Project 33a-L: In-situ Studies of Strain Rate Effects on Phase Transformations and Microstructural Evolution in β-Titanium

Spring 2019 Semi-Annual Meeting
Iowa State University, Ames, IA
April 3-5, 2019

Student: Benjamin Ellyson (Mines)
Faculty: Amy Clarke (Mines)
Industrial Mentors: Austin Mann (Boeing)
Other Participants: Yaofeng Guo (Mines)

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- Student: Benjamin Ellyson (Mines)
- Advisor(s): Amy Clarke (Mines)

Project Duration
PhD: September 2017 to May 2021

- Problem: Uniform elongation and work hardening of titanium alloys restricts applications.
- Objective: Fundamentally understand microstructural evolution in metastable β titanium alloys to develop an alloy design methodology and tailor microstructures and properties.
- Benefit: Novel titanium alloys for blast and crash resistant applications

Recent Progress

- Ti-10V-2Fe-3Al (wt.%) quasi-static tension study completed
- Initial Ti-1023 dynamic tensile testing underway
- Initial microstructural characterization of Ti-15Mo (wt.%)
- Initial APS dynamic experiments completed

Metrics

Description	% Complete	Status
1. Literature review	70%	●
2. Quasi-static mechanical characterization of Ti-1023 and Ti-15Mo	50%	●
3. Dynamic testing of Ti-1023 and Ti-15Mo	40%	●
4. Microstructural characterization of pre- and post-deformed samples	40%	●
5. *In situ* characterization of microstructural evolution during deformation	20%	●

Industrial Relevance: Development of Blast Resistant Materials for the Navy

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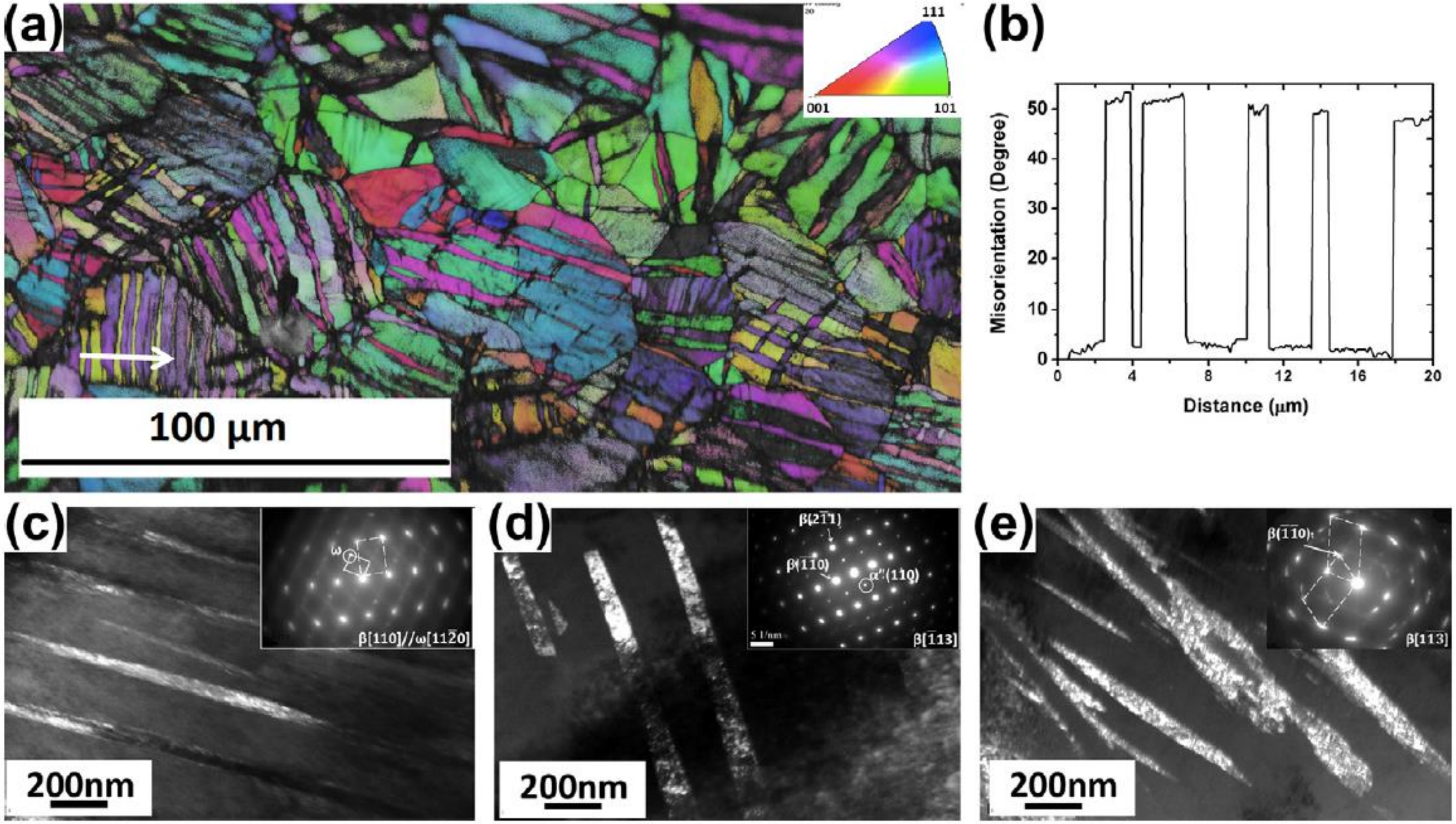
- **Cellular Materials Program**
  - Multifunctional structures
  - **Blast resistance**
  - Thermal management
- **Propulsion Materials Program**
  - **Aircraft and marine engines**

https://www.onr.navy.mil/Science-Technology/Departments/Code-33

Ti-25Nb-3Zr-3Mo-2Sn (wt.%) Alloy Microstructure After Deformation



Deformation-induced ω phase

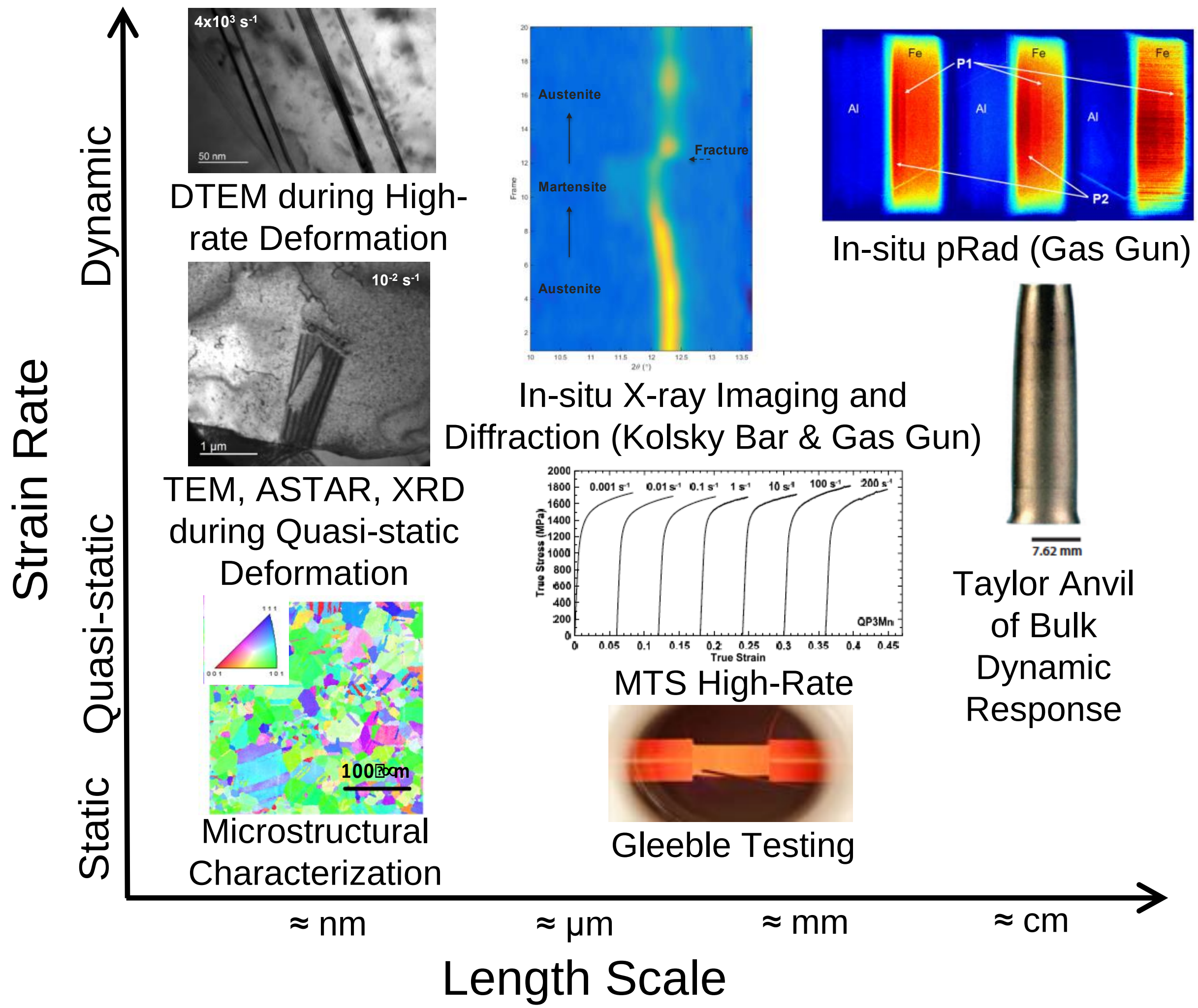
Deformation-induced α'' phase

{112}<111> β mechanical twinning

H. Zhan, et al. 107 Scripta Materialia (2015): 34-37

Compression at 10^{-3} to 0.18 true strain

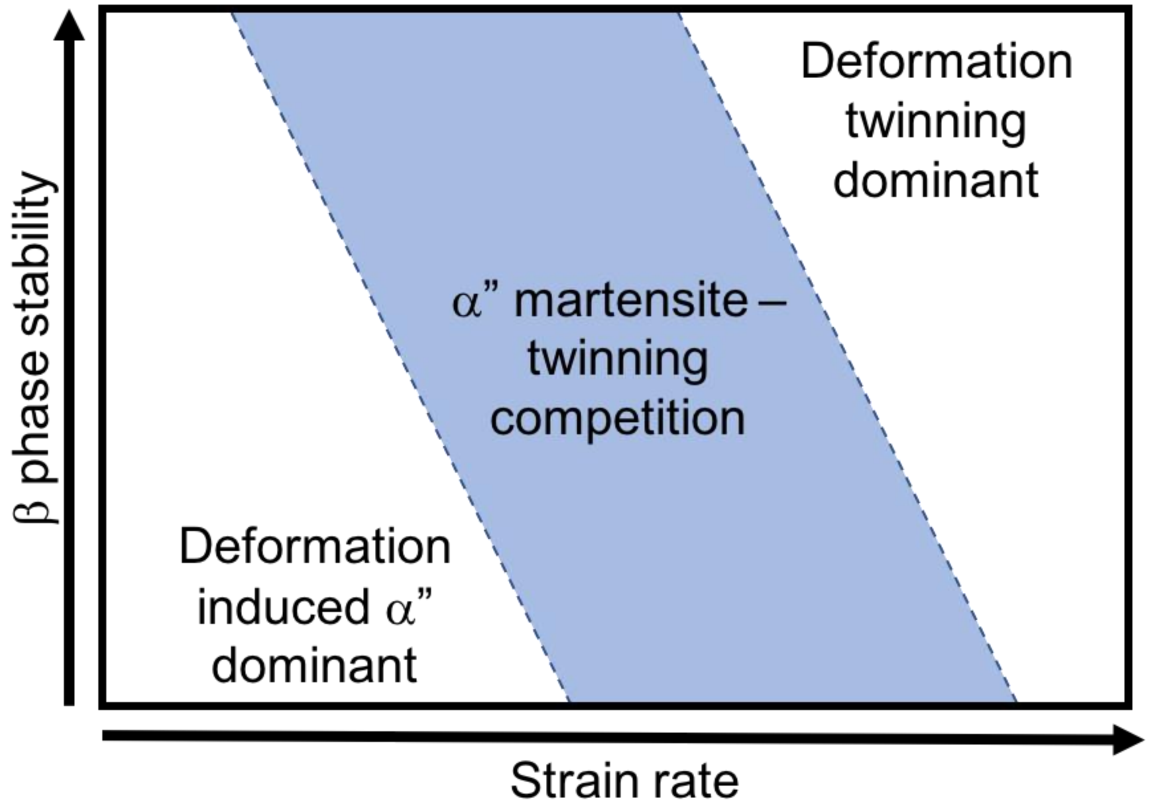
Multi-scale Studies of TRIP/TWIP during High Rate Deformation



