Project 14: Characterization of Regions in Ti-6Al-4V Forgings with Diminished Ultrasonic Inspectability

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Project 14: Characterization of Regions in Ti-6Al-4V Forgings with Diminished Ultrasonic Inspectability

CANFSA CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

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

Project Duration
MS: January 2016 to May 2019

- Problem: Regions of microstructural heterogeneity cause high ultrasonic noise in alpha/beta Ti alloys and limit inspectability via nondestructive methods.
- Objective: Extend understanding of how microstructural heterogeneity evolves during forging; characterize and quantify deformed samples, correlate to ultrasonic scattering.
- Benefit: Observations of features that increase noise may provide insight into how to optimize processes for homogeneity.

Recent Progress

- Microstructural characterization of forged (α+ß) Ti
- Data Analysis
- Thesis Writing

Metrics		
Description	**% Complete**	**Status**
1. Survey of current knowledge	95%	●
2. Extraction of regions of low ultrasonic quality	100%	●
3. Sample preparation and characterization of regions of high ultrasonic quality	90%	●
4. Characterization of regions of low ultrasonic quality	80%	●
5. Quantification of microstructures and data analysis	20%	●

Presentation Outline

- Industrial relevance
- Background information
  - Ultrasonic testing of (α+ß) titanium alloys
- Current progress
  - Characterization of regions with high ultrasonic noise
- Future work
  - Characterization of regions with low ultrasonic noise for comparison
  - Quantification of microstructures and data analysis
  - Thesis writing
- Summary

Industrial Relevance

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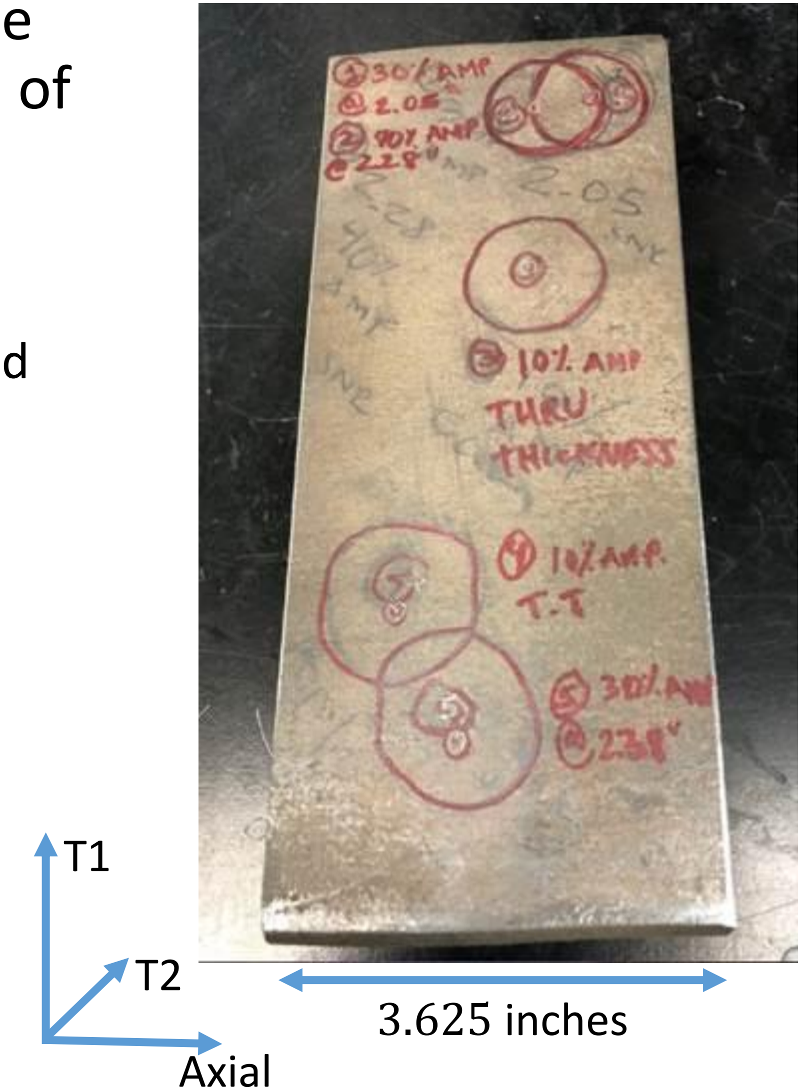
- Ti-6Al-4V is widely used in many industries
- Properties of (α+ß) Ti-alloys can vary greatly
  - Dependent on α morphology and orientation
  - Necessitates rigorous inspection
    - Commonly done via ultrasonic testing (UT)
- Prone to heterogeneous deformation and localized texture during thermomechanical processing (TMP)
  - Scatter ultrasonic signals used for inspection
    - Can cause parts to be rejected ($$$$$)
    - Hard to predict where localized texture will form, and how severe it will be *<u>even in simple forgings</u>*!

Project Goal

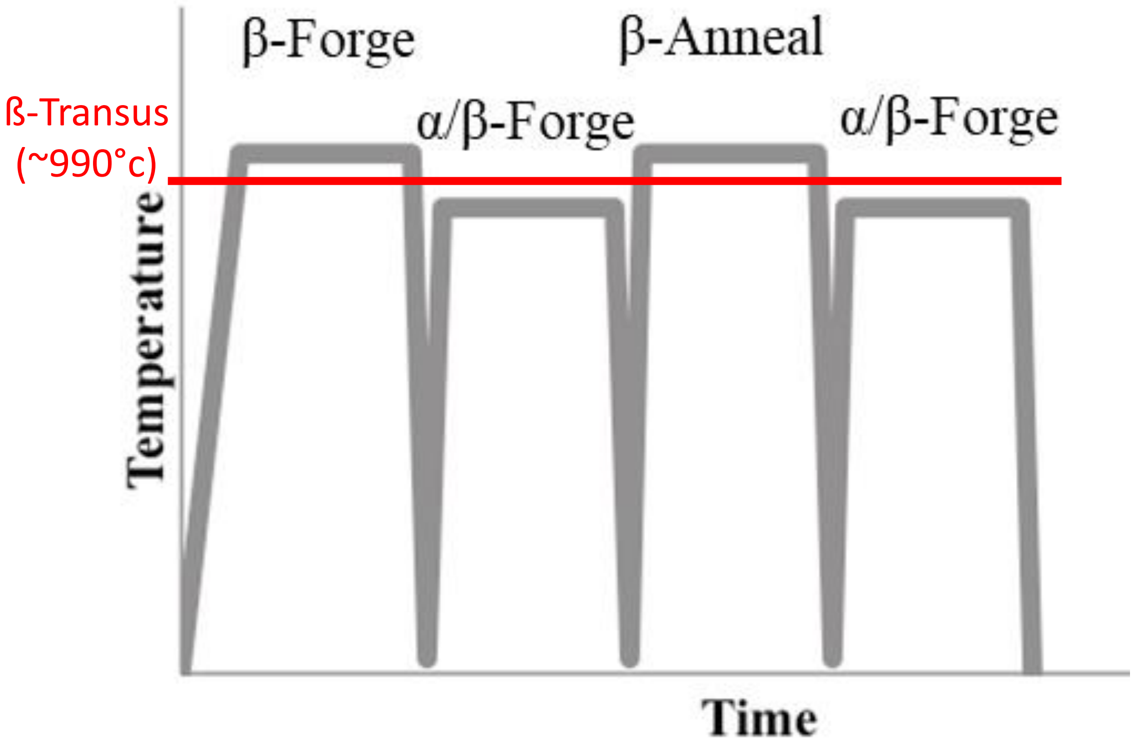
- Investigate microstructure of simple forging (on right), determine origin of features that impeded ultrasonic inspection
  - 5 areas were tested, increased noise observed in three of them at indicated depths
- Extend understanding of microstructural features that contribute to uncertainty in UT of Ti-64 forgings
  - Electron microscopy and orientation mapping via electron backscatter diffraction (EBSD)



Background Information

- How are (α+ß) Ti-forgings typically processed?
- How are forgings ultrasonically inspected?
- What complicates ultrasonic inspection of alpha/beta Ti-alloys?
- What are microstructural aspects that contribute to noise?

