient can be easily changed via TSL/OIM software

	Min	Max	Total Fraction	Partition Fraction
	3.1772	9.49506	0.999	0.999

(photo of 950°C sample not available, scan location shown on 900°C sample for reference)

Center Proprietary – Terms of CANFSA Membership Agreement Apply

Deformation Axis can be Easily Rotated

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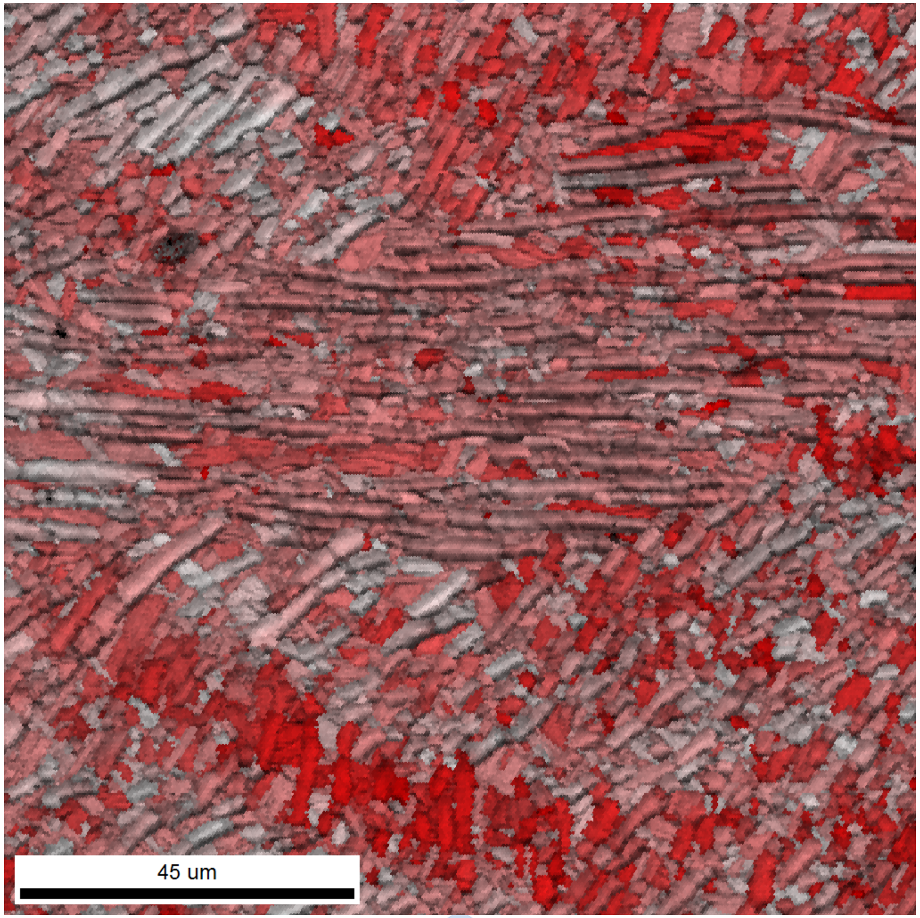


70% avg. height reduction, T = 950°C

Taylor factors calculated with pure vertical compression

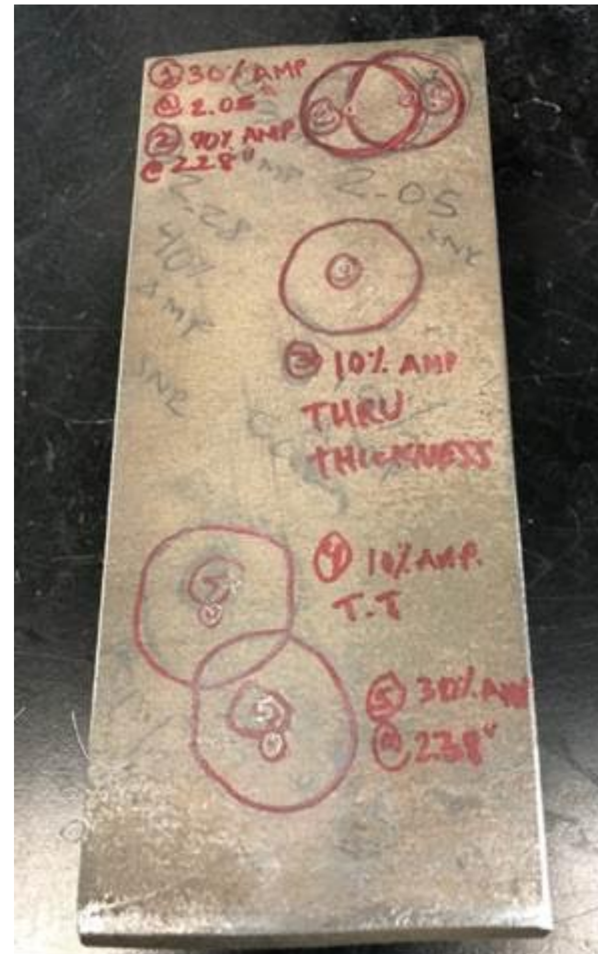
- Hard-oriented regions depend on imposed deformation
- Deformation gradient can be easily changed via TSL/OIM software