Center Proprietary – Terms of CANFSA Membership Agreement Apply

The Effect of Strain Rate on Deformation Mechanisms During Compression of a Ti-10V-3Fe-3Al (wt.%) Alloy

- **Deformation mechanisms present at all strain rates:**
  - Stress-induced α” martensite
  - {332}<113> β twinning (dominant)
  - Stress-induced ω phase
  - Slip



Ahmed, M., et al. 104 Acta Materialia (2016): 190-200

Work Hardening and Evidence of TRIP/TWIP

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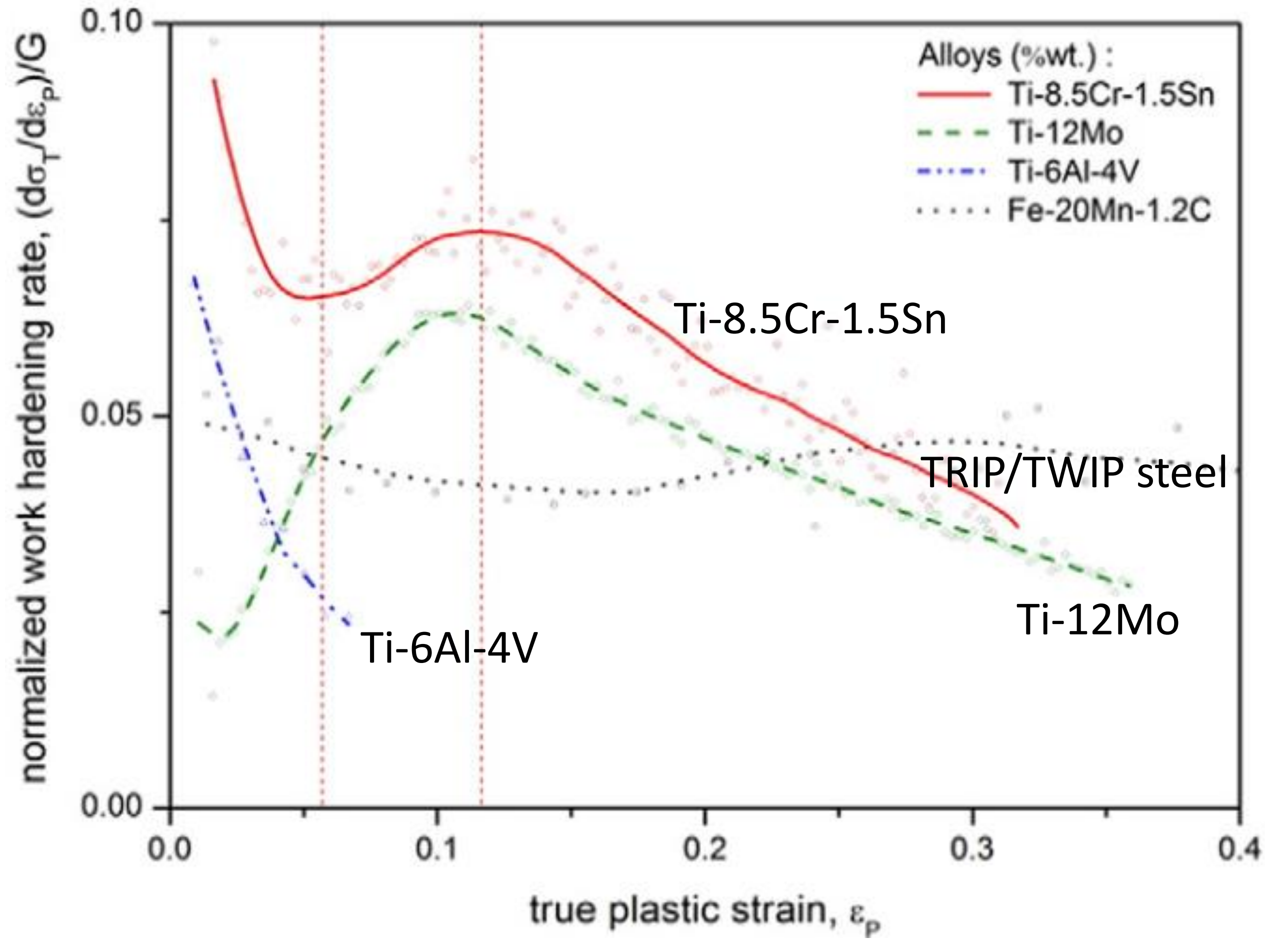
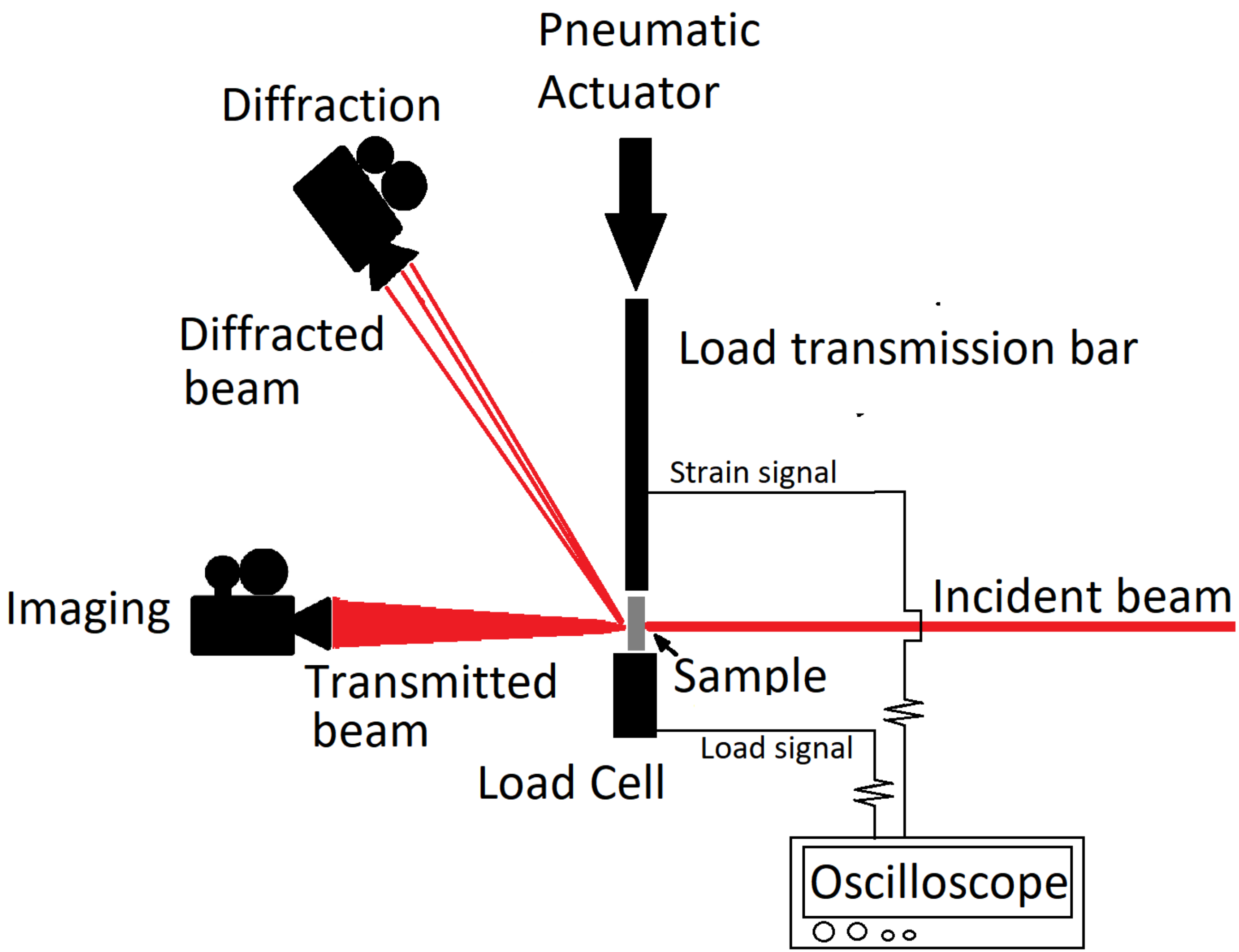
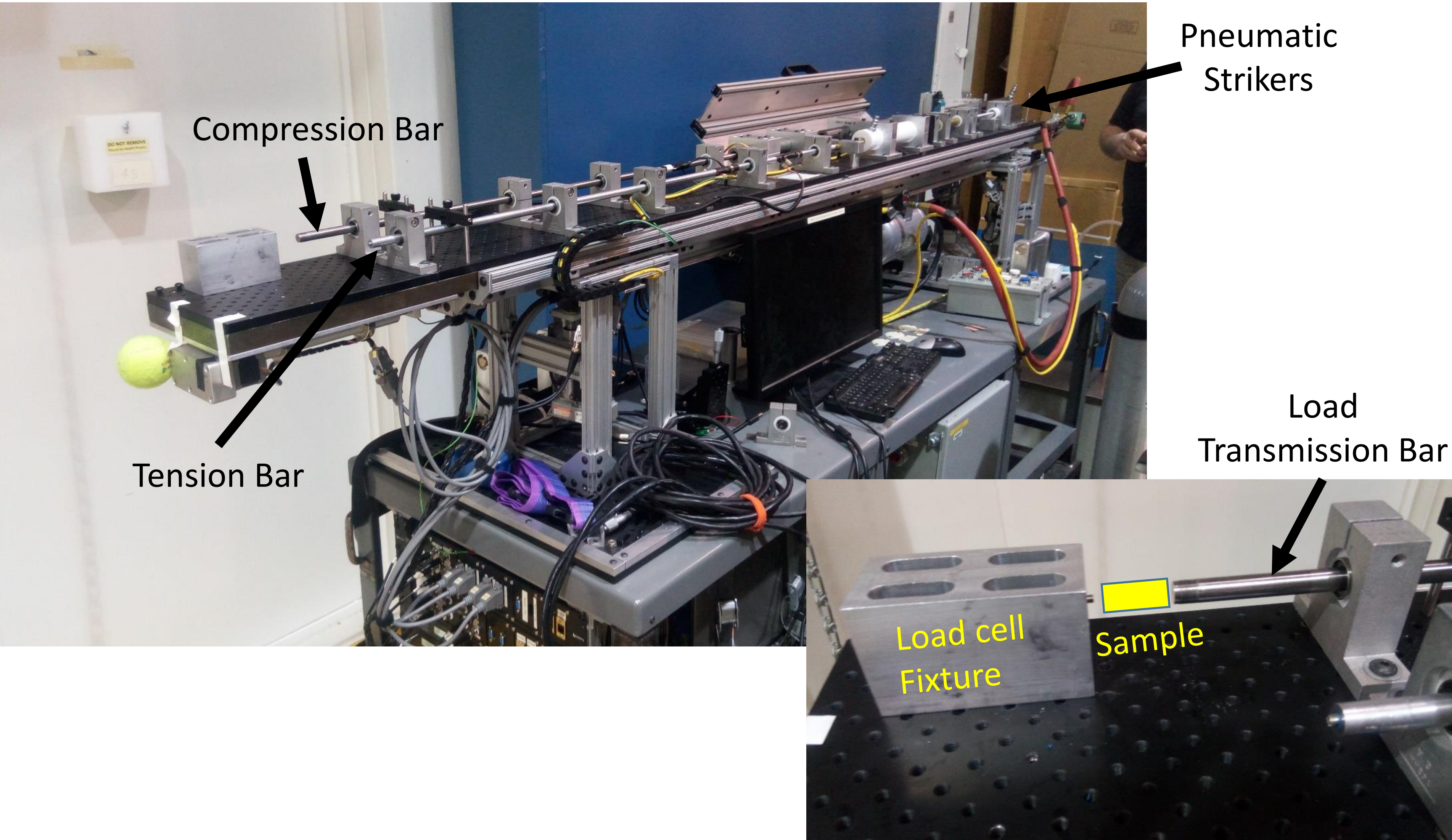