Background Information: (α+ß) Titanium Alloy Processing



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

Step 0: Ingot Solidification

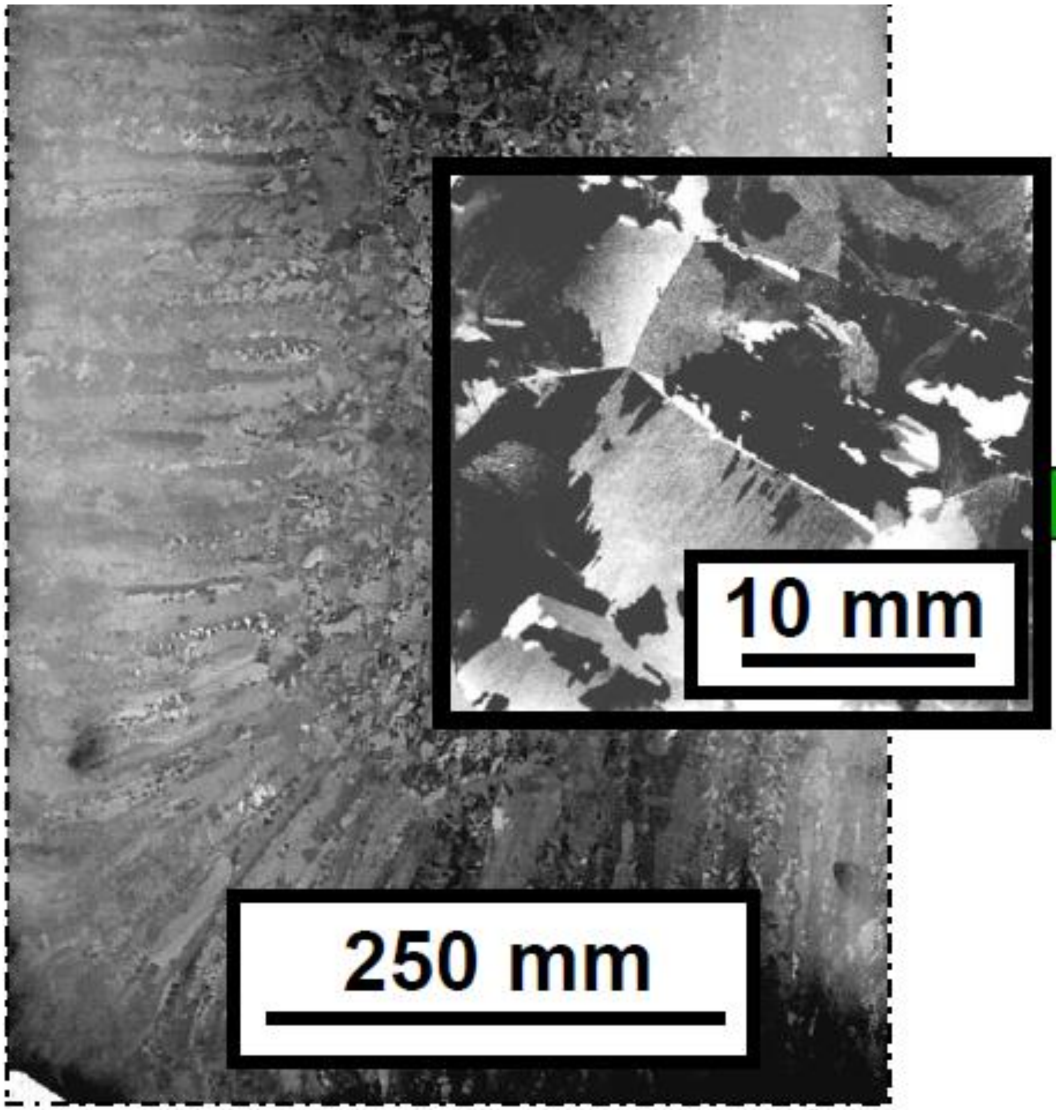


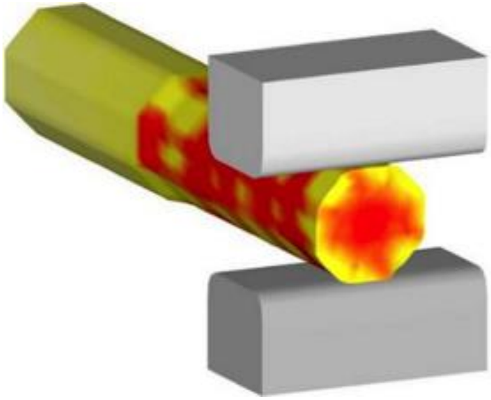
Figure Credit: S.L. Semiatin, 2018

- ß-grains solidify, can be equiaxed or columnar
  - Can be ~cms in size
- α colonies grow from ß grain boundaries during cooling
  - Will be related to parent ß by Burgers orientation relationship:

    $\{110\}_{ß}$ // $(0001)_{\alpha}$
    $\langle 111 \rangle_{ß}$ // $[2\bar{1}\bar{1}0]_{\alpha}$
  - 12 possible variants, usually between 3 and 5 will form

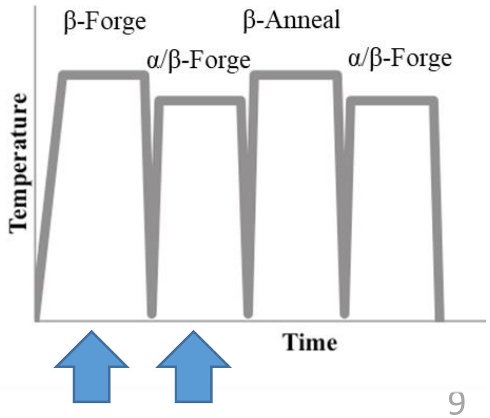
Steps 1+2: ß and Initial (α+ß) Hot Working of Ingot

- Ingot is cogged, elongating longitudinal axis
- ß-worked initially because ß is softer than α
  - T > 1050°C
  - Produces ß grains ~mms in size
- (α+ß) worked to introduce hot work used to fuel recrystallization during ß anneal
  - 900°C < T < 990°C
  - α colonies will deform, albeit less than ß
  - Strain partitioning b/t phases is hard to predict
    - "Hard" vs. "Soft" oriented α colonies
    - Temperature- and rate-dependence of ß



DEFORM-3D simulation of cogging

http://wildeanalysis.co.uk/fea/software/deform/deform-3d-suite/deform-cogging



Step 3: ß-Anneal and Quenching

- ß grains recrystallize during brief hold above ß-transus
  - Grains grow rapidly until ~1-2mm
- Rapidly quenched in water
  - Suppresses grain-boundary α
  - Produces fine α colonies that are easily deformed and recrystallized

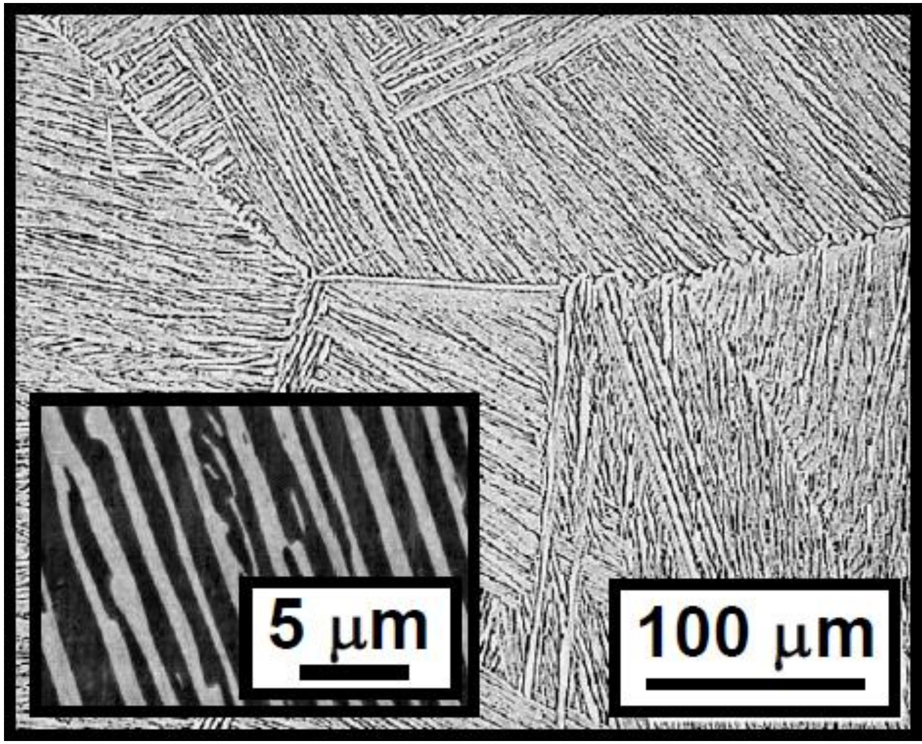


Figure Credit:
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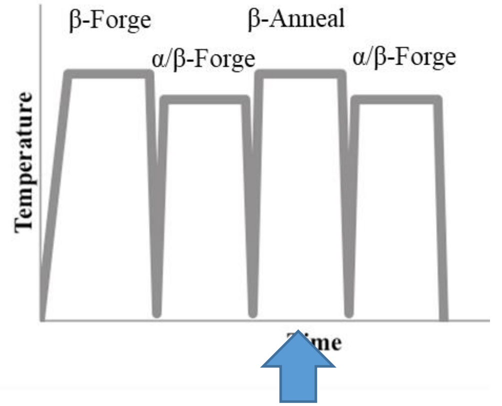
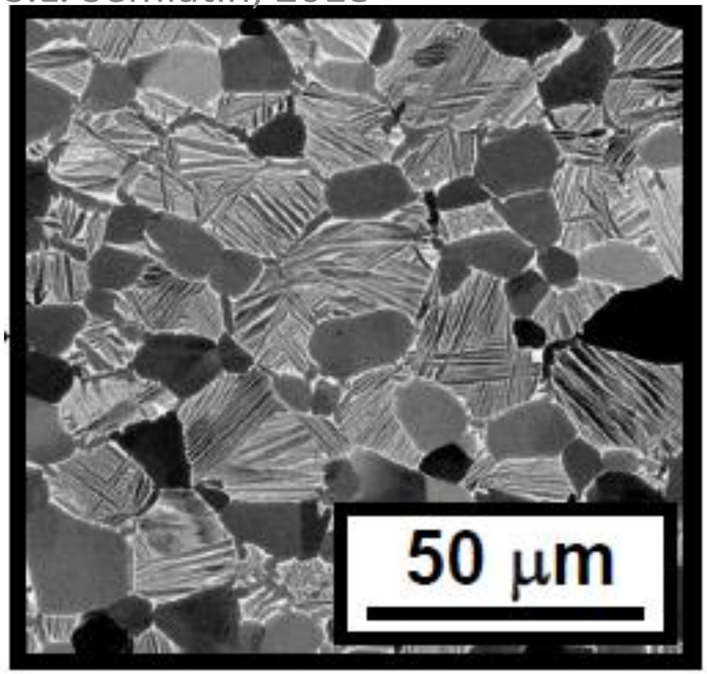
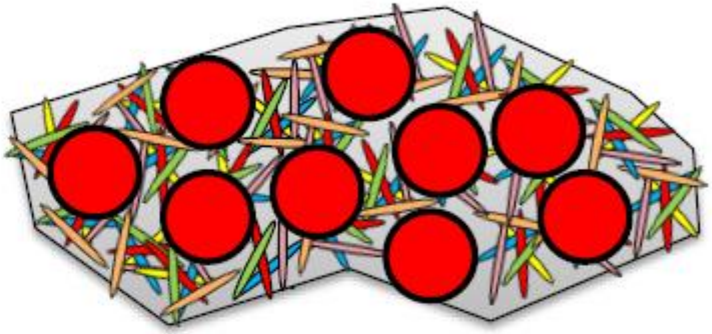


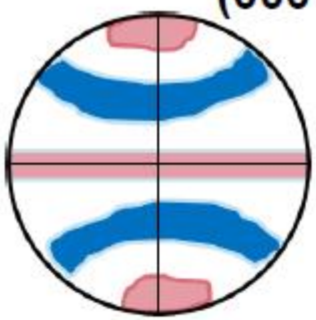
Step 4: (α+ß) Forging

- Produces equiaxed primary α grains in a matrix of transformed ß (secondary α platelets and remnant ß at boundaries)
  - Average grain size usually ~15-20um following heat treatment
- Ideal: Any primary α texture is insulated by randomly oriented secondary α -> homogeneity!
  - *…ideally*

