Project #33:In-situ Studies of Strain Rate Effects on Phase Transformations and Microstructural Evolution in β-Titanium and Multi-Principle Element Alloys

Spring 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
April 11-12, 2018

Student: Benjamin Ellyson (Mines)
Faculty: Amy Clarke (Mines)
Industrial Mentor(s): TBD
Other Participants: Yaofeng Guo (Mines)

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

- 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

- Heat treatment performed to obtain β phase microstructures that exhibit TRIP/TWIP
- Compressive testing of solution treated samples partially completed
- Investigation of low-temperature, short soak time treatments is under way
- Initial thermo-mechanical testing completed in the Gleeble

Metrics

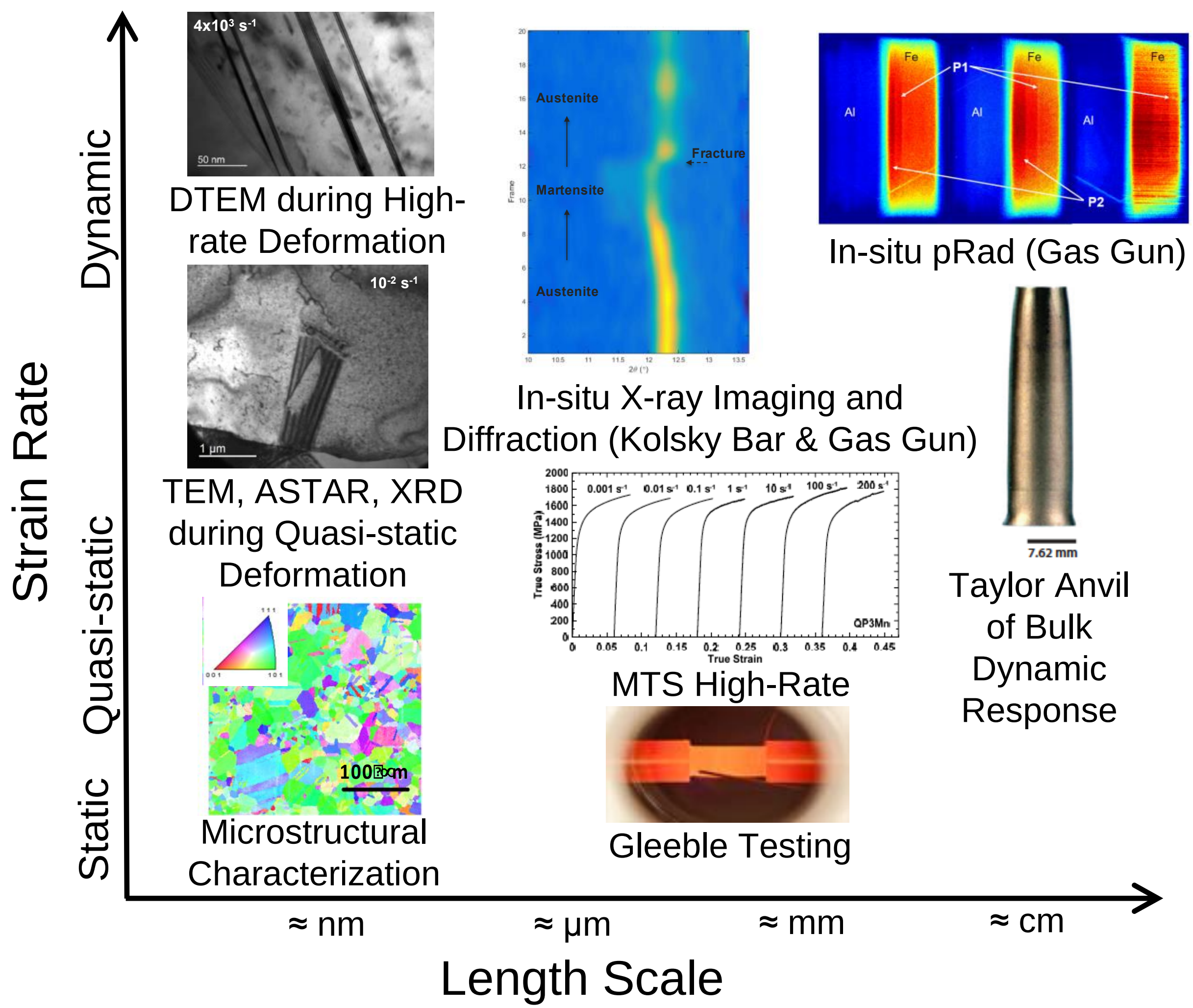
Description	% Complete	Status
1. β solution treatments	95%	●
2. Literature review	50%	●
3. High-throughput quasi-static compression testing to β solution heat treatment	90%	●
4. Optical microstructural characterization of pre and post compression conditions	80%	●
5. EBSD/TEM microstructural characterization of pre and post compression conditions	10%	●

Industrial Relevance: Development of Blast Resistant Materials for the Navy

- **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

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



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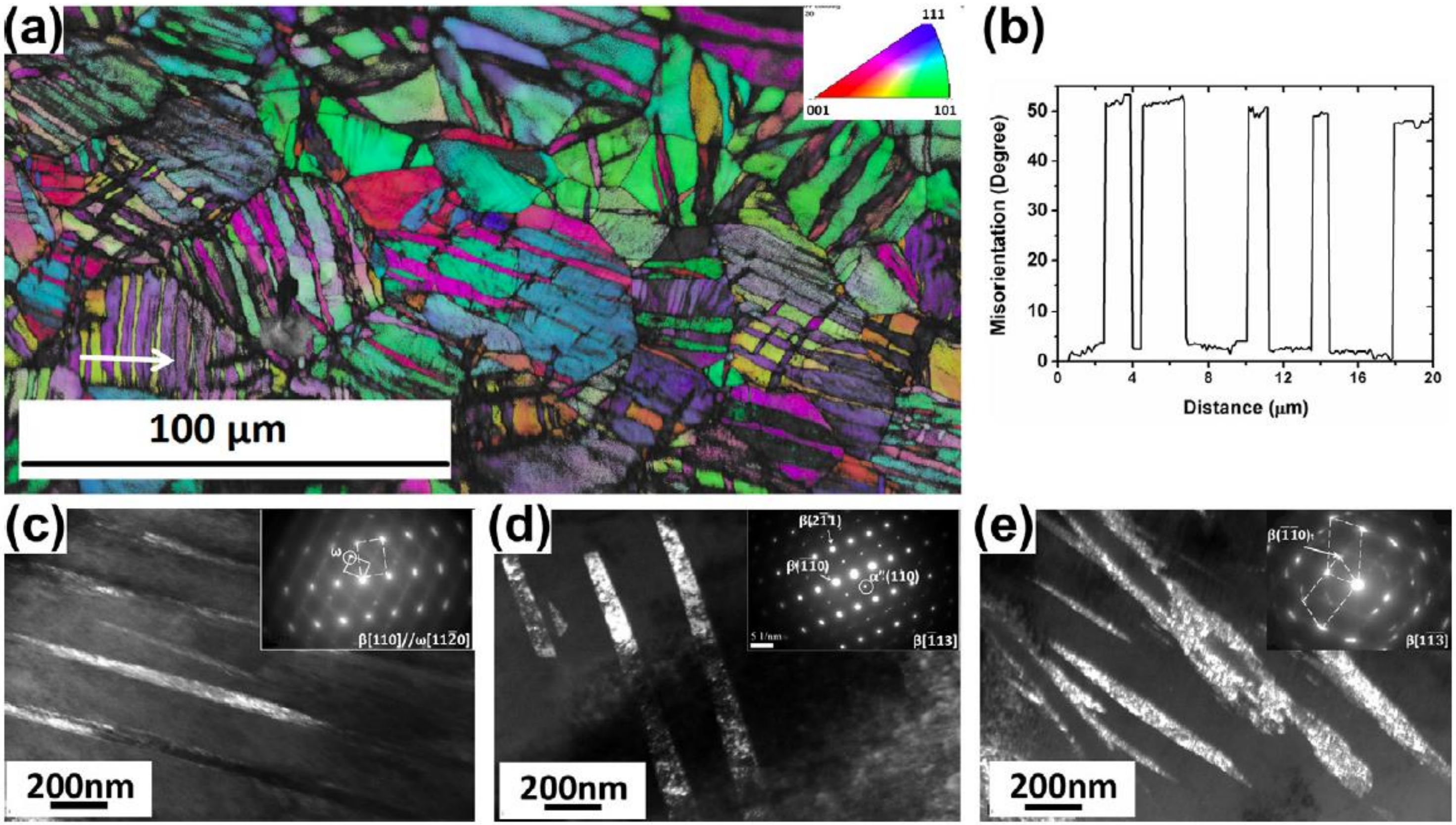
Ti-25Nb-3Zr-3Mo-2Sn (wt.%) Alloy Microstructure After Deformation at 10^{-3} s^{-1} and 0.18 True Strain



Deformation-induced ω phase

Deformation-induced α□ phase

{112}<111> β mechanical twinning

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

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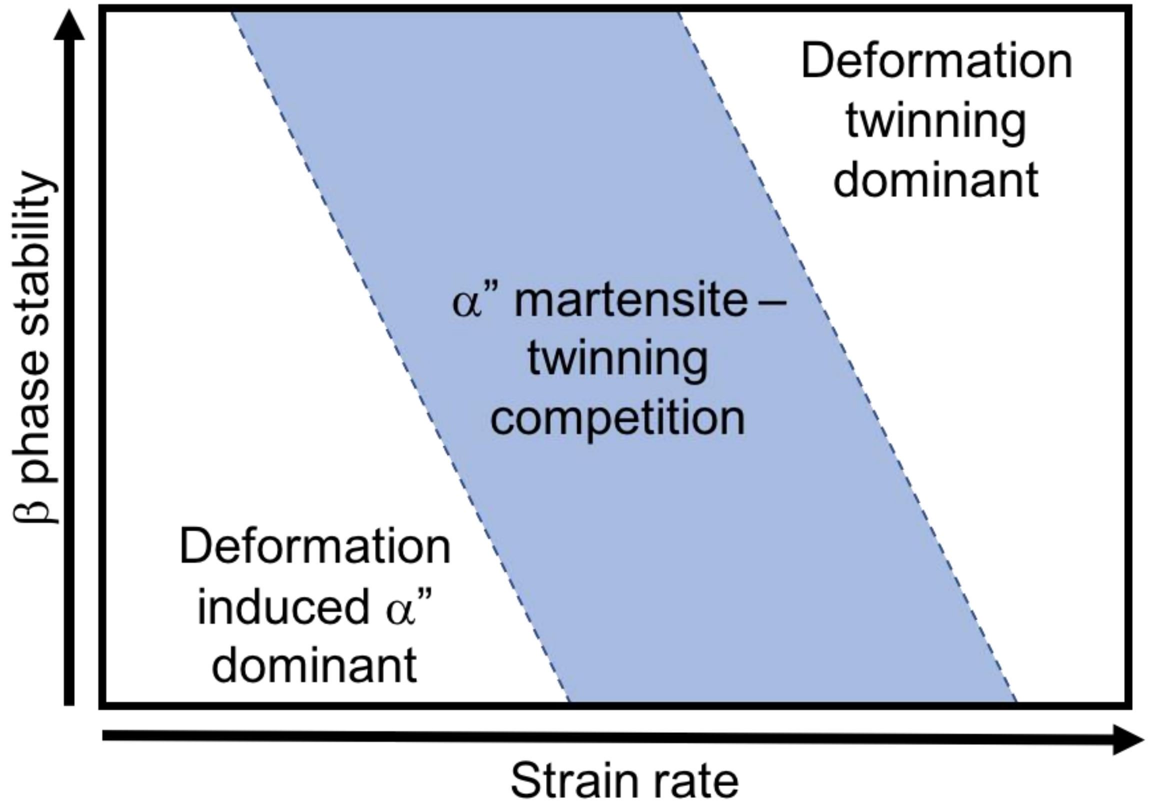
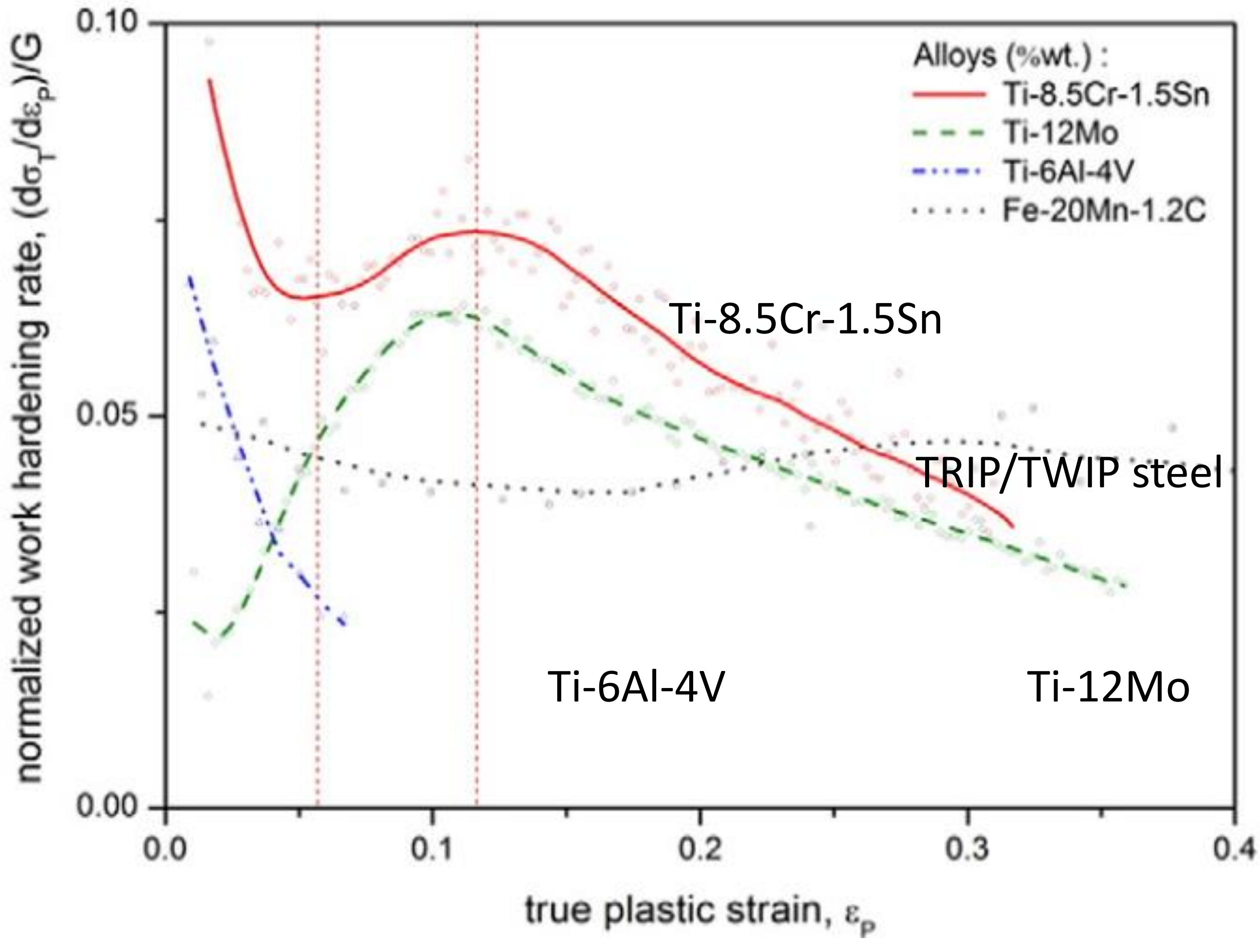
The Effect of Strain Rate (10^{-3}, 10^{-1}, 10^{1}, 10^{2} s^{-1}) on Deformation Mechanisms during Compression of a Ti-10V-3Fe-3Al (wt.%) Alloy

