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

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

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

- Student: Benjamin Ellyson(Mines)
- Faculty: Prof. Amy Clarke (Mines)
- Industrial Mentors: Austin Mann (Boeing)
  Clarissa Yablinski (LANL)
- 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 methodology and tailor microstructures and properties.
- Benefit: Novel titanium alloys for blast and crash resistant applications

Recent Progress

- Ti-10V-2Fe-3Al (wt.%) (Ti-1023) aging study concluded
- Quasi-static Ti-15Mo (wt%) tensile testing completed
- Intermediate strain rate testing of Ti-1023 and Ti-15Mo partially completed
- APS high-rate mechanical and diffraction data screened and post-processed

Metrics

Description	% Complete	Status
1. Literature review	80%	●
2. Quasi-static mechanical characterization of Ti-1023 and Ti-15Mo	90%	●
3. Dynamic testing of Ti-1023 and Ti-15Mo	60%	●
4. Microstructural characterization of pre- and post-deformed samples	50%	●
5. *In situ* characterization of microstructural evolution during deformation	30%	●

Industrial Relevance: Development of Blast Resistant Materials for the Navy

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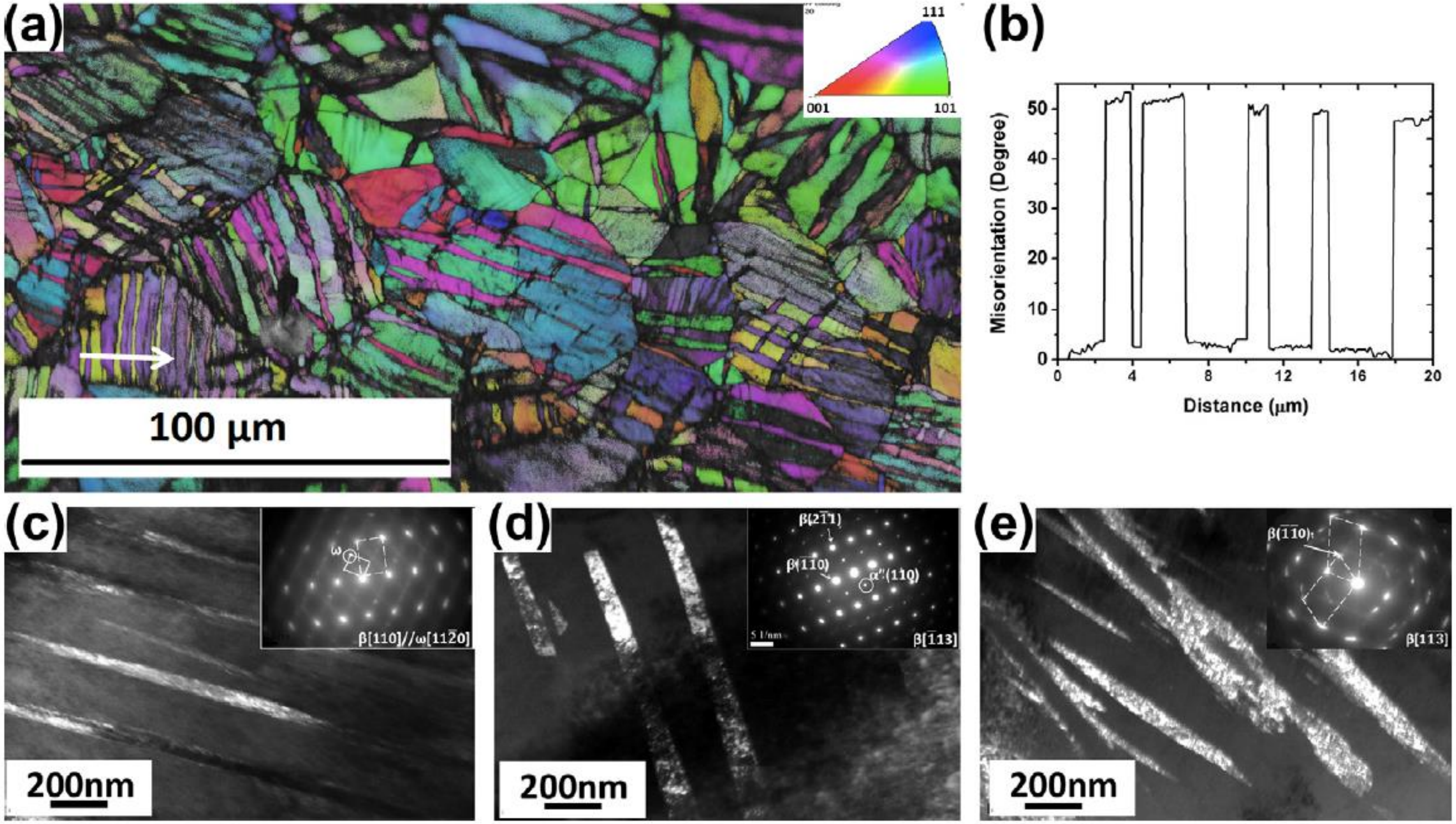
- **Cellular Materials Program**
  - Multifunctional structures
  - **Blast resistance**
  - Thermal management

- **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

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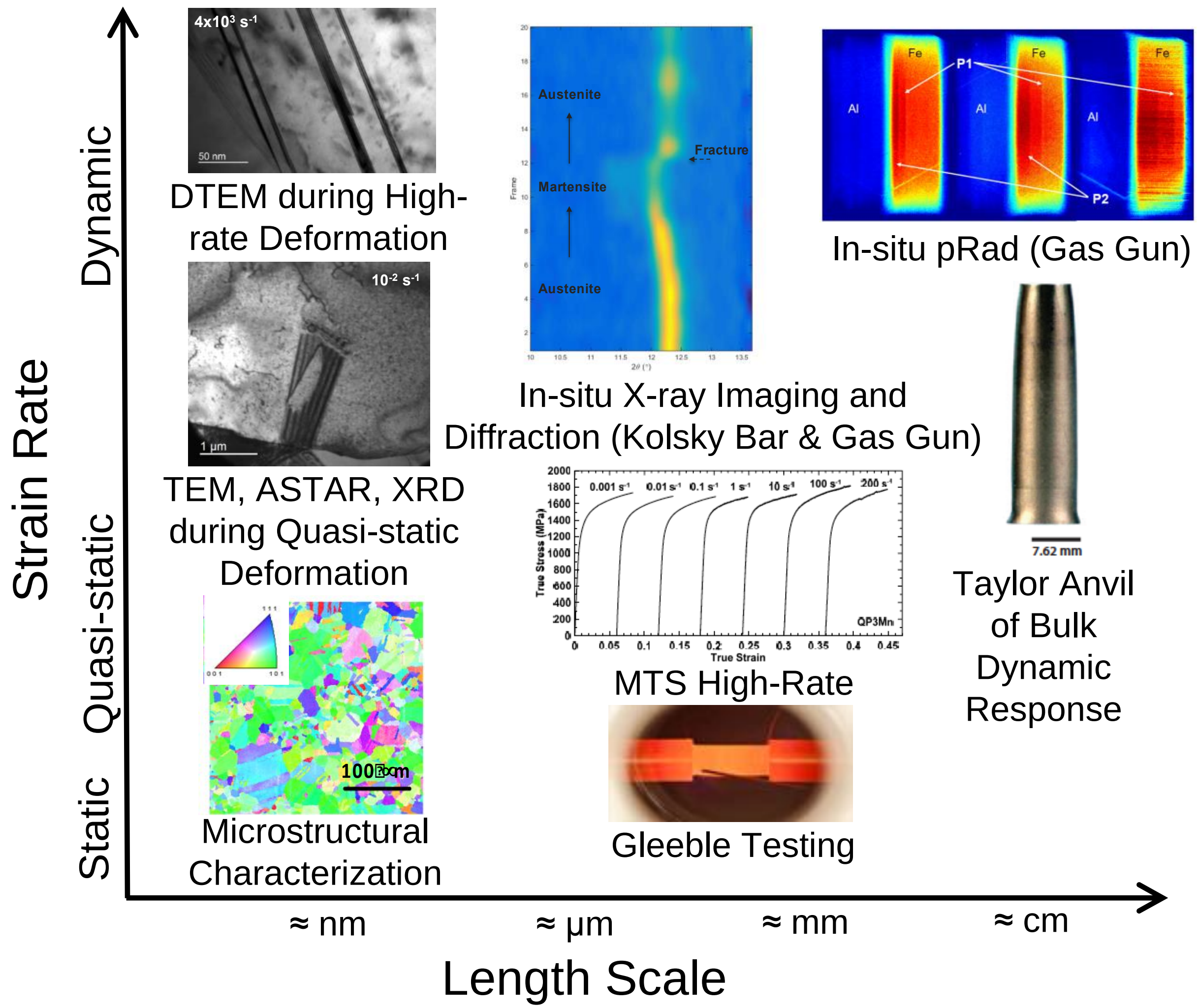

The Effect of Strain Rate on Deformation Mechanisms During Compression of a Ti-10V-3Fe-3Al (wt.%) Alloy

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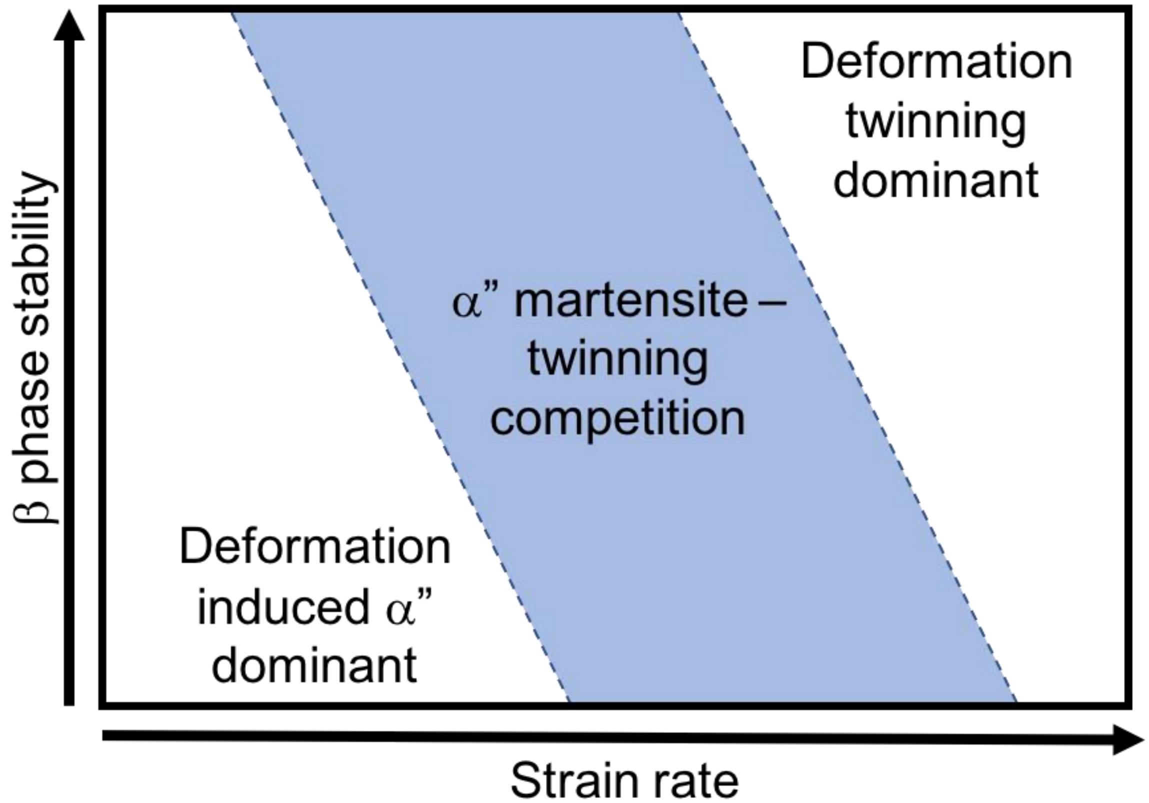
- **Deformation mechanisms present at all strain rates:**
  - Stress-induced α” martensite
  - {332}<113> β twinning
  - Stress-induced ω phase
  - Slip



