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

Spring Meeting

April 7-9, 2020

- Student: Benjamin Ellyson(Mines)
- Faculty: Prof. Amy Clarke (Mines)
- Industrial Mentors: Austin Mann (Boeing), Clarissa Yablinsky (LANL), John Foltz (ATI)
- Other Participants: Jonah Klemm-Toole (Mines)

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

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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 methodologies and tailor microstructures and properties

•Benefit: Novel titanium alloys for blast and crash resistant applications

Recent Progress

- Advanced Photon Source (APS) February 2020 beamtime completed
- Transmission electron microscopy (TEM) of aged Ti-10V-2Fe-3Al (wt.%) (Ti-10-2-3) tensile specimens is underway
- TEM of intermediate strain rate tensile specimens of Ti-15Mo (wt.%) and Ti-10-2-3 is beginning
- Dilatometry of Ti-15Mo and Ti-10-2-3 is near completion

Metrics		
Description	**% Complete**	**Status**
1. Literature review	80%	●
2. Quasi-static mechanical characterization of Ti-10-2-3 and Ti-15Mo	95%	●
3. Dynamic testing of Ti-10-2-3 and Ti-15Mo	70%	●
4. Microstructural characterization of pre- and post-deformation samples	60%	●
5. *In situ* characterization of microstructural evolution during deformation	40%	●

Industrial Relevance: Development of Blast Resistant Materials for the Navy

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- **Cellular Materials Program**
  - Multifunctional structures
  - **Blast resistance**
  - Thermal management

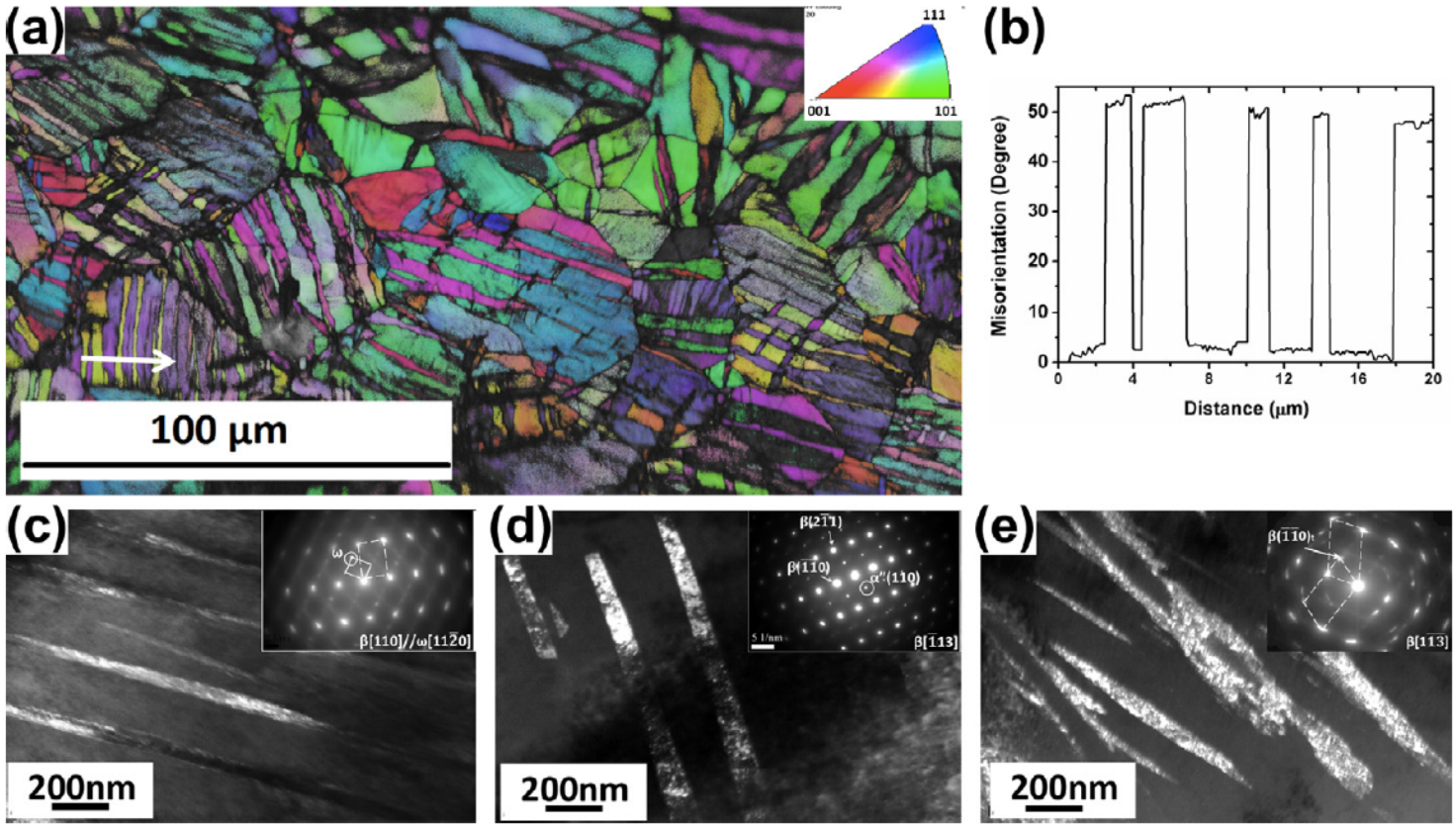
https://www.onr.navy.mil/Science-Technology/Departments/Code-33

- **Propulsion Materials Program**
  - **Aircraft and marine engines**

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

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

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



Deformation-induced ω phase | **Deformation-induced α'' phase** | **{112}<111> β mechanical twinning**