	Min	Max	Total Fraction	Partition Fraction
	3.2356	9.50021	0.999	0.999

(photo of 950°C sample not available, scan location shown on 900°C sample for reference)

Future Work

- Complete EBSD characterization of Gleeble samples (5 currently remaining)
- Section and investigate new material:
  - 5 regions of interest:
    1. 30% noise, 2.05” depth
    2. 40% noise, 2.28” depth
    3. 10% noise through thickness (control)
    4. 10% noise through thickness (control)
    5. 30% noise, 2.38” depth
- Propose methods to avoid MTRs in future forgings based on findings



3.625 inches

Gantt Chart

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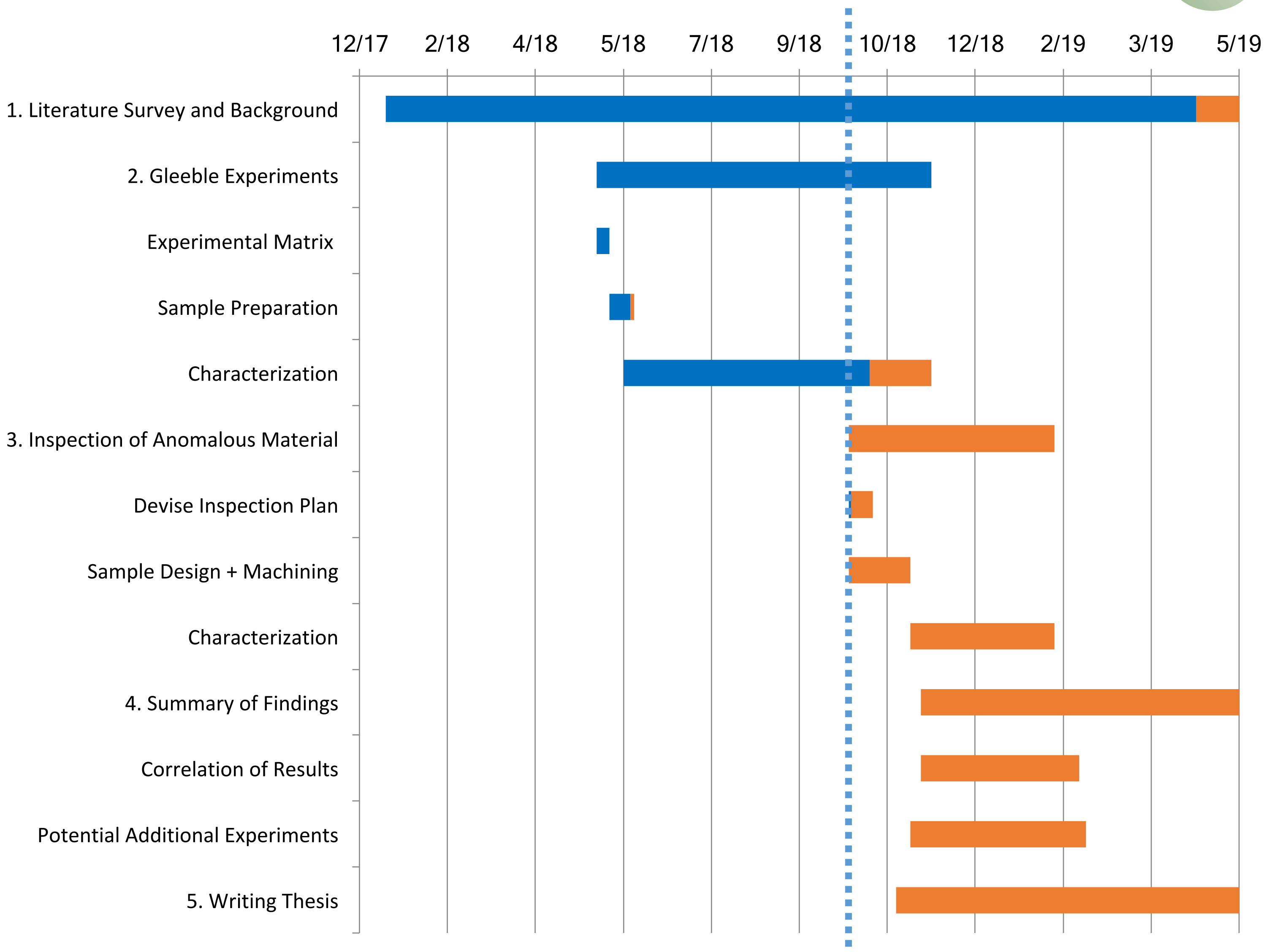