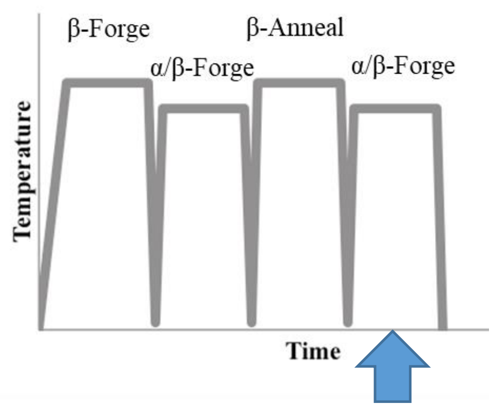
S.L. Semiatin, 2018







A. L. Pilchak, 2018

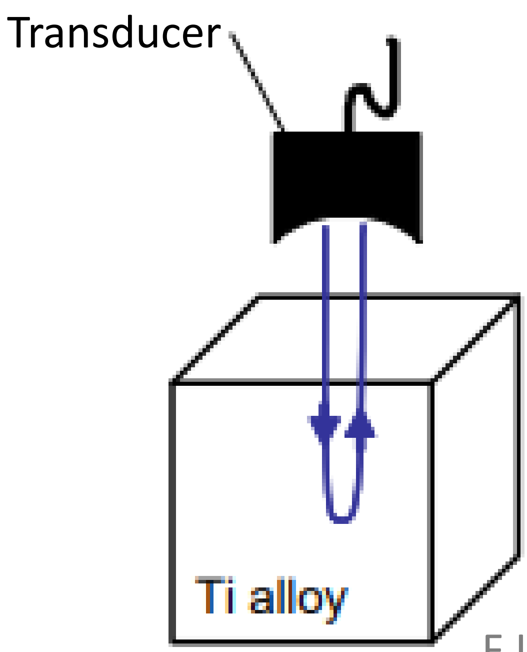


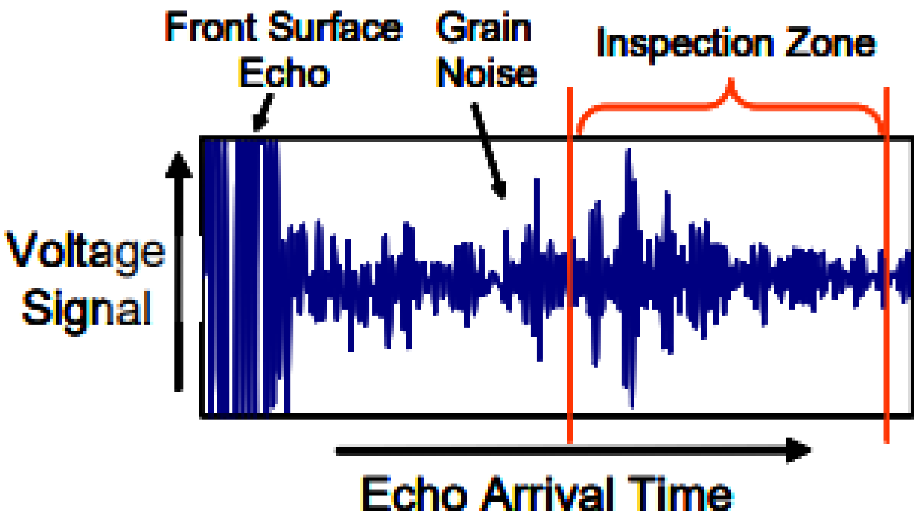
Background Information

- How are (α+ß) Ti-forgings typically processed?
  - ~4 step process with intent of producing uniform, fine grains
- How are forgings ultrasonically inspected?
- What complicates ultrasonic inspection of alpha/beta Ti-alloys?
- What are microstructural aspects that contribute to noise?

How are Forgings Ultrasonically Inspected?

- "Pulse/Echo" Inspection
  - Immersed transducer supplies an ultrasonic **pulse** into the material
  - The **echo** is then recorded as a voltage signal
    - Reflections occur wherever there is a difference in density
  - Initially developed to detect cracks, pores, and voids, has been refined to determine more about microstructure

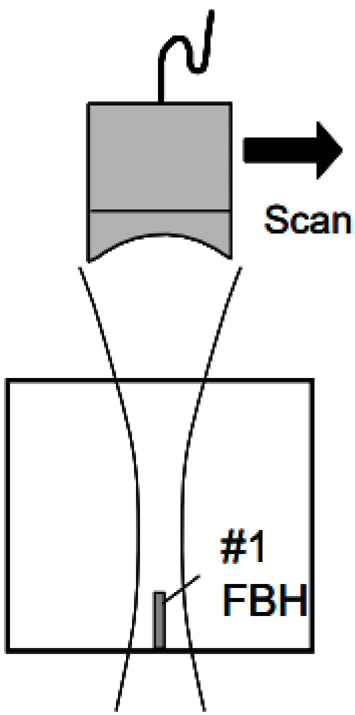




F.J. Margetan, J. Umbach, et al. (2007)

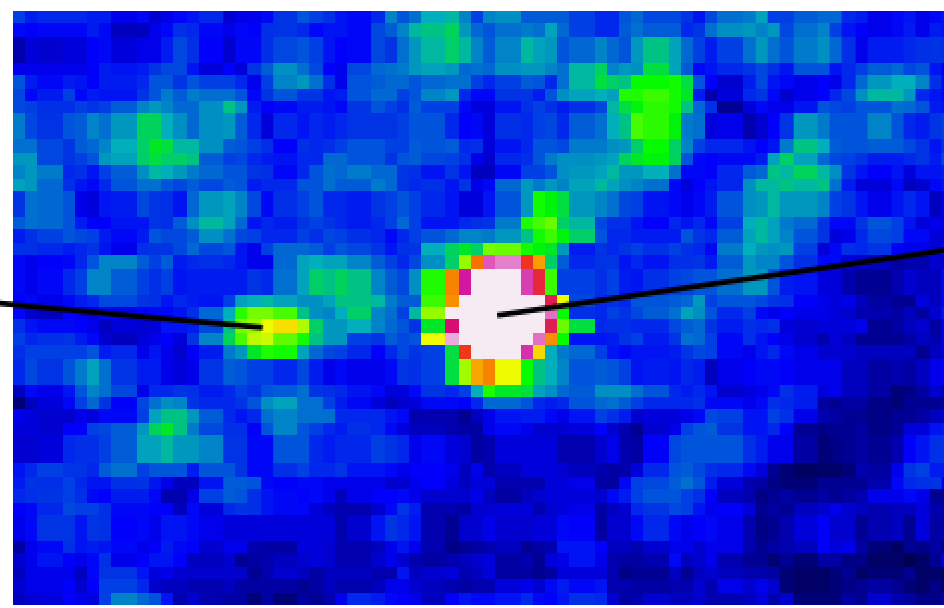
How are Forgings Ultrasonically Inspected? (Cont.)

- Calibrated using a flat-bottom hole (FBH) standard
  - Machined flaw serves as a reflector in a known location to ensure accuracy of measurements
  - Permits calculation of a signal-to-noise ratio (SNR)



$$\frac{S}{N} = \frac{Peak\ Defect\ Amplitude}{Peak\ Noise\ Amplitude}$$

Peak Noise Amplitude



Peak Defect Amplitude

“Heatmap” of amplitude

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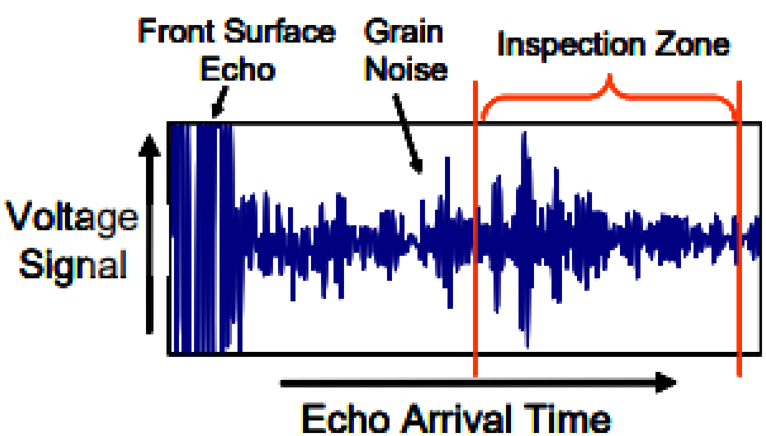
What Complicates Ultrasonic Inspection of Ti-Forgings?

- Complex ultrasound-microstructure interactions
- Difficult-to-interpret readings near surfaces
  - Dents and scratches serve as reflectors
- Reflections at grain boundaries
  - Difference in (c) and (a) plane density and elastic modulus
- Localized preferred crystallographic orientation



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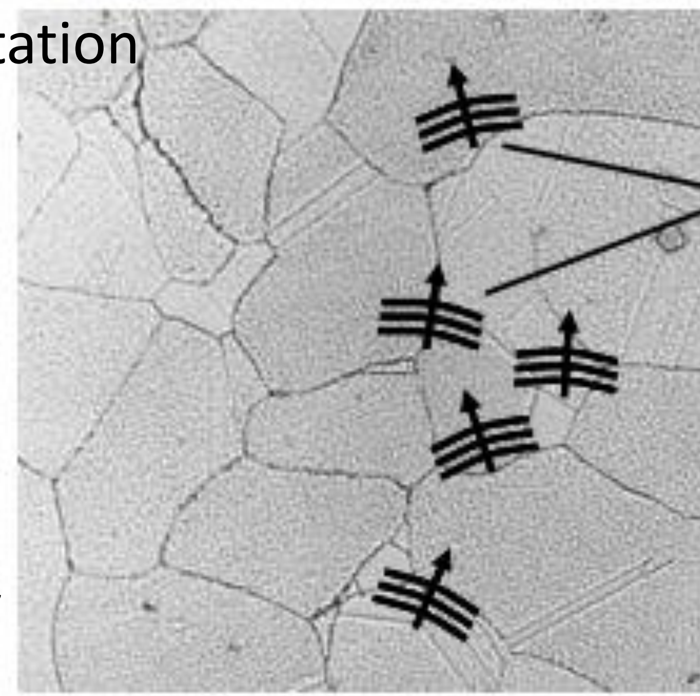
Incident Sound Pulse