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

Natural Aging in Ti-1023

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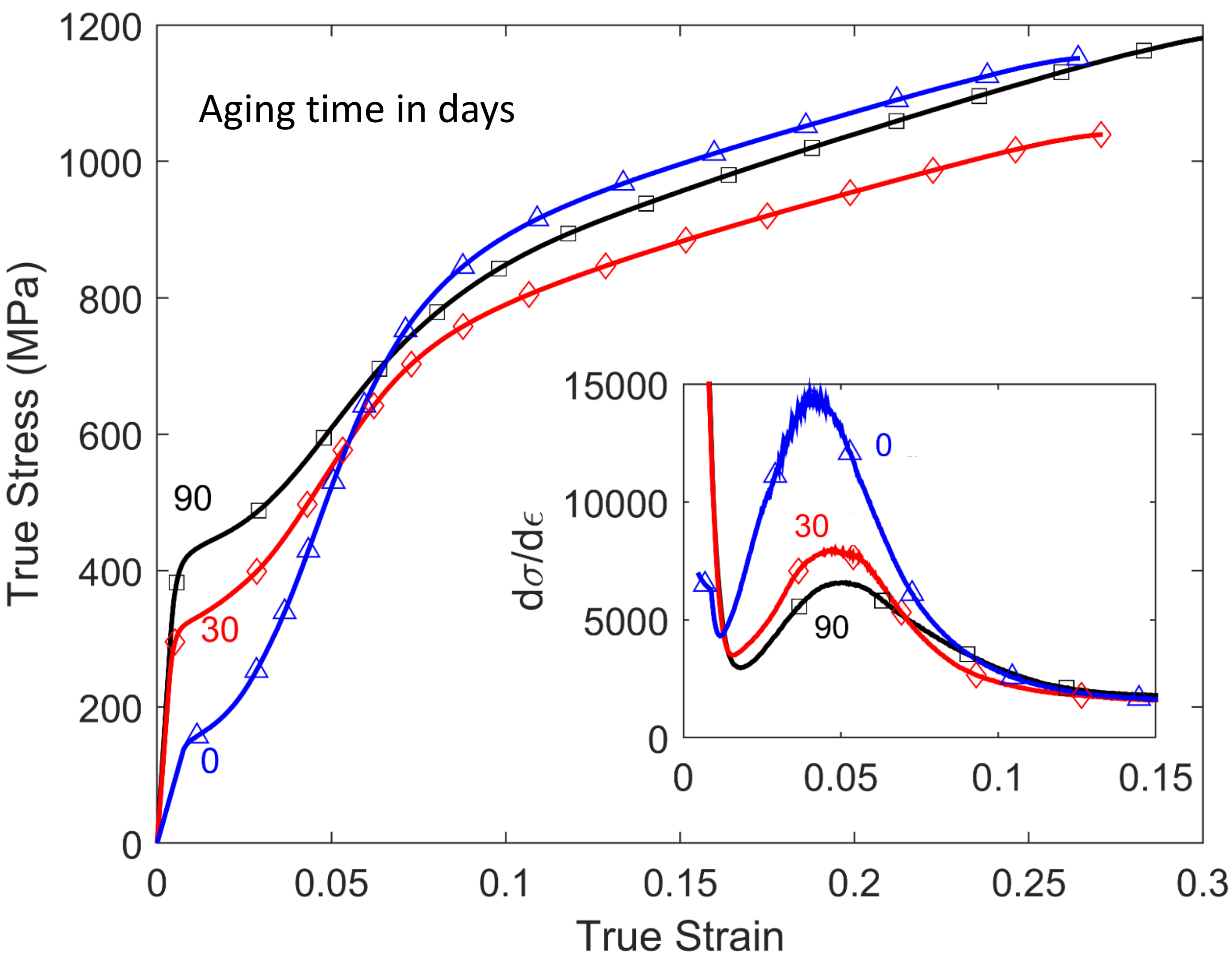
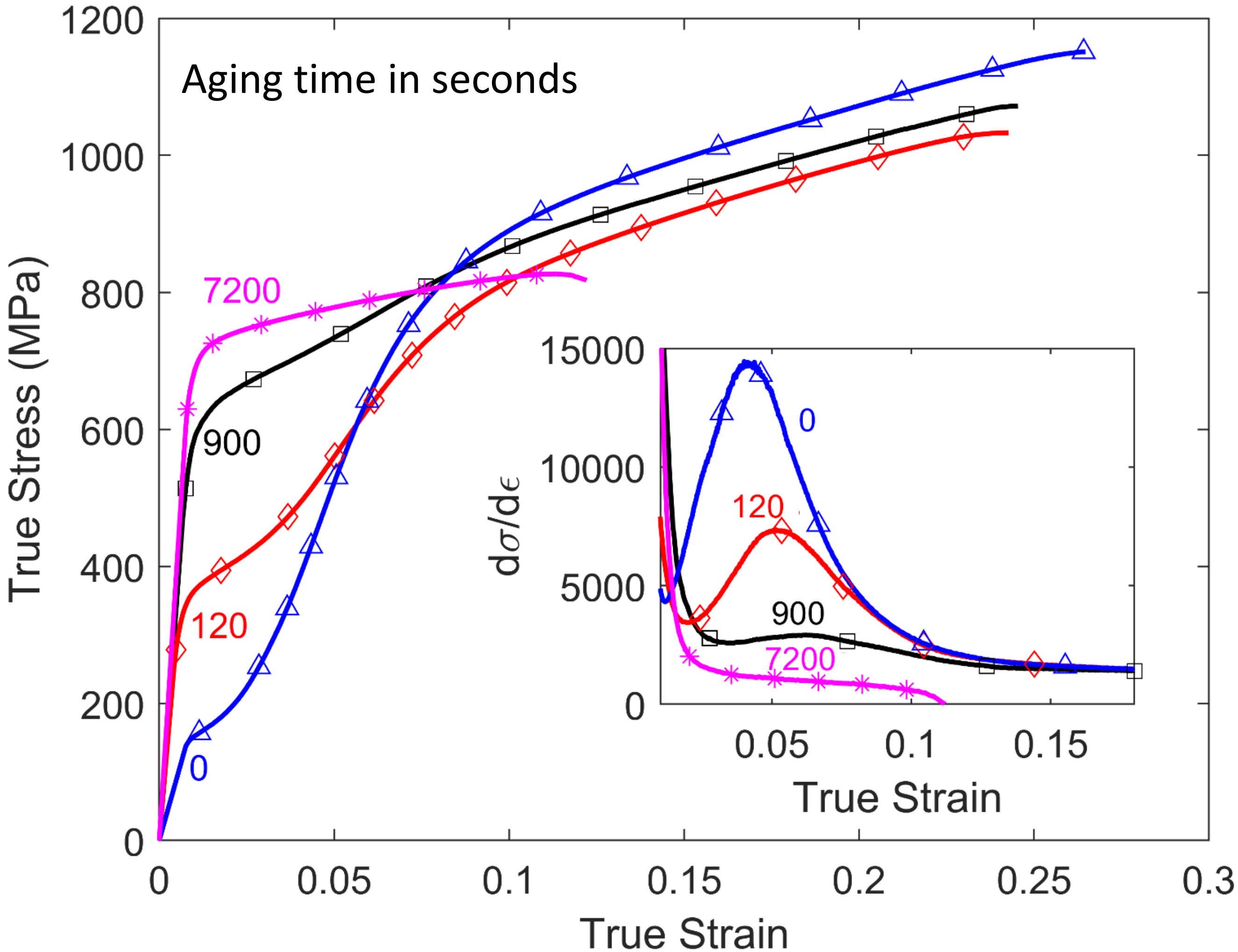


Artificial Aging in Ti-1023 at 423K



TEM of ω-phase Aging

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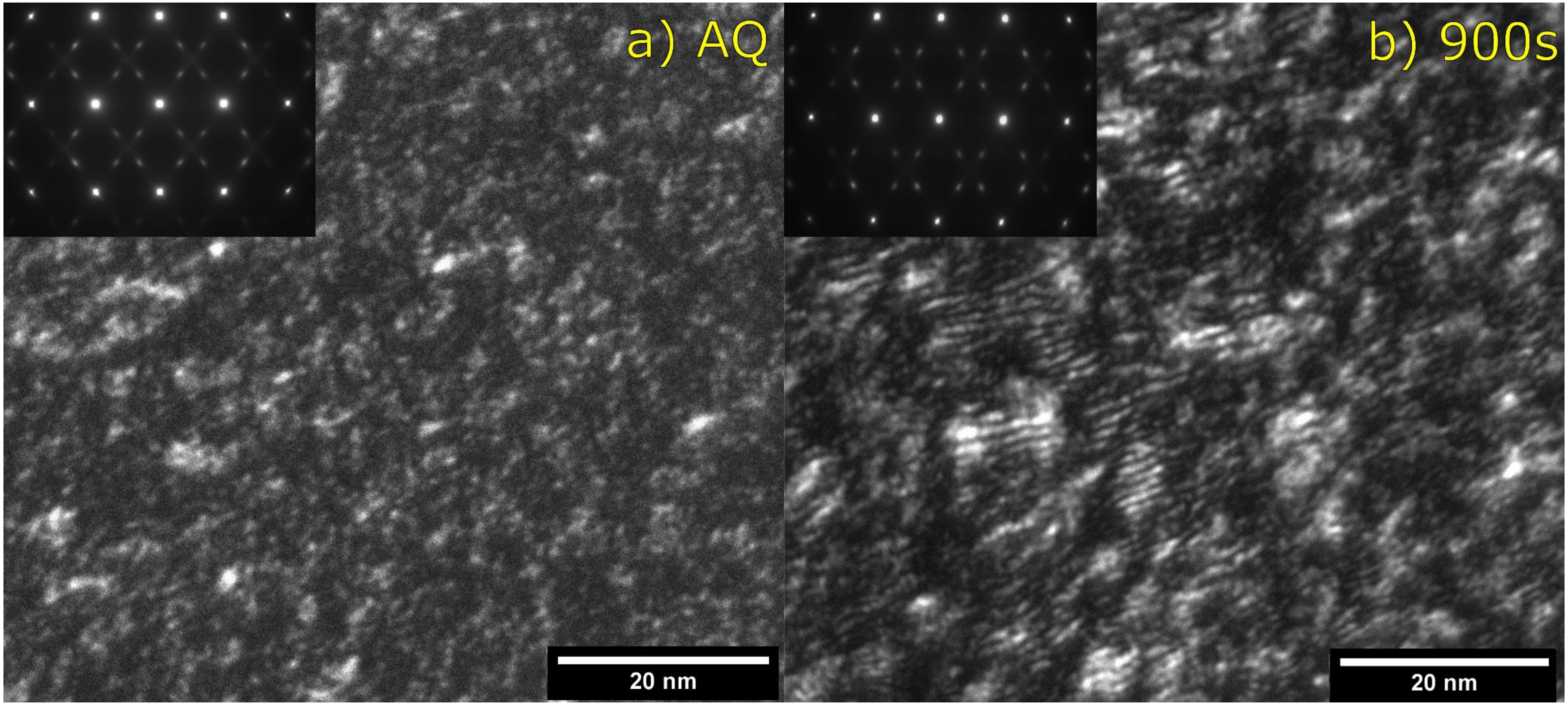