- **As strain rate increases:**
  - Stress-induced α” martensite (dominant) + {332}<113> β twinning + stress-induced ω phase + slip
  - Stress-induced α” martensite + {332}<113> β twinning + stress-induced ω phase + slip
  - 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



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

Ti-1023 Heat Treatments to Obtain Fully β Microstructures

To promote TRIP/TWIP:

- Single phase β microstructure
- Fully homogenized
- Small grain size promotes TRIP
- Large grain size promotes TWIP

Li, C., et al. *Materials Science and Engineering: A* 528.18 (2011): 5854-5860
Bhattacharjee, A., et al. *Scripta materialia* 53.2 (2005): 195-200

Solution Heat Treatment Matrix

- Hold temperature and quench rate effect on martensite fraction
- Response surface for martensite phase fraction dependence
- Water and helium to vary quench rate

Temp (°C)	Time (h)	Quench medium
900	2	Water or He
1000	2	Water or He
1100	2	Water or He
1200	2	Water or He

Sample Nomenclature

Sample denomination will be as follows:

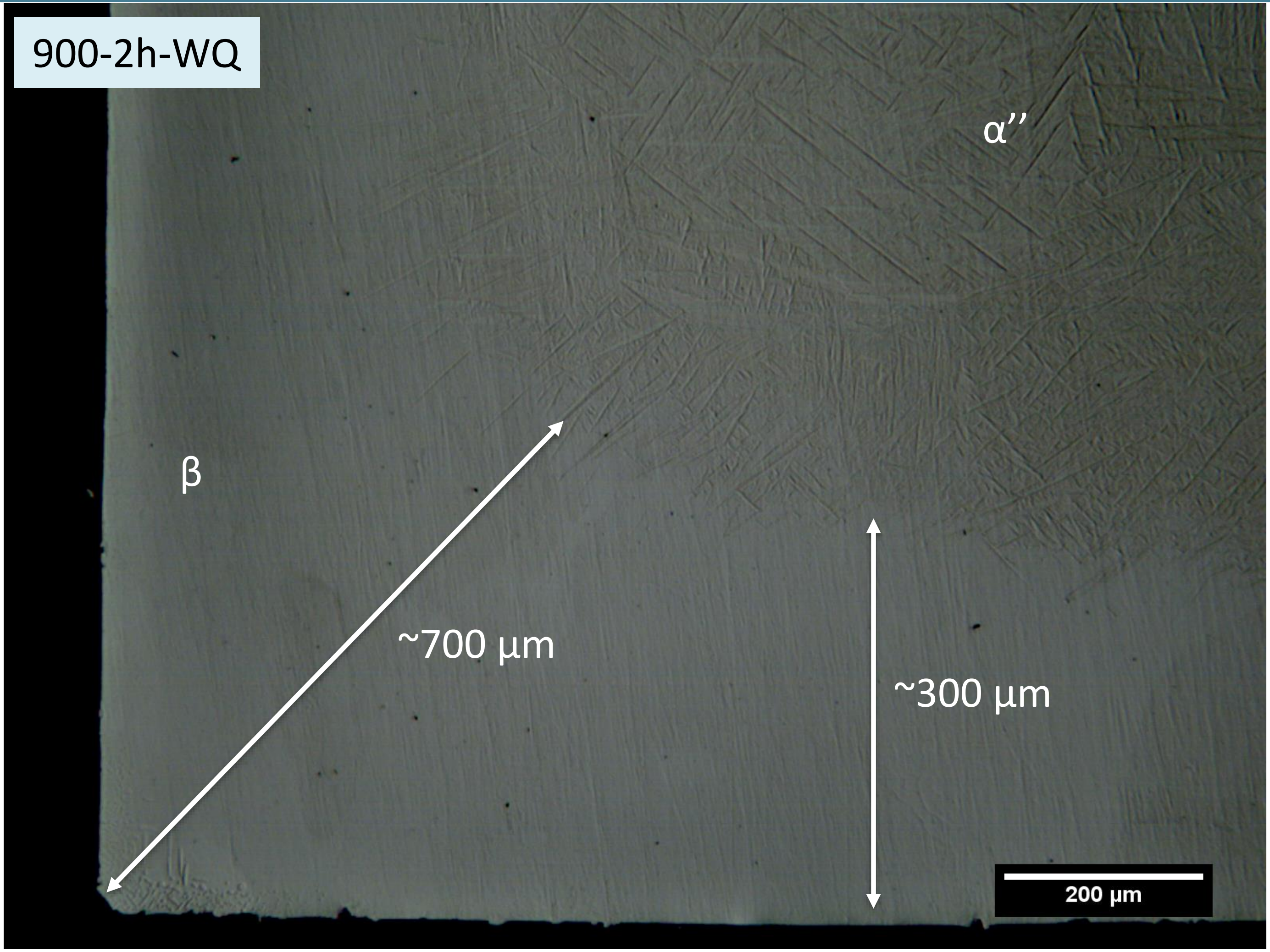
Temperature-time-quench-condition

900-2h-WQ-pre

900-2h-WQ-post

900-2h-WQ-10^{-2}

Preliminary Water Quench Results



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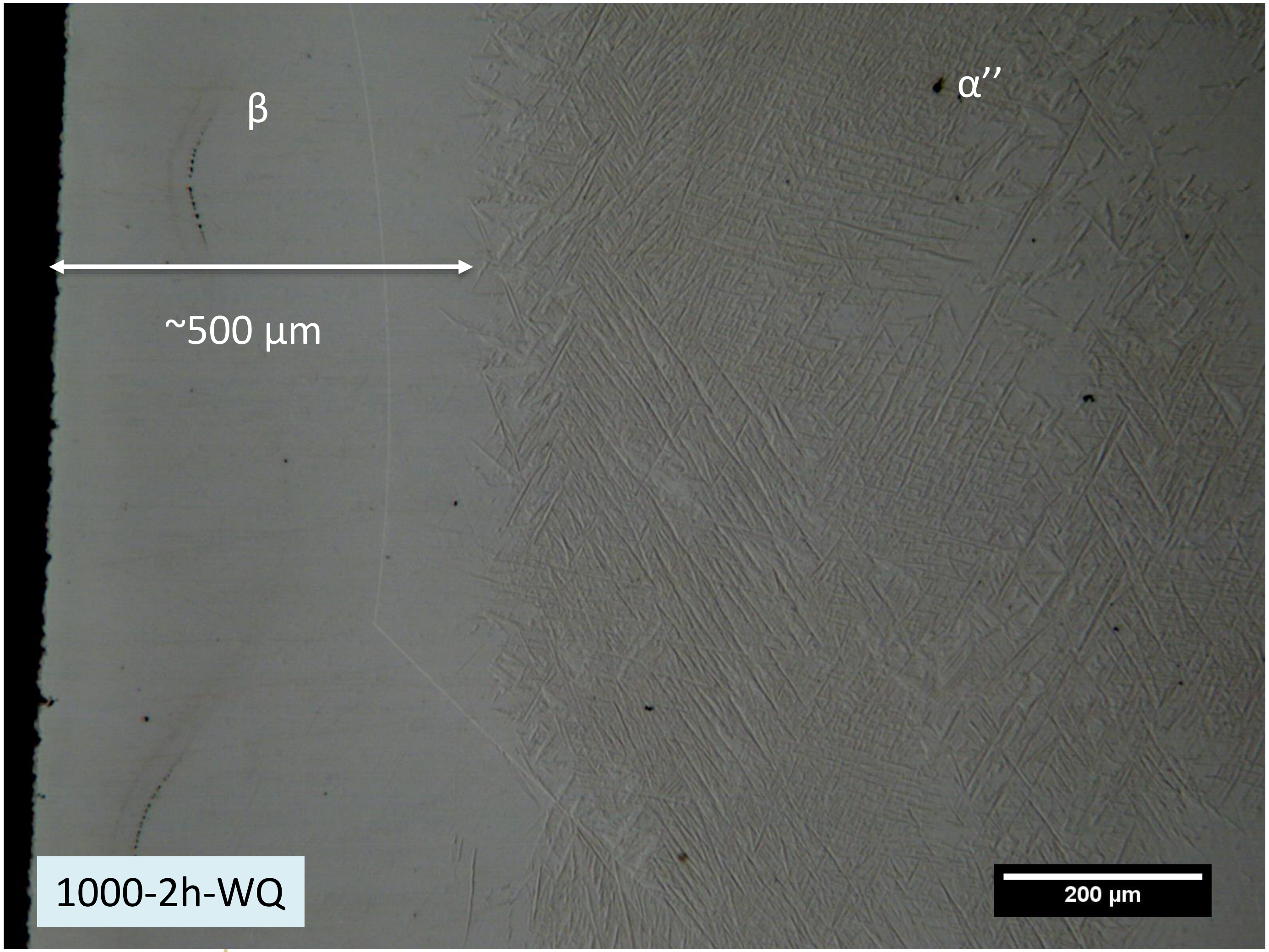
Representative of 1000°C and 1100°C



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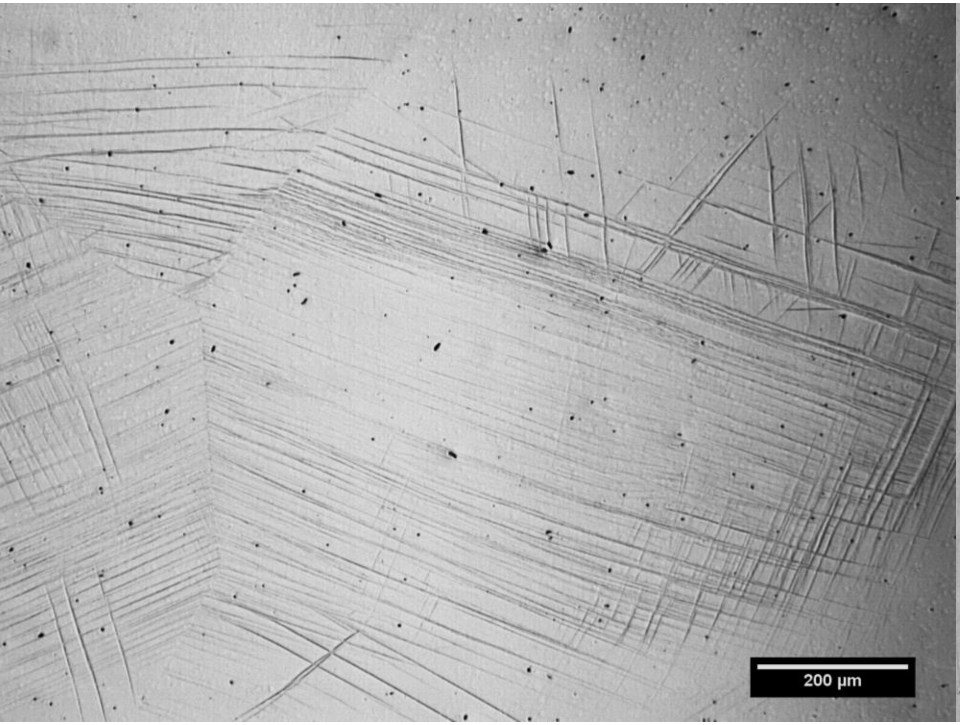
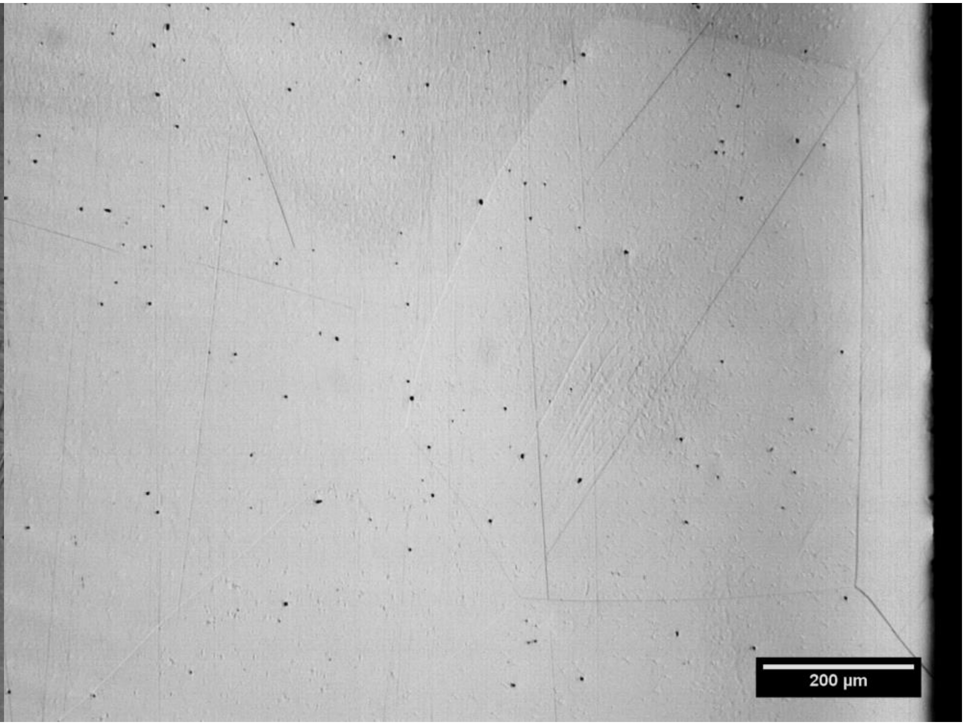
Challenges in Obtaining Fully β Microstructures in Ti-1023