TRIP: Transformation Induced Plasticity

TWIP: TWinning Induced Plasticity

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

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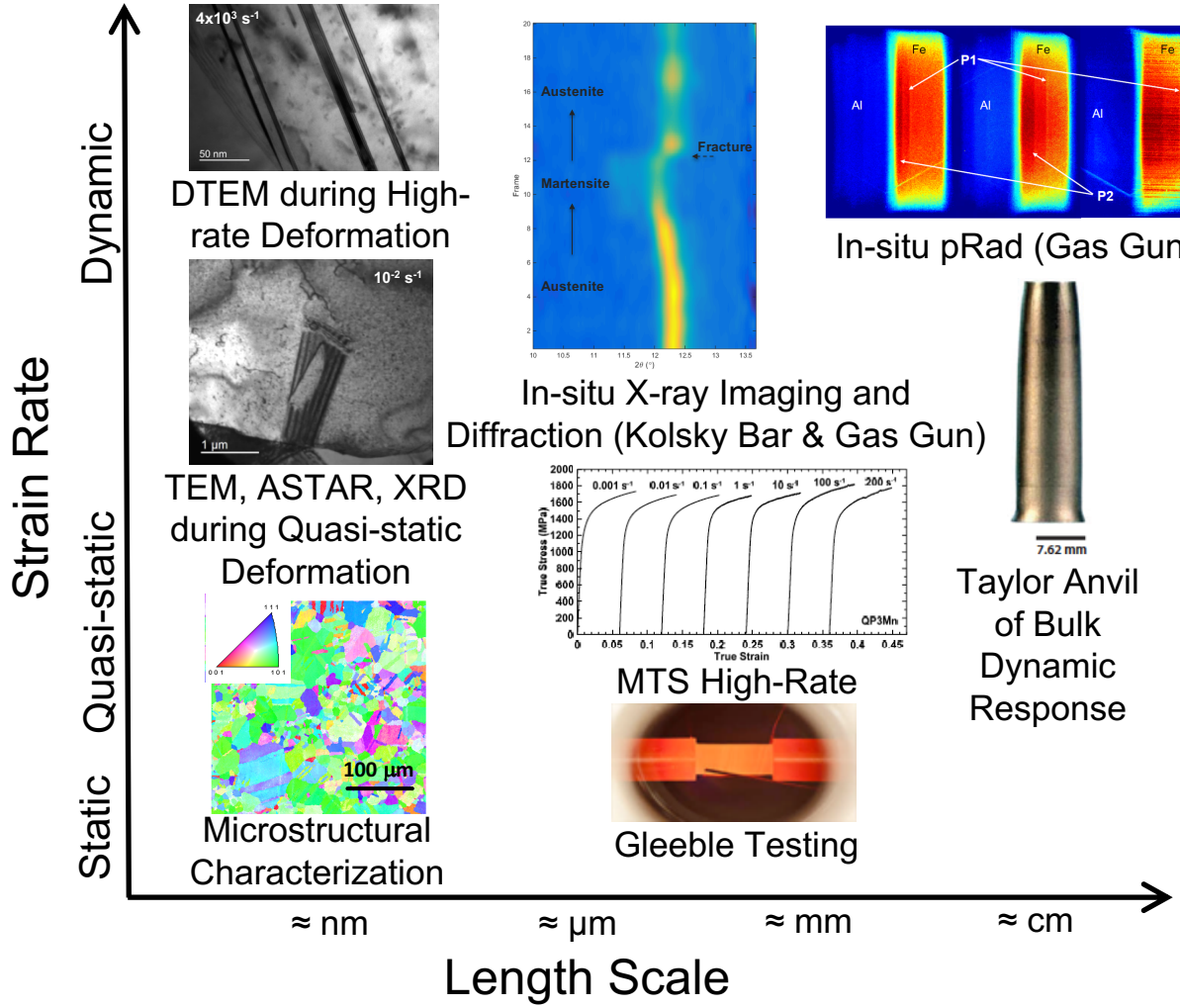

TRIP: Transformation Induced Plasticity, TWIP: TWinning Induced Plasticity, DTEM: Dynamic Transmission Electron Microscopy, TEM: Transmission Electron Microscopy, XRD: X-Ray Diffraction, pRad: Proton Radiography, ASTAR: Automatic Crystal Orientation and Phase Mapping , MTS: Materials Test Systems

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

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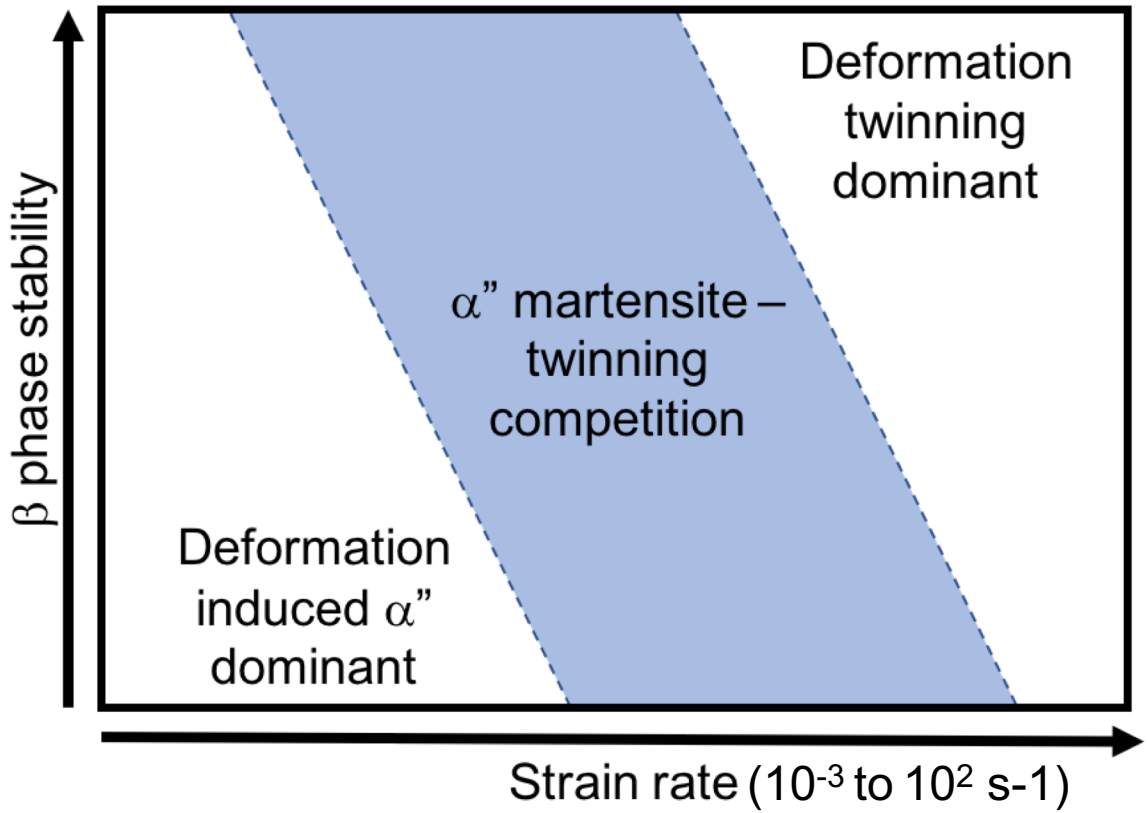
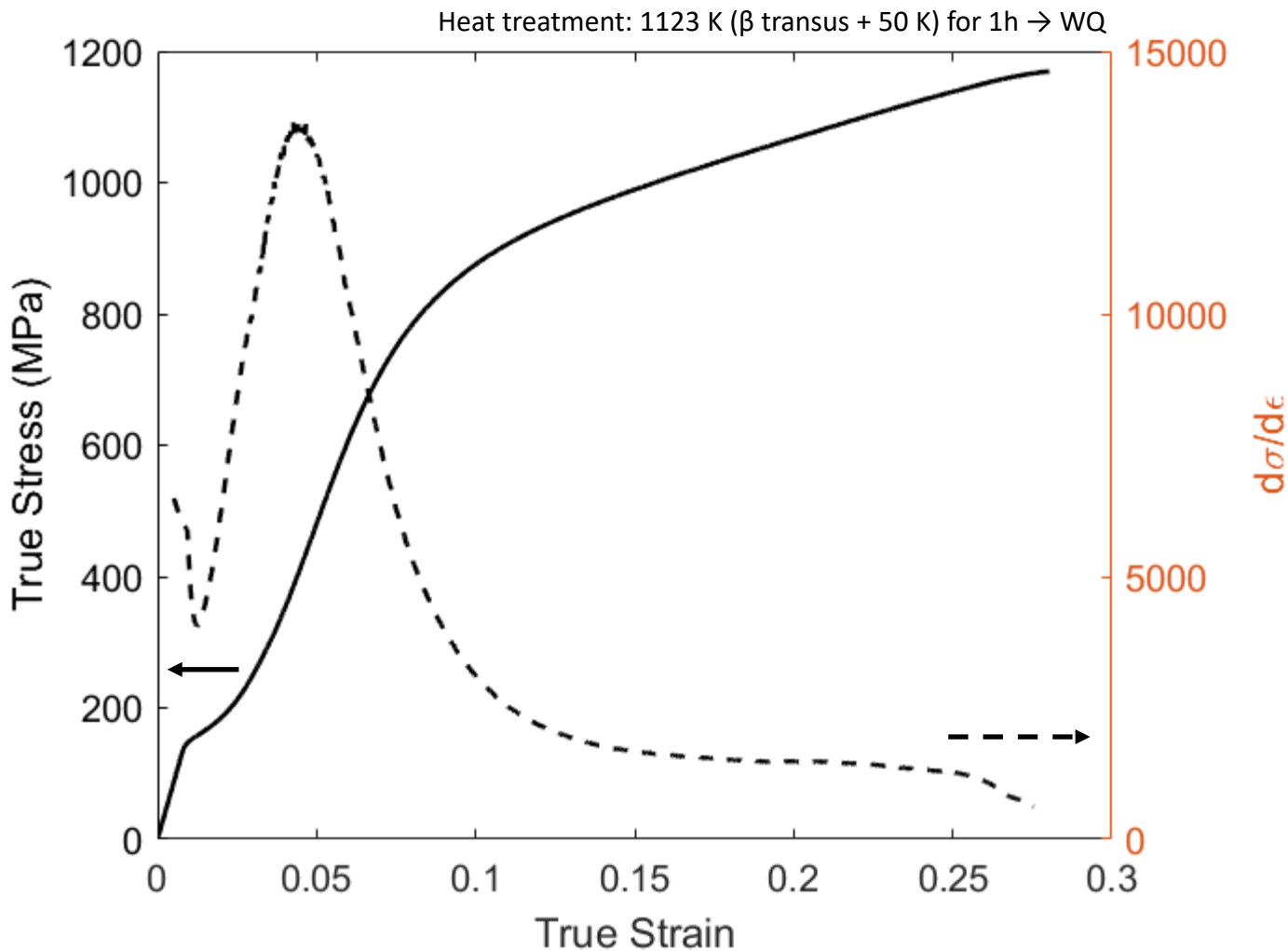
- **Deformation mechanisms present at all strain rates :**
  - Stress-induced α" martensite
  - {332}<113> β twinning
  - Stress-induced ω phase
  - Slip