Over-Aged Specimen (7200s)

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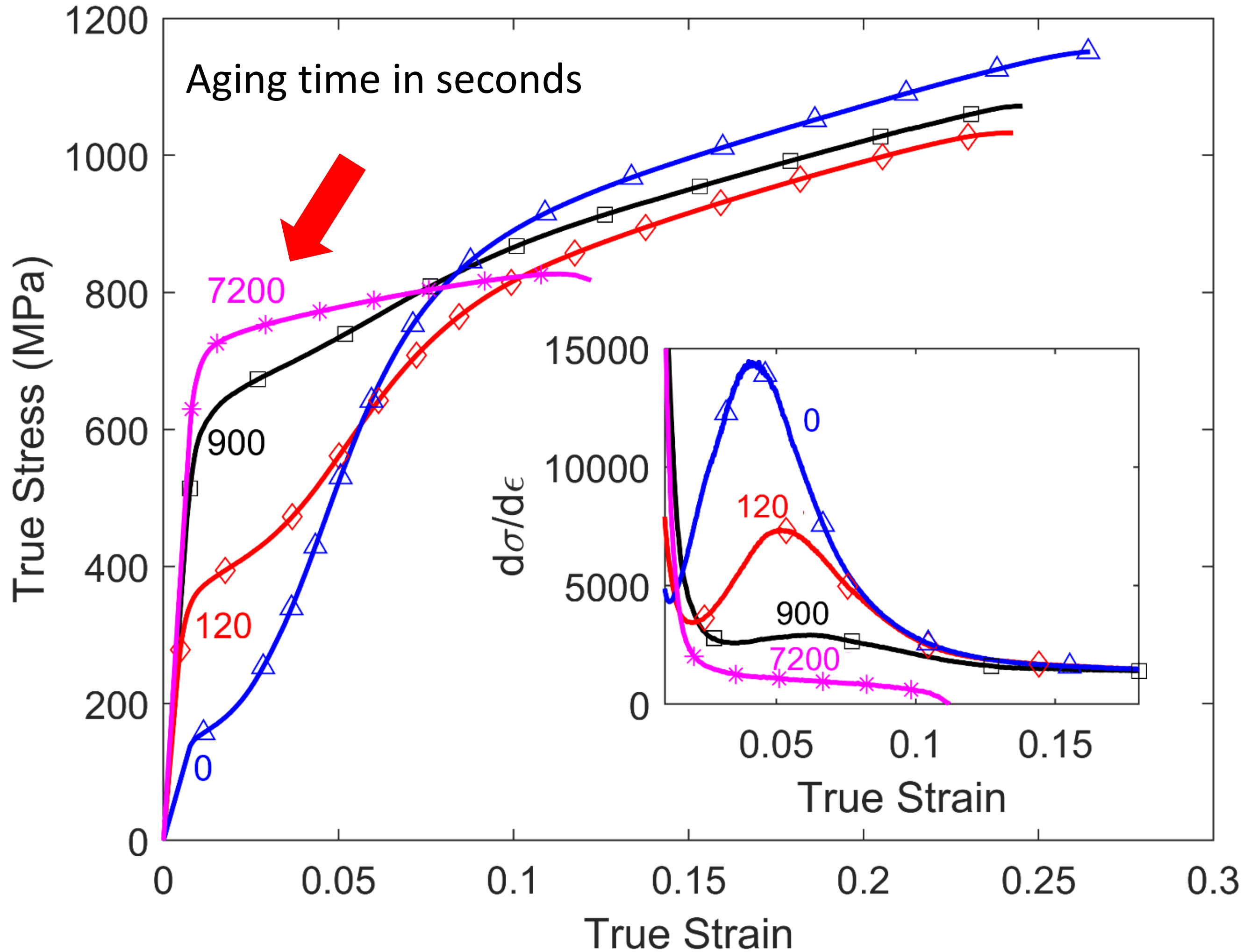
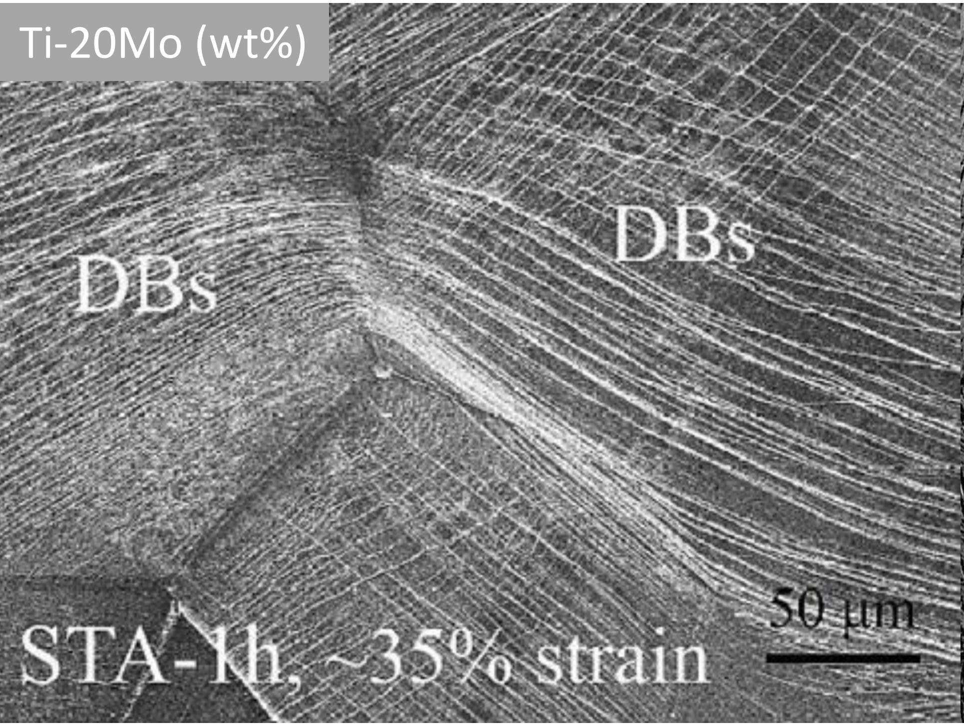


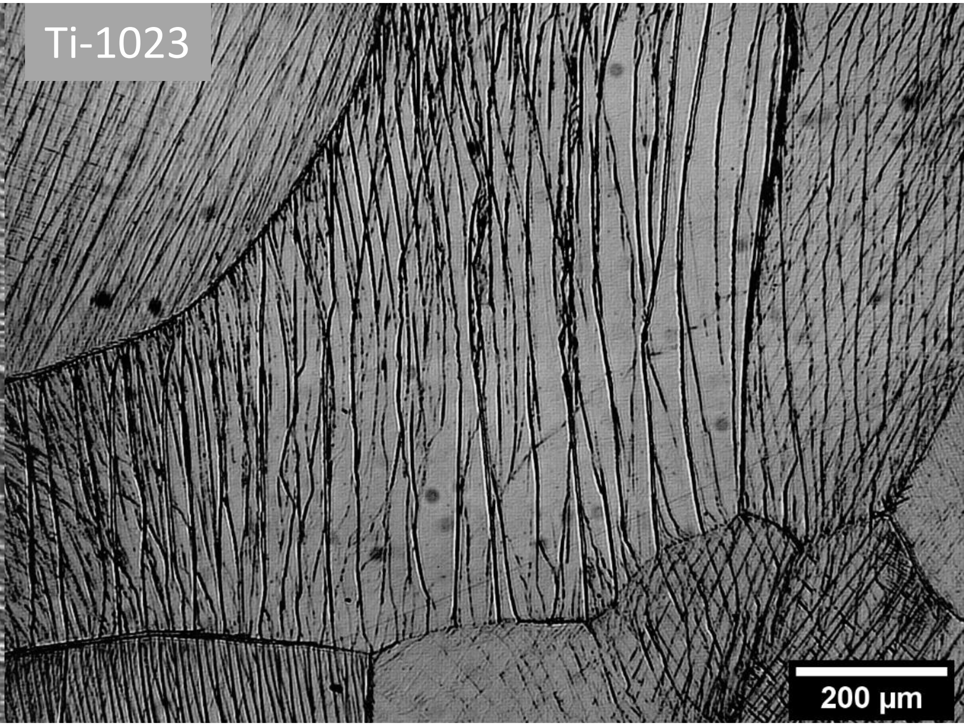
Center Proprietary – Terms of CANFSA Membership Agreement Apply

Comparison of Over-Aged (7200s, 423K) Microstructure of Ti-1023



Chen et al., *Acta Materialia* (2019).