- Obtaining a fully-retained β structure in Ti-1023 requires severe quench rates and thin sections

Bhattacharjee, A., et al. *Scripta materialia* 53.2 (2005): 195-200
Duerig, T. W., et al. Acta Metallurgica30.12 (1982): 2161-2172
Neelakantan, S., et al. Materials Science and Technology 25.11 (2009): 1351-1358

1200-2h-WQ Exhibits Larger Grain Size and Inhomogeneous Response





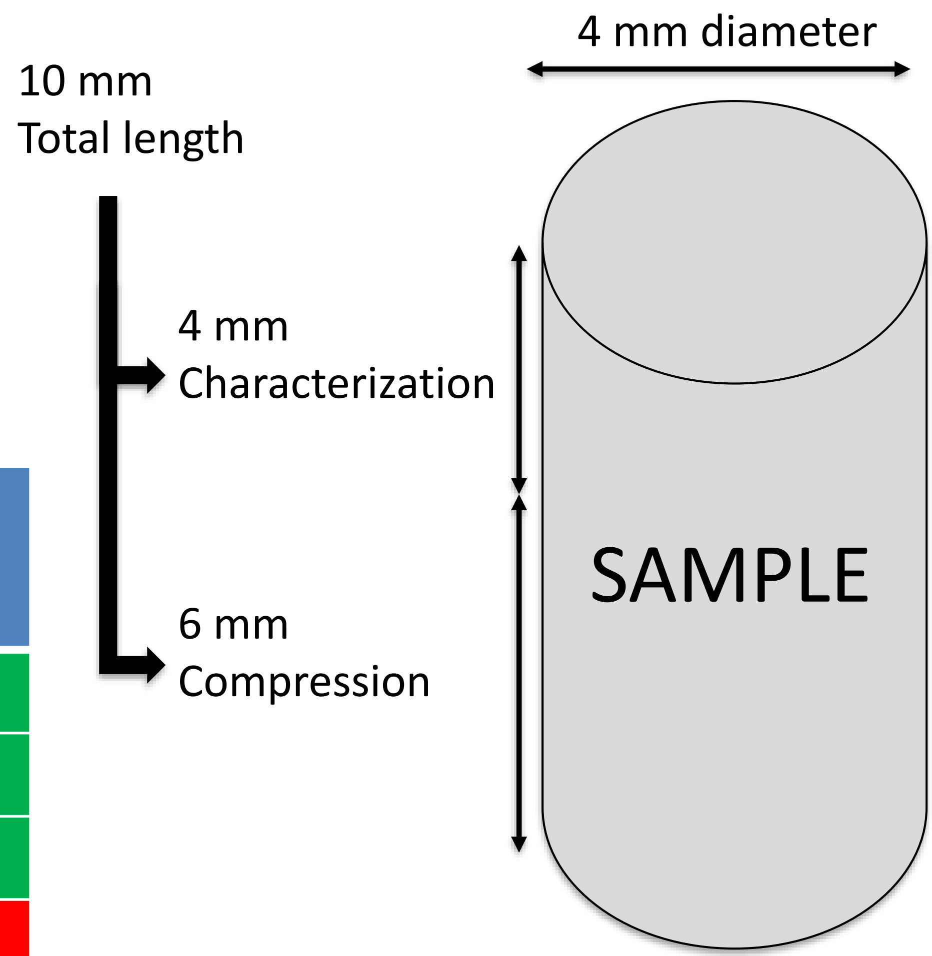
Less nucleation sites for martensite

Lessons Learned

Factors controlling the ability to produce fully β microstructures:

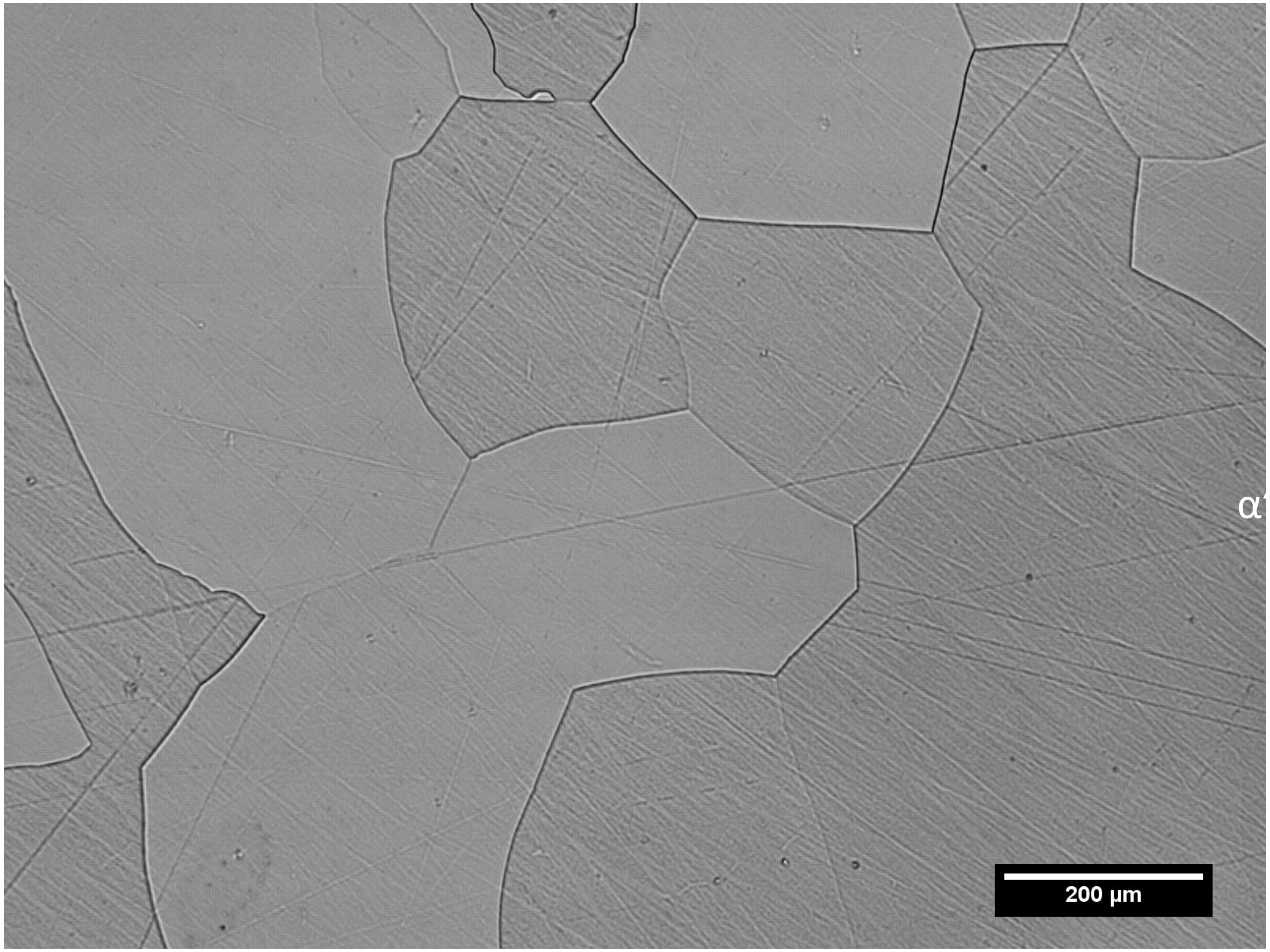
- Sample size
- Quench delay
- Quench rate
- Grain size

Sample Geometry - Compression

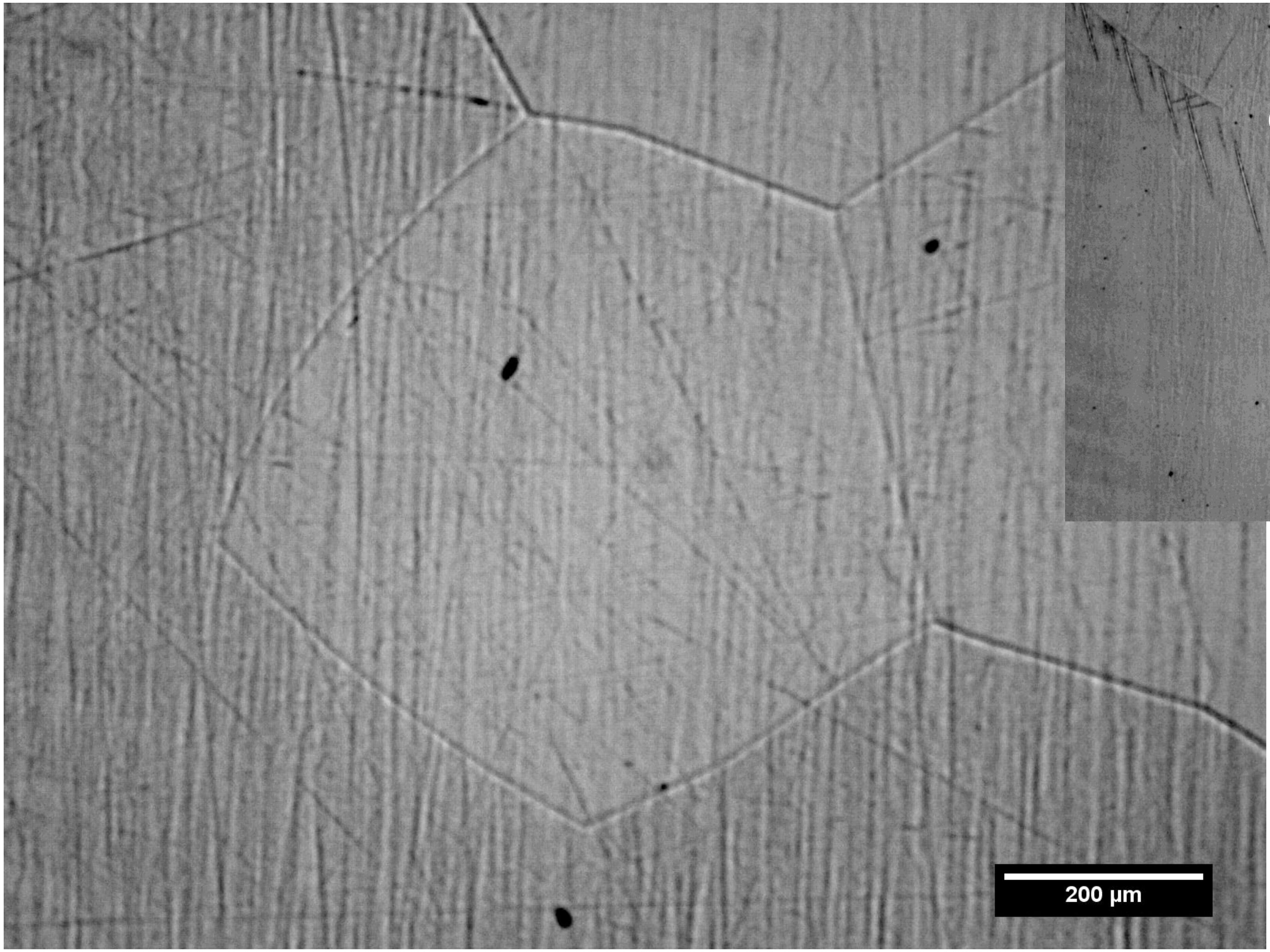


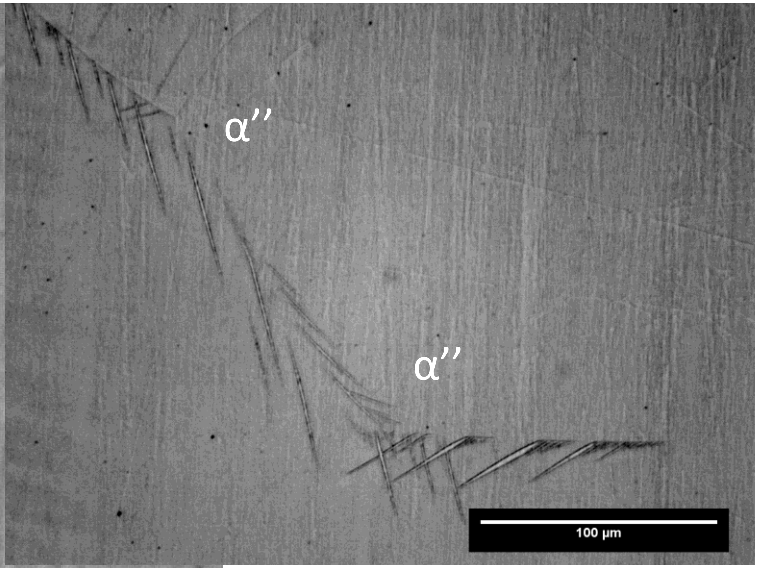
Temperature (°C)	Helium Quench	Water Quench
900		
1000		
1100		
1200		