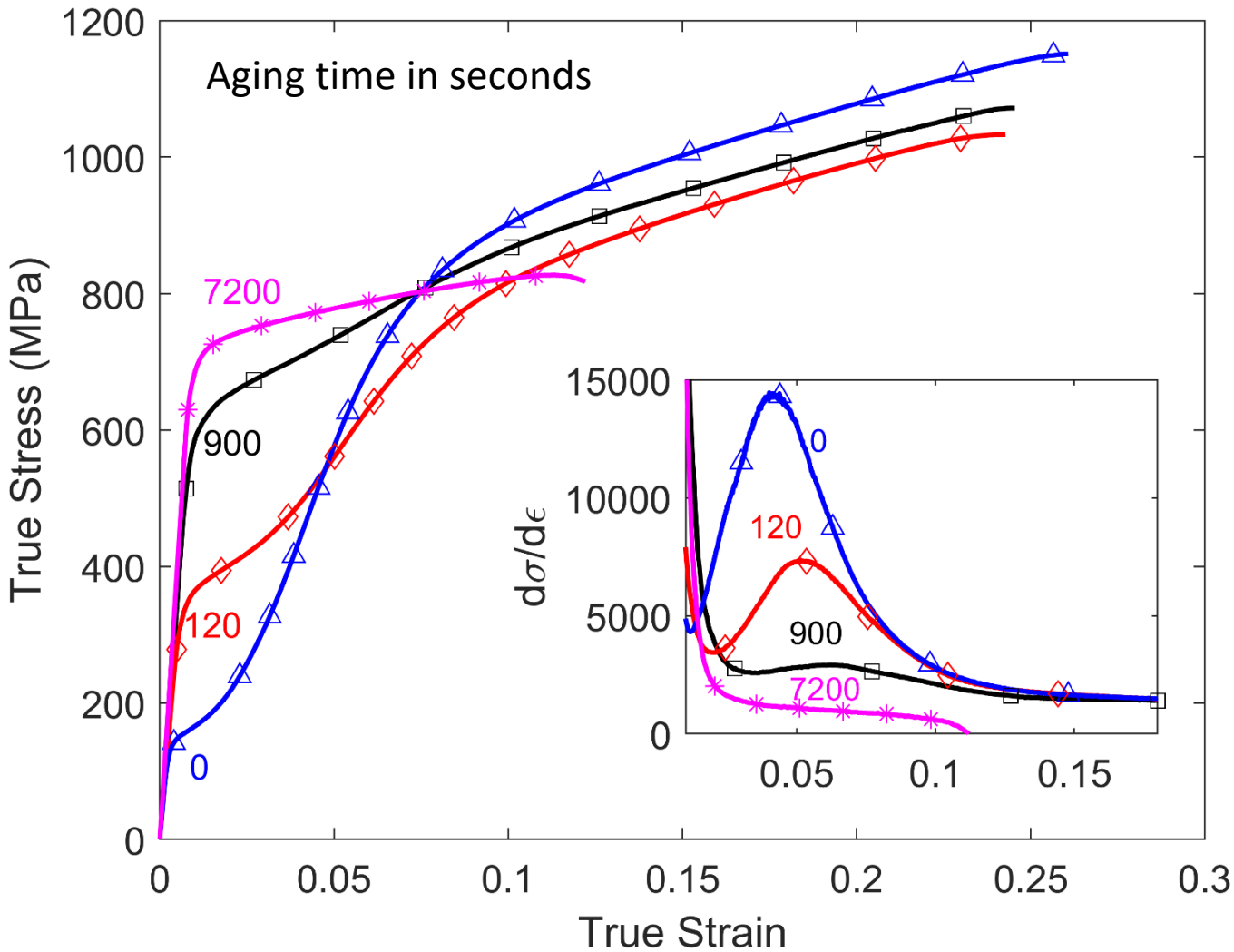


Ahmed, M., et al. 104 Acta Materialia (2016): 190-200

As-Quenched Quasi-static Tension of Ti-10-2-3



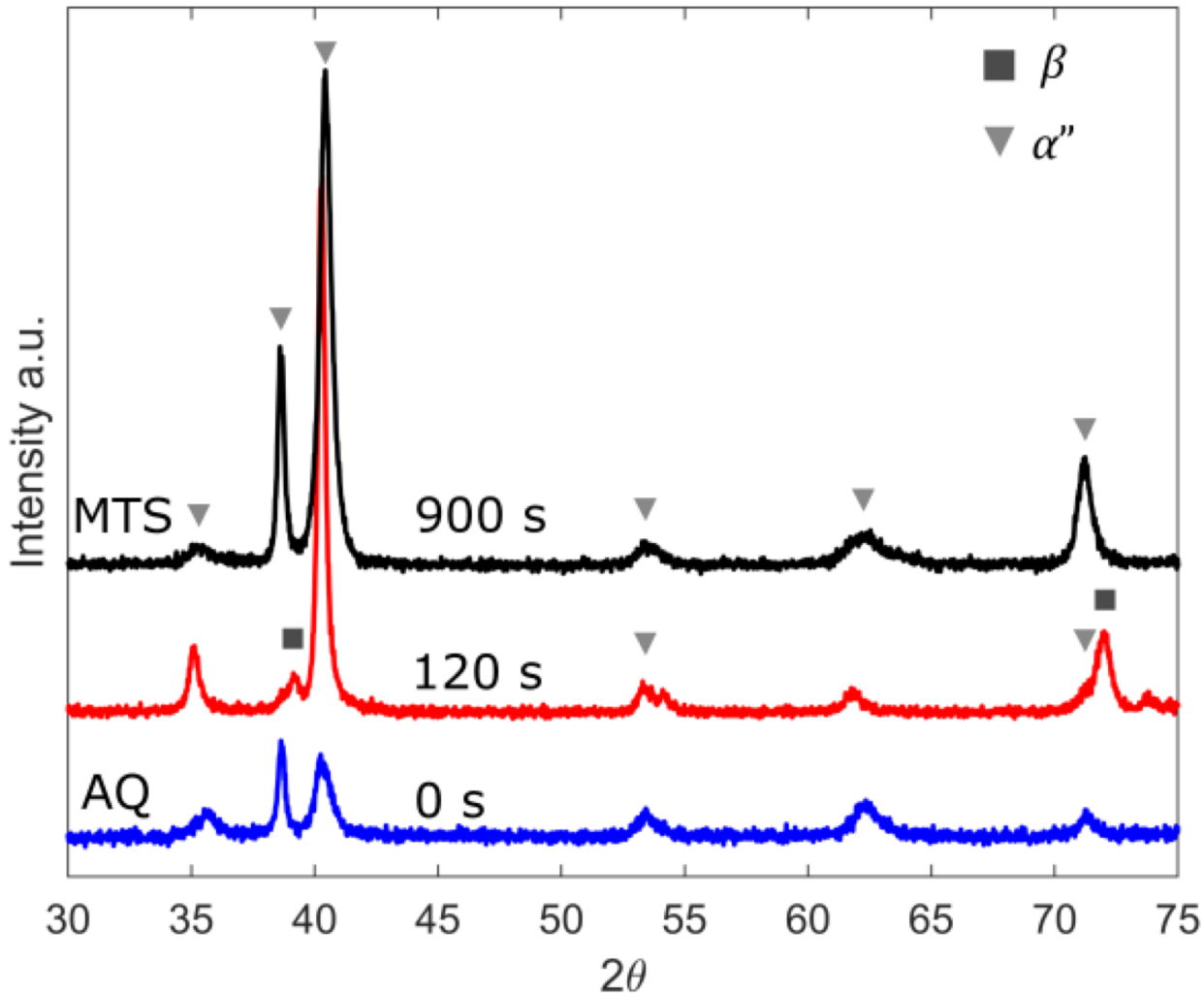