Schematic of grain boundary scattering

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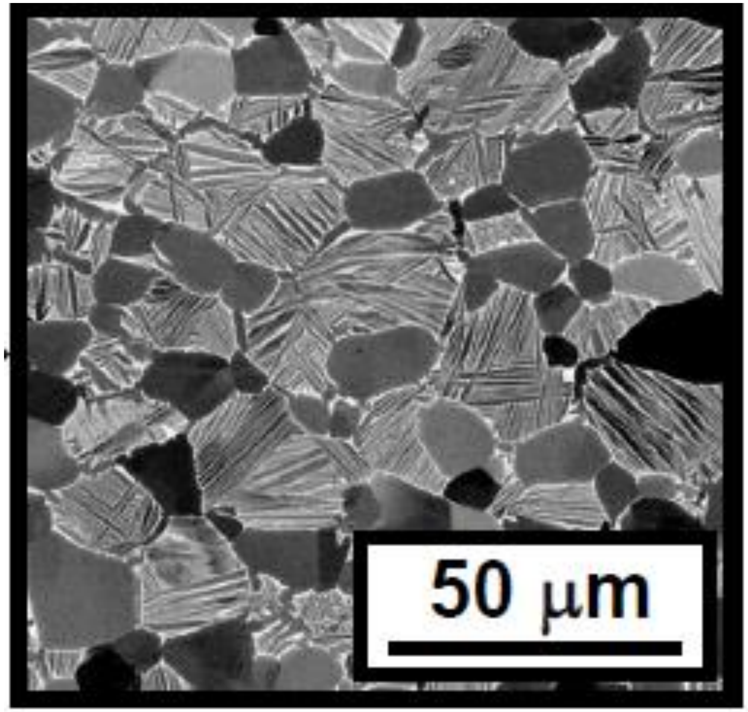
- What complicates ultrasonic inspection of alpha/beta Ti-alloys?
  - Complex ultrasound-microstructure interactions
  - Surface defects, variations in grain noise, and localized texture
- What are microstructural aspects that contribute to noise?

What Aspects of Microstructure Contribute to Noise?

- Backscattering at grain boundaries due to acoustic mismatch
  - Grain morphology (particularly elongation)
  - Grain orientation (relative to incident beam)
- Wavelength of ultrasonic pulse relative to average grain size
  - If $\lambda > 2\pi D$, "Rayleigh" scattering occurs
    - Improves inspectability
  - If $\lambda < 2\pi D$, "Stochastic" scattering occurs
    - Increases attenuation (energy loss)
- With sufficient attenuation, dangerous defects can appear to be less dangerous



S.L. Semiatin, 2018

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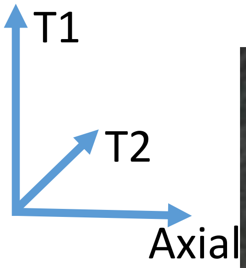
- What are microstructural aspects that contribute to noise?
  - Grain elongation and preferred orientation
  - Grains that are larger than expected (>15-20μm)

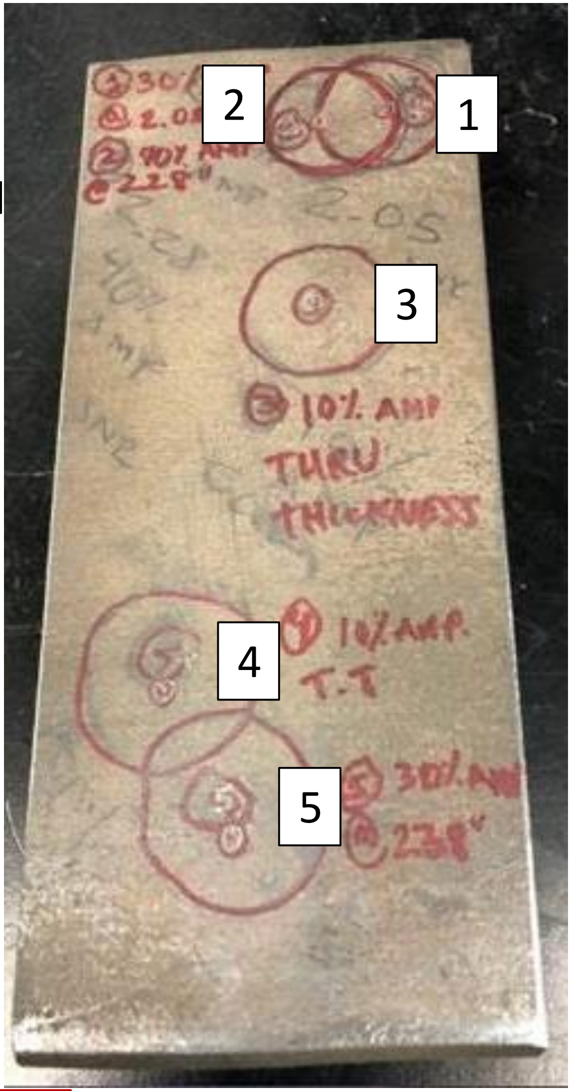
Recent Progress

- Removal of regions of interest via wire EDM
- Bulk texture measurement via x-ray diffraction
- Scanning electron microscopy of samples

Removal of Regions of Interest

- 5 regions scanned by Weber Metals:
  1. 30% SNR, 2.05” depth
  2. 40% SNR, 2.28” depth
  3. 10% SNR through thickness (control)
  4. 10% SNR through thickness (control)
  5. 30% SNR, 2.38” depth
- Regions were extracted via wire EDM
- 1 and 2 were cut to indicated depths
  - Referred to as “Square 1” and “Square 2,” respectively
- 5 was cut into “coins” parallel to the top surface at depths of 2.23”, 2.38”, and 2.53” for XRD and BSE analysis
  - Referred to as “Coin 1,” “2,” and “3,”





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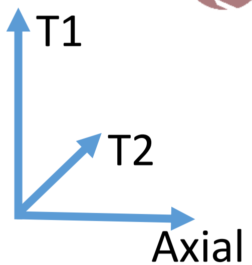

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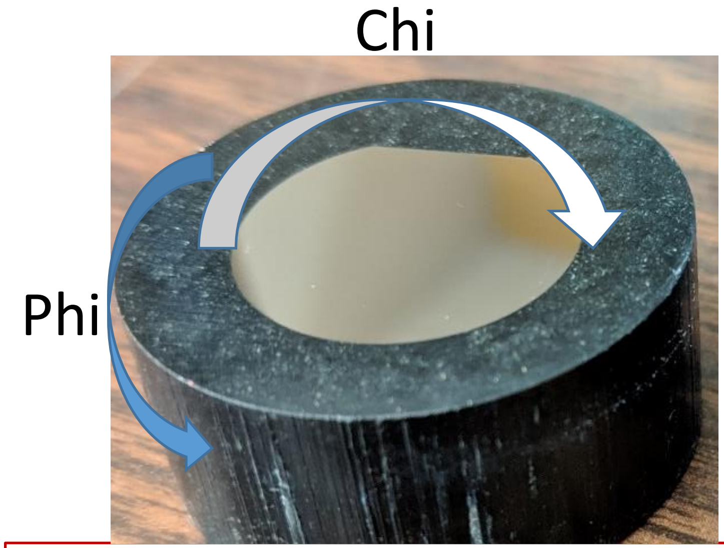
Texture Measurements via XRD

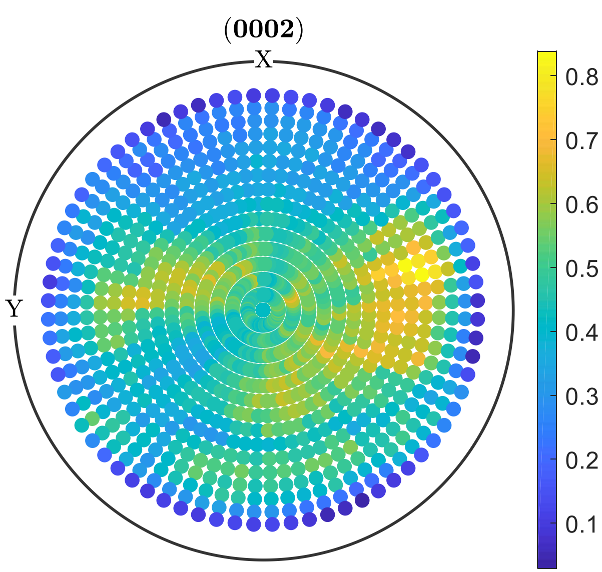
- Coin 2 was mounted and polished for XRD analysis
  - Recall that coin 2 was cut @ depth of ultrasonic indication
- Full texture scan was conducted:
  - Scan for Bragg condition for (a), (c), and (a+c) planes (hkl-α)
  - Set condition, rotate samples through phi = 0°-359° and chi = 0°-80°
  - Higher intensity = more planes aligned with that orientation
  - Defocusing and background scans were also performed



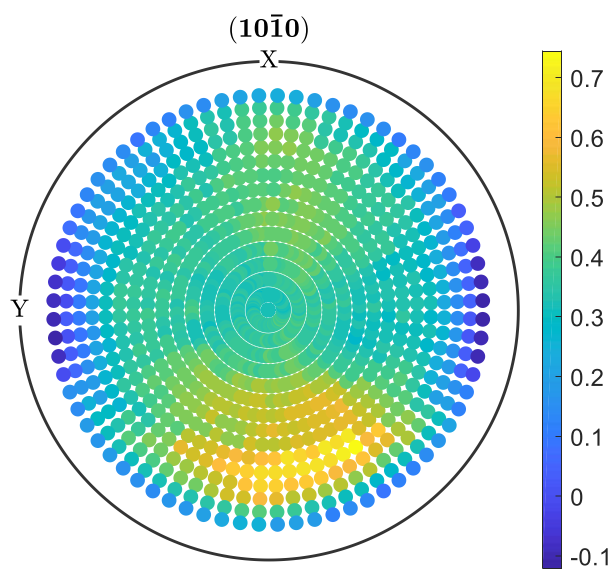
"Coin 2" Bulk Texture XRD

- Pole figure results show evidence of weak texture
  - Max intensity of 1.2x random is weak, expected values of at least 2x
  - Scan area = ~1cm^2, not detecting "localized" texture