900-2h-HeQ-pre Exhibits Equiaxed β

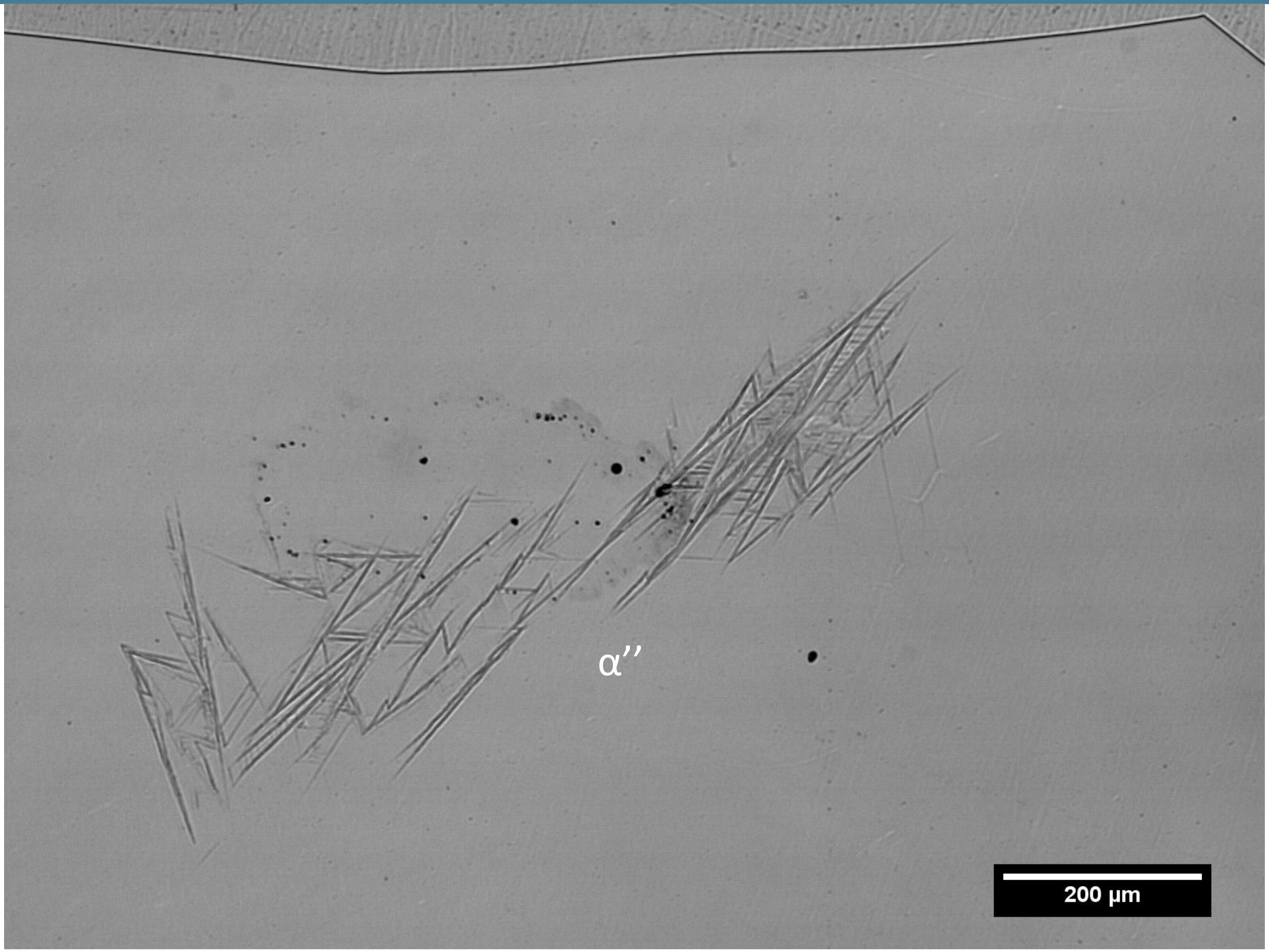


1000C-2h-WQ-pre equiaxed β

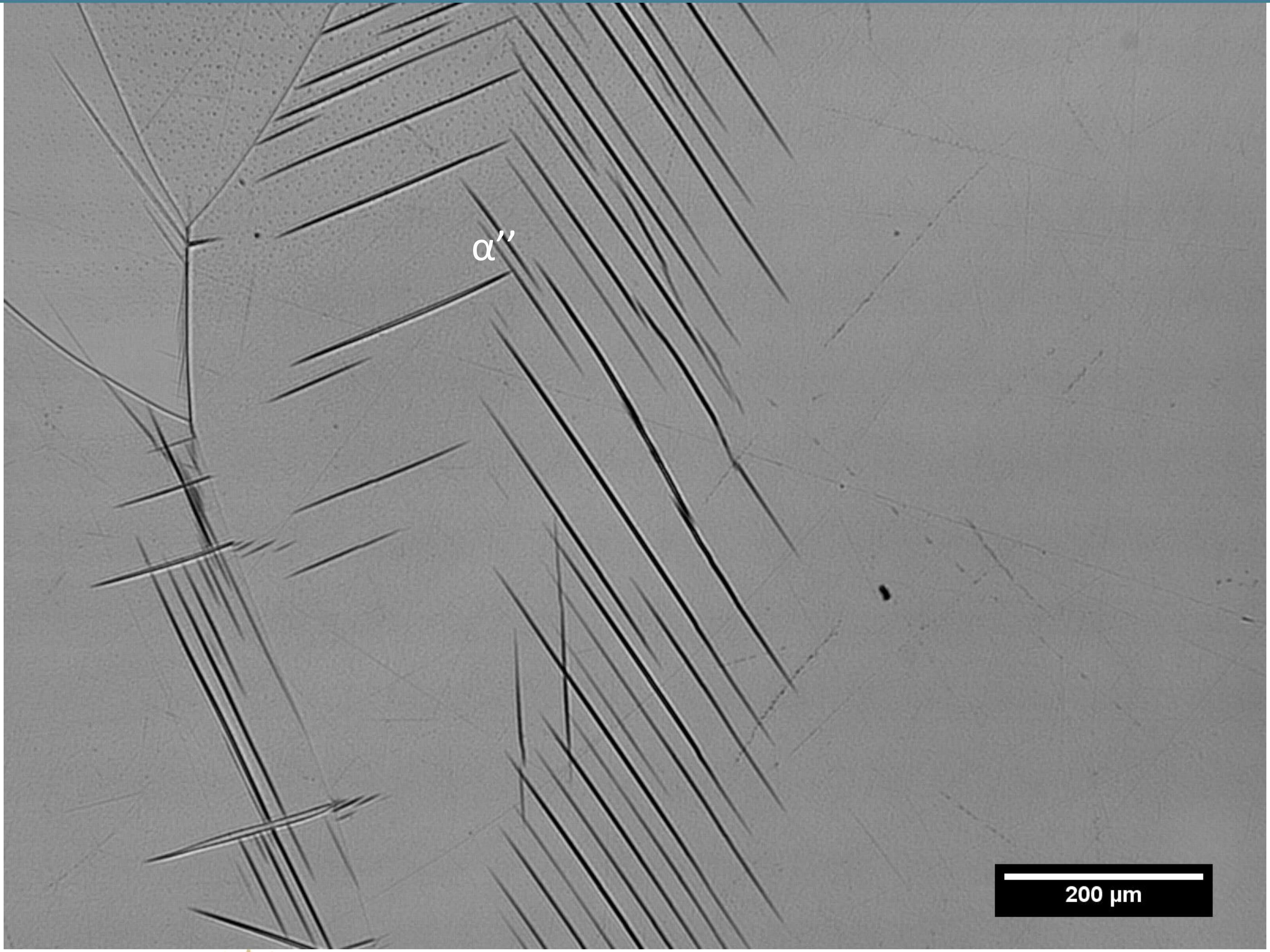




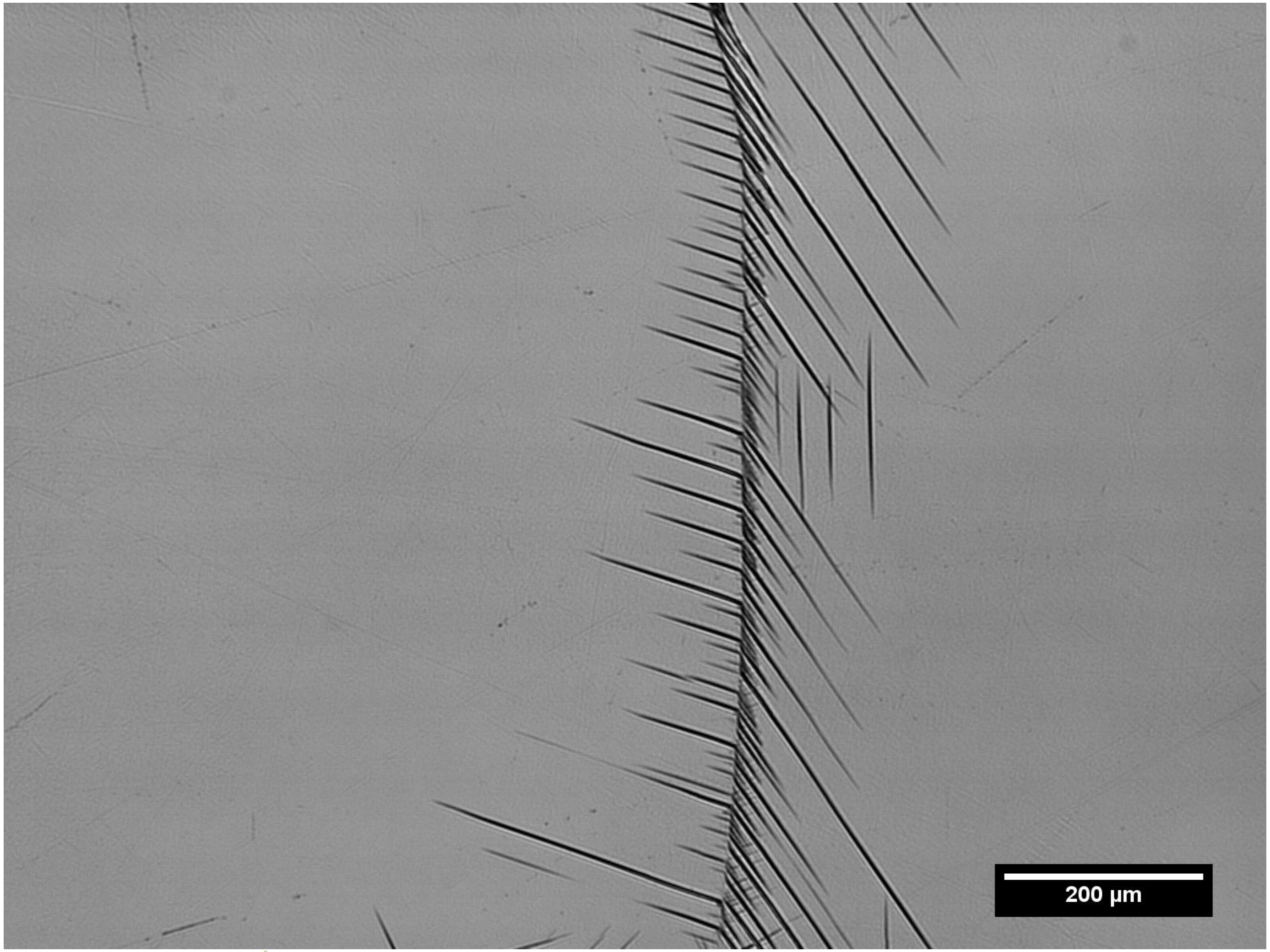
1100C-2h-HeQ-pre equiaxed β



Traces of α” in the 1200-2h-HeQ-pre



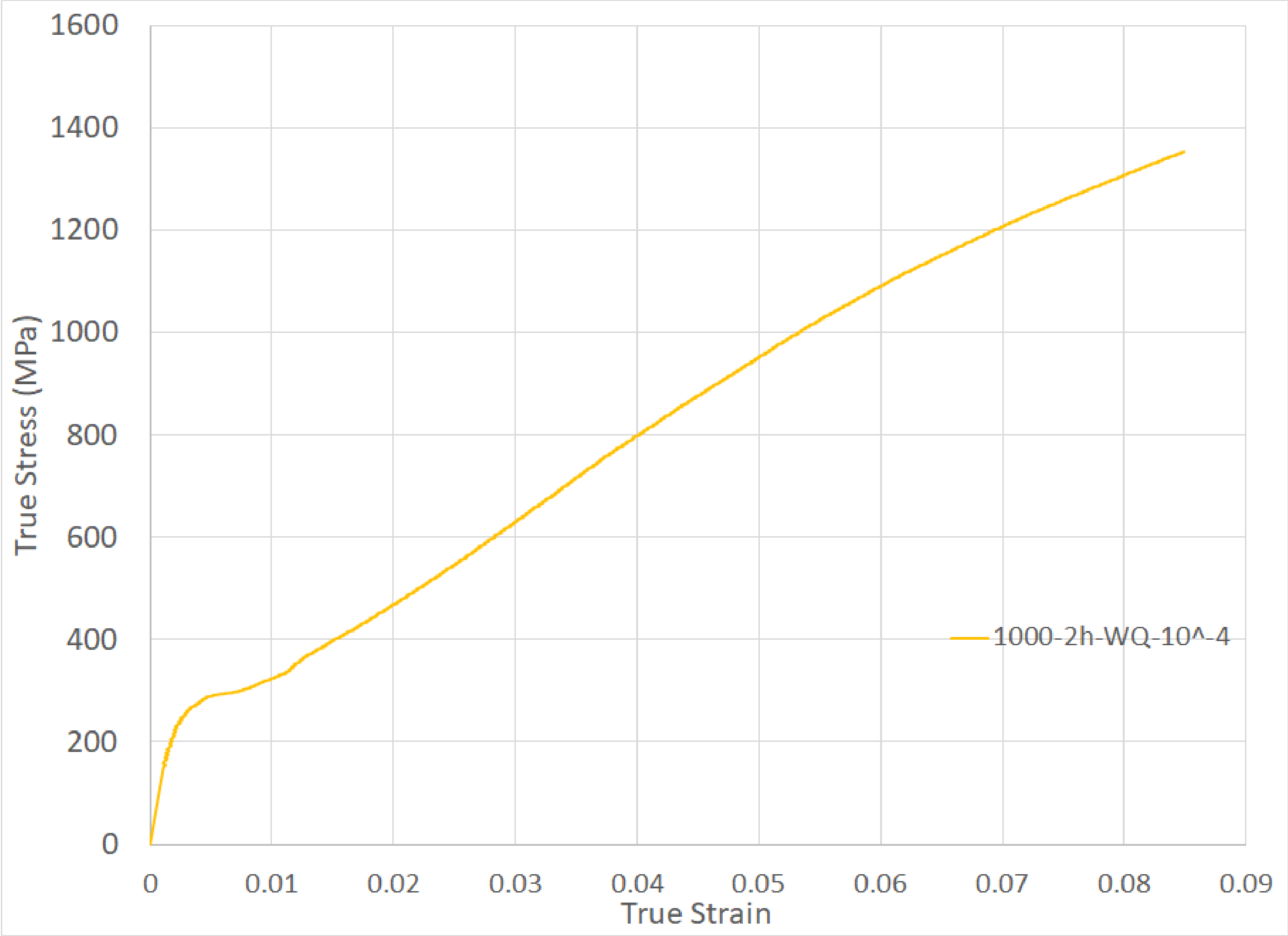
Only a Single Grain Boundary in the 1200-2h-HeQ-pre cross-section



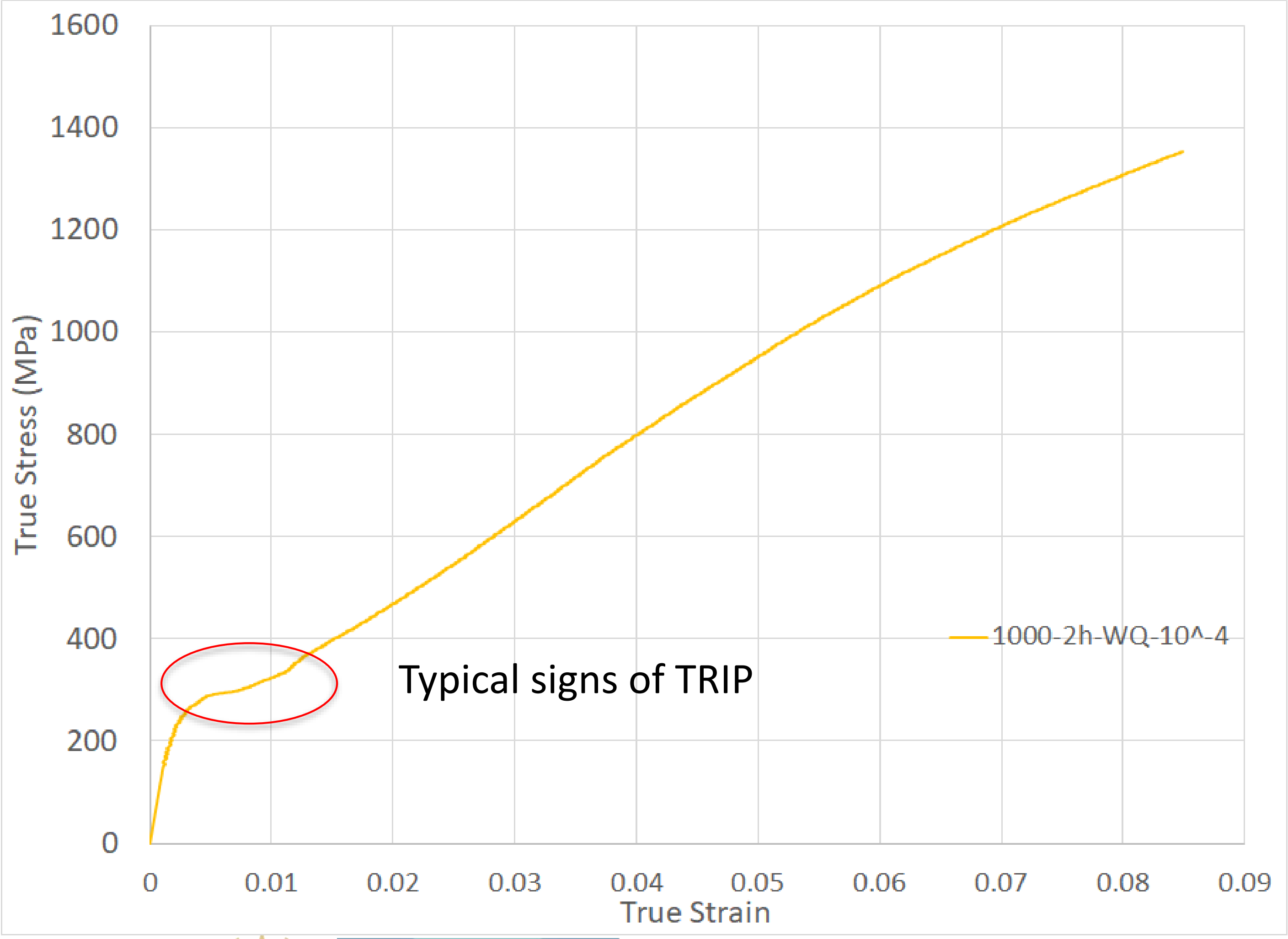
Optical Microstructural Characterization Summary