Artificial Aging of Ti-10-2-3 at 423K and Quasi-static Tensile Testing



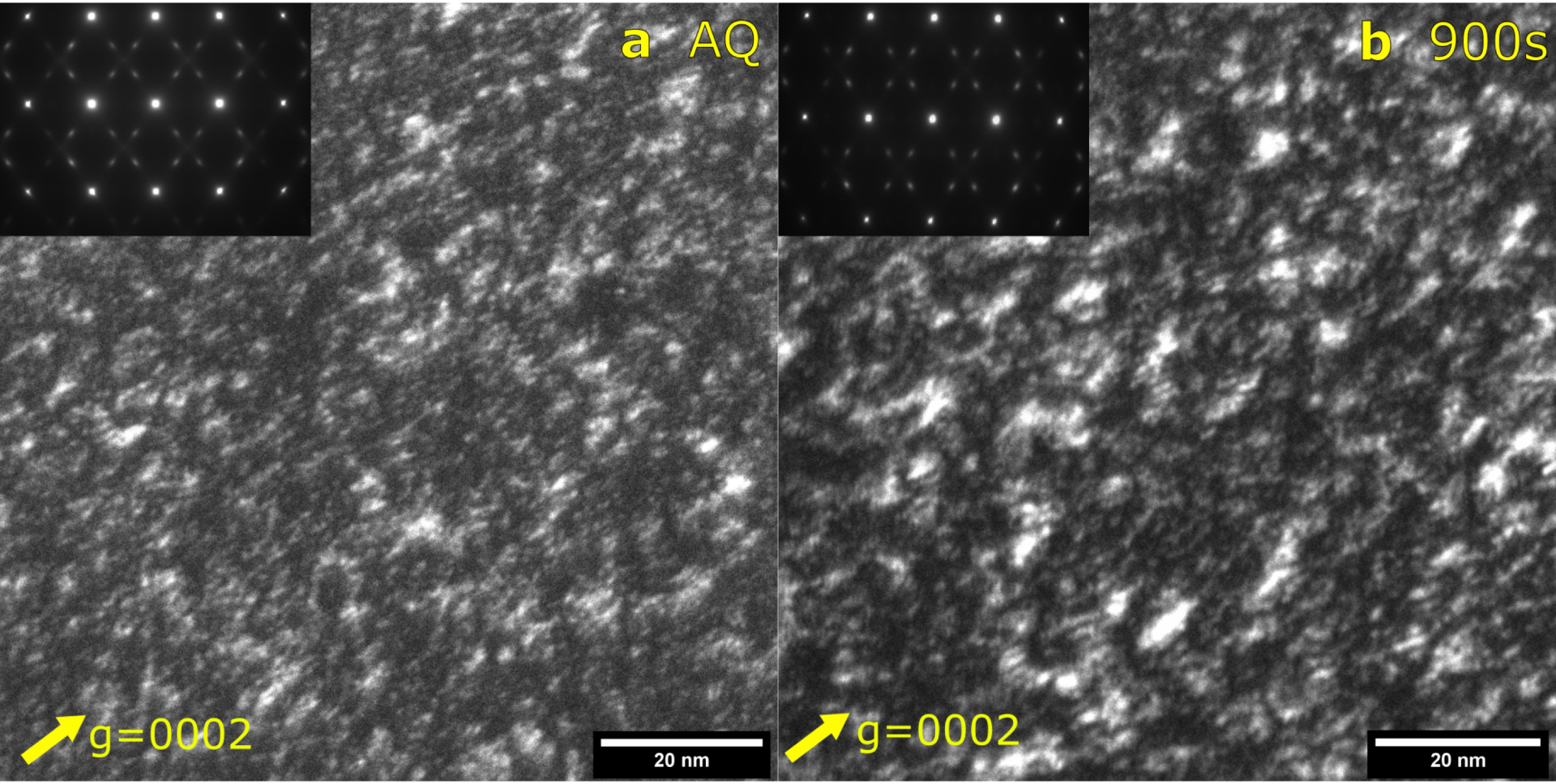
X-Ray Diffraction (XRD) of Aged and Deformed Specimens