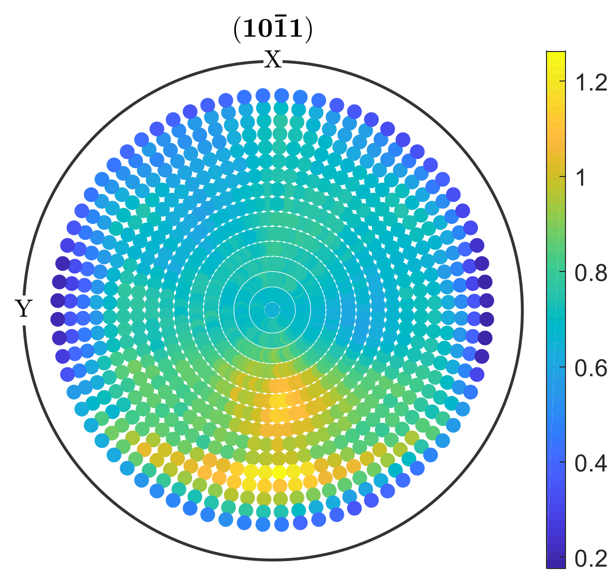
(C) Planes



(A) Planes



(C+A) Planes



Recent Progress

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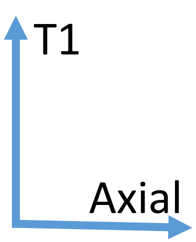
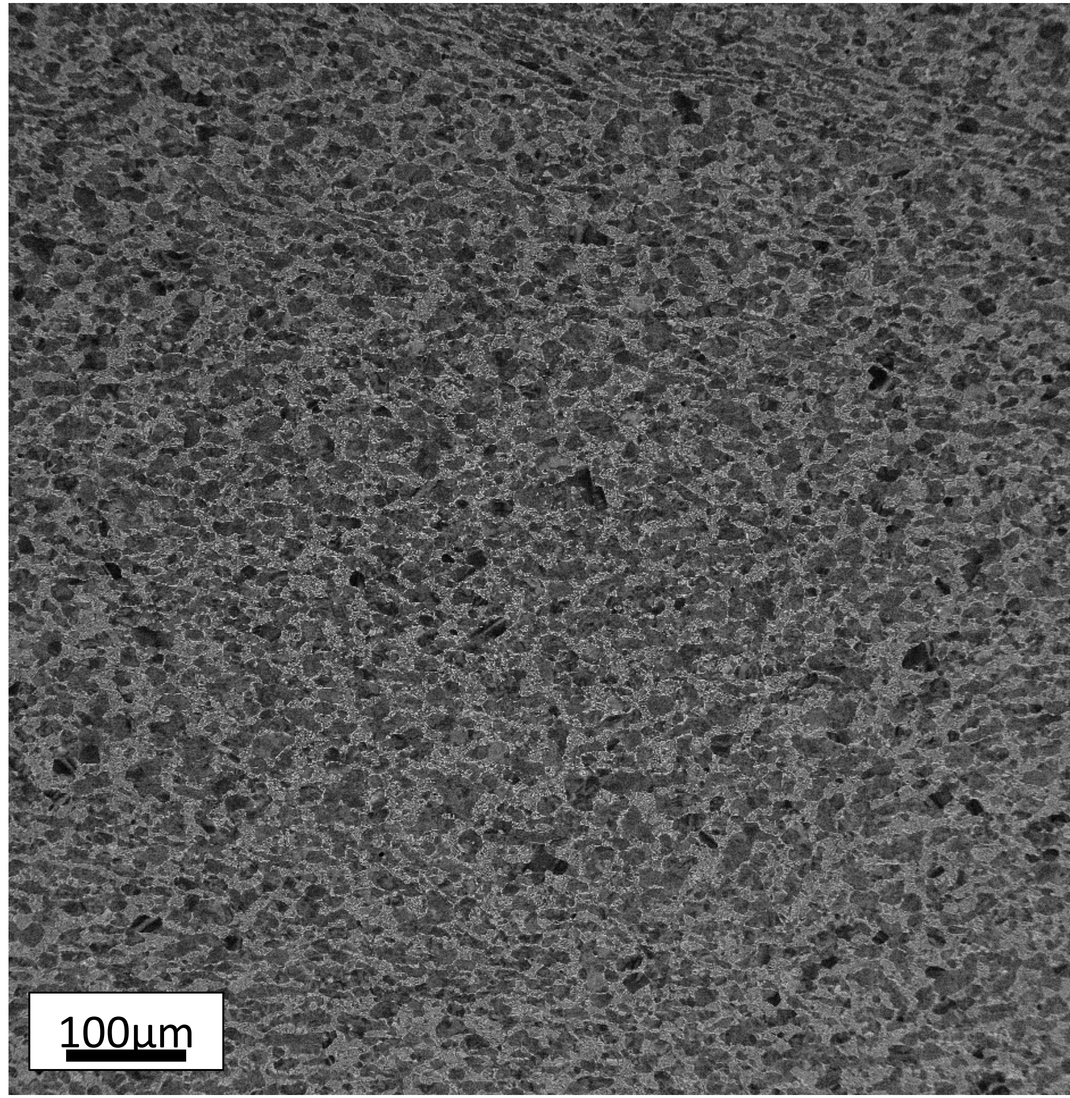
  - Were not (α+ß) annealed
- Bulk texture measurement via x-ray diffraction
  - Bulk texture was very weak (1.2x random for pyramidal planes)
- Scanning electron microscopy of samples

SEM of Coin 1 (above location with 30% SNR)

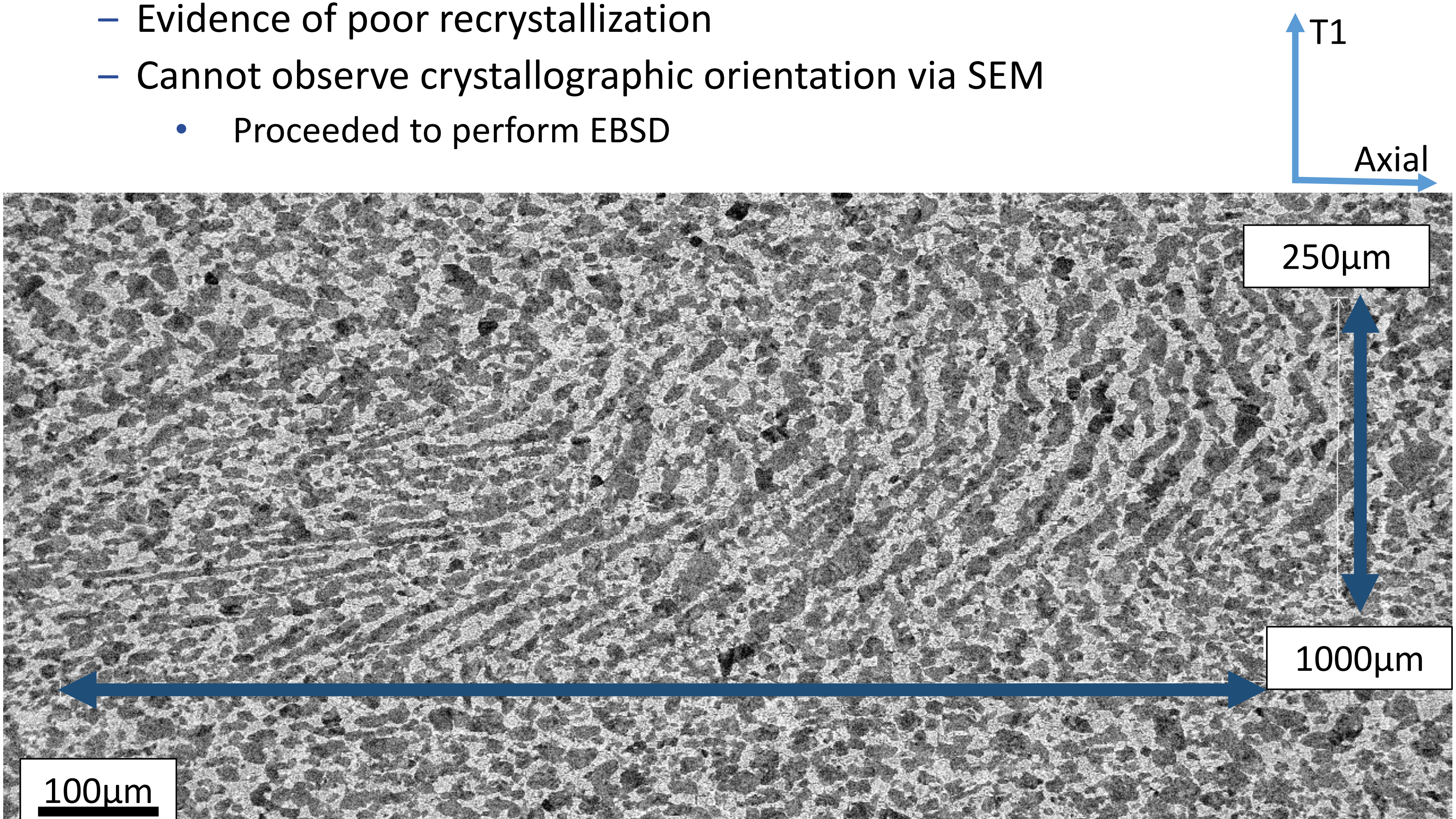
- “Control” samples above/below indication
- Expected for non-heat treated microstructure
  - Nominally equiaxed α
  - Nothing too coarse
  - Small amount of elongated α