Condition	Martensite Fraction	# of Grains in Φ4 mm Cross Section
900-2h-WQ	~ 15%	~50
900-2h-HeQ	~ 2%	~ 60
1000-2h-WQ	< 1%	~ 17
1000-2h-HeQ	~ 0%	~ 12
1100-2h-HeQ	~ 2%	~ 3
1200-2h-HeQ	~ 6% (only @ GB)	~ 2

Compression of 1000-2h-WQ at 10^{-4} /s



Compression of 1000-2h-WQ at 10^{-4} /s



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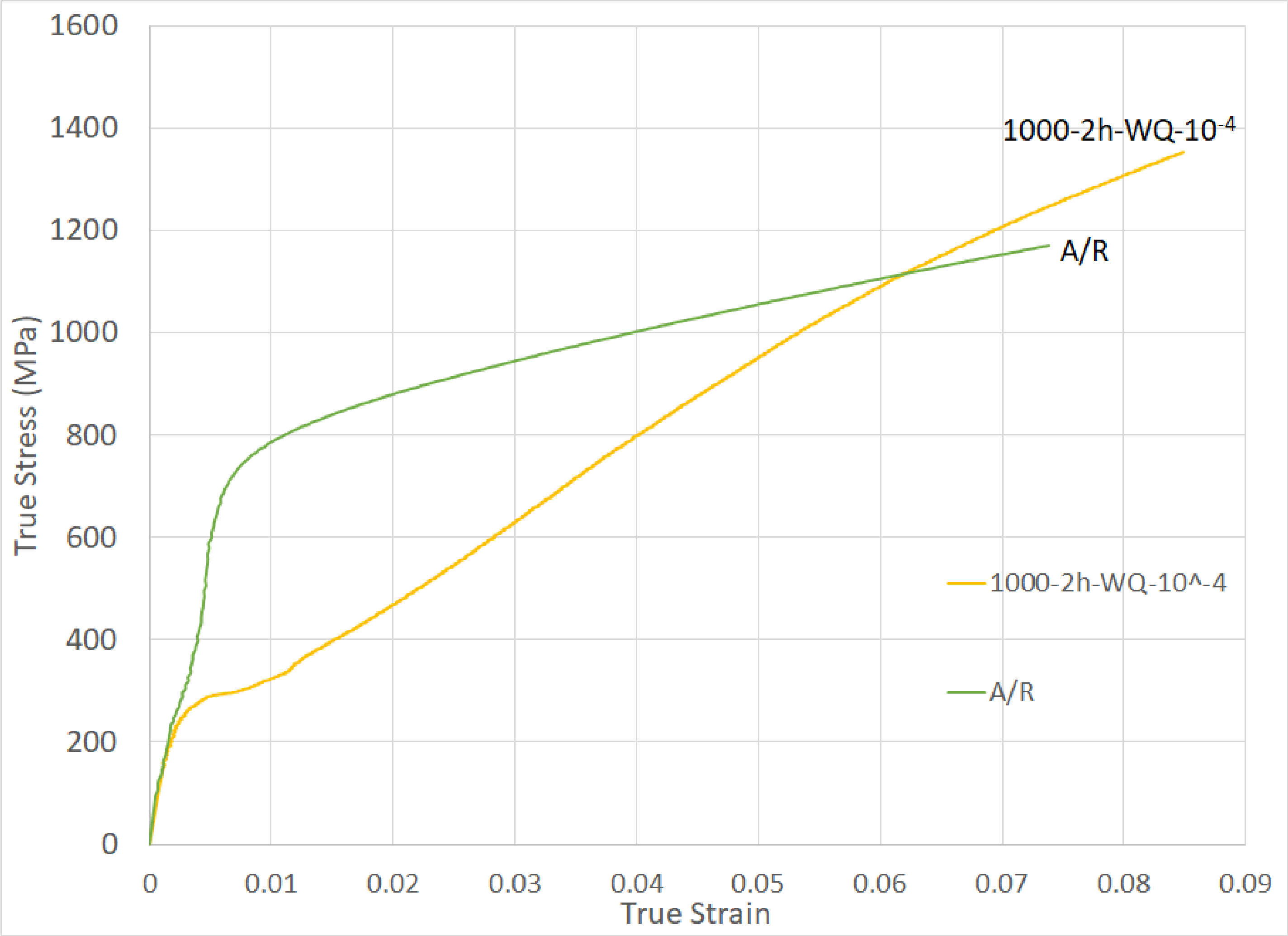
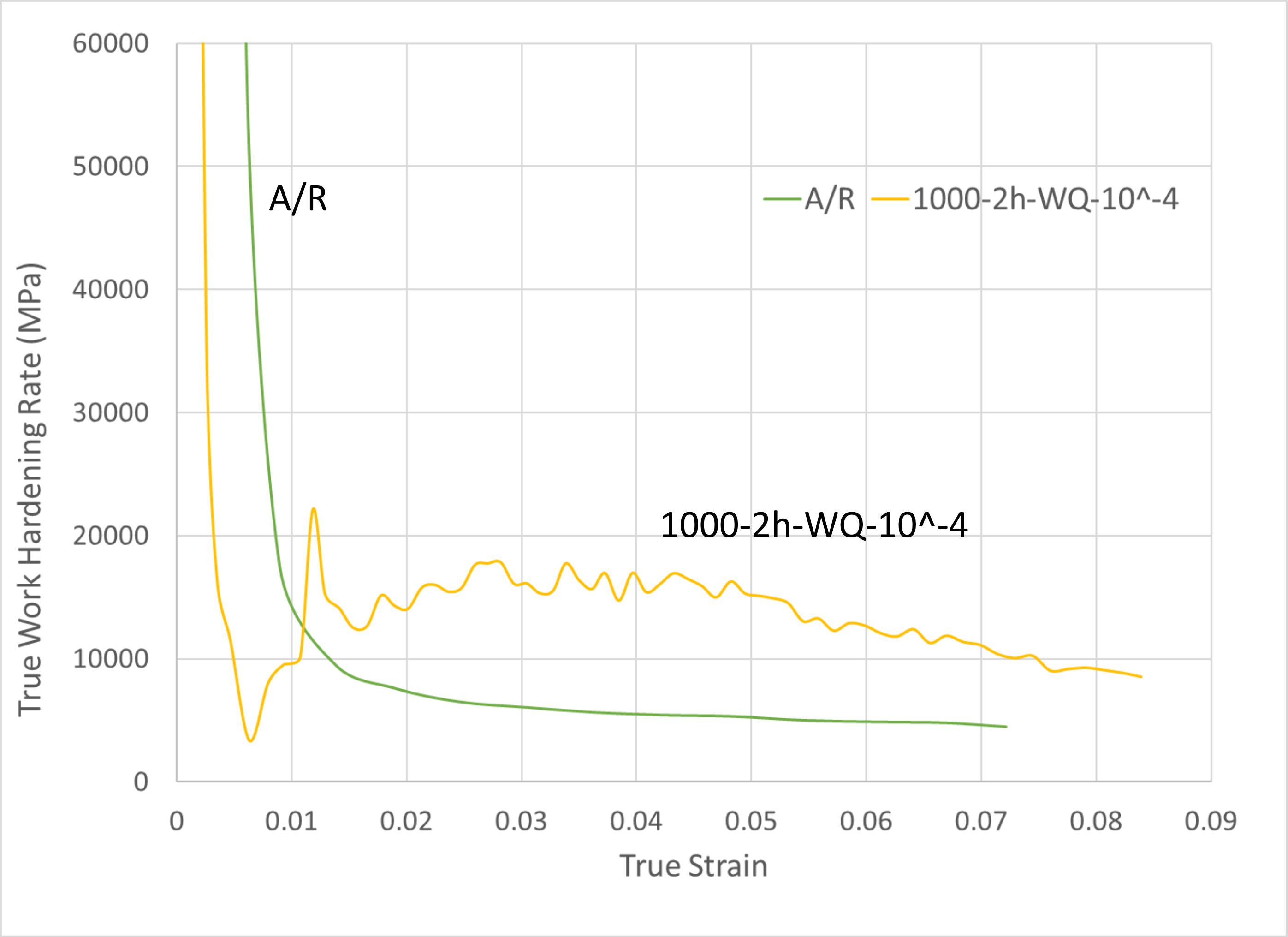
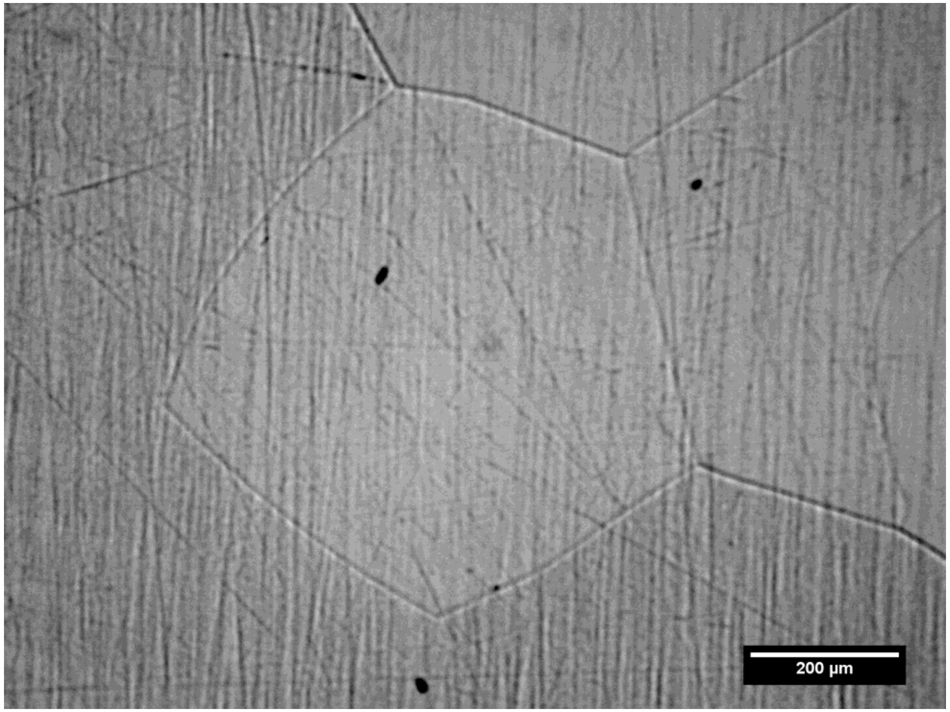
Comparison of As-received and 1000-2h-WQ-10^{-4}