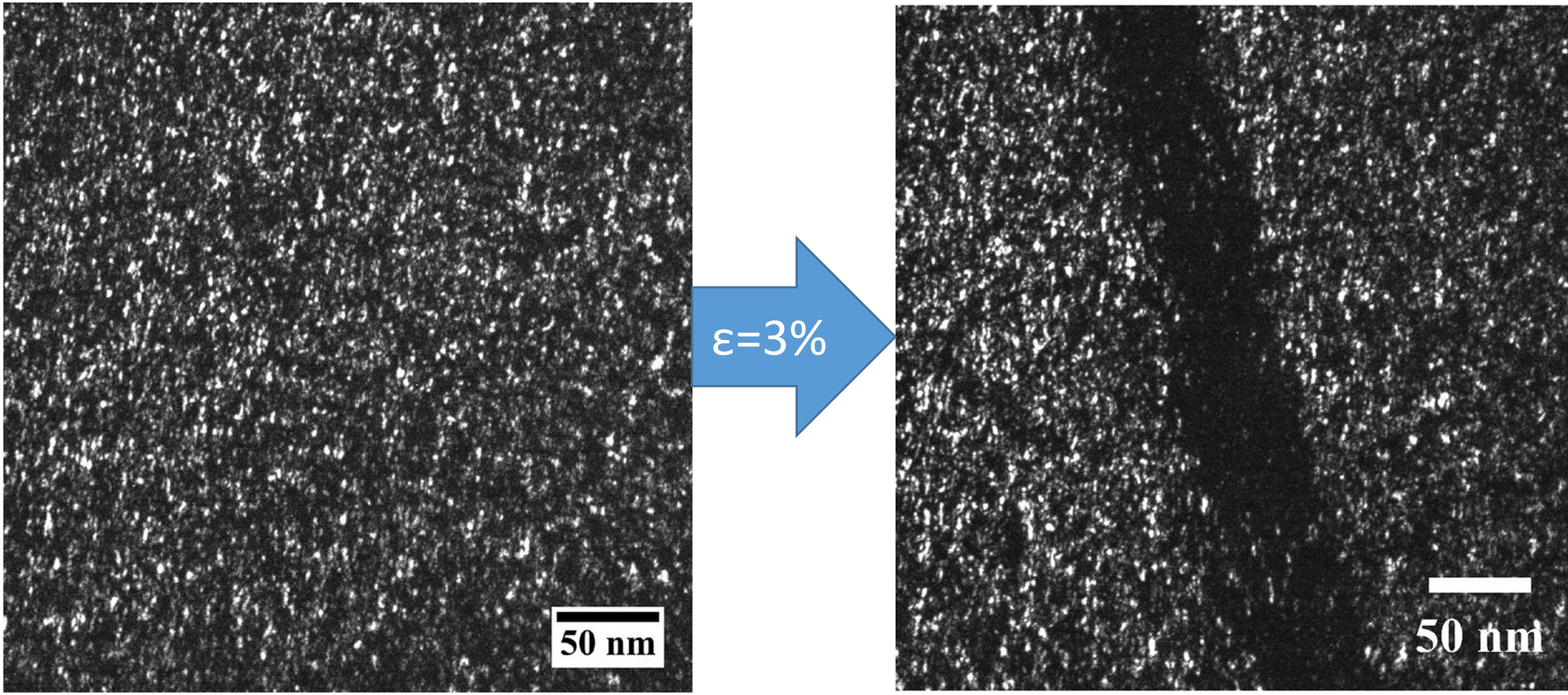
DBs : Dislocation bands



XRD indicates that the material is still single phase β, i.e. no martensite is present

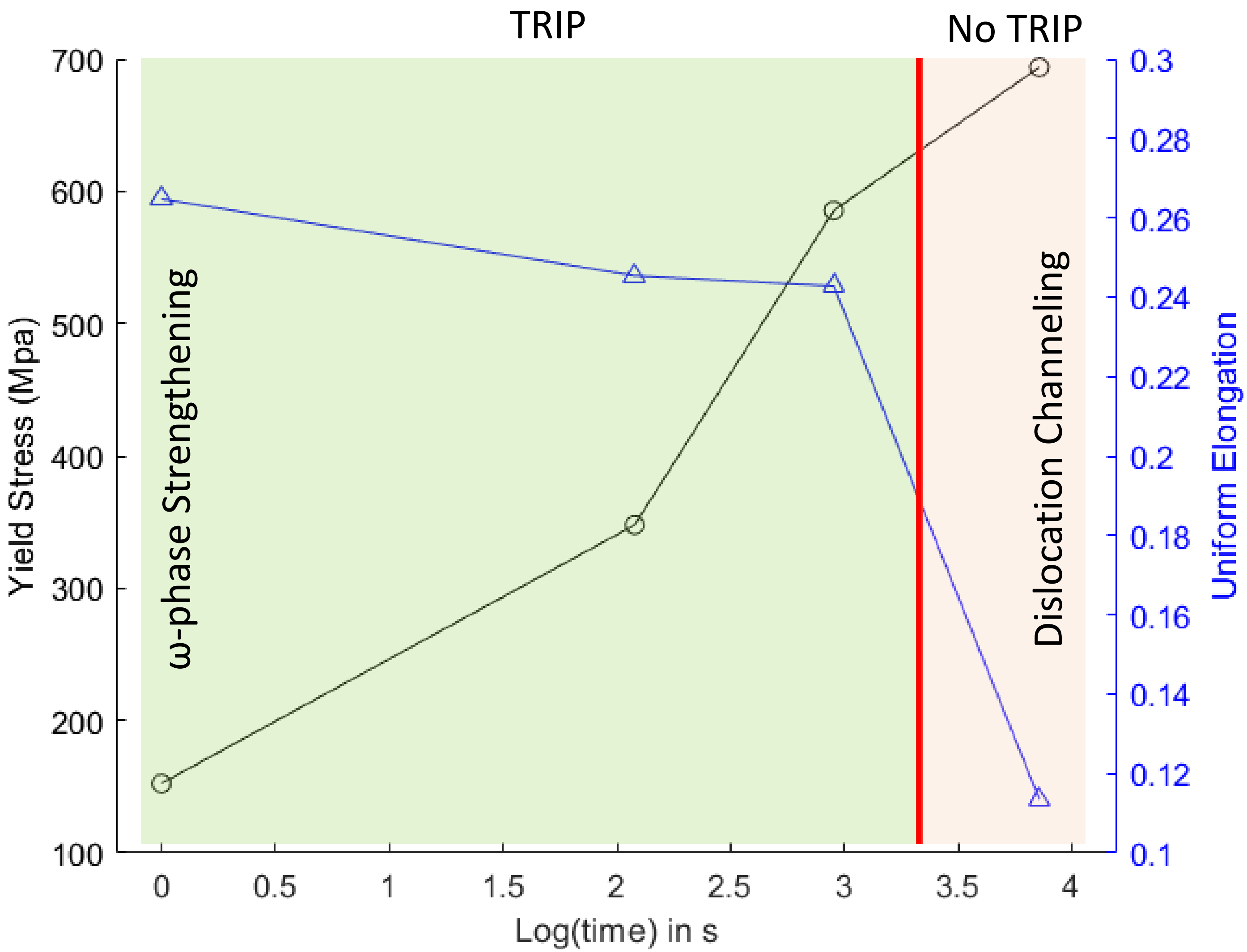
Artificial Aging of Ti-1023 for 7200s at 423K inhibits stress-induced martensite and causes dislocation bands to form

Dislocation Channeling

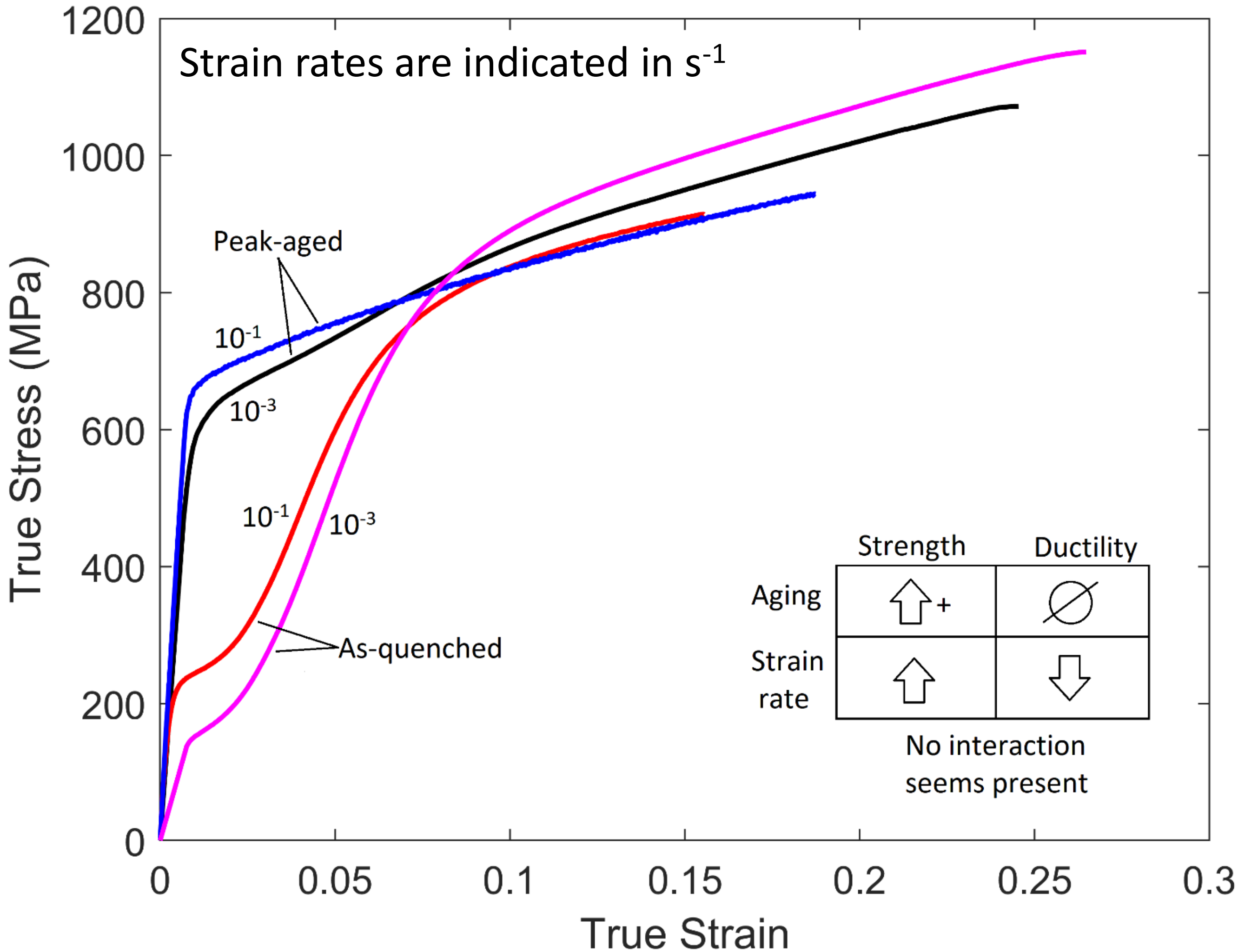


Lai et al. *Acta Materialia* 151 (2018): 67-77.