Brozek, C., et al. Scripta Materialia 114 (2016): 60-64

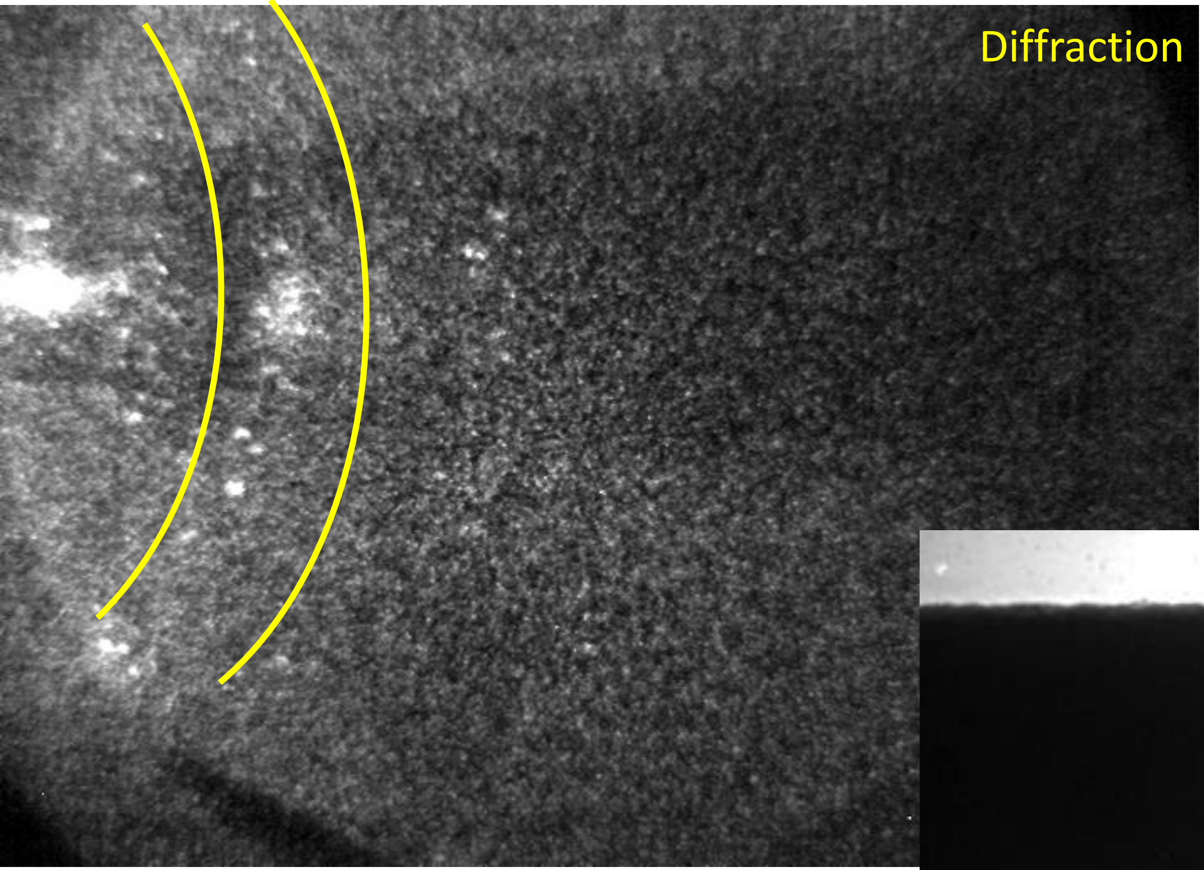
APS Kolsky Bar Setup

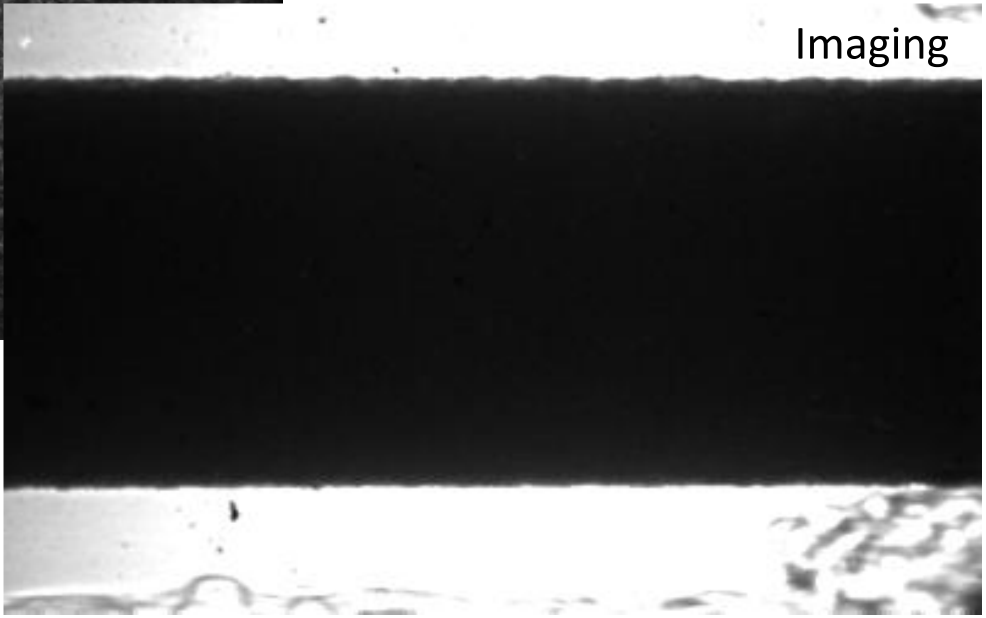


APS Kolsky Bar Setup



Example of In-situ Data, Ti-15Mo



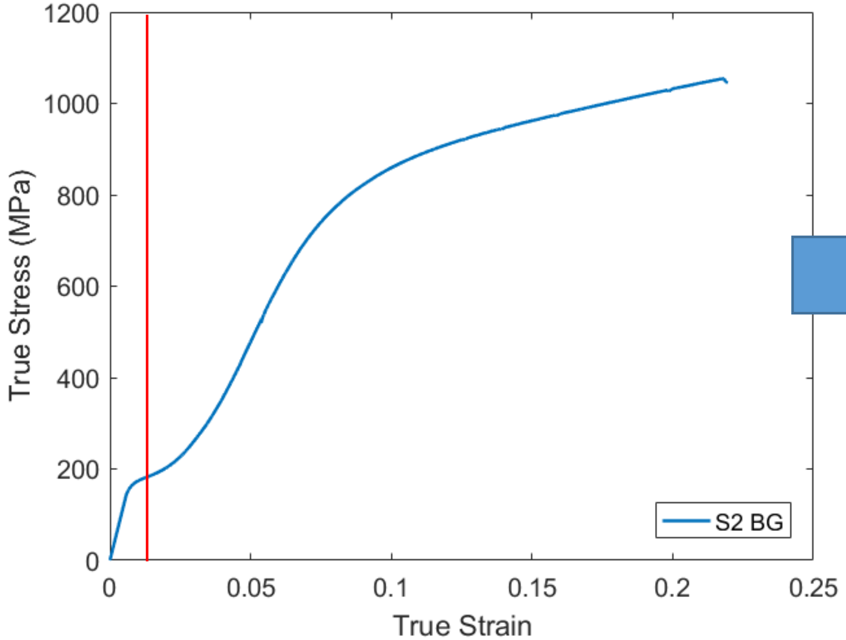


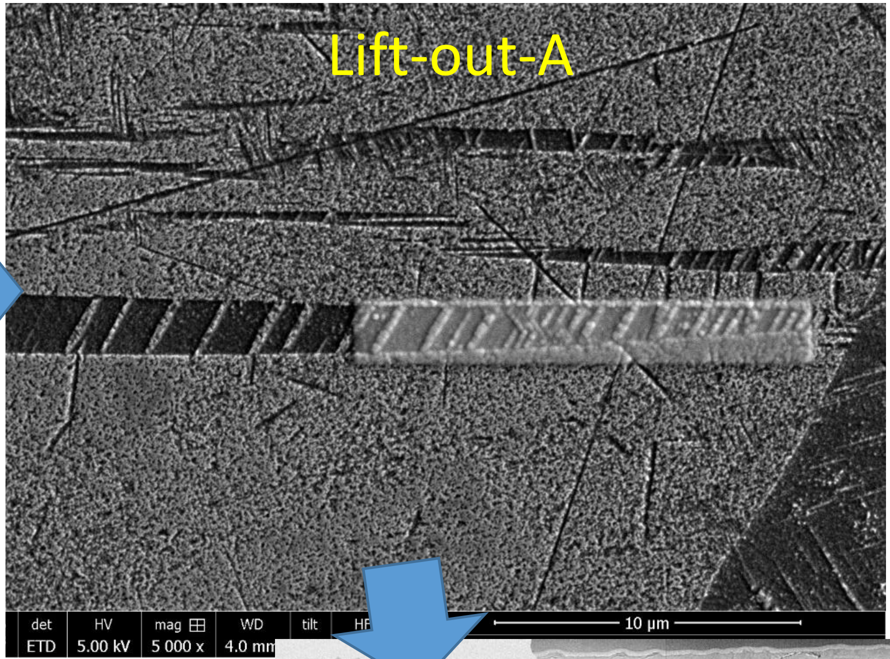
APS Experimental Matrix

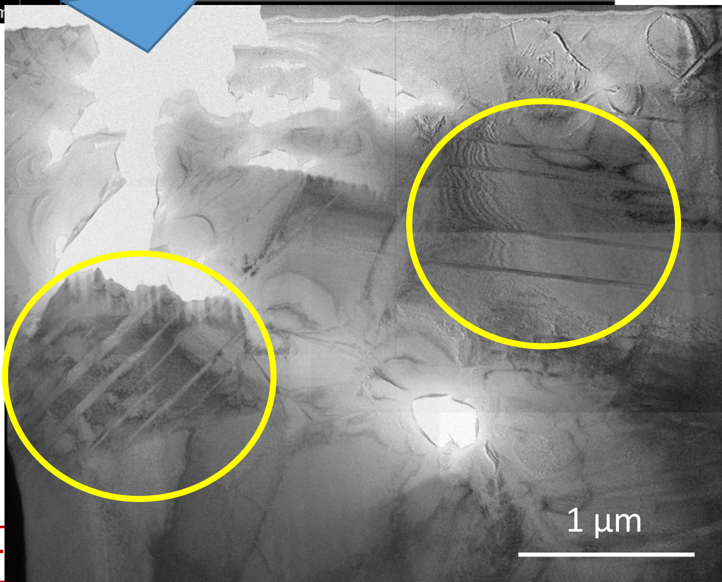
Alloys (wt %)	Heat Treatments (Expected Microstructure)	
Ti-10V-2Fe-3Al	As-received (α+β)	850-1h-WQ (β+ω)
Ti-15Mo	As-received (α+β)	800-1h-WQ (β+ω)
Ti-35Zr-10Nb	700-1h-FC (α+α’’)	700-1h-WQ (α’’)
TiZrNb	700-1h-WQ (β)	