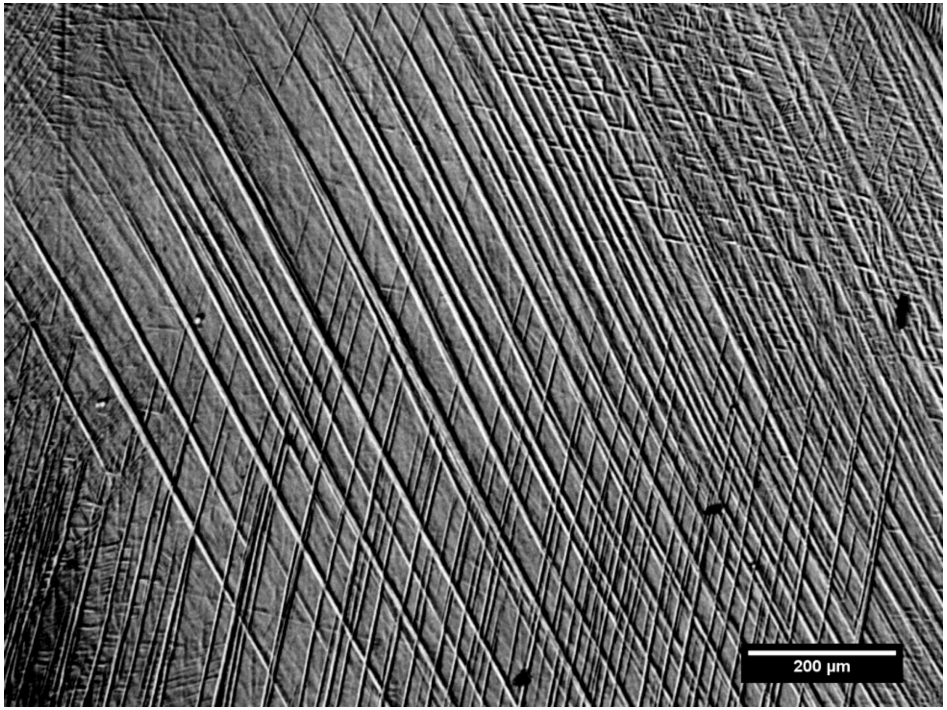


Instantaneous Work Hardening Rate comparison

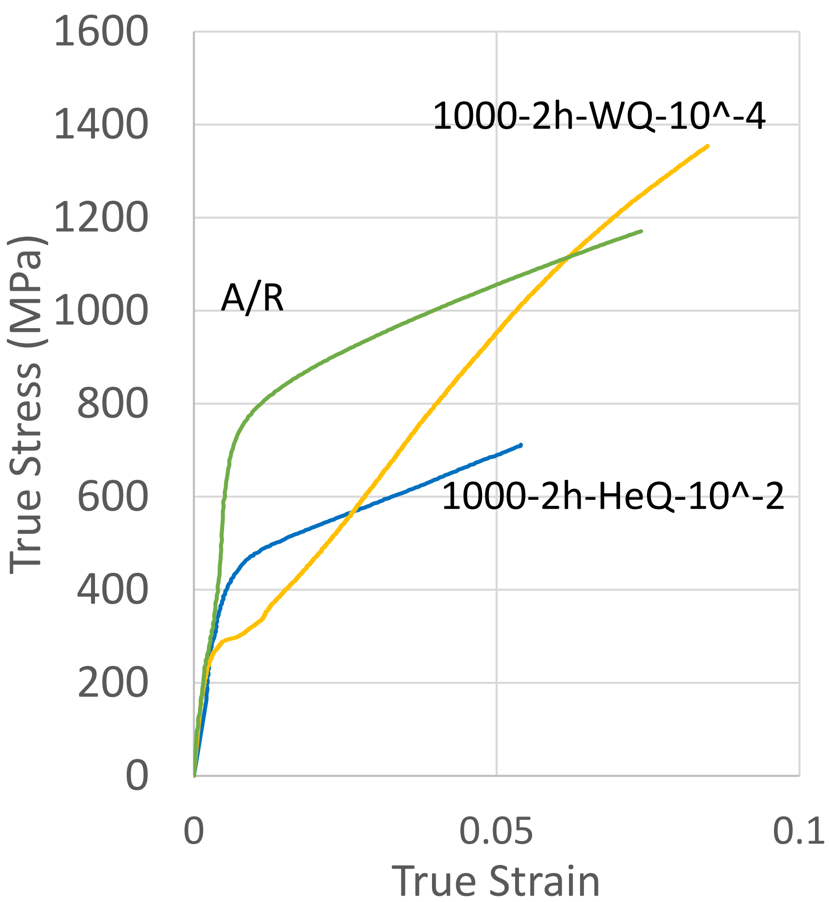


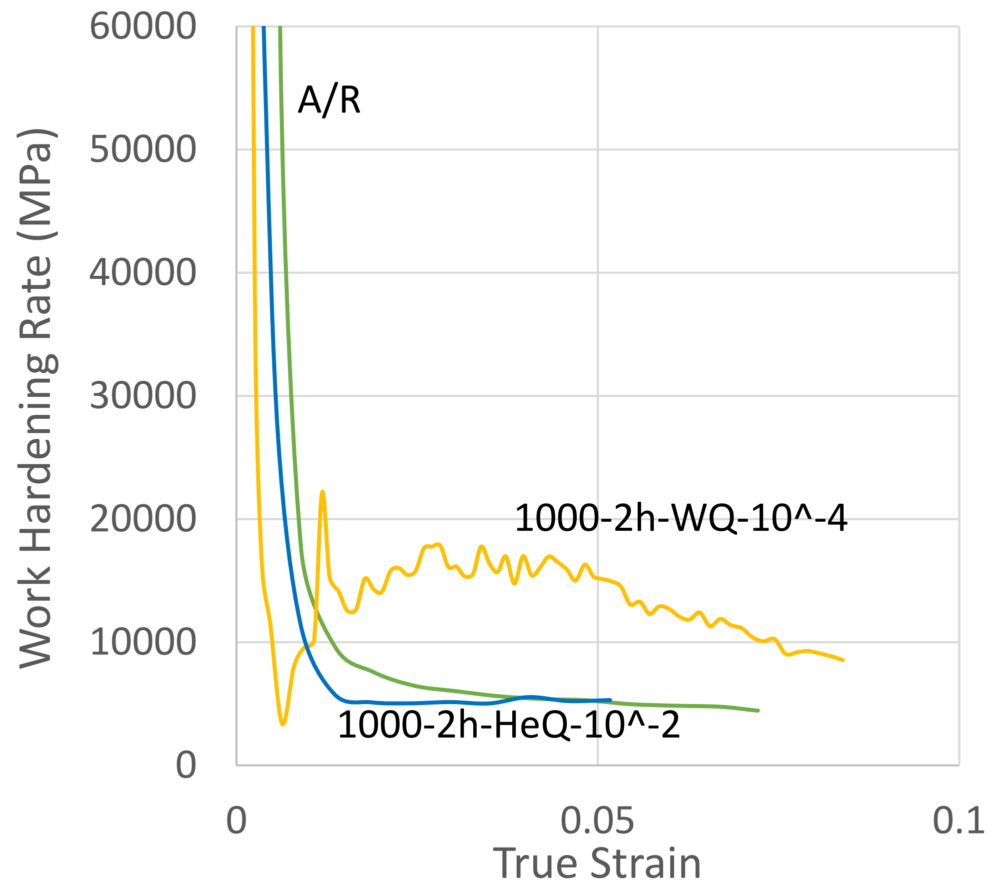
Comparison of Pre- and Post-Compression Microstructure of 1000-2h-WQ-10^{-4}