Max TRIP stress →

As-Quenched →

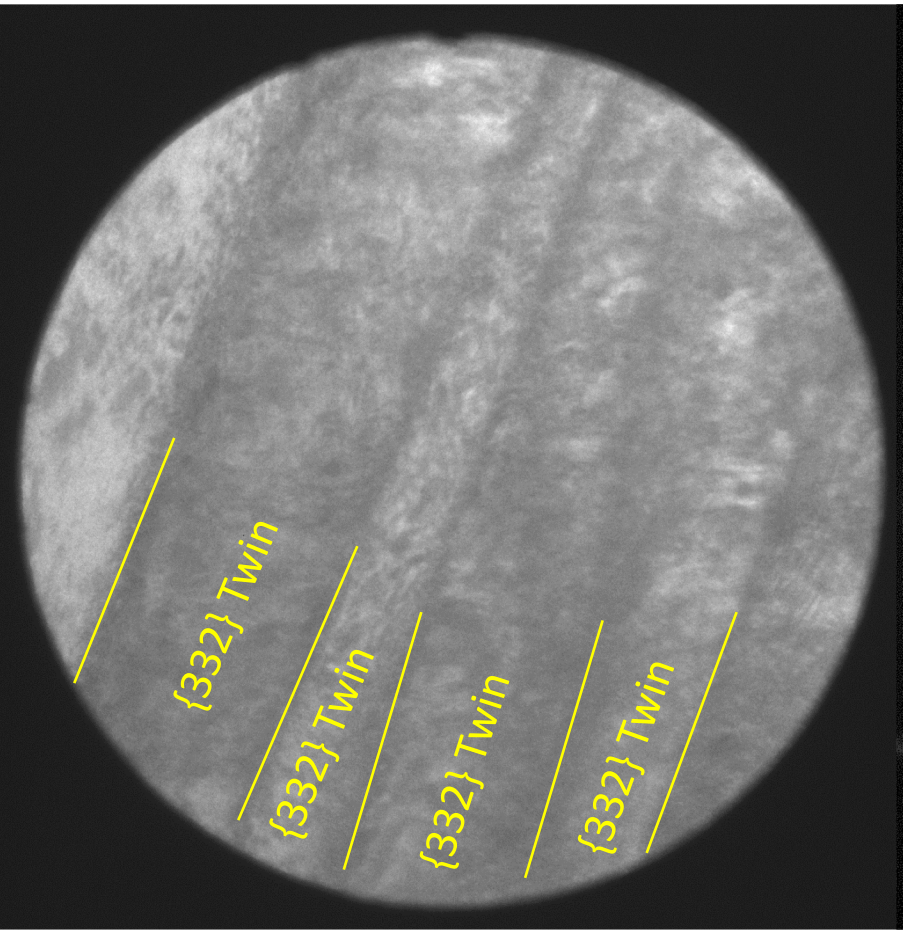


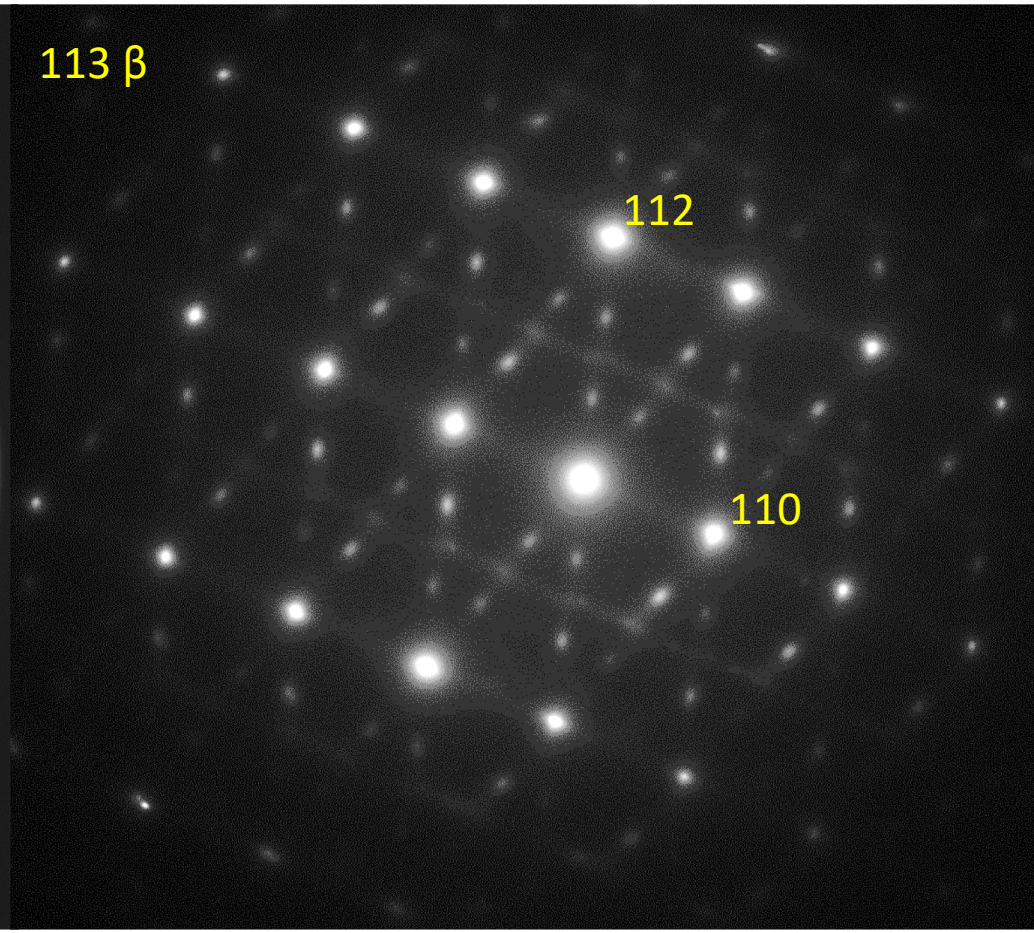
ω-phase in Aged Ti-10-2-3



{332} TWIP in Max TRIP Stress (MTS) Condition of Ti-10-2-3

SADP taken from all twins along the twinning direction

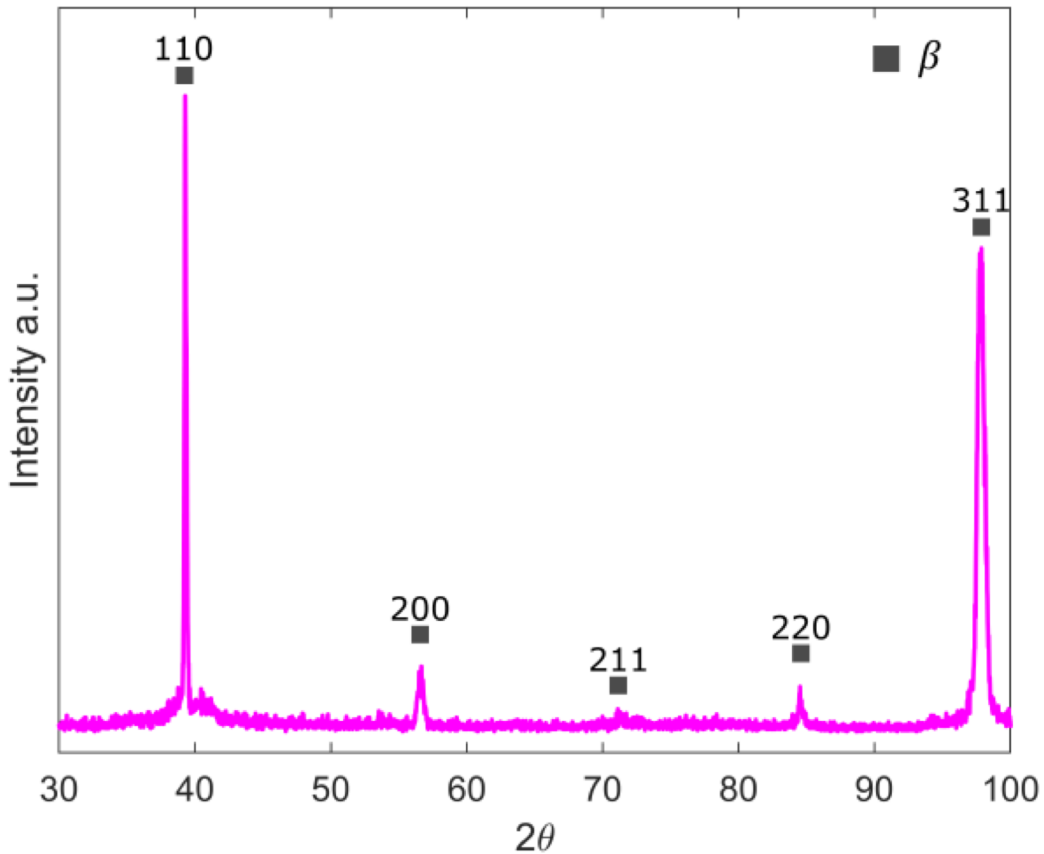


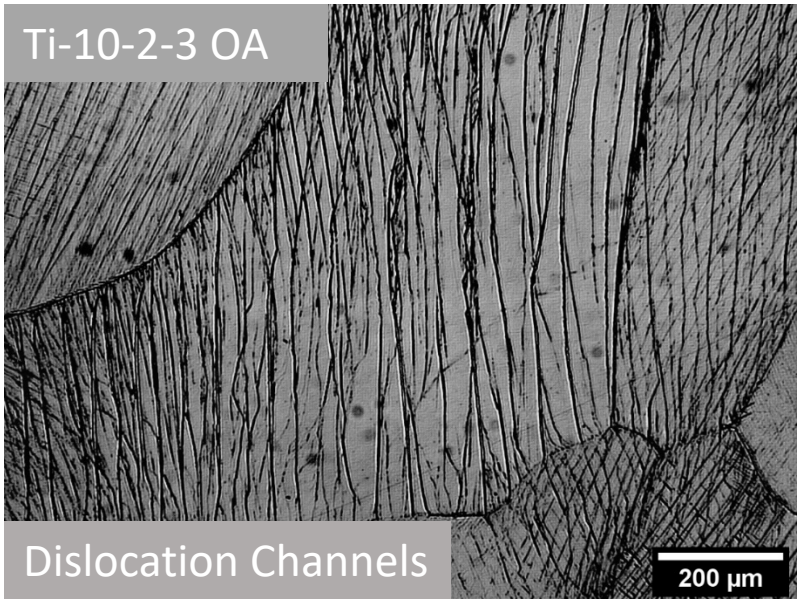


Aged 900 s at 423 K specimens fractured in tension at 10^{-3}/s

Deformed Microstructure of TRIP Inhibited (TI) Condition