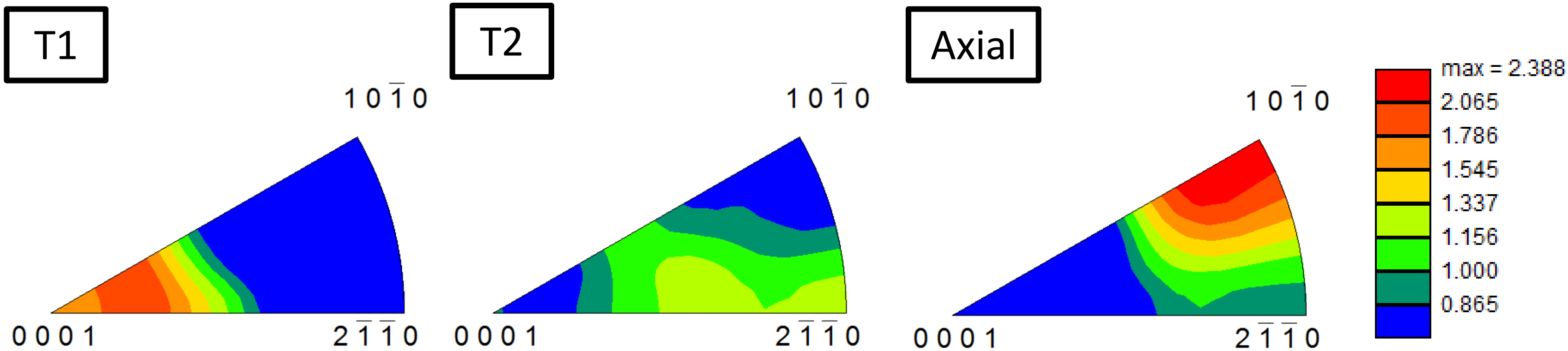


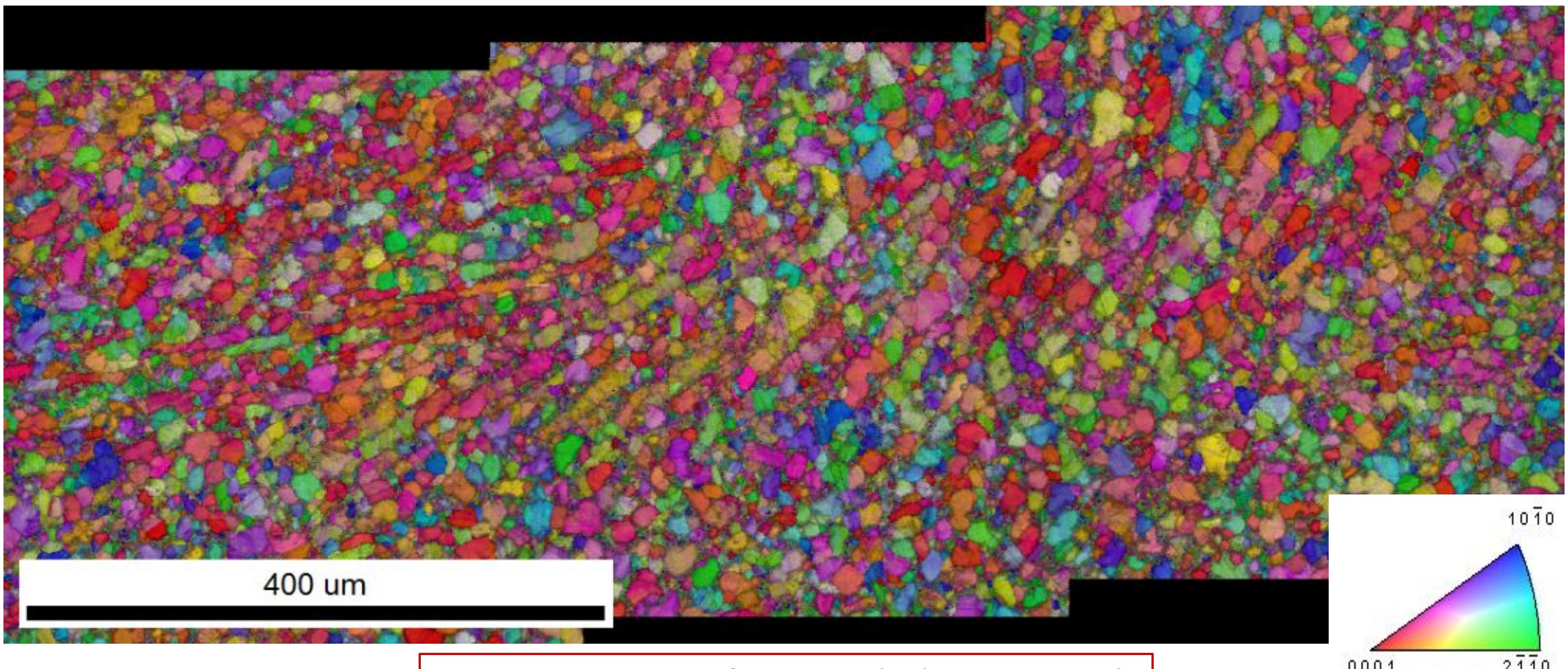
SEM of Coin 2 (30% SNR)

- Large, bent α colony remnants observed
  - Evidence of poor recrystallization
  - Cannot observe crystallographic orientation via SEM
    - Proceeded to perform EBSD



EBSD of Coin 2





SEM of Square 2

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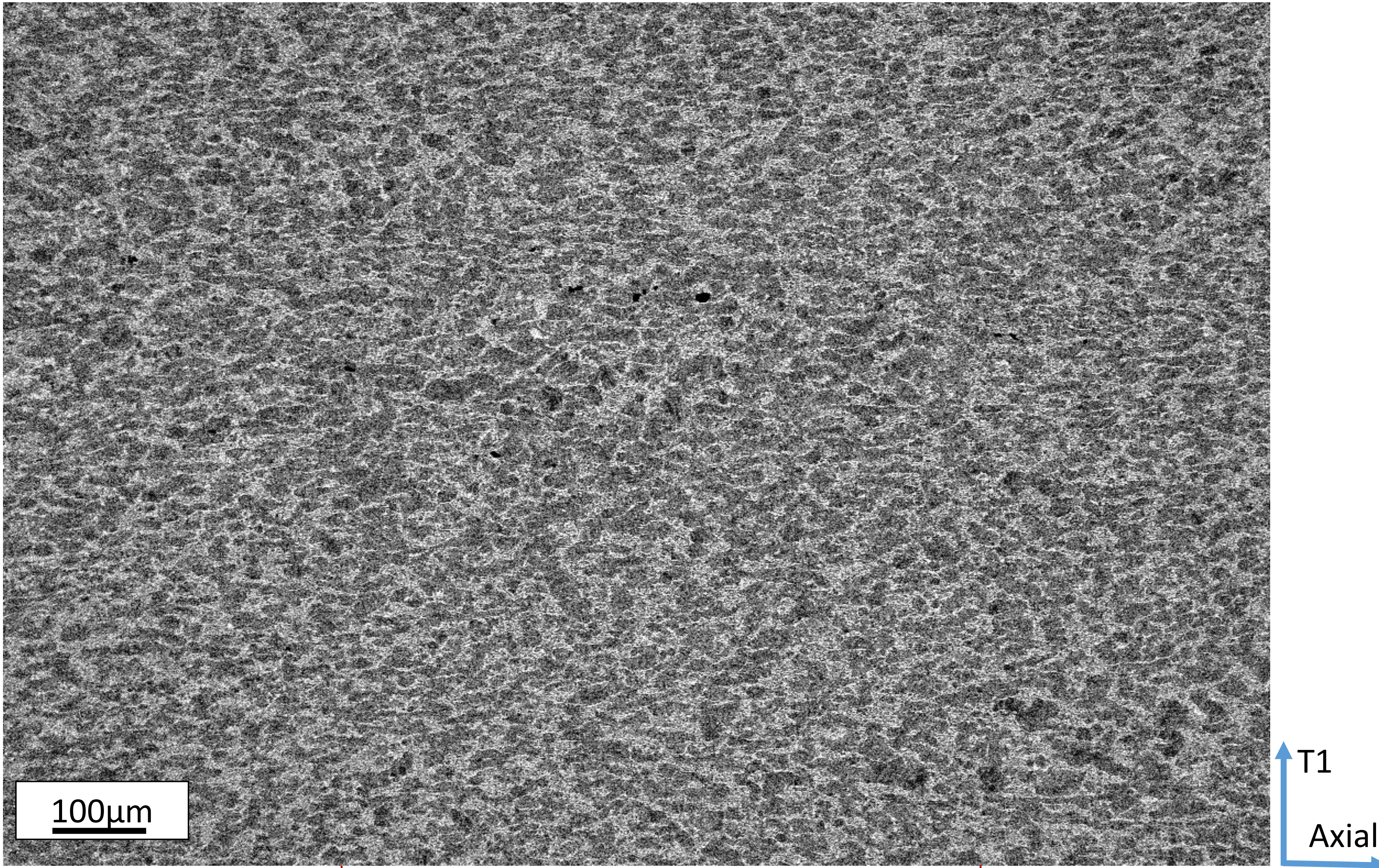
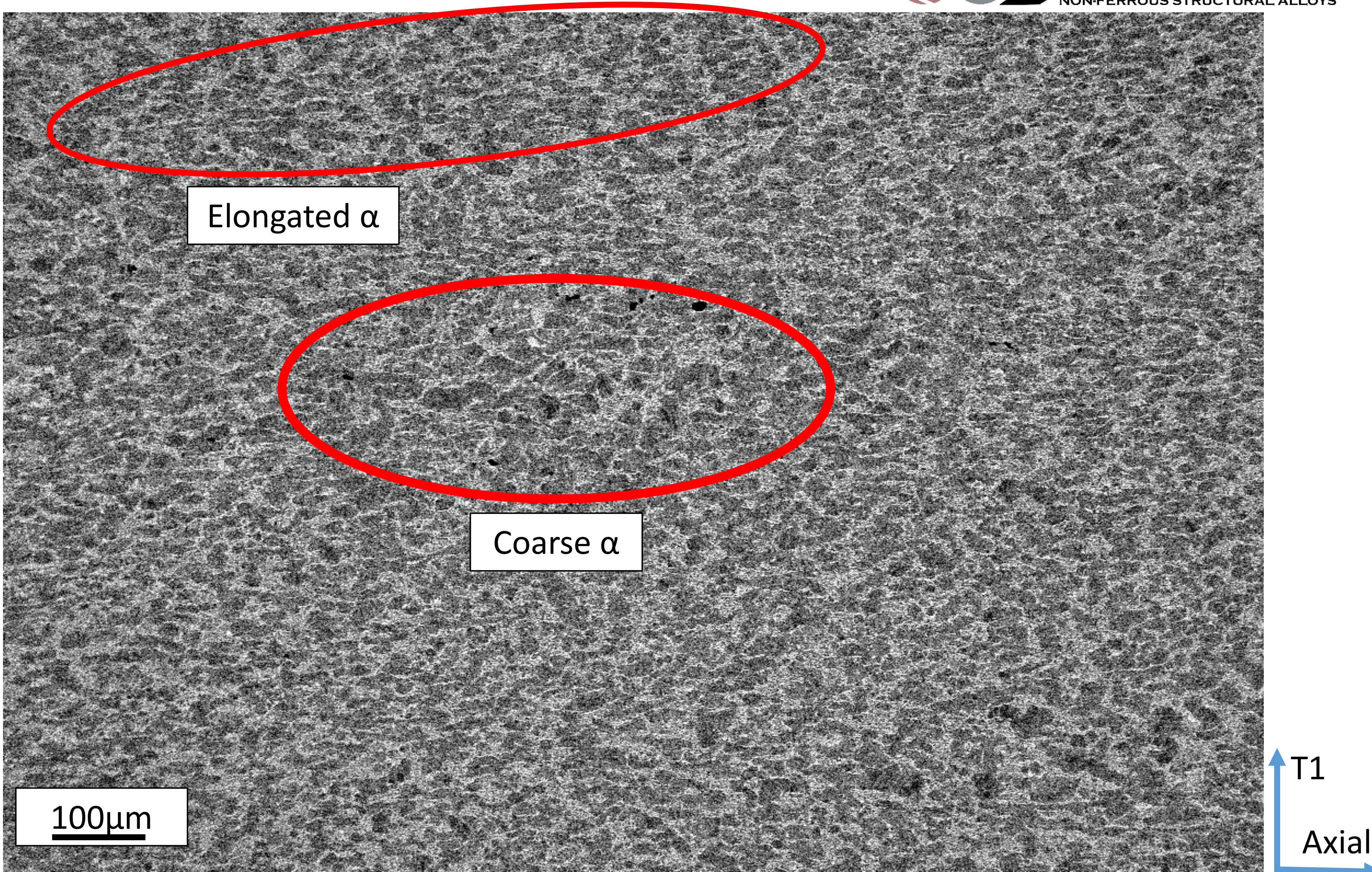
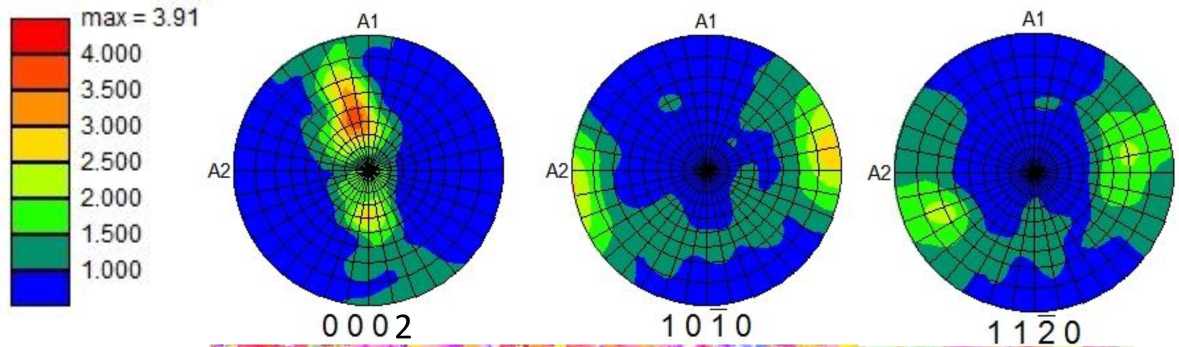