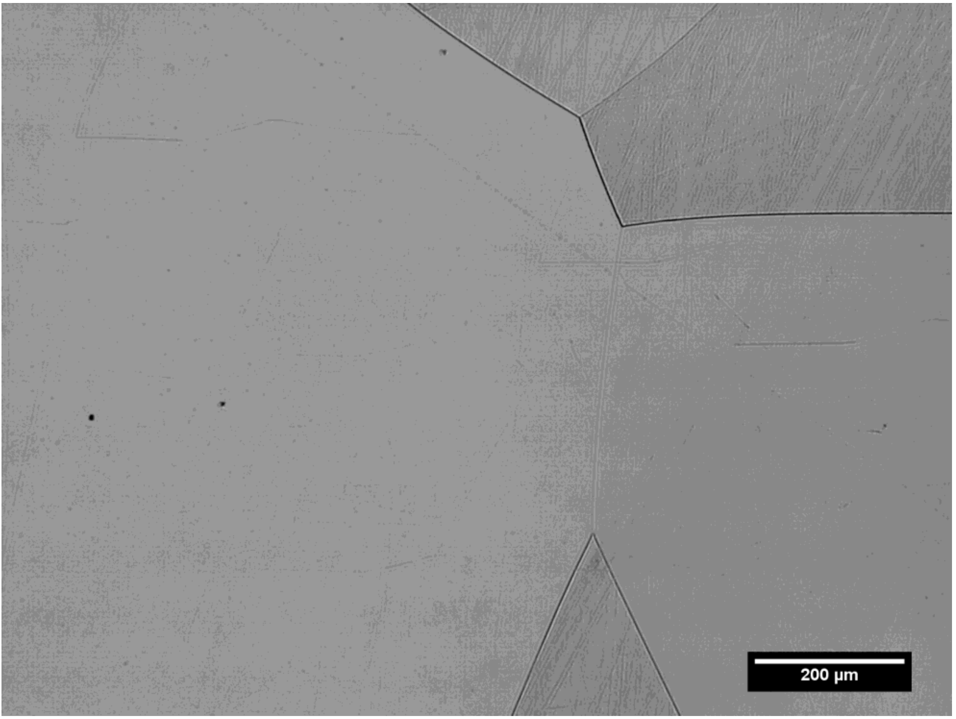


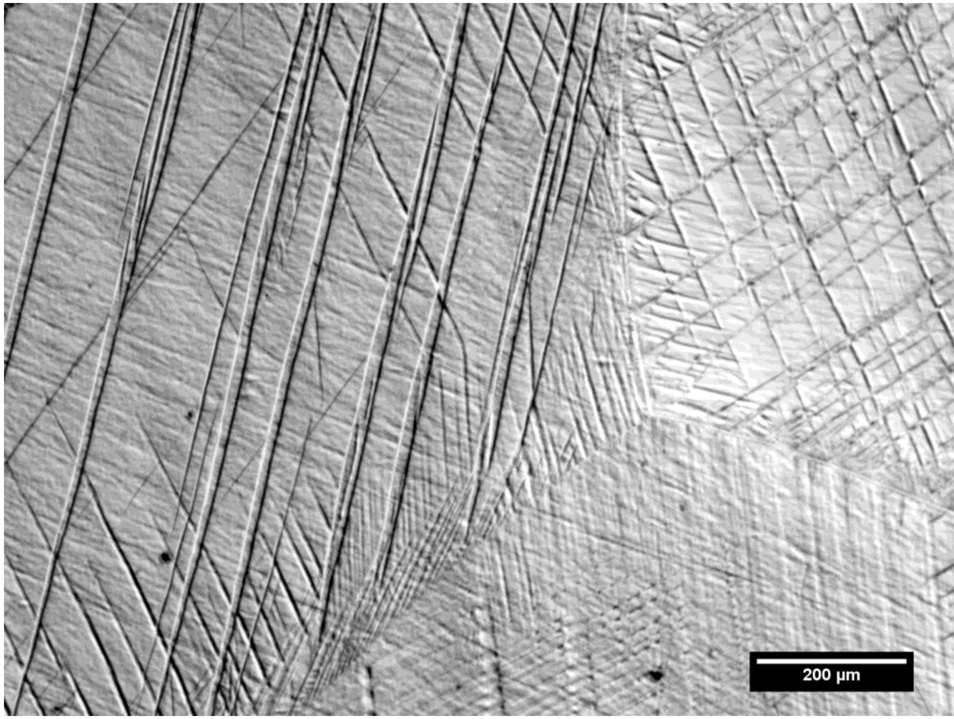
Stress-Strain Behavior does not Suggest TRIP/TWIP …



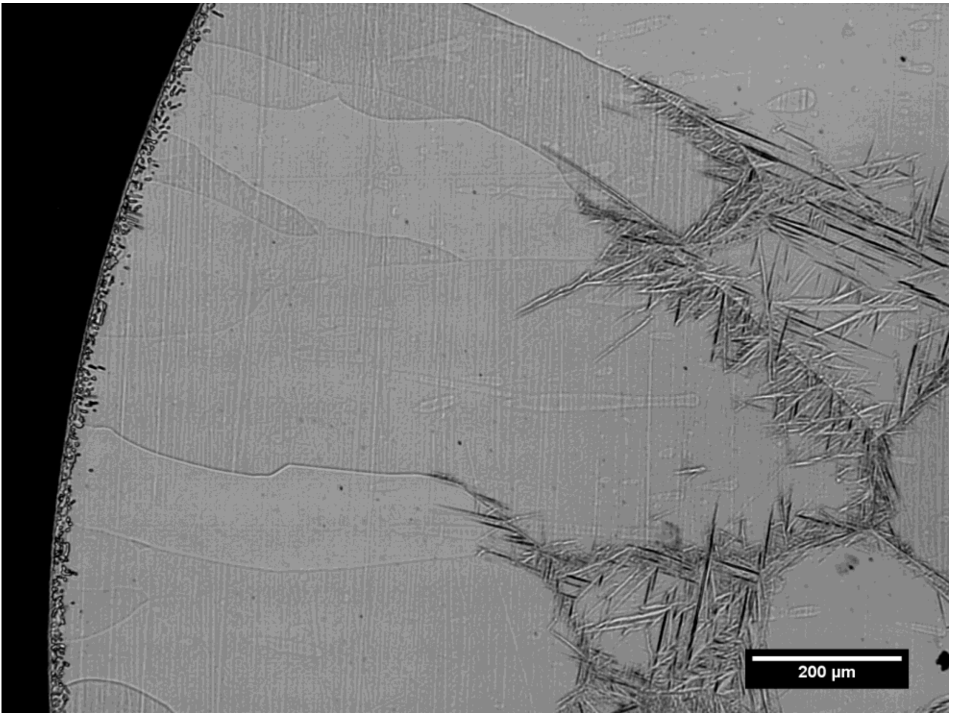


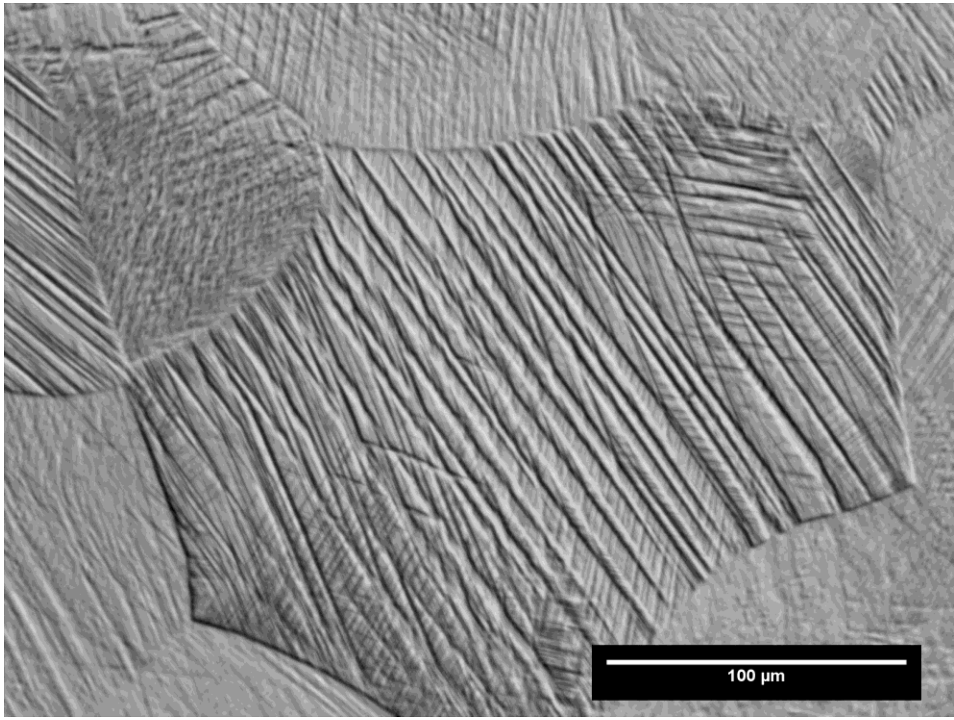
Comparison of Pre- and Post-Compression Microstructure of 1000-2h-HeQ-10^{-2}



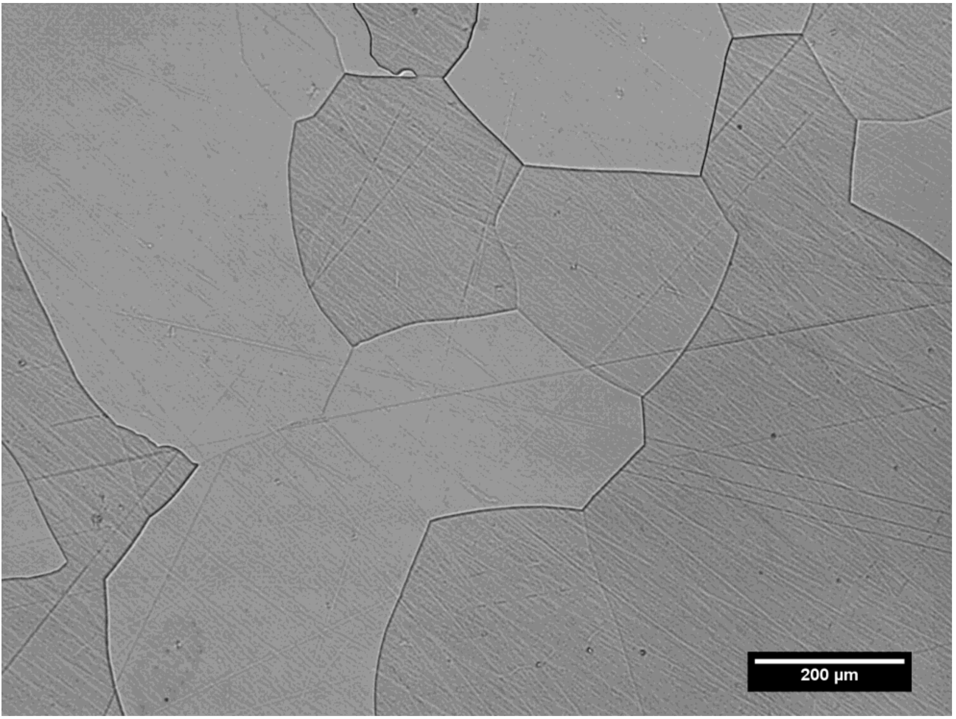


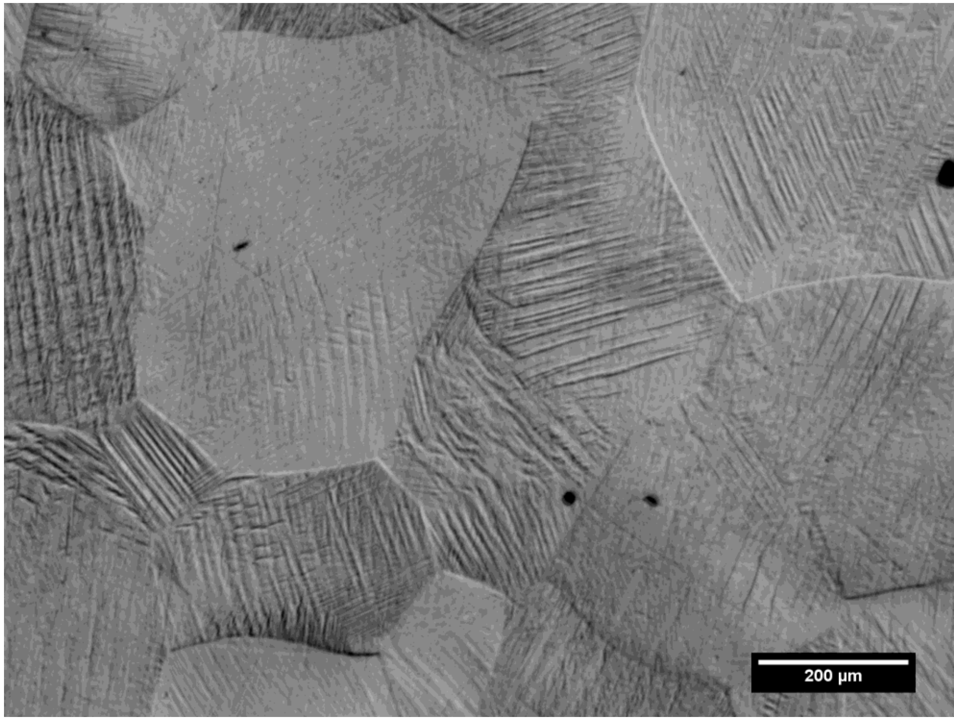
Comparison of Pre- and Post-Compression Microstructure of 900-2h-WQ-10^{-2}