Aged 7200 s @ 423 K & fractured in tension at 10^{-3}



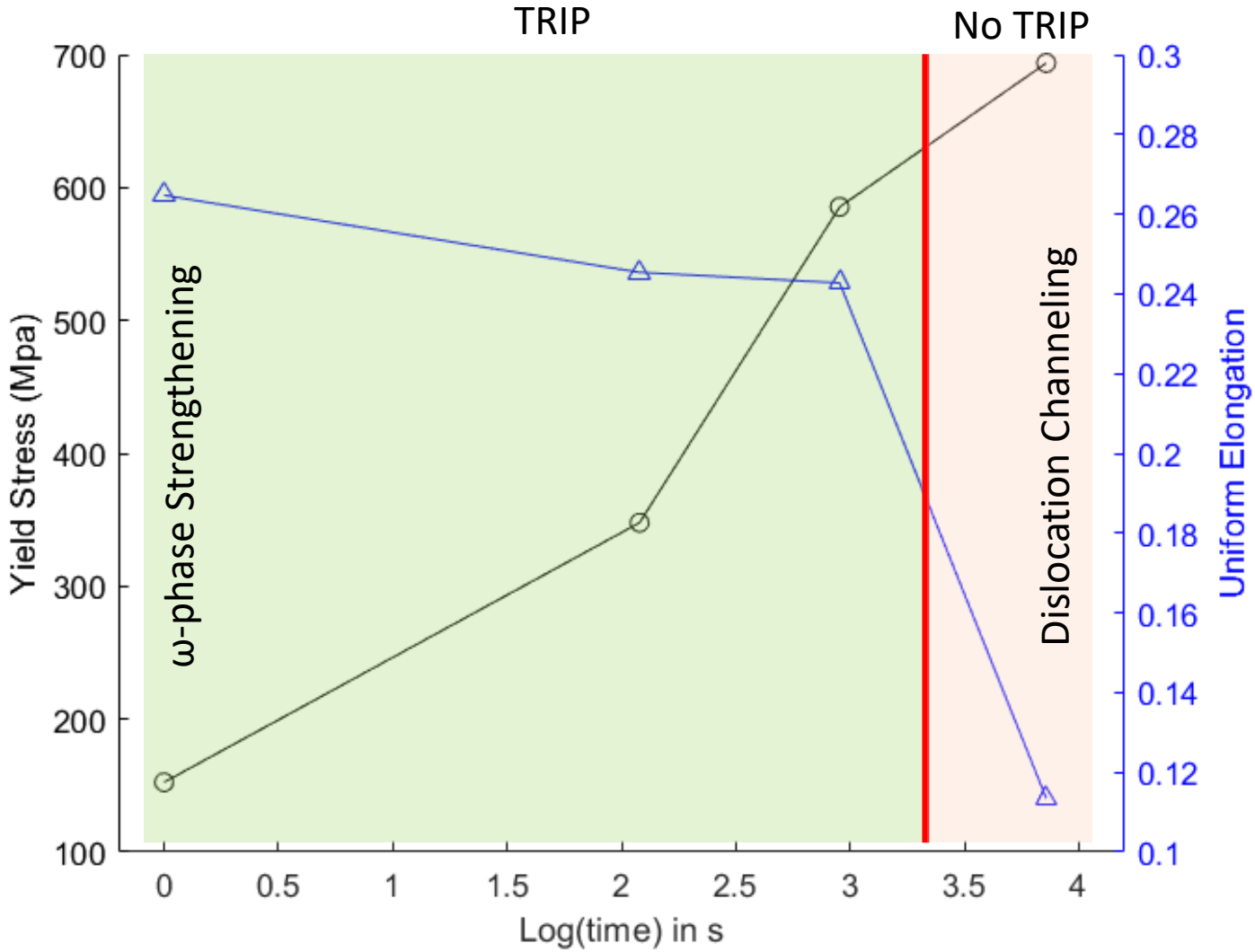


Over-aging of Ti-10-2-3 inhibits stress-induced martensite and causes dislocation bands to form

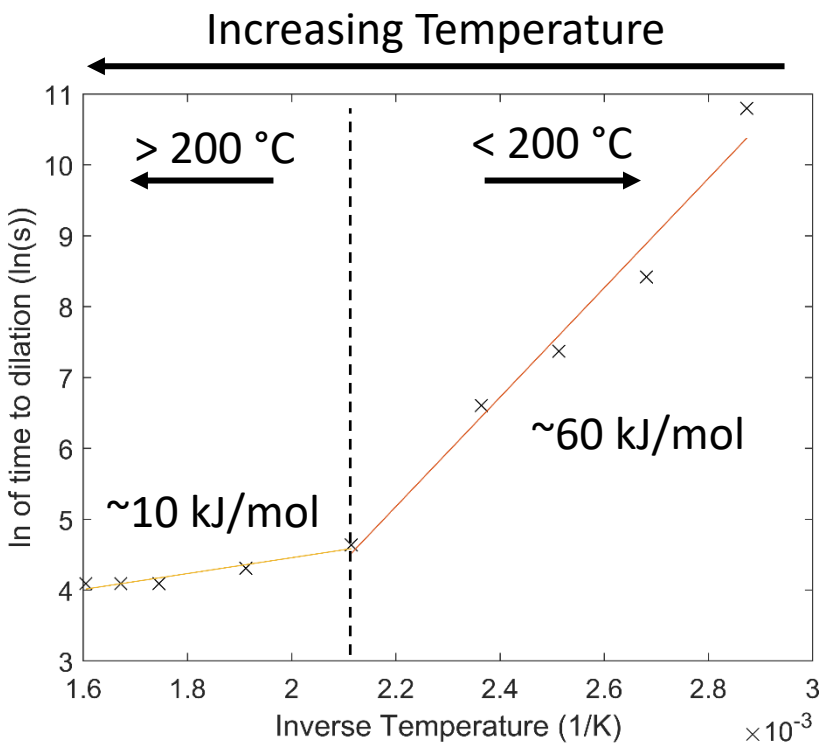
Similar to results reported in :

Chen, Wei, et al. *Acta Materialia,* 2019, 170, 187-204.
Lai, M. J., Tong Li, and Dierk Raabe. *Acta Materialia,* 2018, 151, 67-77.
Mantri, S. A., et al. *Scripta Materialia,* 2017, 130, 69-73.
Wang, Weilin, et al. *Materials & Design,* 2020, 186, 108282.