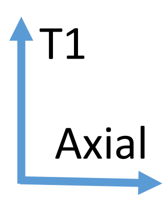
SEM of Square 2 - Annotated

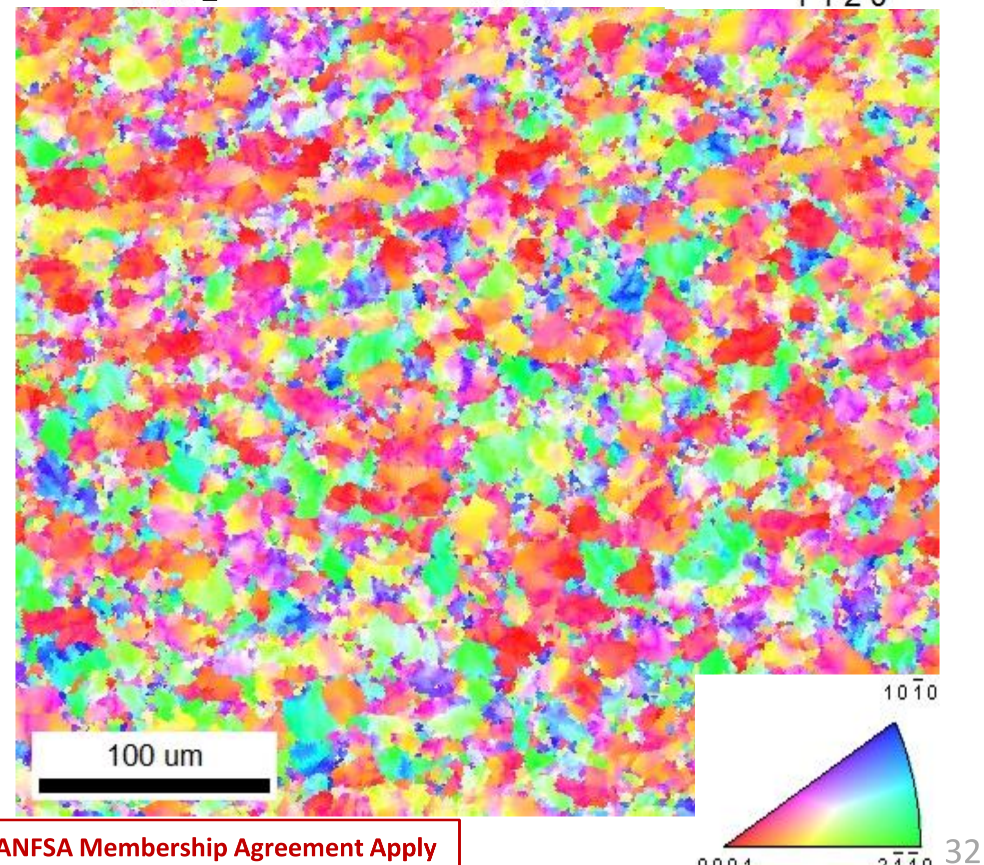


EBSD of Square 2 (40% SNR)



- Locally, texture intensities measured of 3.9x random
- Two dominant preferred orientations in this location
  - Red more dominant in this case
- Locations scanned were approximately below the transducer location





EBSD of Square 2 (40% SNR)