All temperatures in °C
FC: Furnace cooled
WQ: Water Quenched

Ti-1023 Tension - 1.7% Plastic Strain



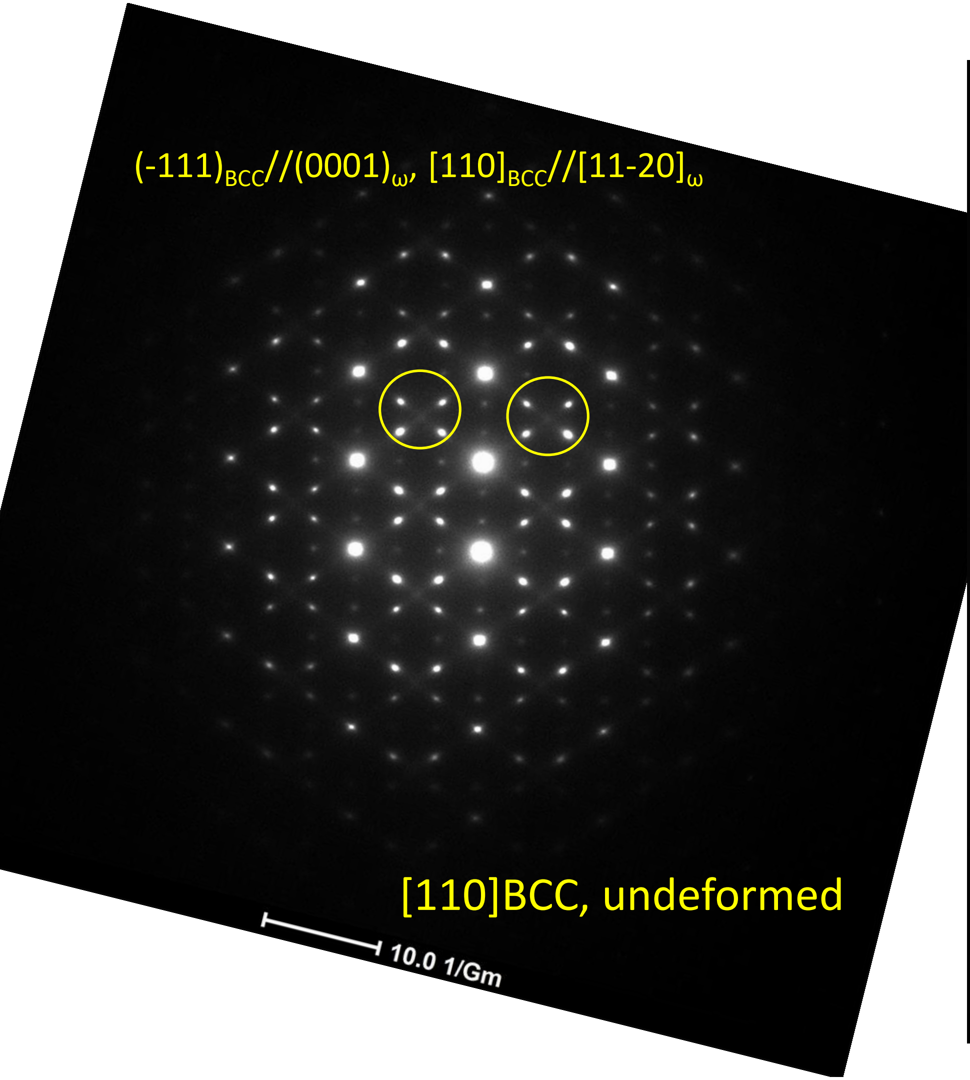


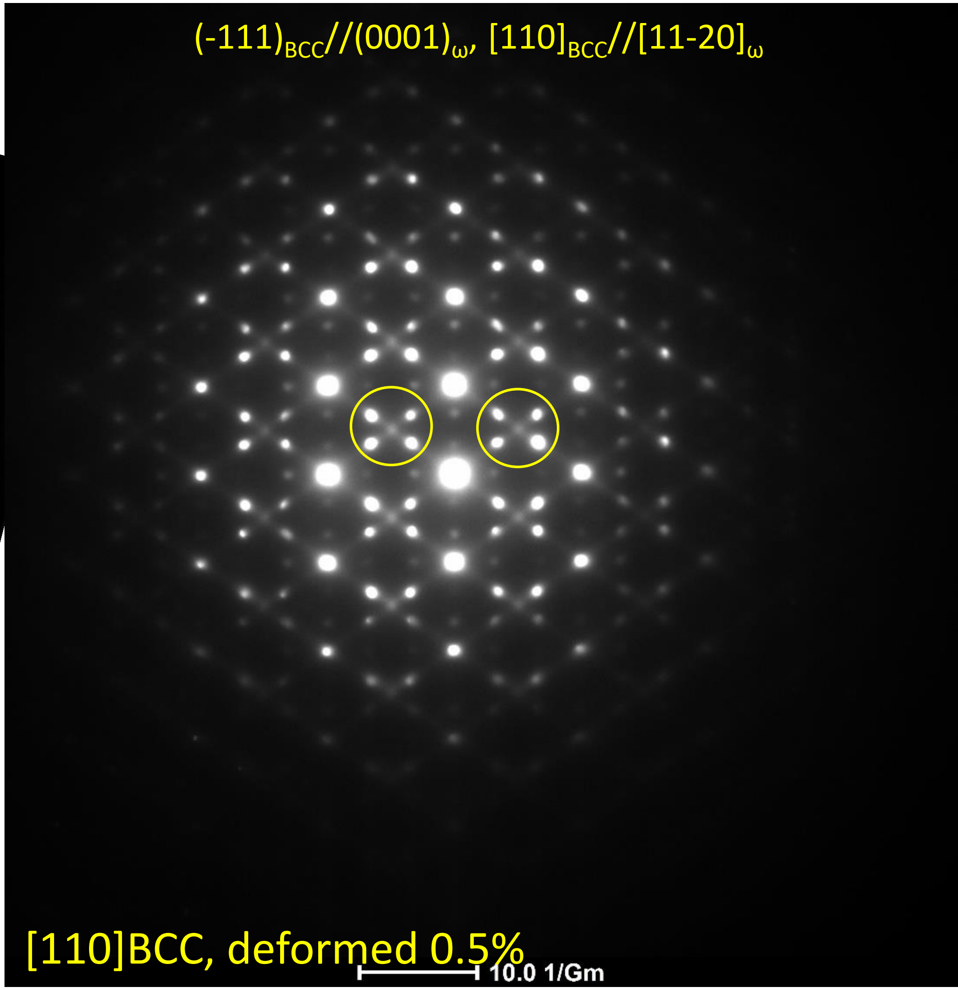


Small grain sample (400 microns grain size): 700C-1h anneal followed by 850-1h water quench.

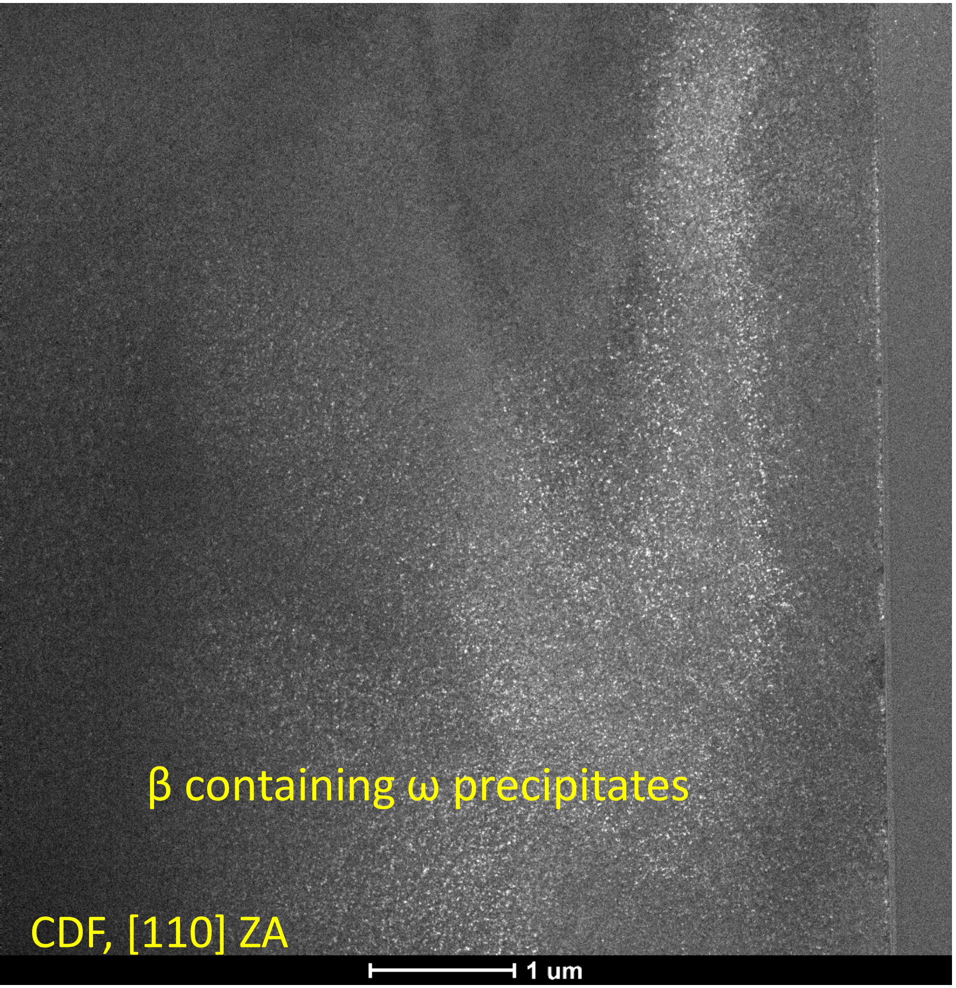
Martensite (α'') was found in both circled regions

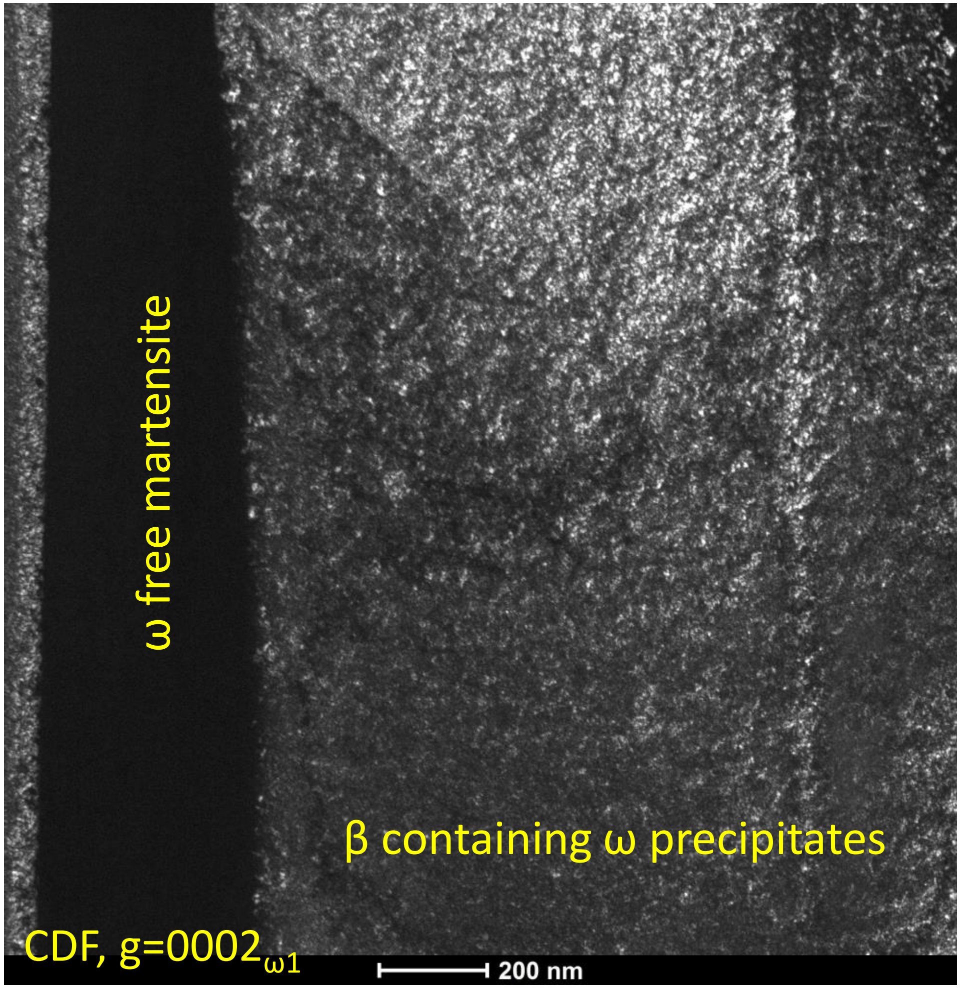
Matrix and ω: Undeformed vs 0.5% Deformed