ω-phase Strengthening of Stress-induced Martensite in Ti-10-2-3: Overview and Limits



Dilatometry and ω Kinetics



- Ti-10-2-3 shows two stage precipitation response
- Higher T (300-350 °C) dilation shows a reversal of trend at longer aging times
- Comparison with Ti-15Mo is planned to rationalize trends vs. lattice misfit or ternary Al content

System	Lattice misfit	
	Initial (%)	Final (%)
Ti-10Mo (at.%)	+0.42	+0.88
Ti-20V (at.%)	+1.08	+2.85

Hickman, B. S. *Journal of Materials Science* 4.6 (1969): 554-563.

Sector 32-ID Kolsky Bar Testing at the Advanced Photon Source (APS)

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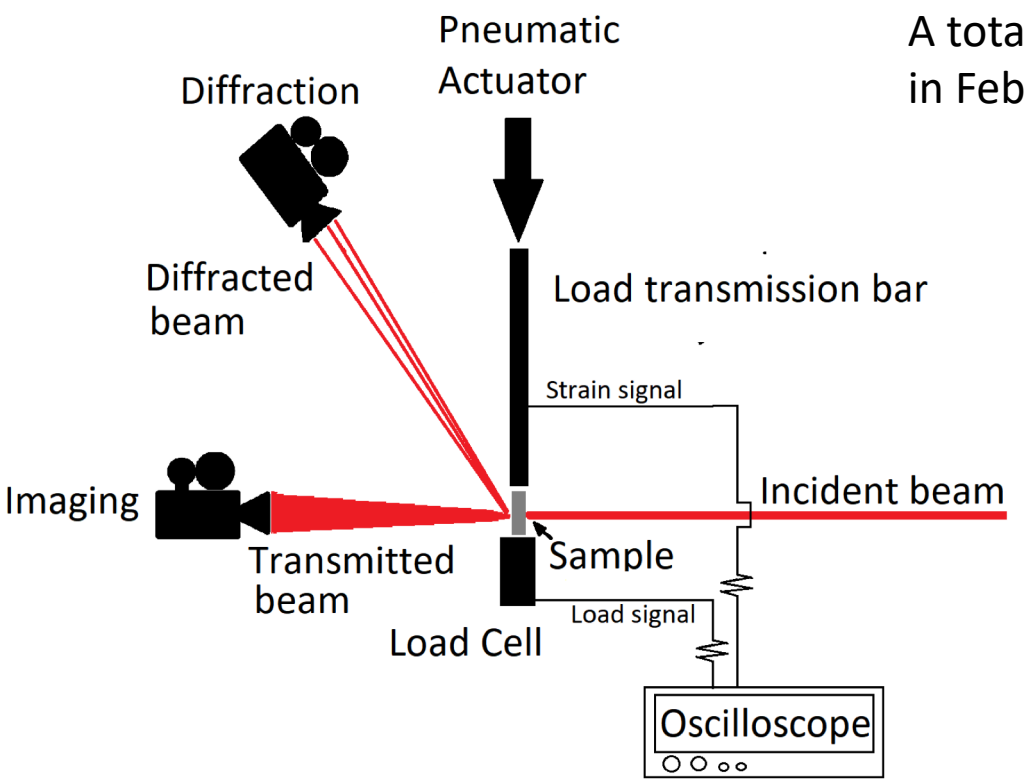
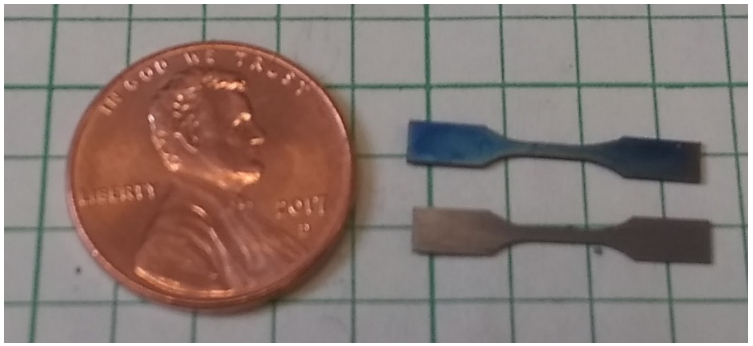
Alloys (wt.%)	Heat Treatment Name and Condition		
Ti-10V-2Fe-3Al	AQ 1123K-0.5h→WQ	MTS AQ+423K-900s	TI AQ+423K-7200s
Ti-15Mo	AQ 800-1h→WQ		
Ti-12Mo	AQ 820-1h→WQ		