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Thank you very much!

Connor R. Campbell

concampb@mines.edu

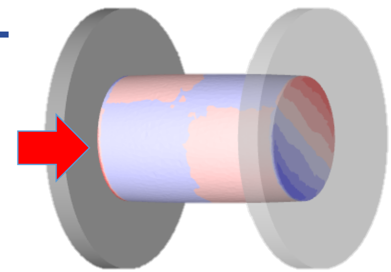
Project 14 – Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings

Student: *Connor Campbell (Mines)*

Faculty: *Terry Lowe and Kester Clarke (Mines)*

Industrial Partners: *Weber Metals (Tony Yao), AFRL (Adam Pilchak)*

Project Duration: *Jan. 2016 – May 2019*



T = 925°C   T = 950°C

Achievement

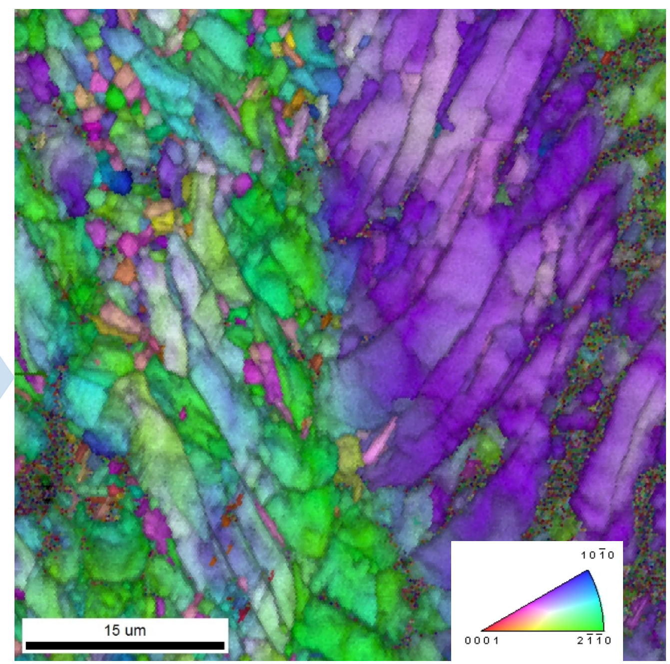
- Electron Backscatter Diffraction and Taylor factor analysis of compressed Ti-6Al-4V at varying temperatures in (α+ß) field

Significance and Impact

- Inspection and analysis of a part with heterogeneous microstructure will provide methods to promote homogeneity

Research Details

- Data collection regarding α colony breakdown, correlation to microstructural heterogeneity that failed ultrasonic inspection



Project 14 – Measurement and Modeling of Anisotropy in Ti-6Al-4V Forgings

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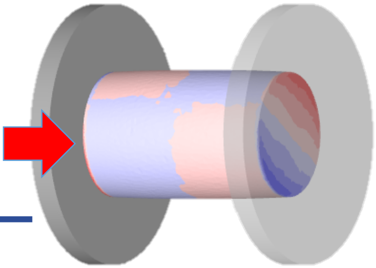