Distribution of ω in Matrix





Absence of ω in 1.7% Deformed Sample

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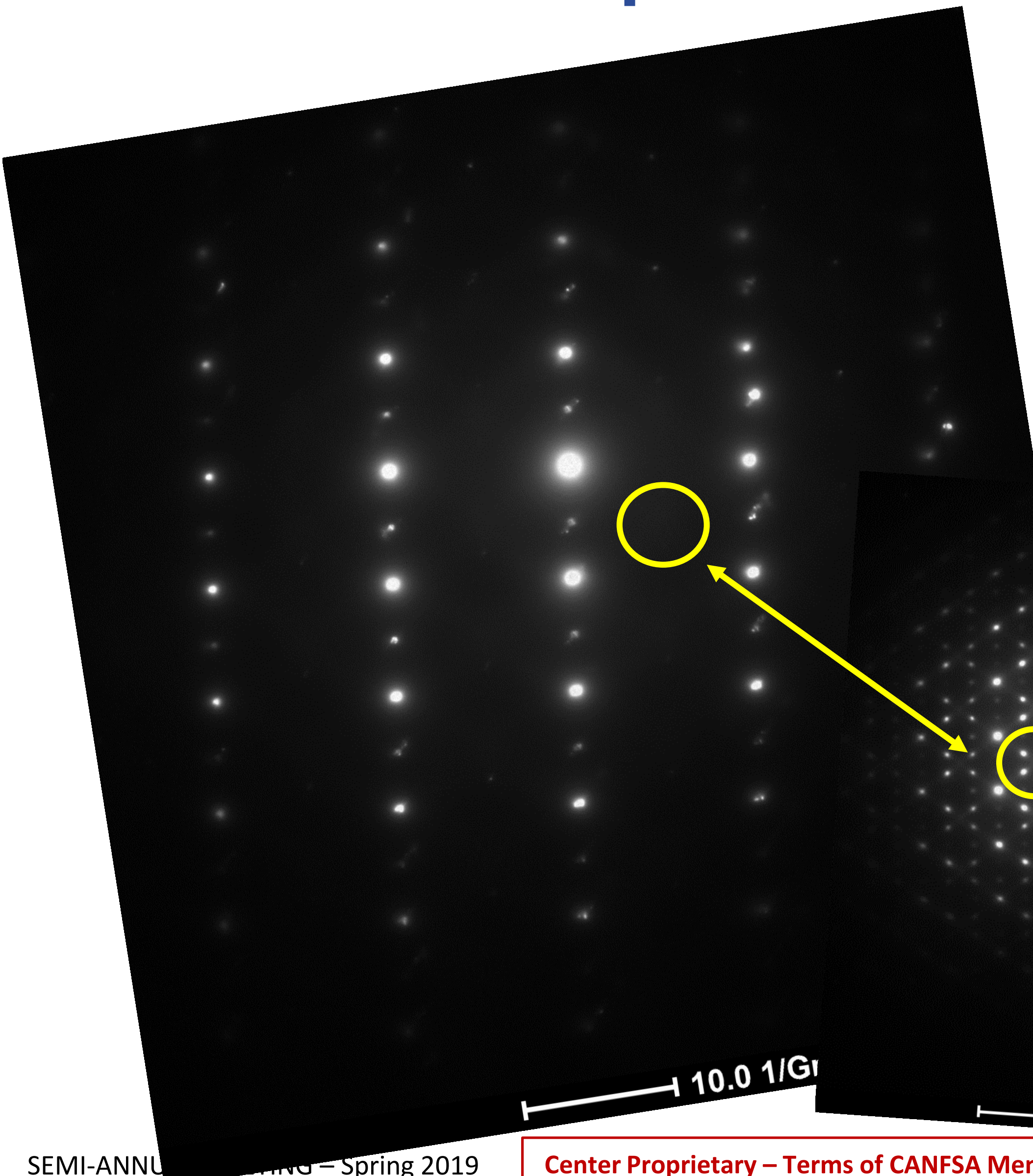
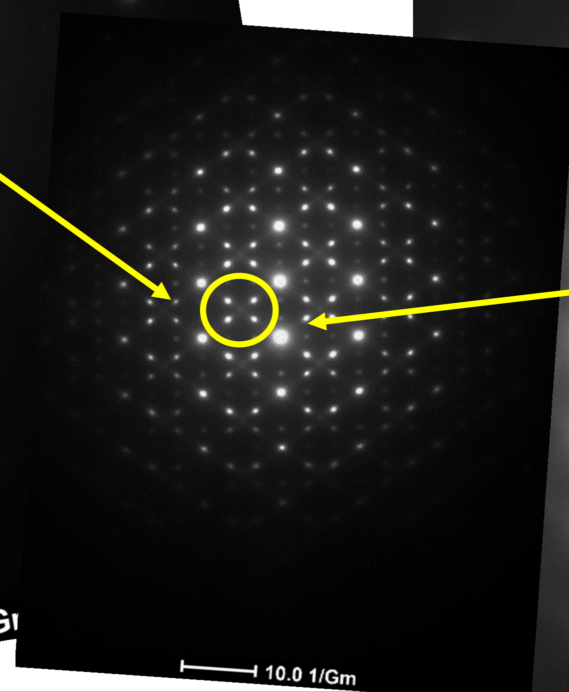
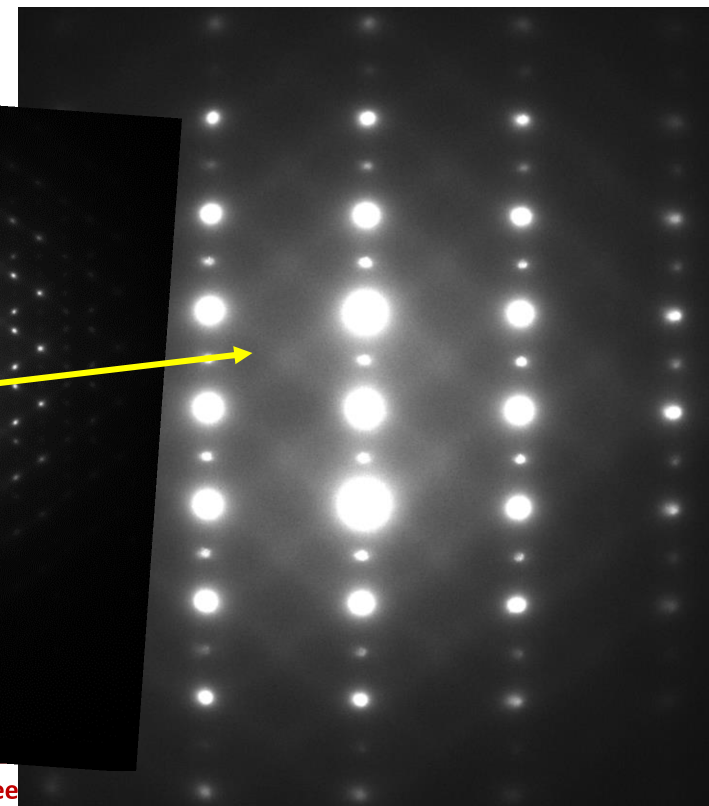
The SADPs taken from the [110] ZA do not contain any ω reflections. This was confirmed over the entire thin foil in both regions and represents a novel finding.







Heat Treatment scheduleTi-1023 Tensile Testing

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- Hypothesis of heat treatment plan:
  - Grain size/solution temperature have a controlling effect on work hardening behavior and yield stress
  - Effect of grain size and holding temperature need to be separated

1. 700°C-1h for full annealing
2. 1100°C-3h for grain growth treatment for large grain sample
3. 850°C-1h for final homogenizing solution treatment

Grain Size Effect on Yield Stress of Ti-1023

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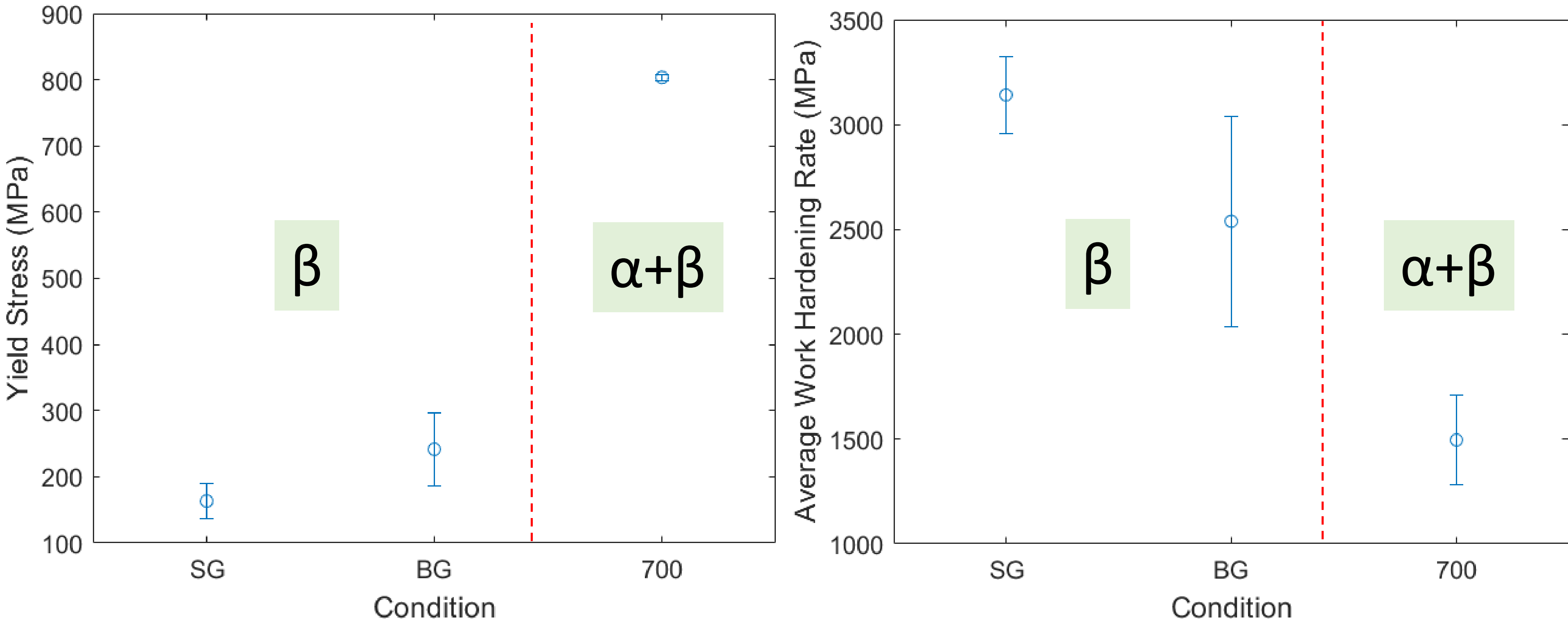
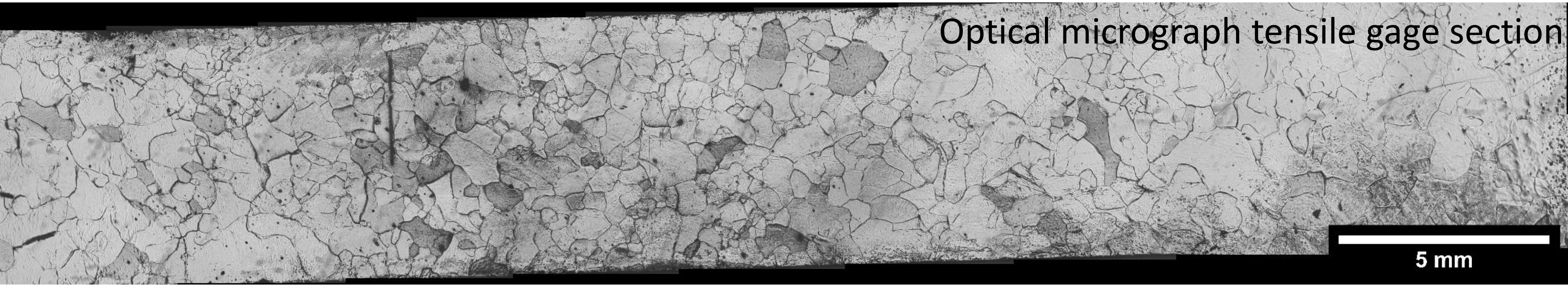


Grain size effects on yield stress and work hardening rate are not statistically significant for the material tested. In other words, the difference between grain sizes is comparable to variability.