A total of 102 β–Ti samples were tested in February 2020





Current & Future Collaborations

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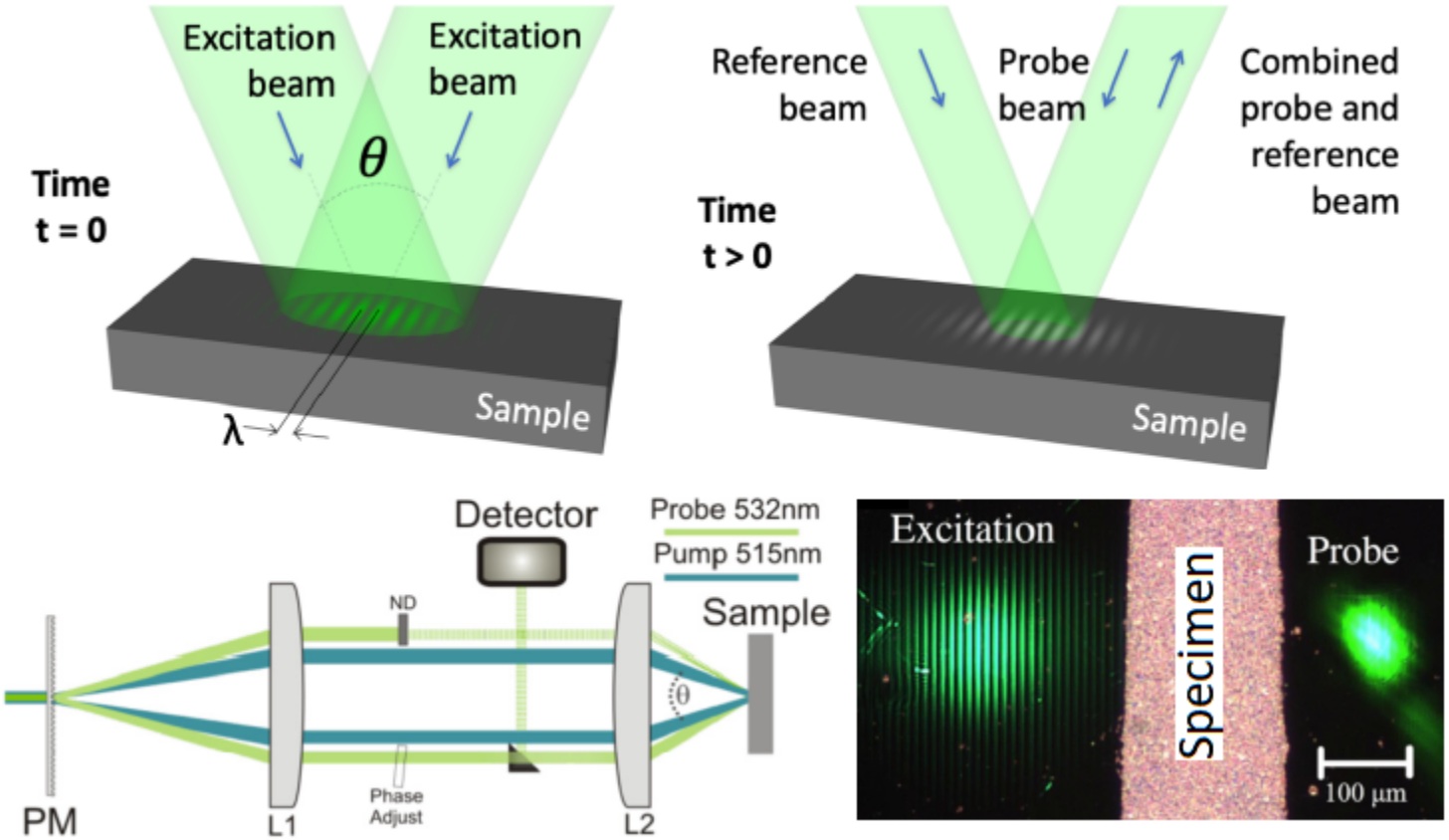
Experiments	Hypothesis/Intent
In-situ heating & quasi-static tensile testing in the TEM @ LLNL	Fine scale ω-phase & α" interactions & ω-phase evolution during aging
Bulk/macroscopic Kolsky bar testing @ LANL	Cleaner mechanical testing data for 10^3 s^{-1} comparison with small-scale APS experiments
Quasi-static, in-situ tensile testing @ the Cornell High Energy Synchrotron Source (CHESS) & Sector 1-ID at the APS	Wide and Small Angle X-ray Scattering (WAXS/SAXS) of ω-phase and α" interactions and ω-phase coarsening during aging
In-situ Transient Grating Spectroscopy (TGS) @ MIT	In-situ measurements of elastic anisotropy during aging

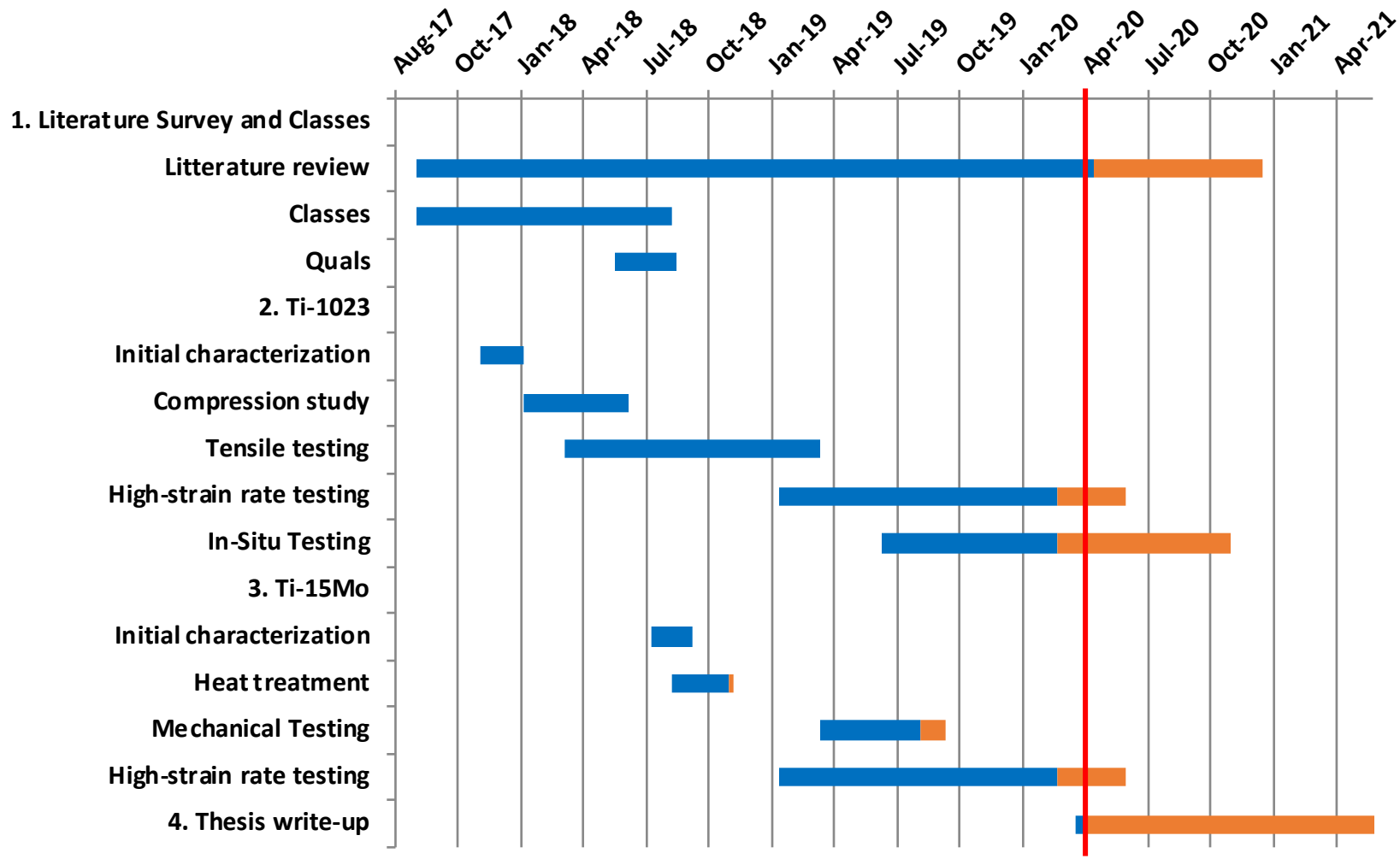
Transient Grating Spectroscopy



TGS measures surface acoustic waves (SAW), which are dependent on the speed of sound in the material, i.e. stiffness

Hofmann, F., Short, M., & Dennett, C. (2019). *MRS Bulletin, 44*(5), 392-402. doi:10.1557/mrs.2019.104

Progress



Challenges & Opportunities

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Challenges

- High Resolution Transmission Electron Microscopy (HRTEM) to investigate the structure of metastable phases
- Mechanical testing data from the APS is noisy (load cell use)

Opportunities

- ω-phase strengthening has similar effects to increasing the β phase stability (TRIP → TRIP/TWIP → TWIP)
- A publication on the precipitation kinetics of ω phase is being prepared (insights for suitbale heat treatments)
- A publication on the effect of low temperature aging on the strength/ductility of Ti-10-2-3 has been prepared and is ready for submisson

Thank you!

Benjamin Ellyson

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