ω-phase Strengthening of Stress-induced Martensite in Ti-1023: Overview and Limits

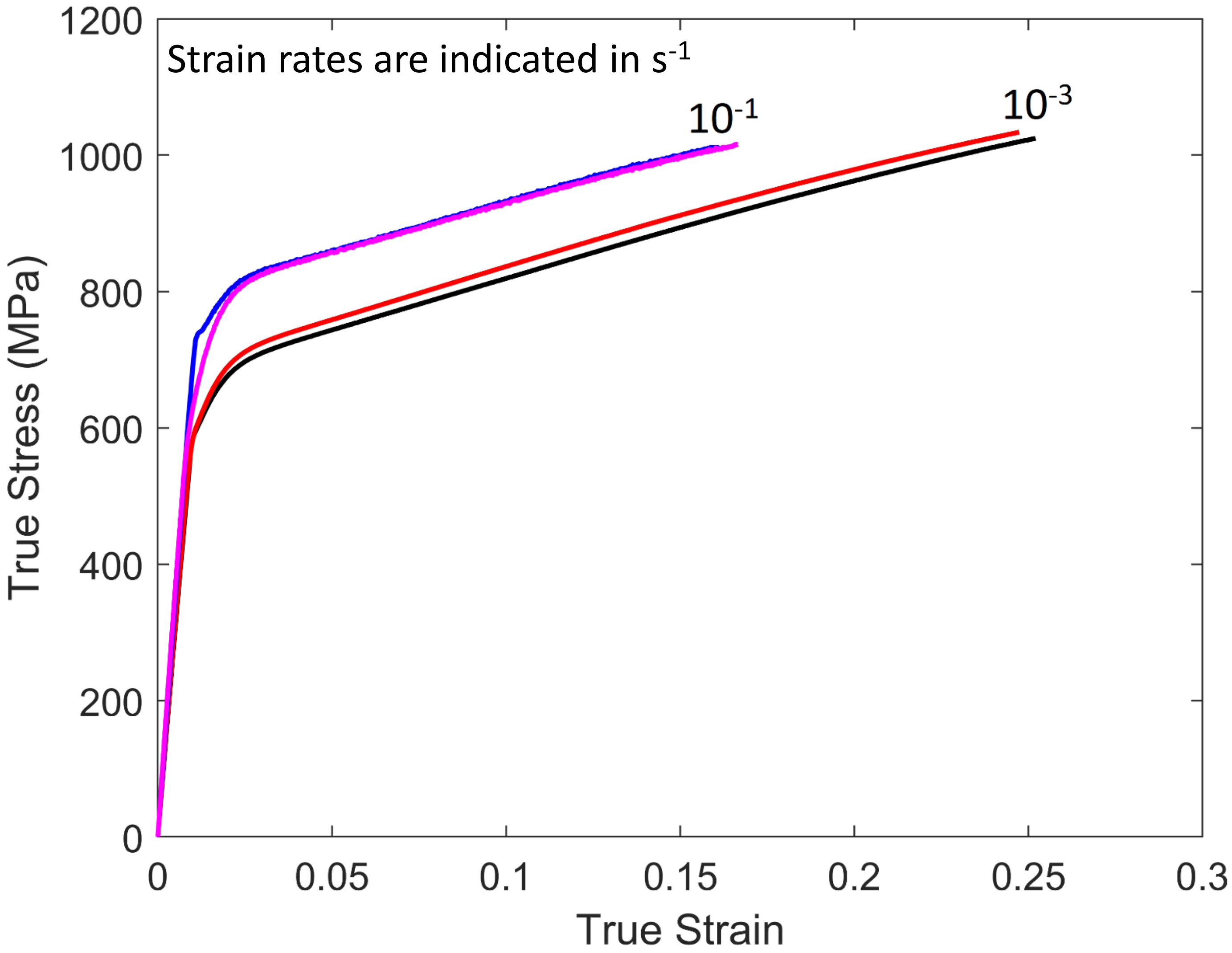


Strain Rate Effects on TRIP Ti-1023

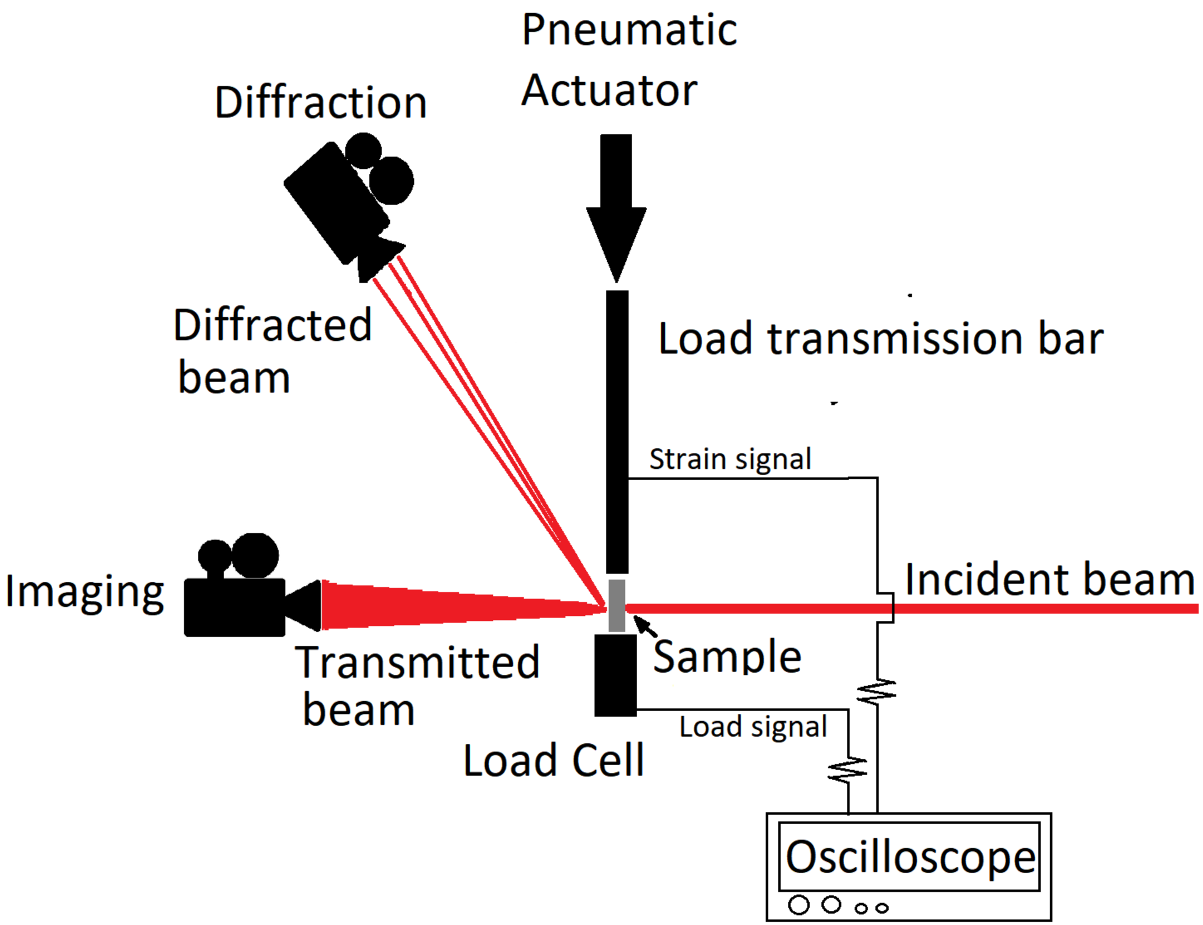


Peak-aged is 900 s at 423K

Strain Rate Effect in TWIP Ti-15Mo

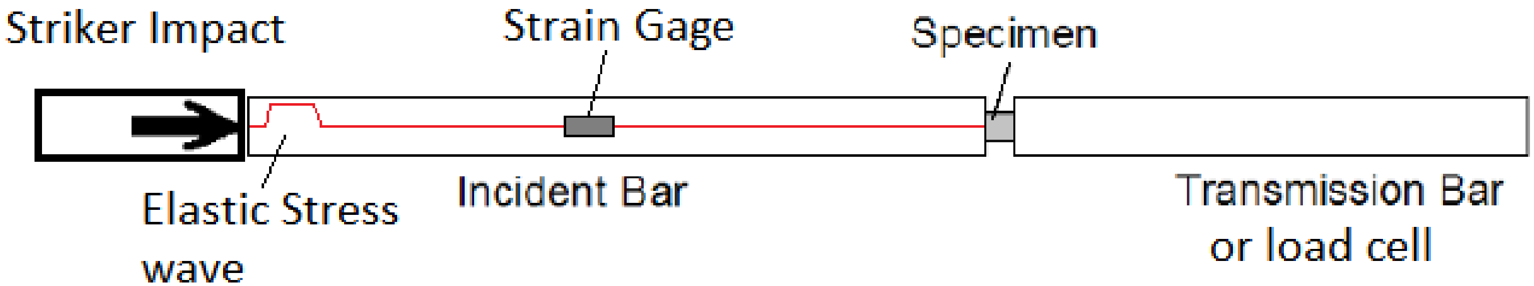


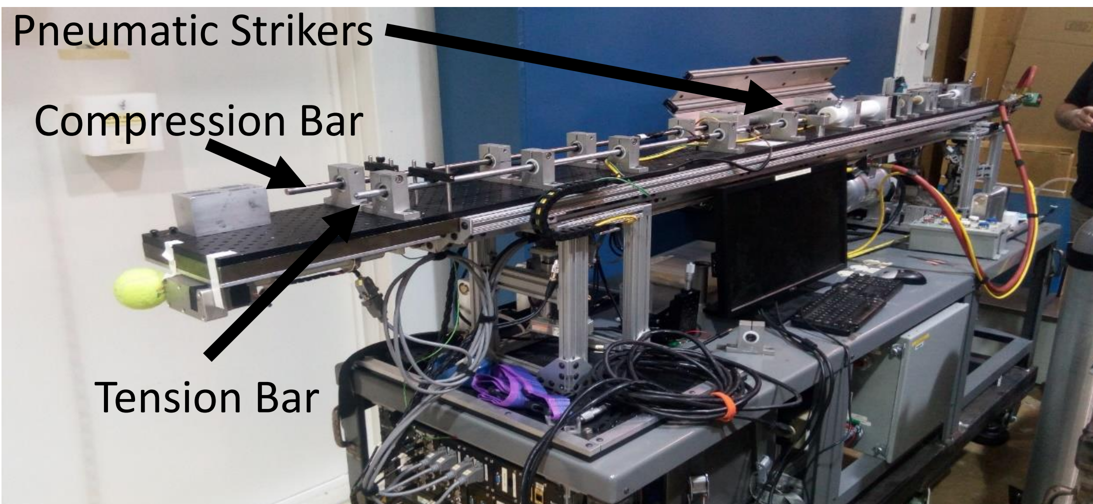
APS High-Rate In-situ Kolsky Bar

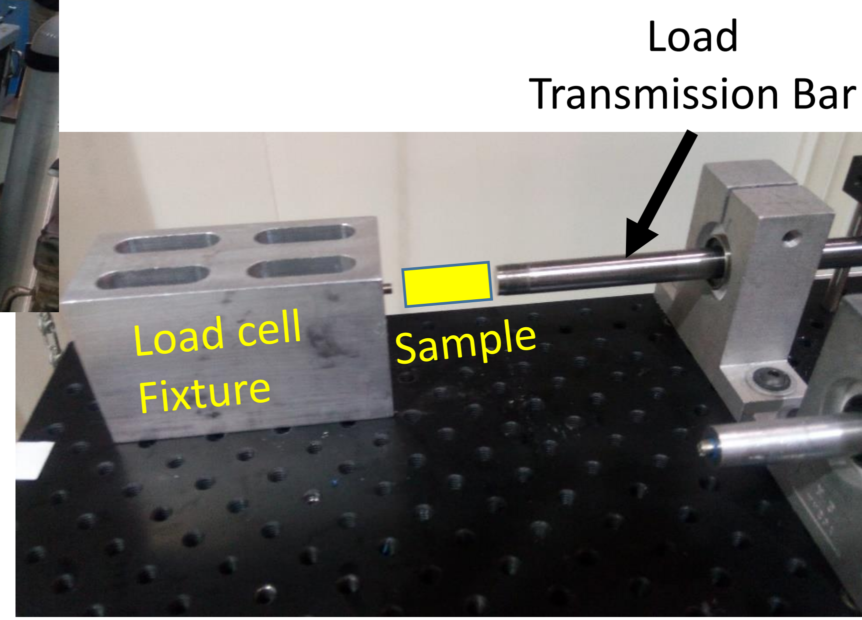


- Strain rates from 10^2 to 10^3/s in tension and compression
- Simultaneous measurement of diffraction, imaging and stress-strain data
- Time resolved data at high sampling rate, $2x10^{-8}$ s for mechanical data and $2x10^{-5}$ s for diffraction data