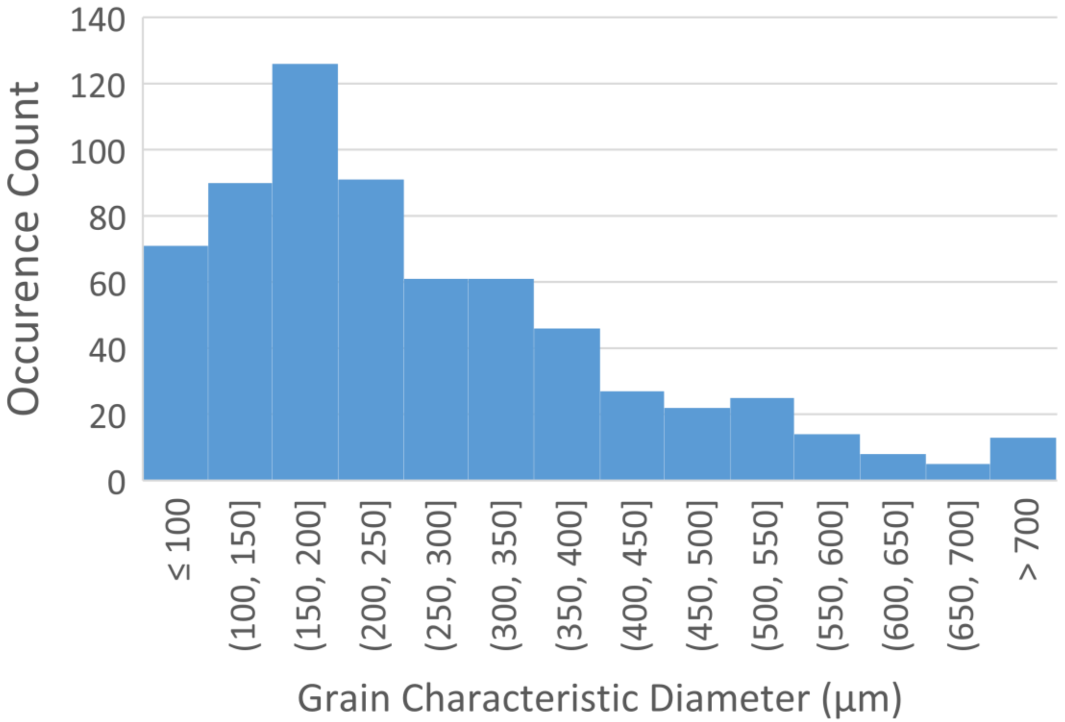
SG=small grain, BG= big grain and 700= 700°C anneal

Grain Size Effect on Yield Stress of Ti-1023: Grain Size Variability



- Small grain samples (SG)
  - Line intercept method: 400 µm
  - Contour method: 150 µm

- Big grain samples (BG)
  - Line intercept method: 900-1200 µm
  - Contour method: 900-1200 µm



Other Sources of Variability

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- Grain size distribution and morphology
- Texture selection during grain growth
- Change in grains per cross-section

Ultimately:

Grain size is not as strong a contributor to YS and WHR in TRIP Ti-1023 as originally thought.

Athermal ω and Low Temperature Ageing

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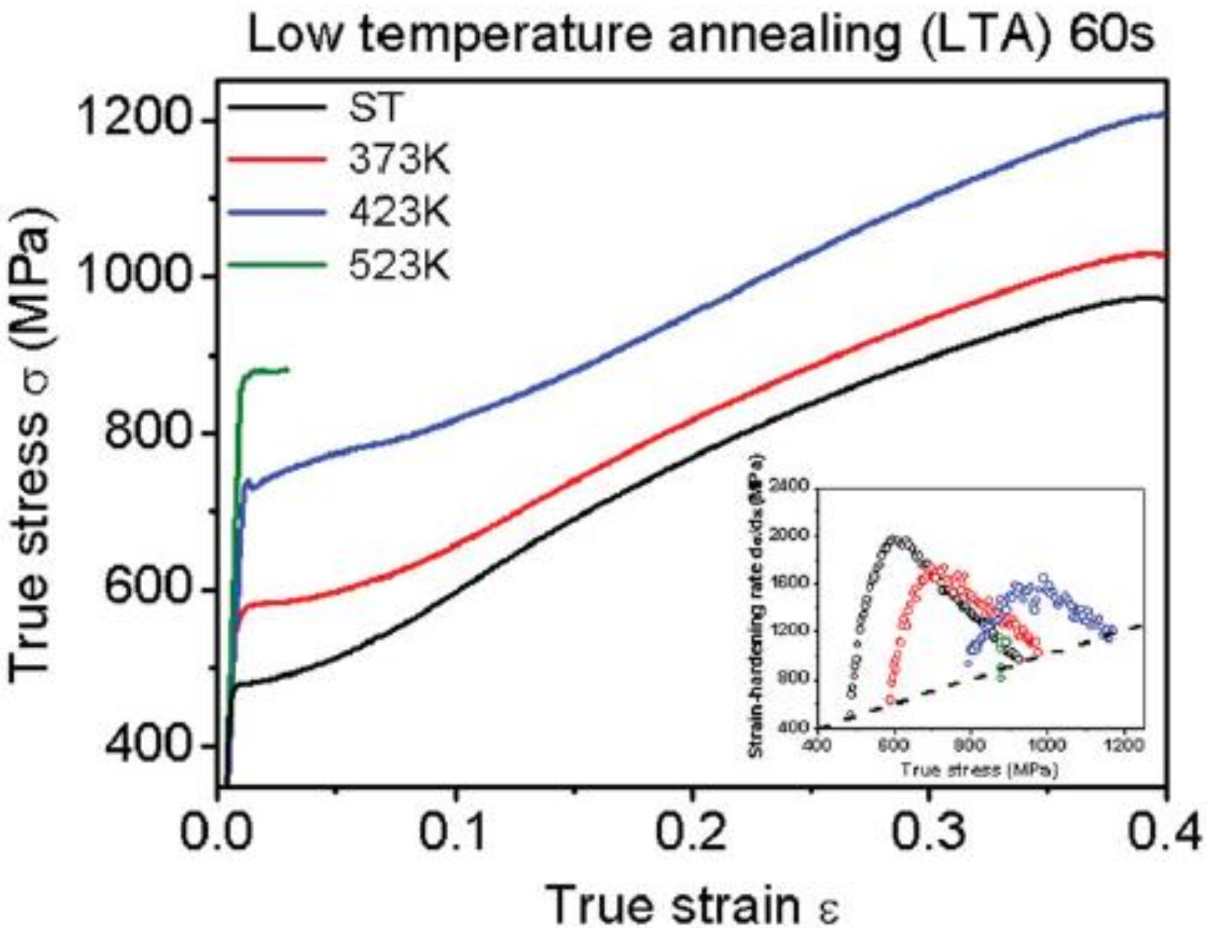
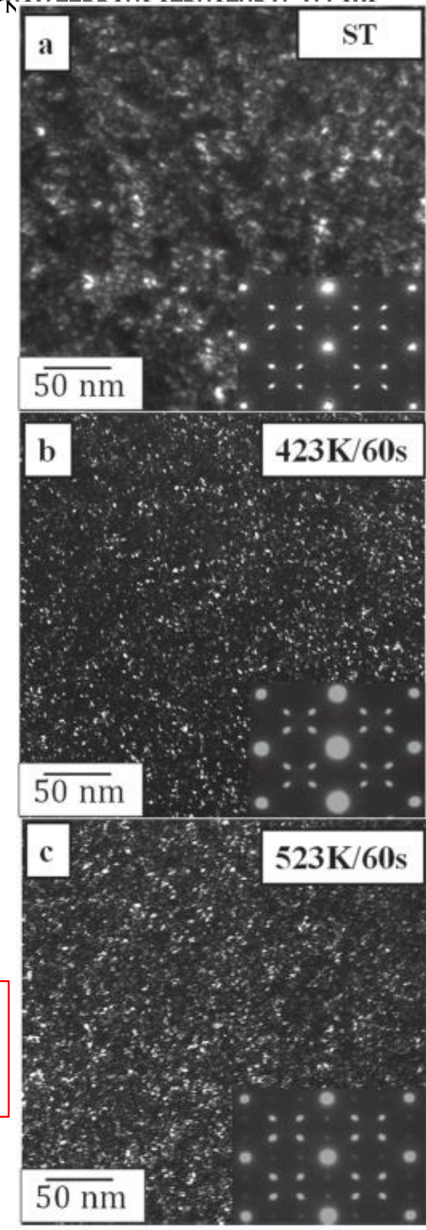
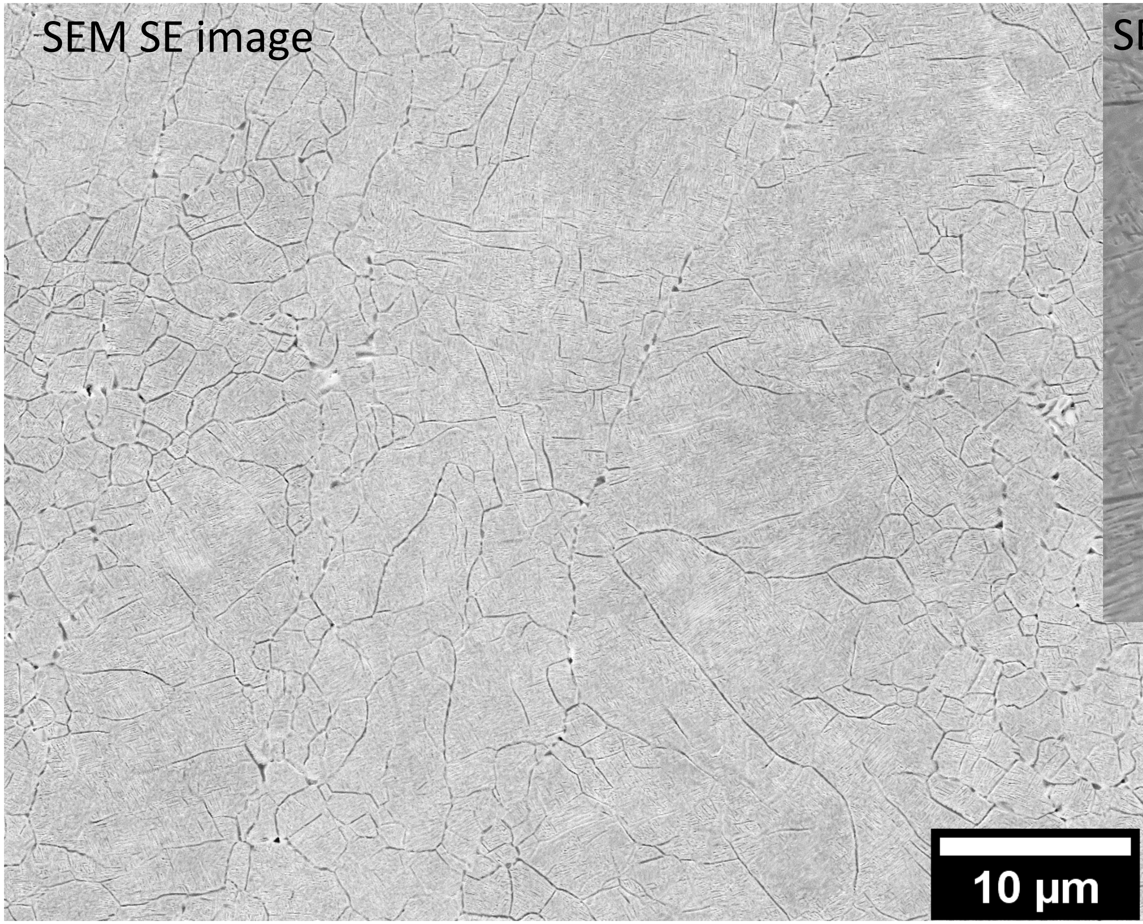


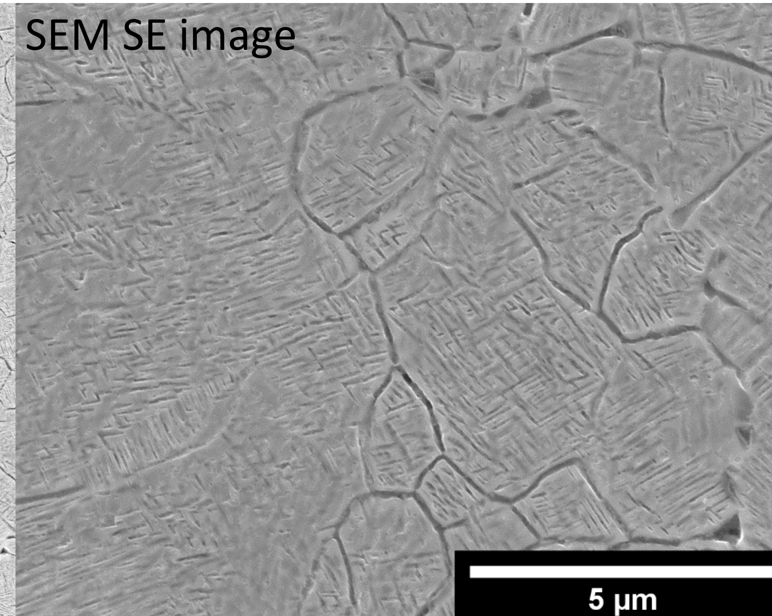


Low temperature aging response of Ti-12Mo leads to a significant increase of yield stress

Sun, F., et al. *Materials Research Letters* 5.8 (2017): 547-553.