T = 925°C

T = 950°C

Achievement

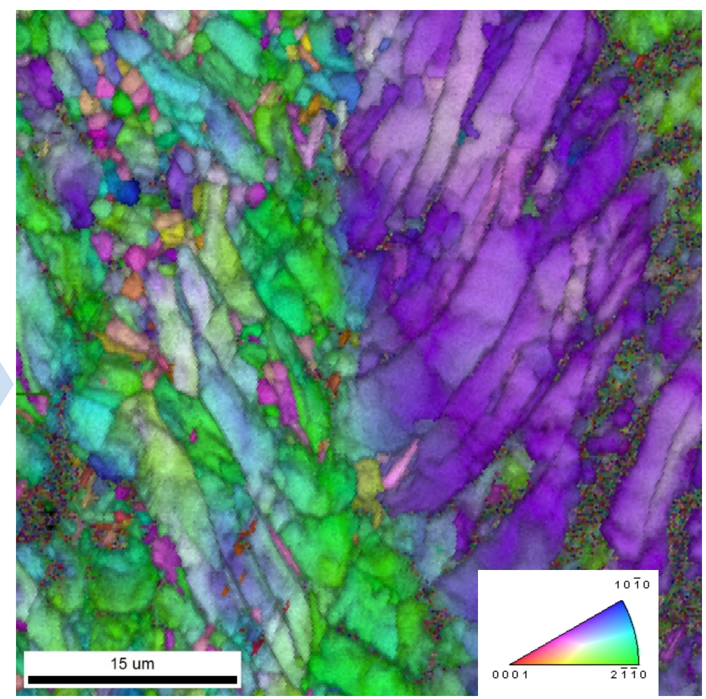
- Electron Backscatter Diffraction and Taylor factor analysis of compressed Ti-6Al-4V at varying temperatures in (α+ß) field

Significance and Impact

- Inspection and analysis of a part with heterogeneous microstructure will provide methods to promote homogeneity

Research Details

- Data collection regarding α colony breakup, correlation to microstructural heterogeneity that led to rejection via nondestructive inspection



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Industrial Partners: *Weber Metals (Tony Yao), AFRL (Adam Pilchak)*

Project Duration: *Jan. 2016 – May 2019*

Program Goal

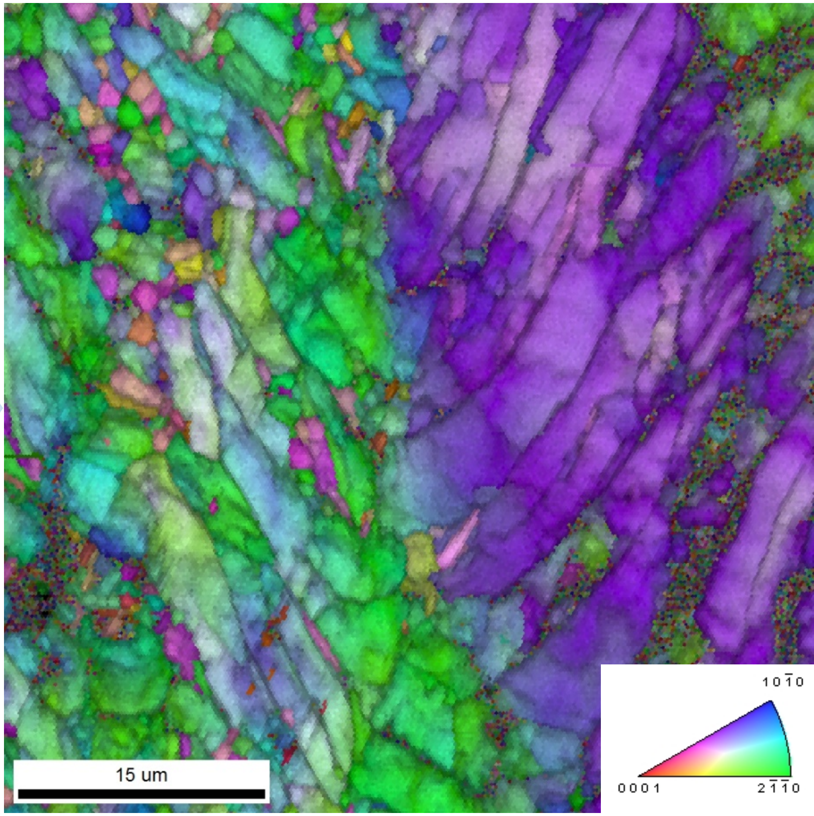
- Extend understanding of how microstructural heterogeneity evolves during forging; characterize and quantify deformed samples, correlate to ultrasonic scattering.

Approach

- Observe evolution of microstructural heterogeneity in early stages of processing at varying temperatures in α+ß field, correlate to heterogeneous microstructure after forging

Benefits

- Improved methods to promote homogeneity in forged products for superior ultrasonic inspectability



Breakup of heavily deformed α colony compressed at 925°C