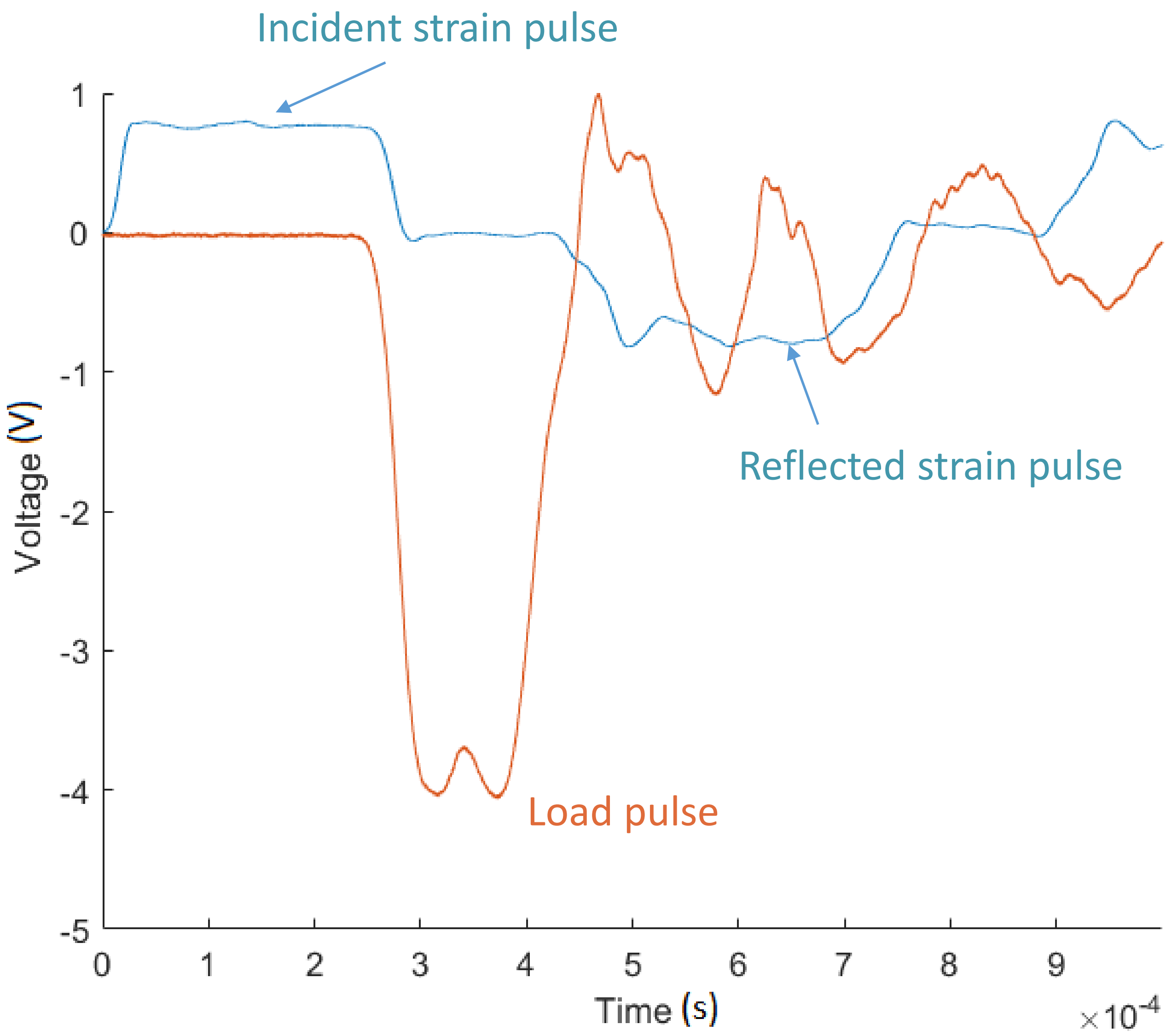
APS Kolsky Bar Setup







Kolsky Bar Raw Data



Post-Processing: Mechanical

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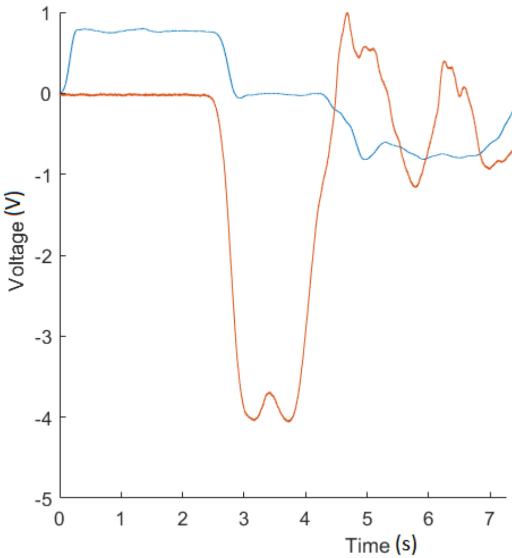
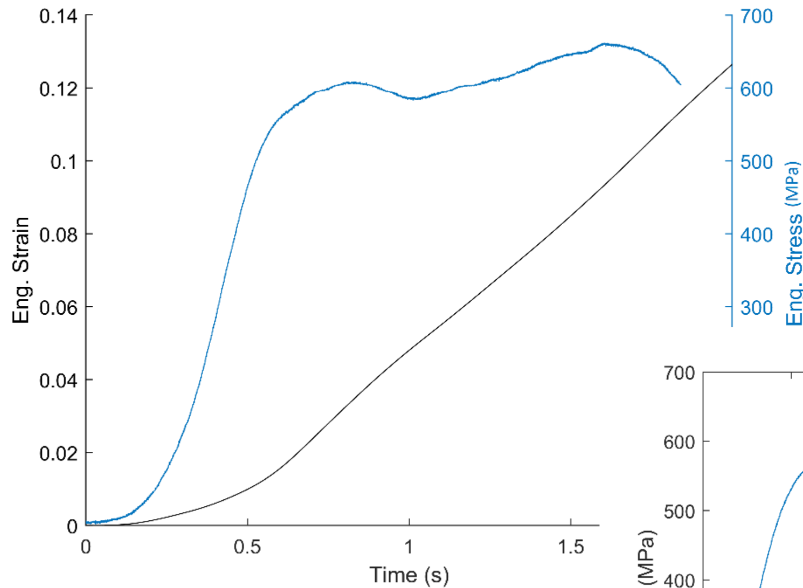
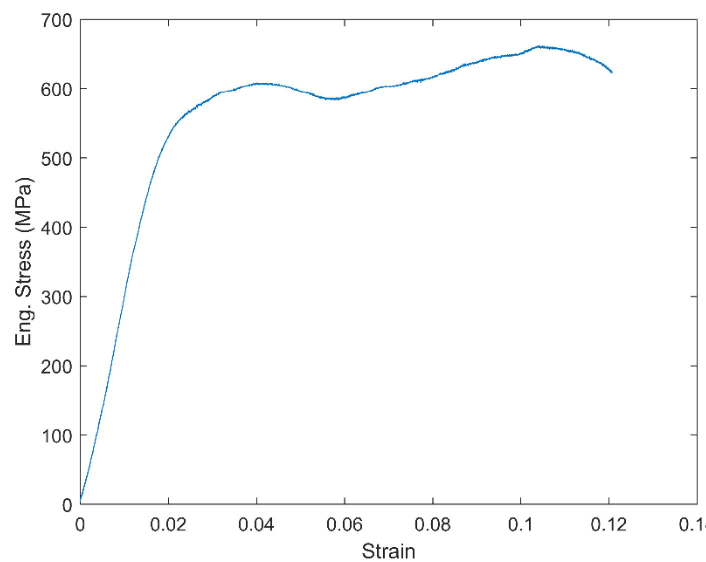


Raw data



Time-resolved strain and stress

Stress-strain curve



Post-Processing: Diffraction

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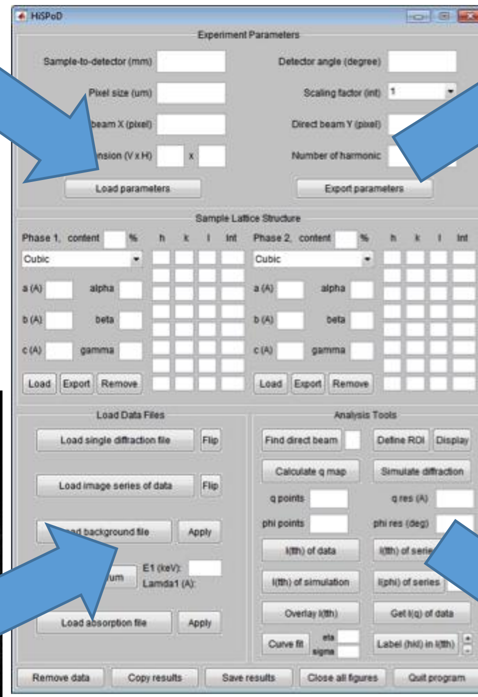
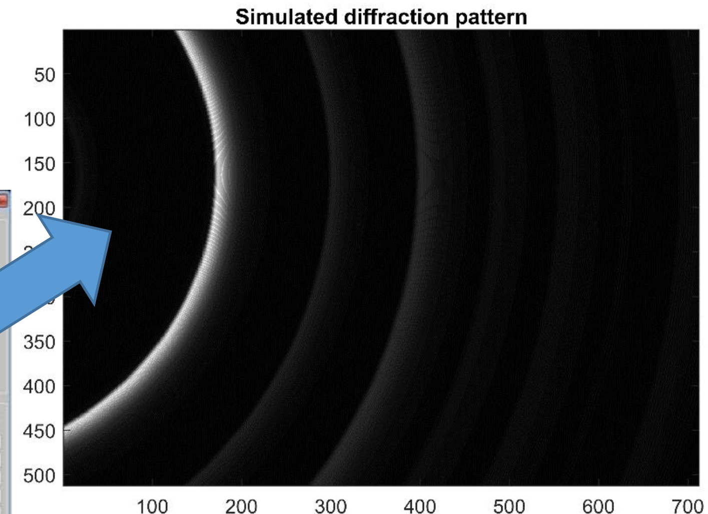
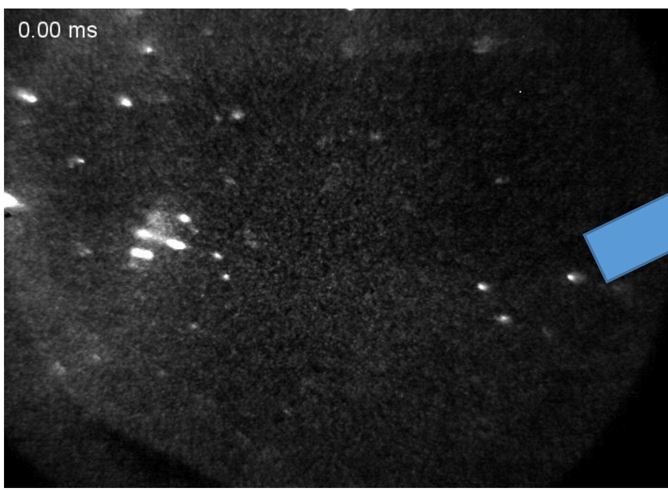
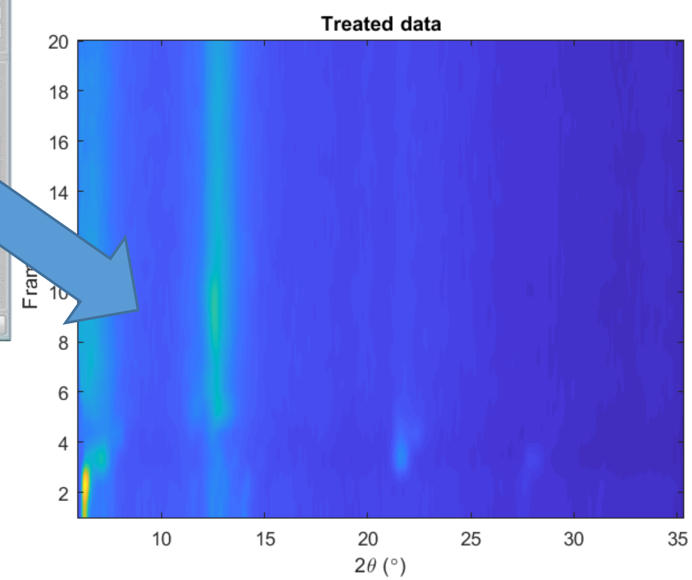
Lattice parameter
Space group
Structure factor
Volume fraction
Beam position
Energy spectrum