Ti-15Mo As-received





As-received microstructure is fine-grained α+β

Scanning electron microscope (SEM) was required to resolve as-received microstructure

Ti-Mo System and Ti-15Mo

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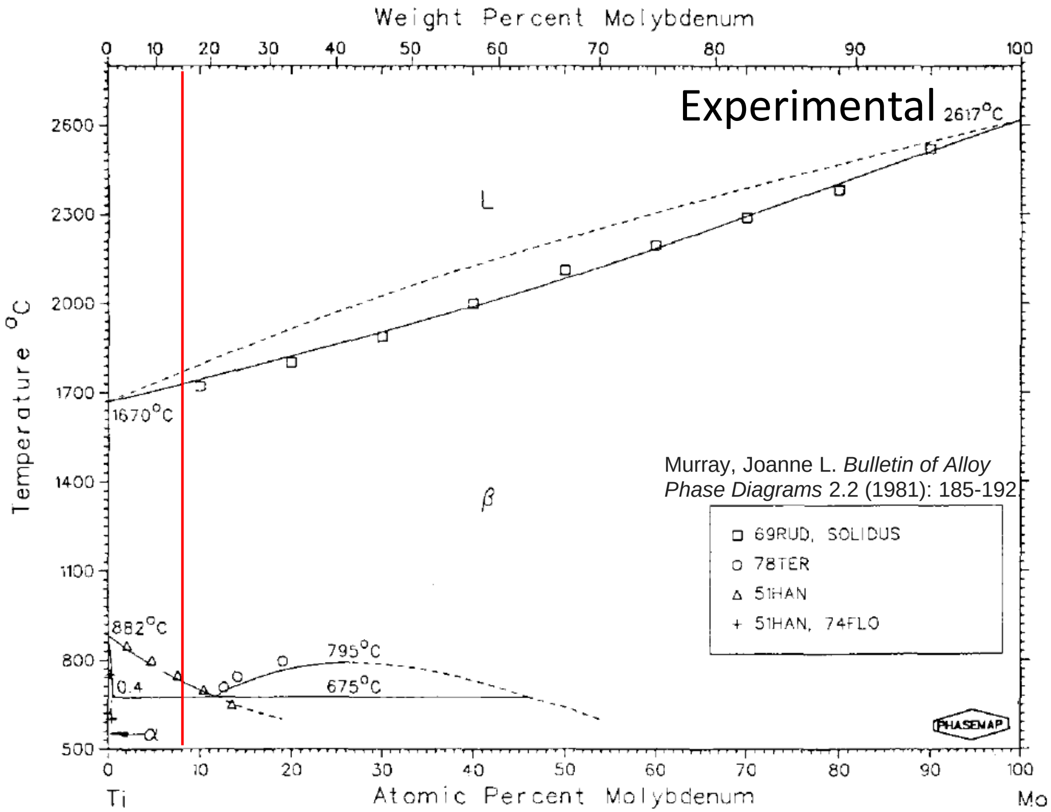
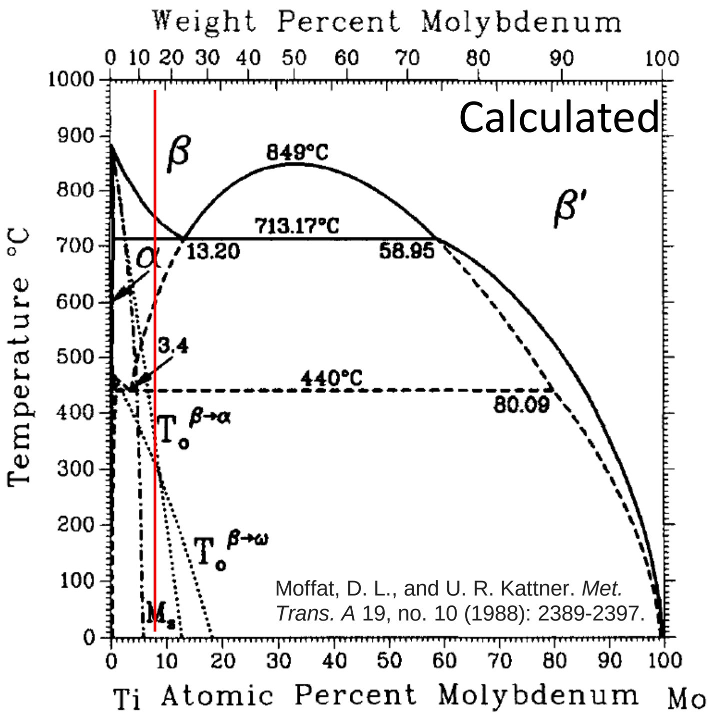
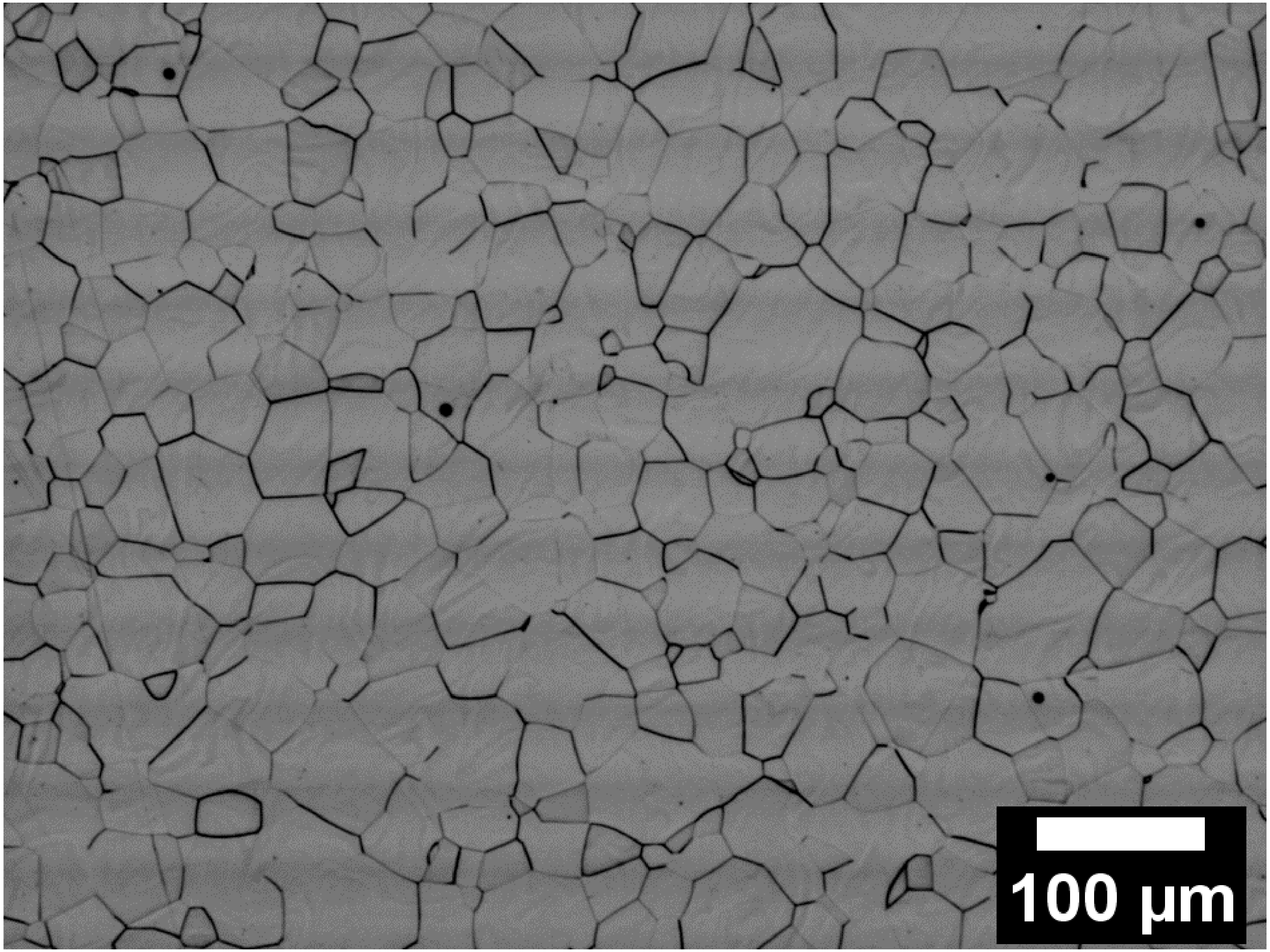




Experimental phase diagram indicates a β-transus at roughly 760 °C
Calculated metastable phase diagram indicates an Ms below 0°C and $T_0^{\beta\rightarrow\omega}$ is roughly 300 °C.