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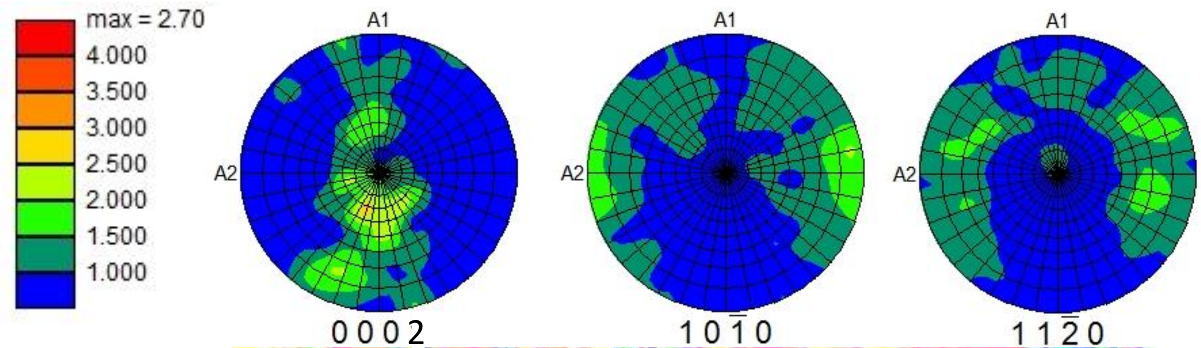
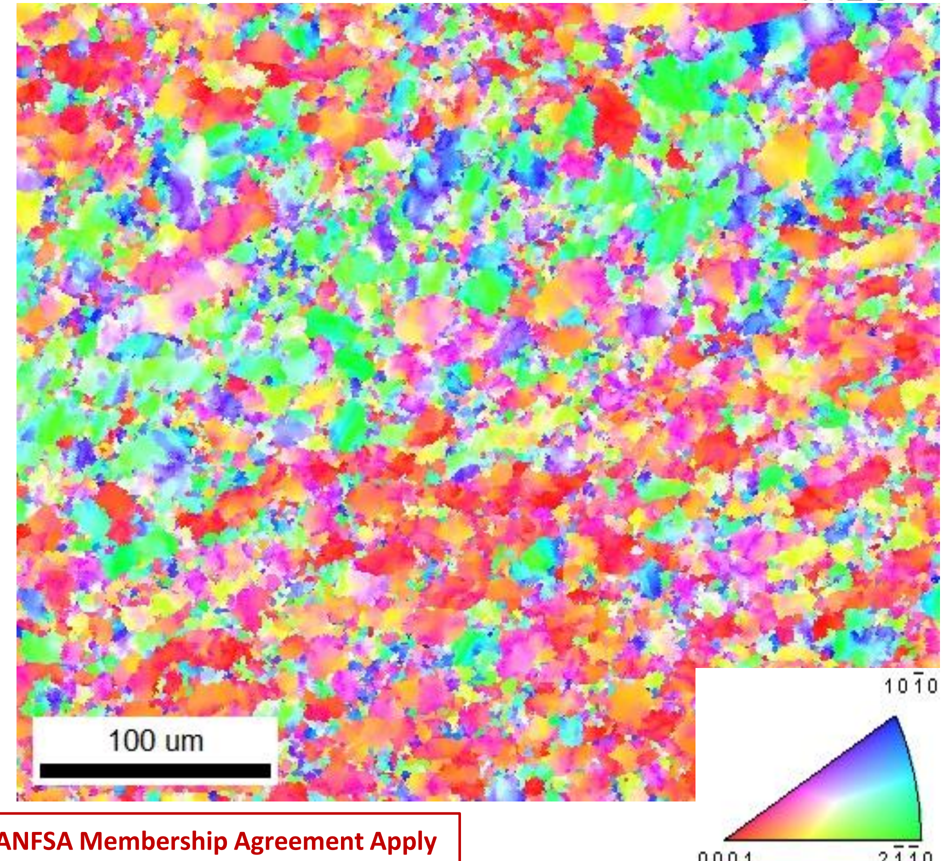
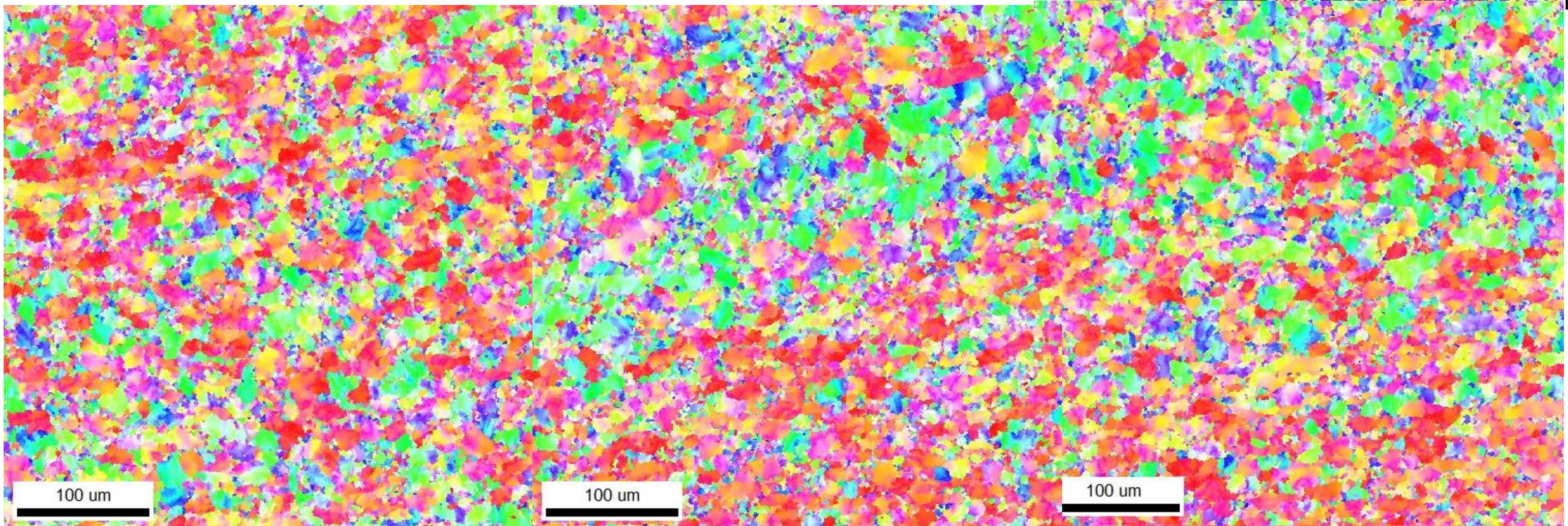
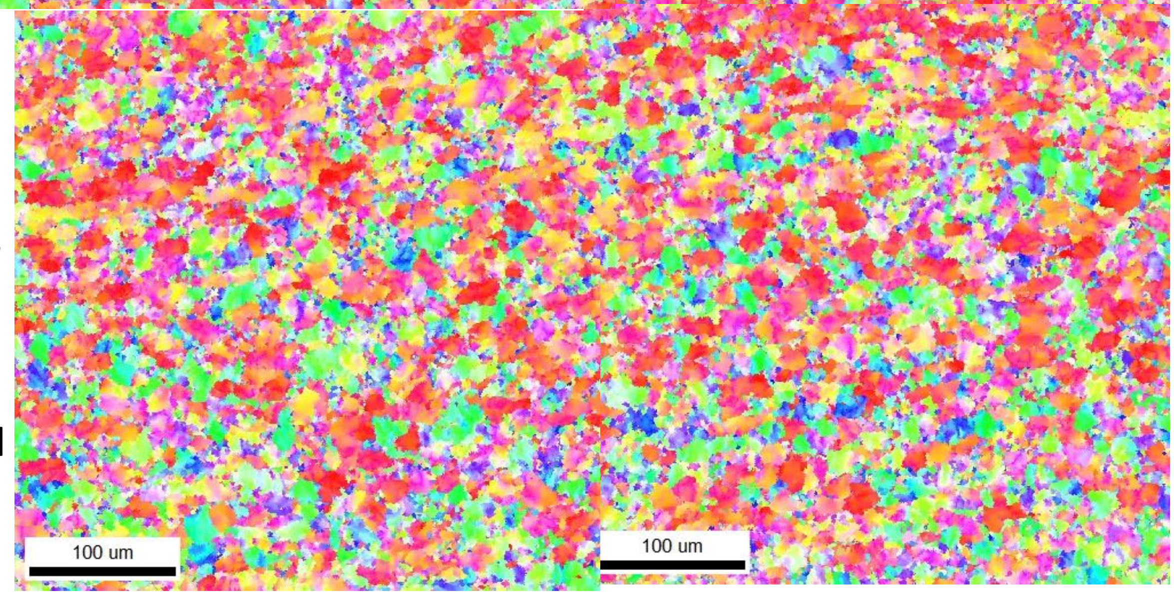


- Two dominant orientations more apparent here
- Appear to be looking within a microtextured region!



"Stitched" EBSD Maps

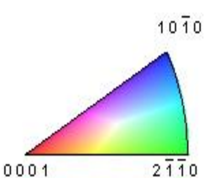




For a bigger picture view…

"I can't do it in TSL/OIM, but I can do it in PowerPoint!"

– Connor Campbell



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  - Samples were ß-forged, ß-annealed, and (α+ß)-forged
  - Were not (α+ß) annealed
- Bulk texture measurement via x-ray diffraction
  - Bulk texture was very weak (1.2x random for pyramidal planes)
- Scanning electron microscopy of samples
  - From regions with high ultrasonic signal, took images of:
    - α colony remnants
    - Elongated and coarse α
    - Preferred orientation

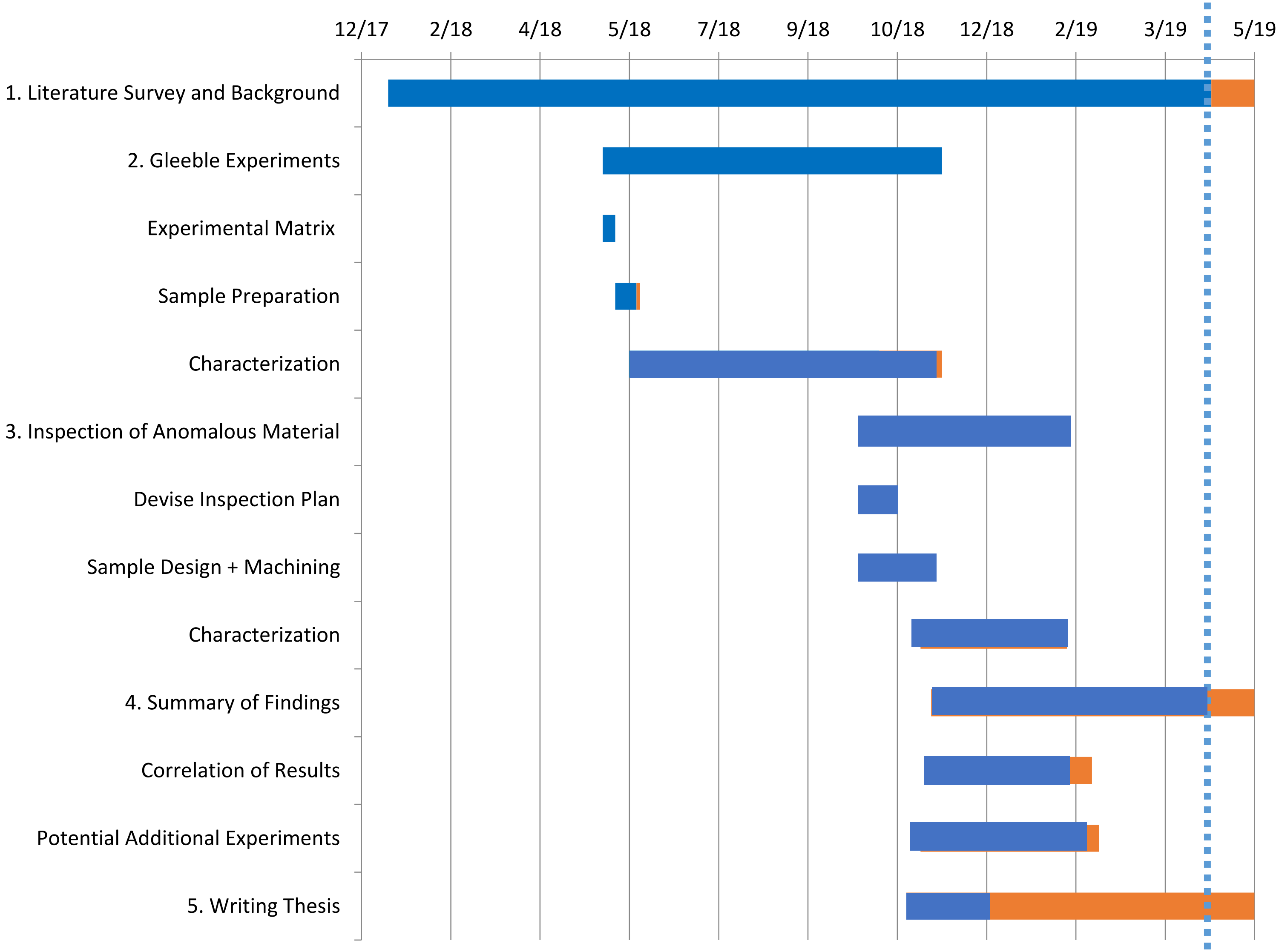
Summary of Recent Progress

- Weak bulk texture detected via XRD
- Stronger local texture detected via EBSD
- Microstructural heterogeneity observed via SEM-BEI
  - α colony remnants
  - Elongated and coarse α (up to 100μm)
  - If UT wavelength was selected for a uniform, fine microstructure, plausible that these features would scatter incident acoustics
- Microstructure appears to have not recrystallized
  - Plausible, given location near surface
  - Thermal losses and friction at dies may have a role in decreasing strain at observed locations

Future Work

- Quantify SEM images by measuring:
  - Size of equiaxed α
  - Volume fraction of equiaxed α
  - Volume fraction of total α
  - Thickness of α laths
- Obtain EBSD maps of control regions for comparison and analysis
  - Regions of low noise and symmetrically equivalent sites
    - i.e. similar depth, but near the top surface
- Finish thesis

Gantt Chart



12/17
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12/18
2/19
3/19
5/19
1. Literature Survey and Background
2. Gleeble Experiments
Experimental Matrix
Sample Preparation
Characterization
3. Inspection of Anomalous Material
Devise Inspection Plan
Sample Design + Machining
Characterization
4. Summary of Findings
Correlation of Results
Potential Additional Experiments
5. Writing Thesis

Thank you very much!

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