HiSPoD



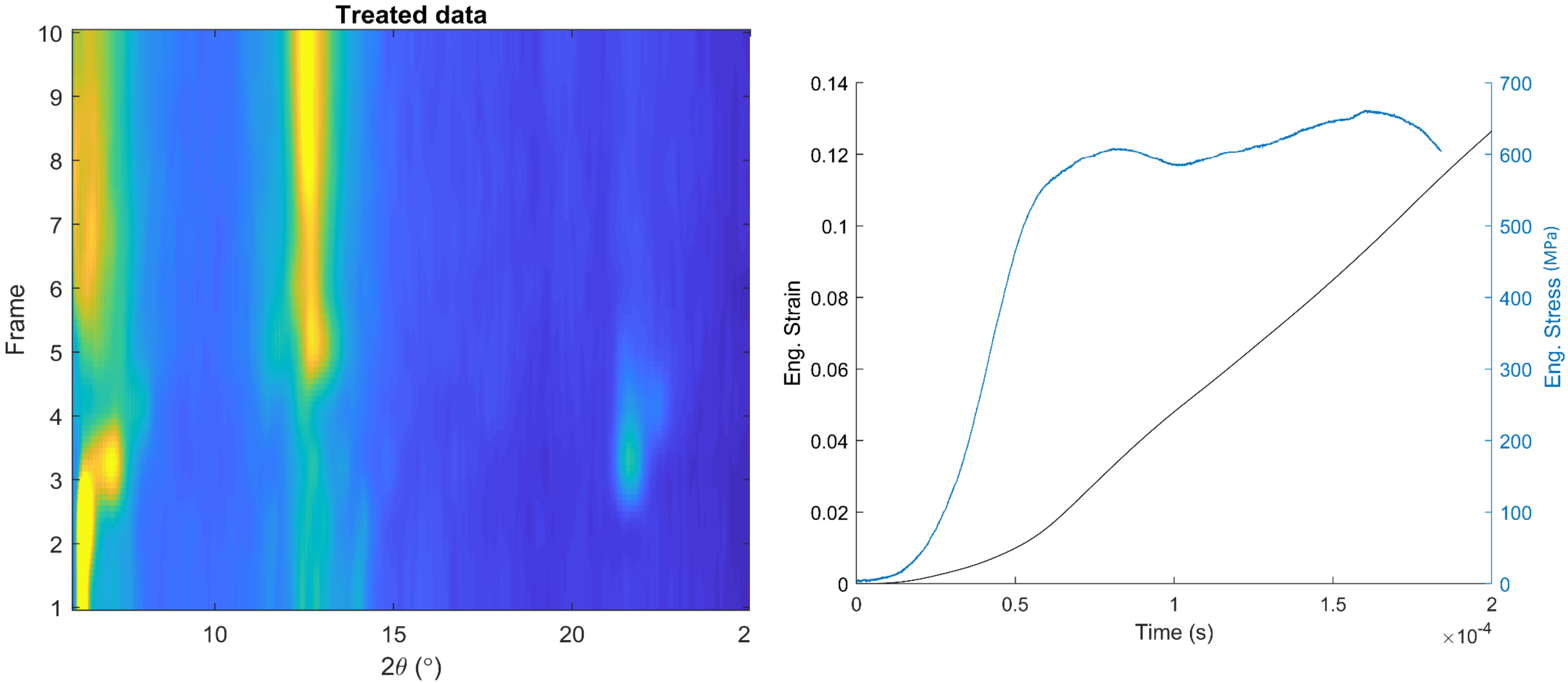






Example from a Ti-1023 Sample

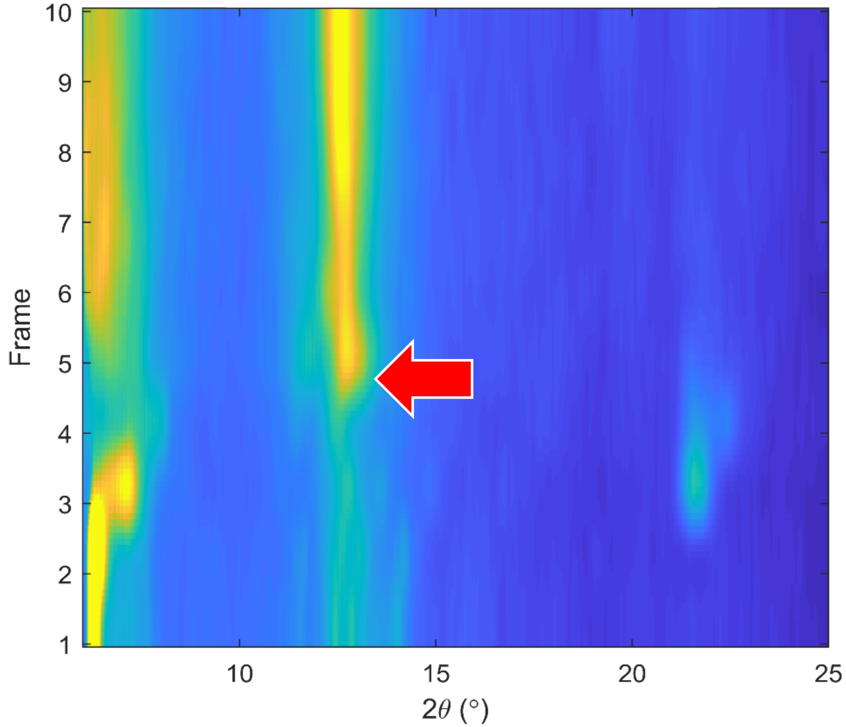
Exact synching remains to be done



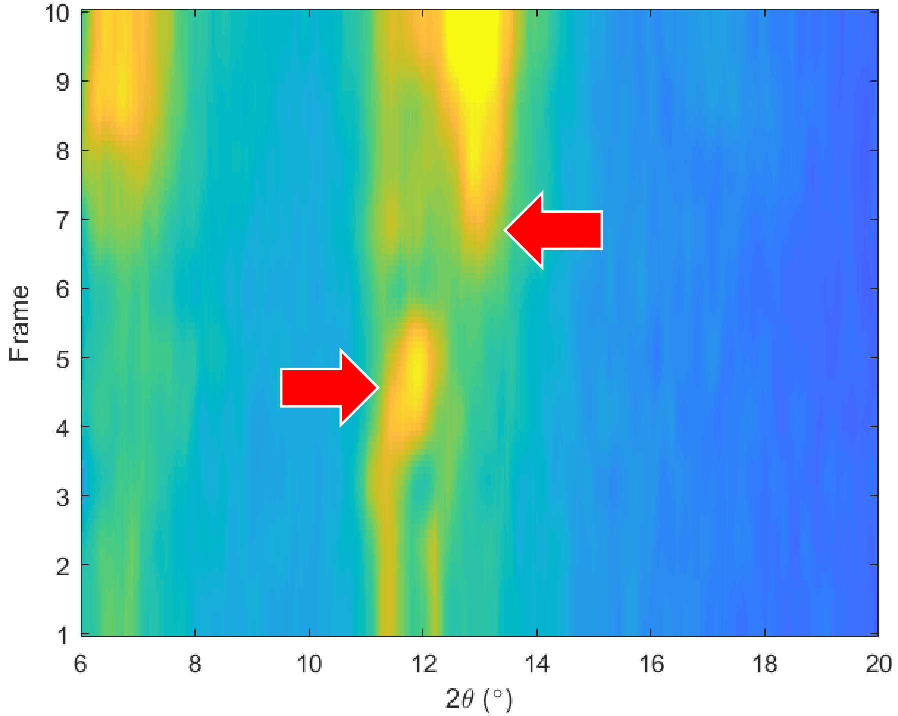
Each frame corresponds to 20 μs interval