Microstructure is expected to be β+ω for a Solution treatment above 760 °C

Ti-15Mo 800°C 1hr WQ

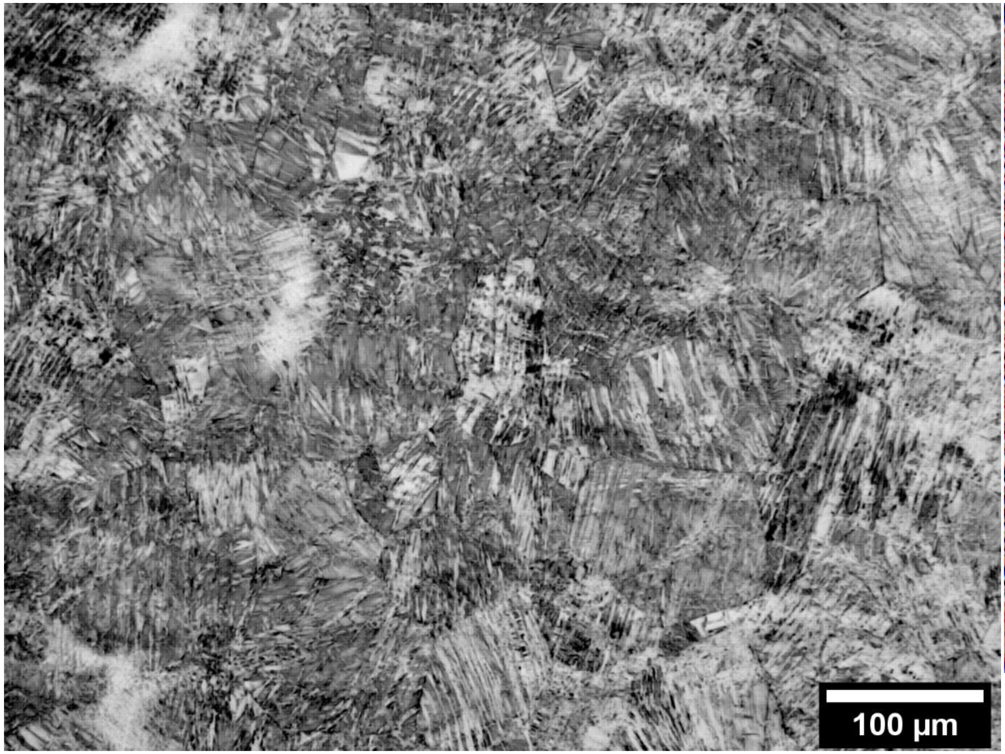


Average grain size is 205 µm

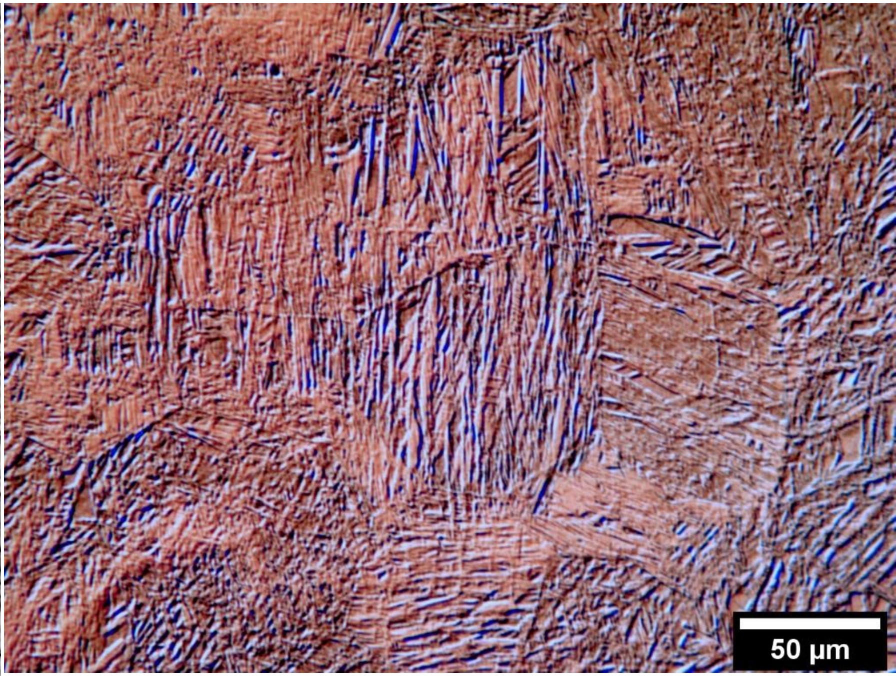
Grayscale under white light, Optical Micrograph

Fine and equiaxed β structure was formed by chosen heat treatment.

Ti-15Mo Rolled, 30% Reduction



Grayscale under white light, Optical Micrograph



Namarski polarization, Optical Micrograph

Plastic deformation leads to the formation of deformation product. Literature indicates they should be solely comprised of {332} twins. XRD is planned to confirm single phase deformed structure.

Progress Update

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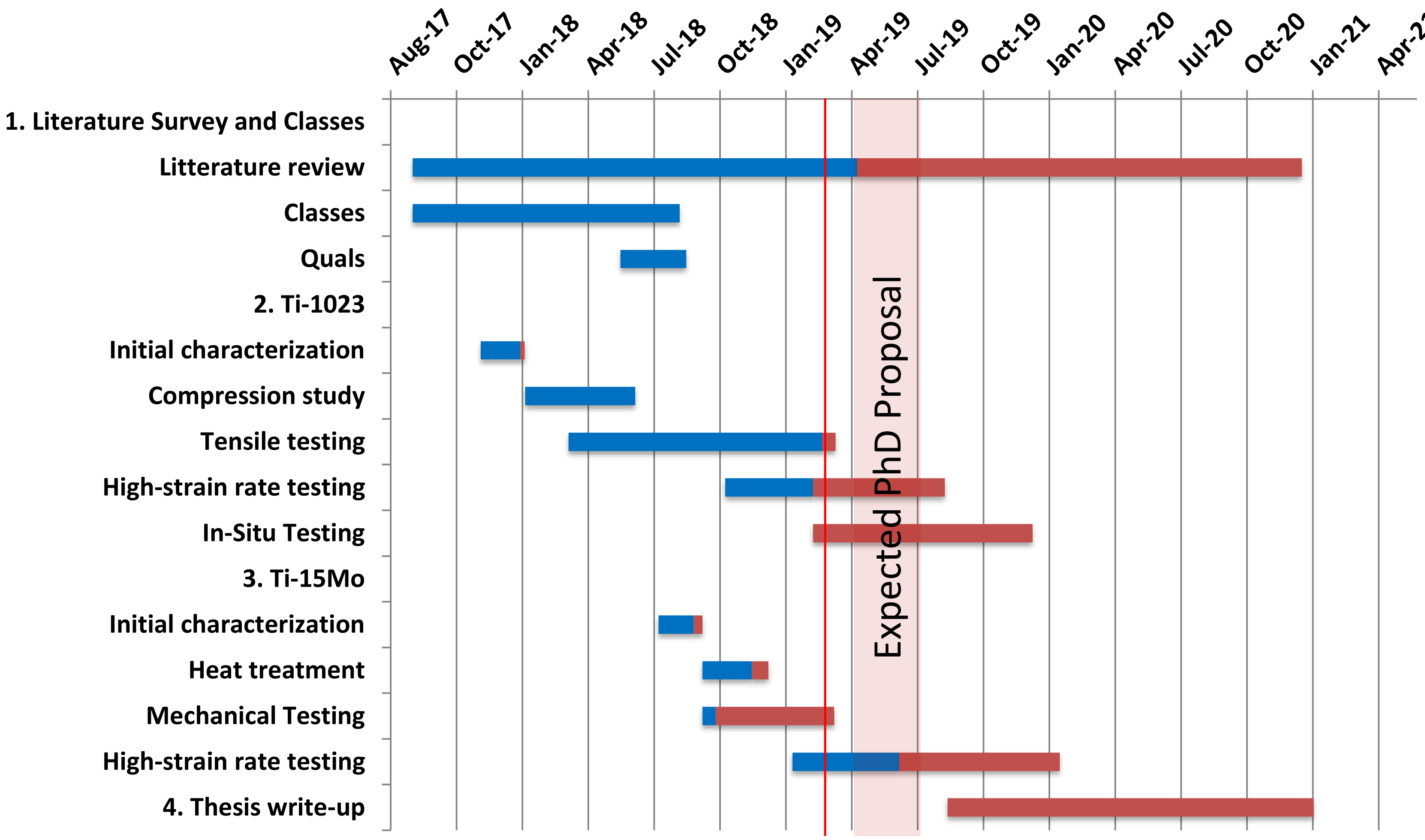

Next Gantt chart will be based on PhD proposal and added modelling work

Thank you!

Benjamin Ellyson
Bellyson@mines.edu

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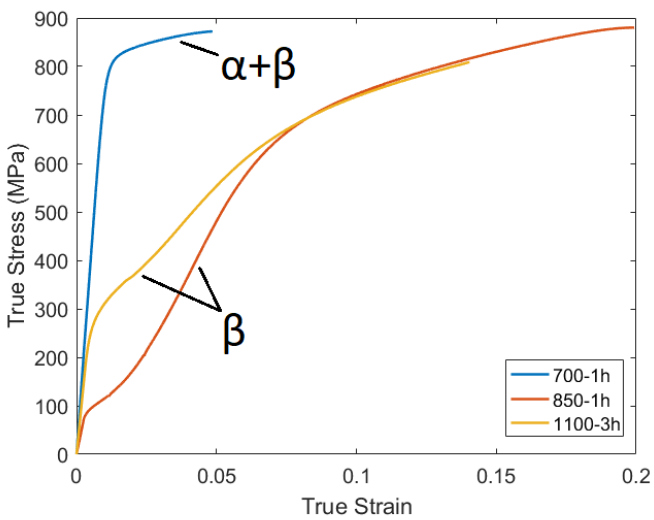
Student: *Benjamin Ellyson*

Faculty: *Amy Clarke*

Industrial Partners: *Boeing (Austin Mann)*

Project Duration: *Sept. 2017 – May 2021*



Achievement

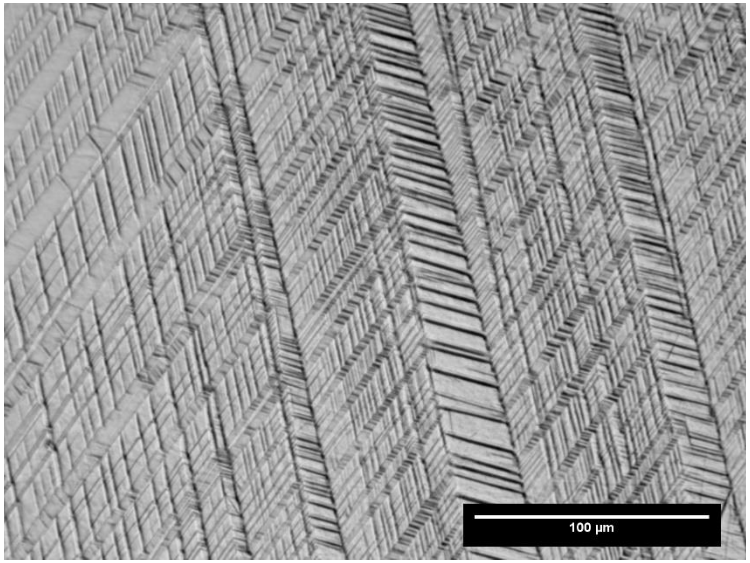
- Develop alloy design methodology to tailor microstructural evolution and mechanical properties for blast resistance

Significance and Impact

- New TRIP/TWIP metastable β-titanium alloys represent a new class of lightweight blast resistant armor and greatly extend formability to complex structural parts

Research Details

- Testing over multiple scales (macroscopic to fine scale) and strain rates (quasi-static to dynamic) will inform alloy design



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Student: *Benjamin Ellyson*

Faculty: *Amy Clarke*

Industrial Partners: *Boeing (Austin Mann)*

Project Duration: *Sept. 2017 – May 2021*

Program Goal

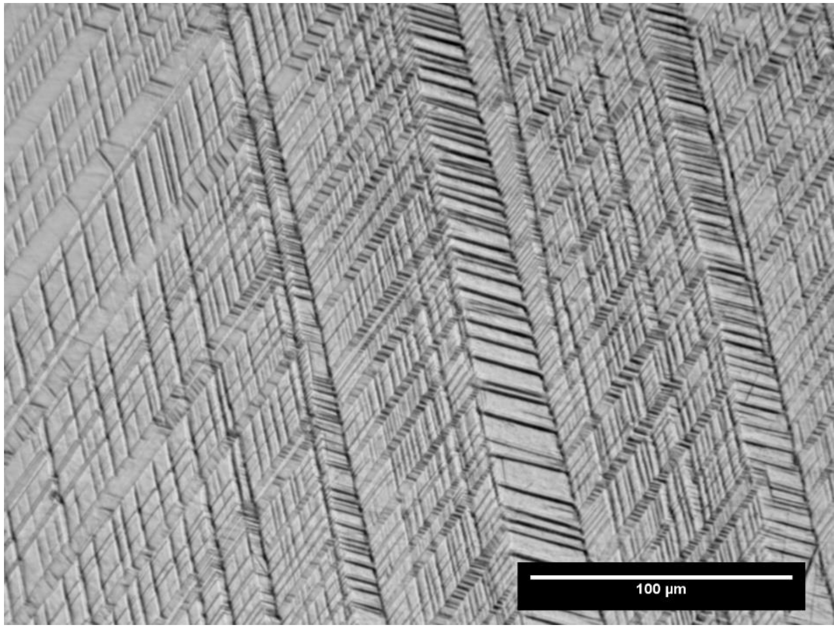
- Understand and model microstructural evolution in metastable β Titanium alloys to tailor properties for blast and crash resistance

Approach

- Utilize testing and in-situ testing and characterization over multiple length scales and decades of strain rates to understand metastable deformation mechanisms

Benefits

- Improved understanding of microstructural evolution in metastable β Titanium alloys and formulation of novel alloys with tailored performance



Microstructural evolution in Ti-1023 compressed to 5%