Interpreting Diffraction Data

Ti-1023 sample F45



Ti-1023 sample F10

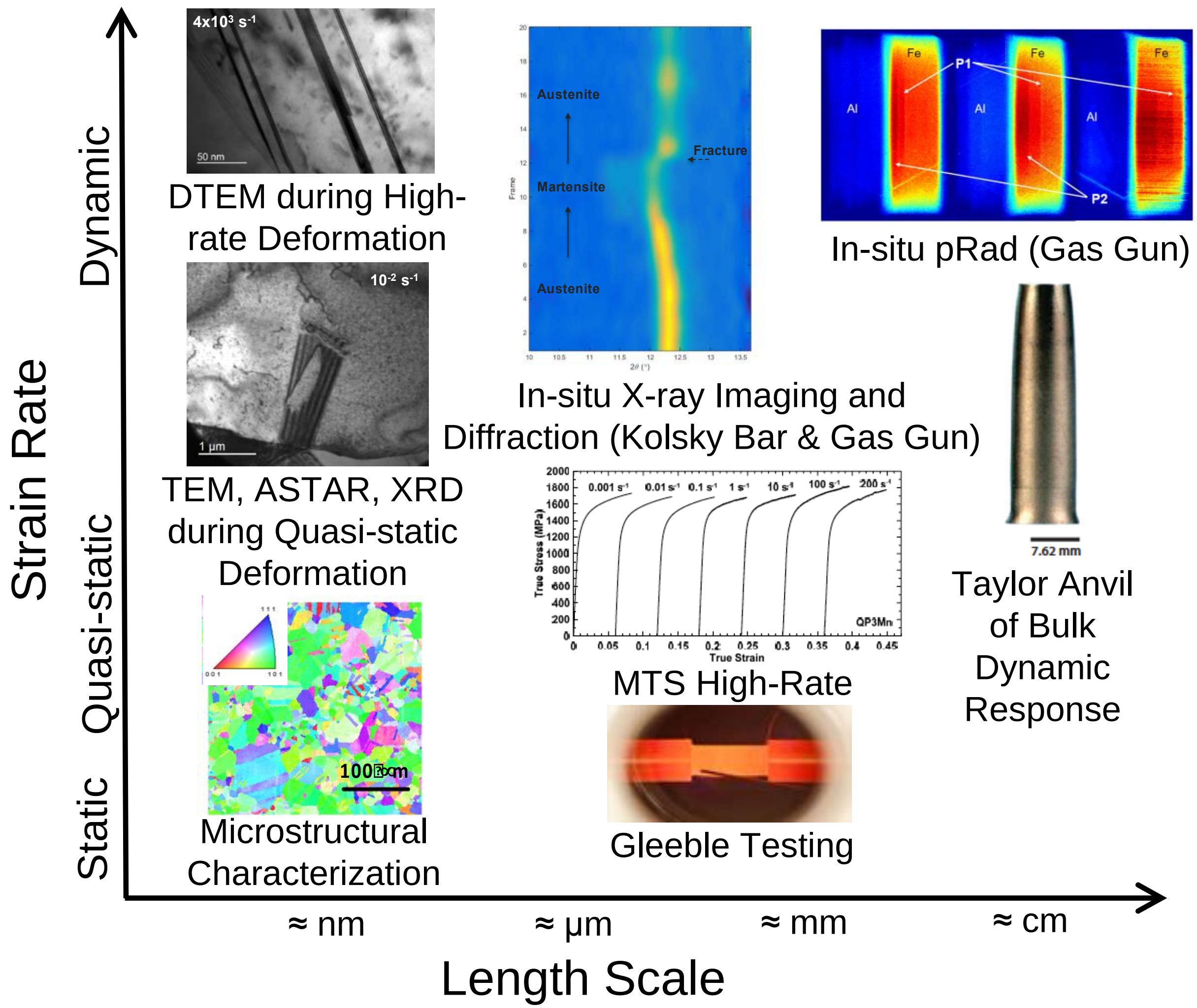


- Shift of peak intensity in 2θ indicates a phase change
- Increase in peak intensity indicates crystallite size refinement (twinning)

Upcoming work

- Synchronize and analyze mechanical/diffraction data from APS
  - ~46 valid data sets: 19 Ti-1023, 12 Ti-15Mo, 10 Ti-3510 and 5 TiZrNb
  - Bulk Kolsky bar testing at LANL
- Finish intermediate strain rate testing of Ti-1023 and Ti-15Mo
- TEM characterization of deformed material
  - In-situ quasi-static TEM straining at LLNL
- Investigate TWIP control mechanisms
- More Beamtime!
  - 2020 Winter/Spring trimester beamtime request approved at APS
  - CHESS proposal for in-situ quasi-static tensile testing has also been approved for the new year (2020)

Strain Rate Vs. Length Scale Overview: Current Progress



Strain Rate Vs. Length Scale Overview: Current Progress

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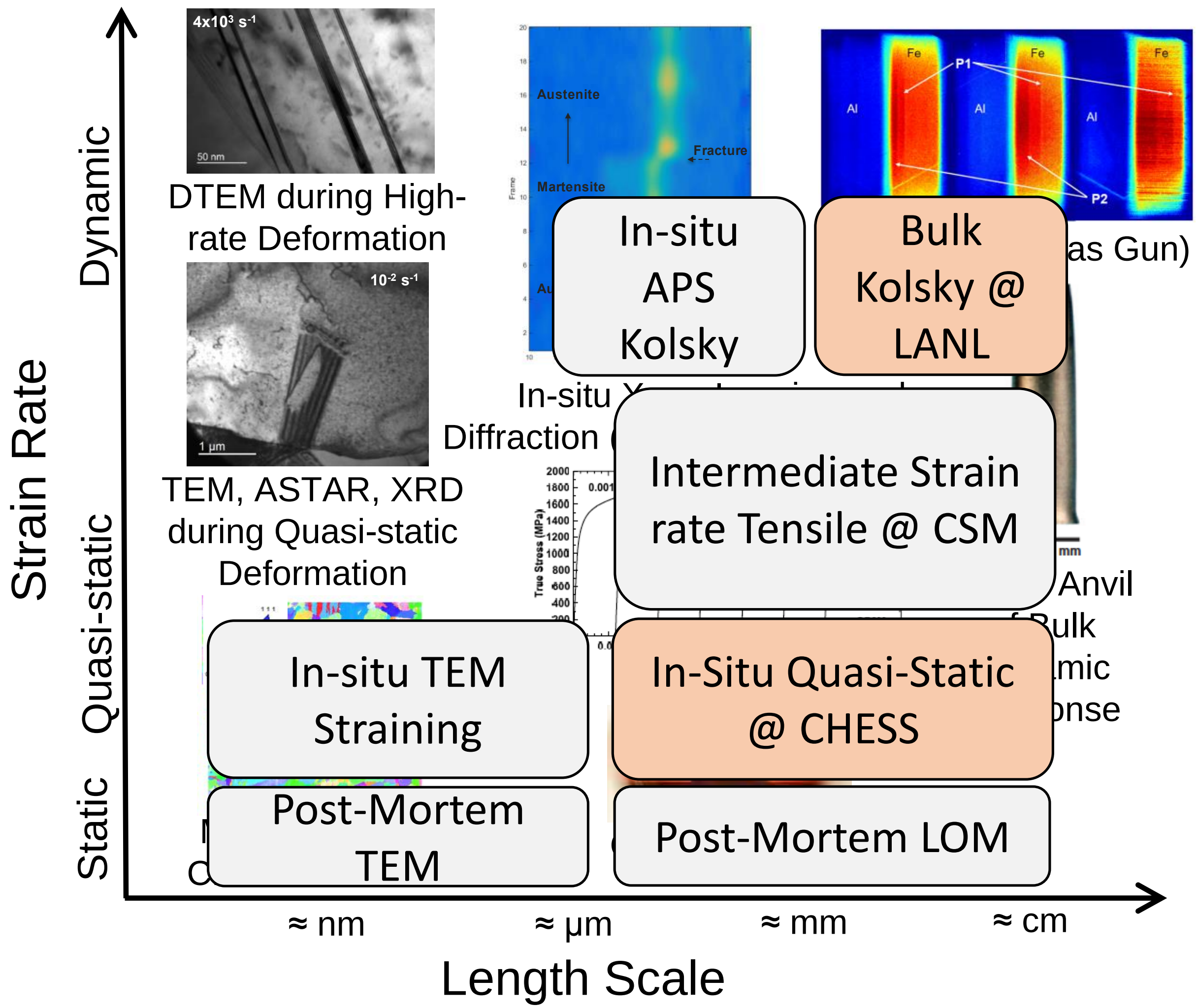

Progress

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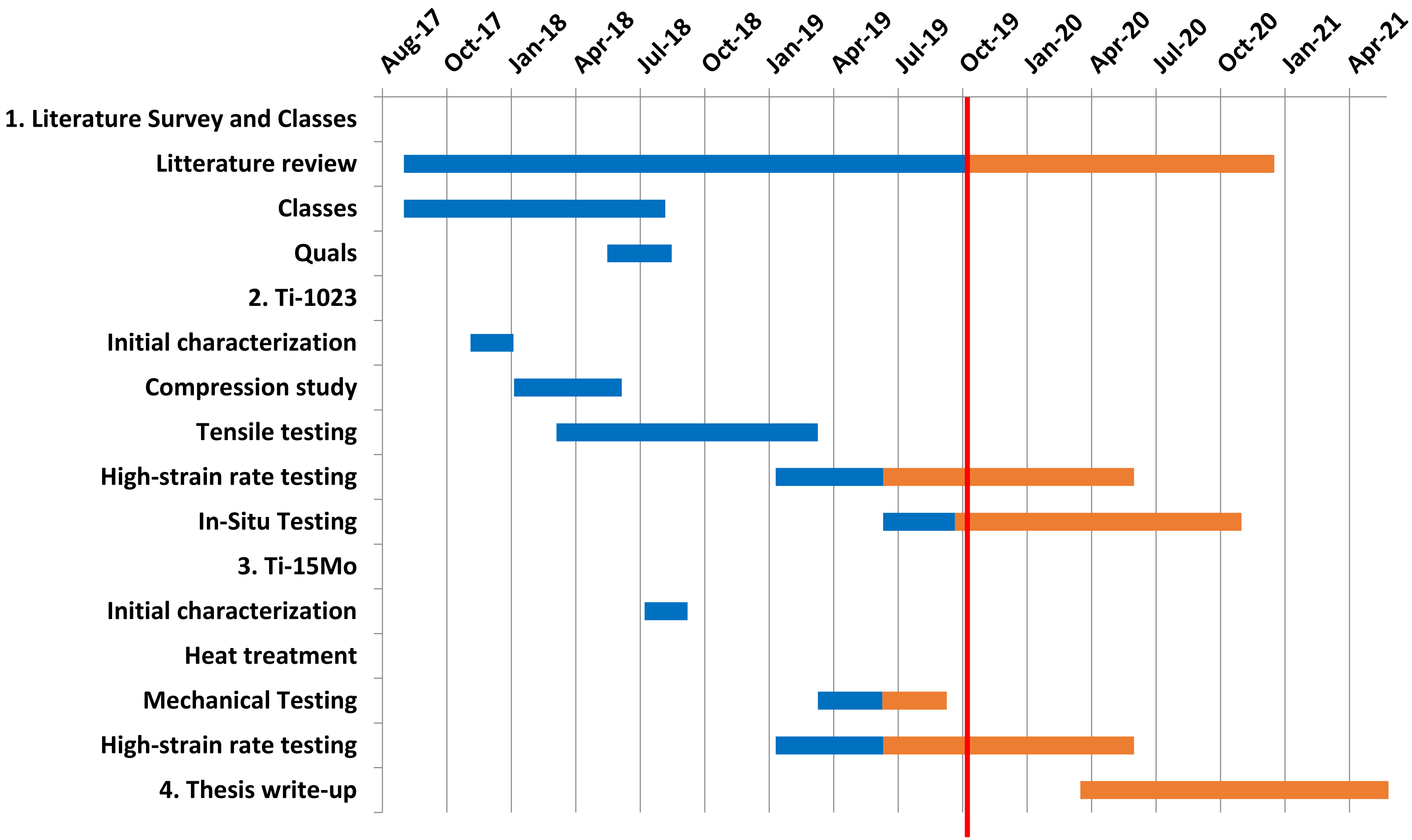

Challenges & Opportunities

- Fine-grained material for Synchrotron experiments is necessary for high-quality diffraction data and consistent small-scale mechanical data
- ω-phase strengthening of TRIP alloys presents a significant opportunity for novel alloy and heat treatment development
- Natural aging of TRIP Ti alloys also presents a novel un-explored avenue in Ti alloy design

Thank you!

Benjamin Ellyson

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