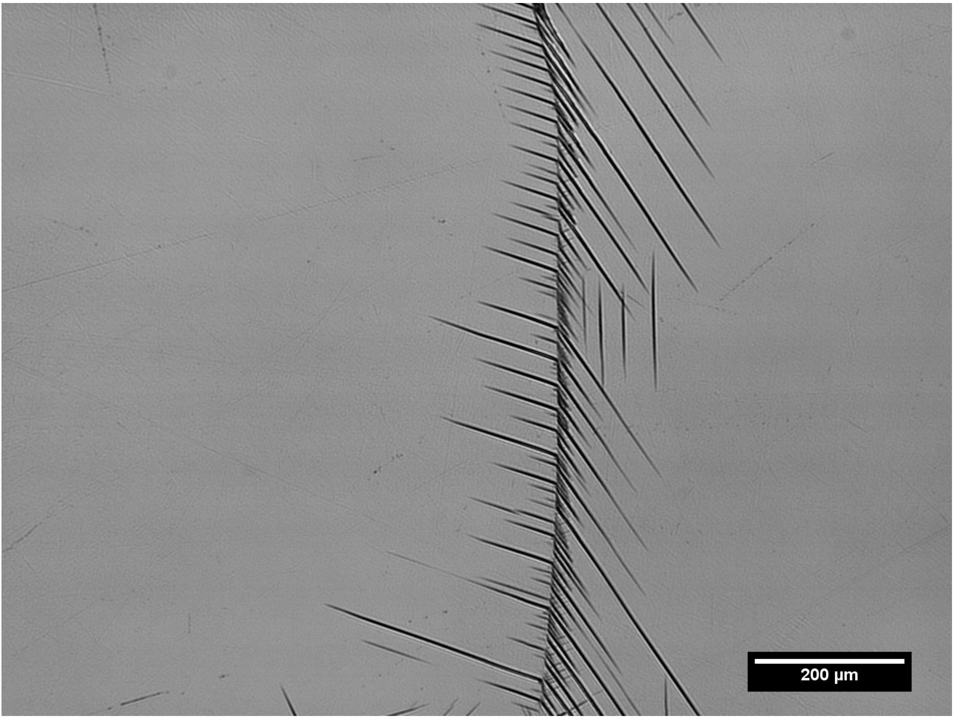


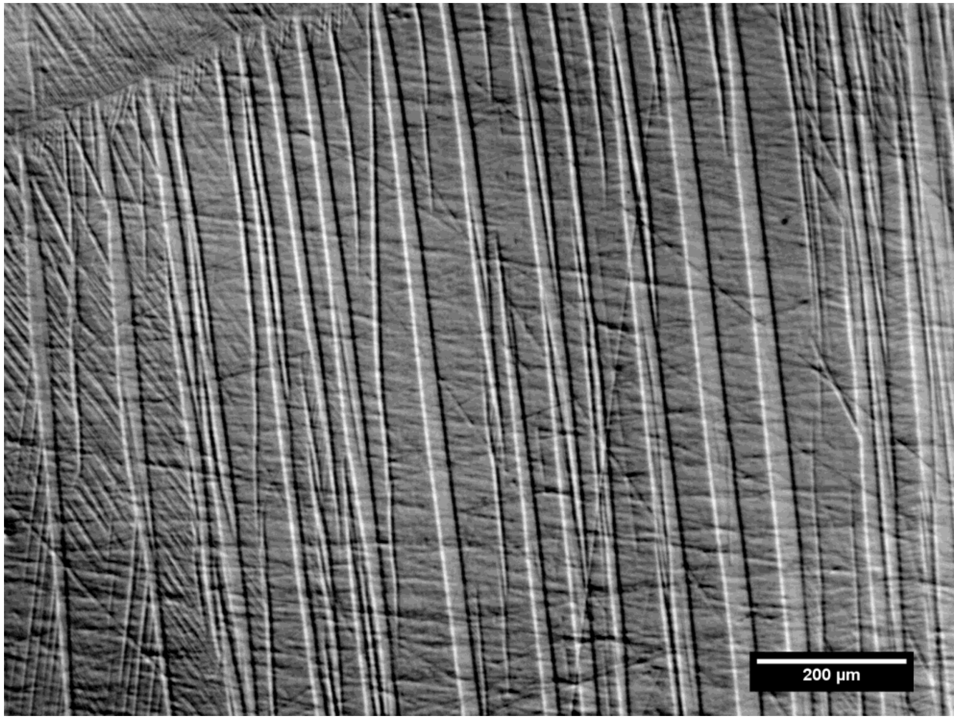
Comparison of Pre- and Post-Compression Microstructure of 900-2h-WQ-10^{-2}





Comparison of Pre- and Post-Compression Microstructure of 1200-2h-HeQ-10^{-2}

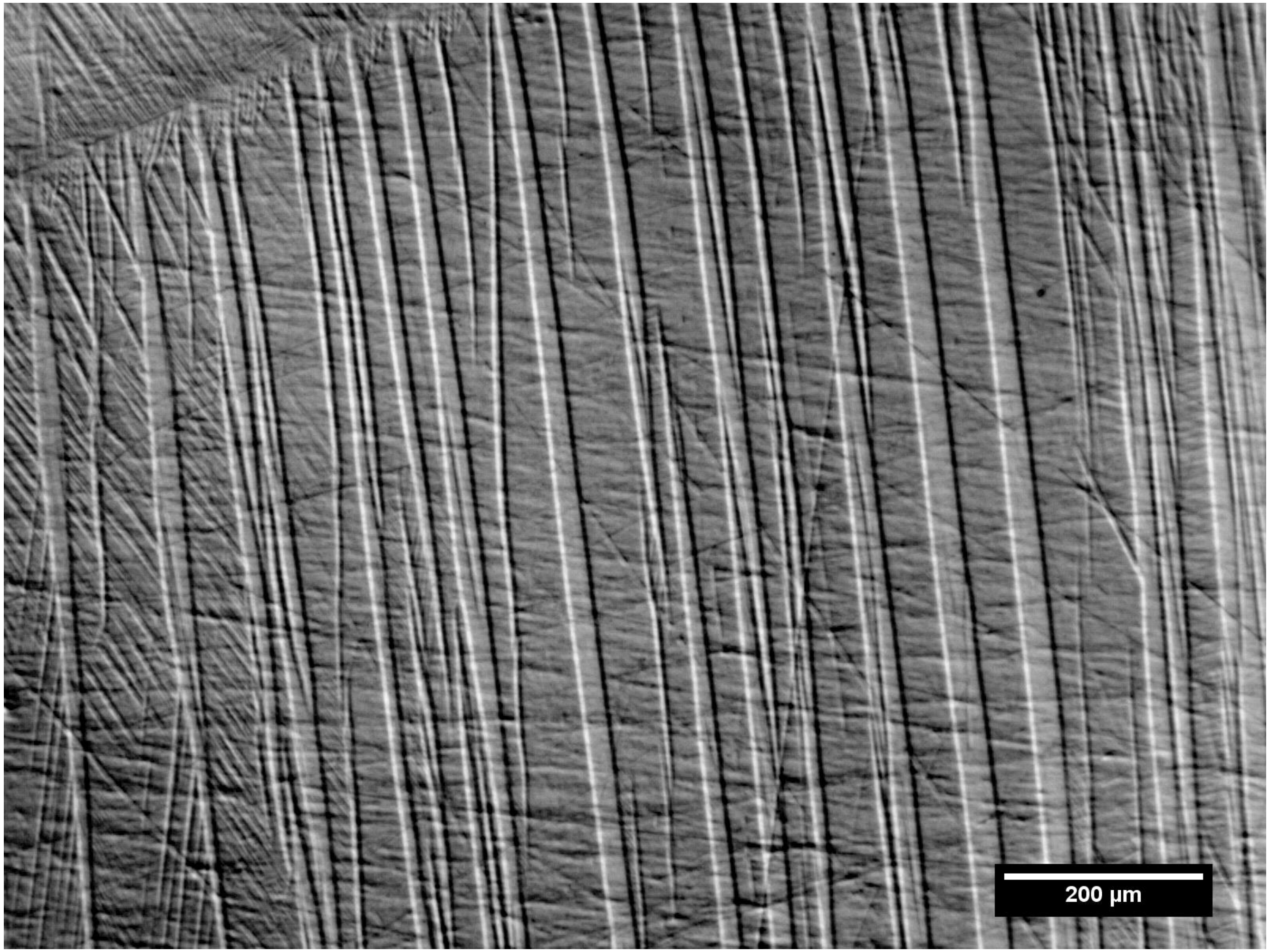




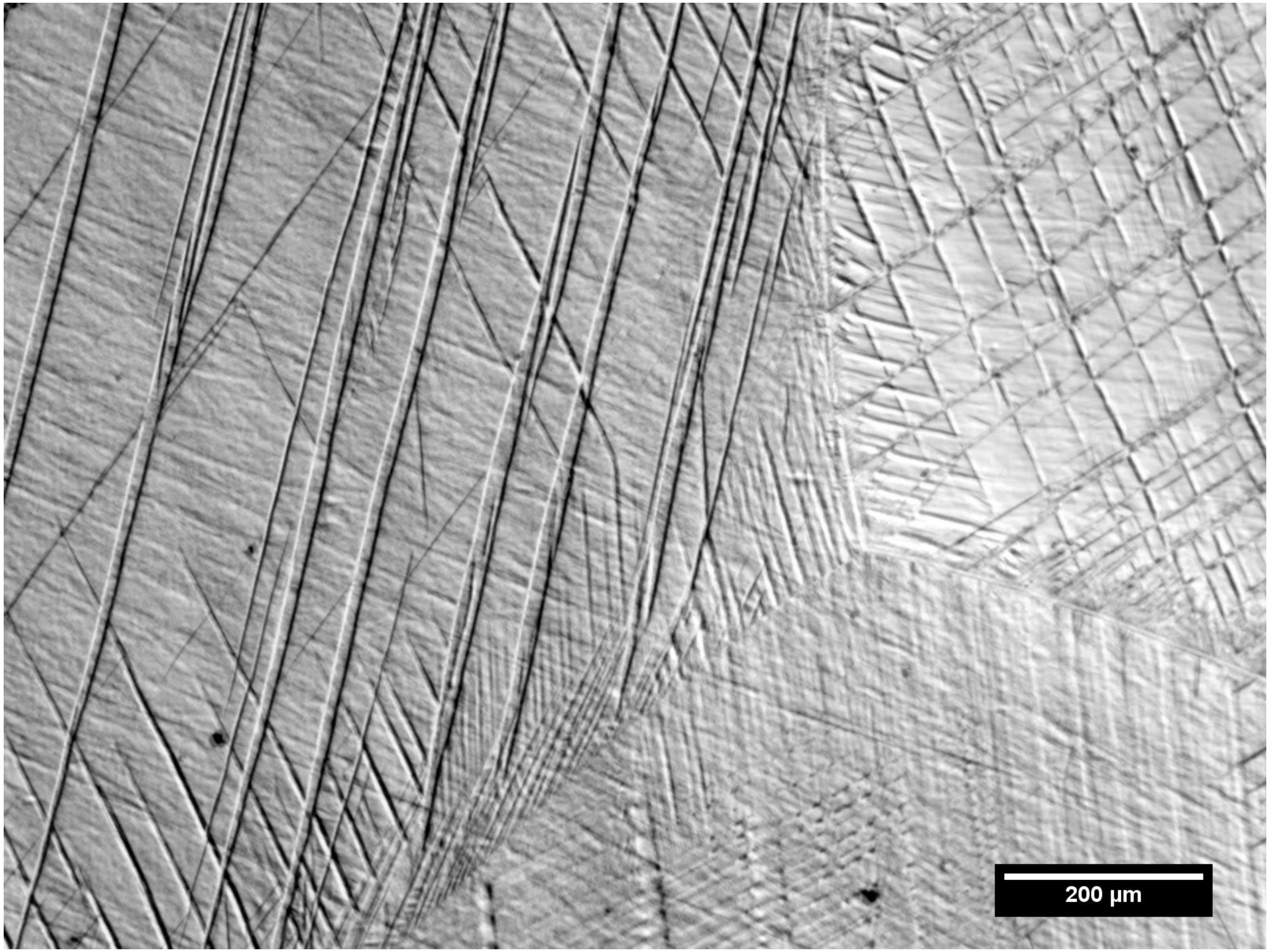
Compression Study Summary

Every heat treatment investigated shows TRIP/TWIP in post-compression microstructure

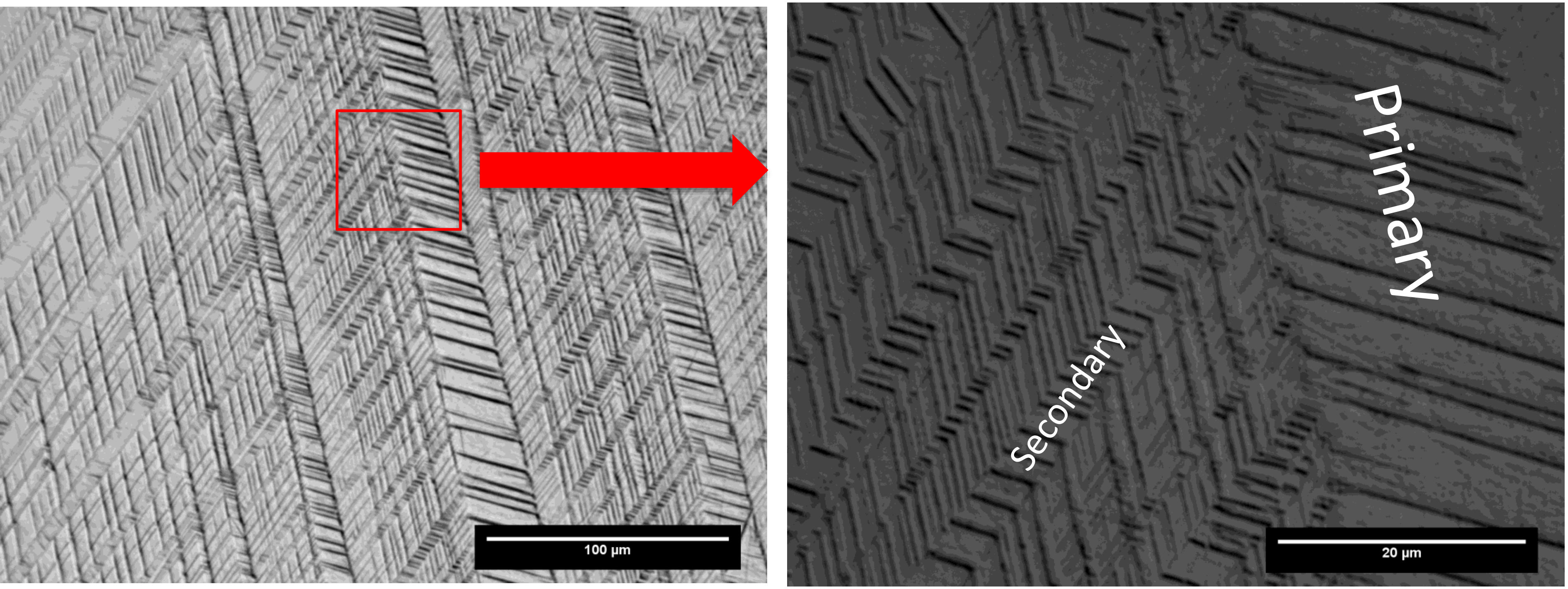
Orientation of Product Similar Within a Single Grain



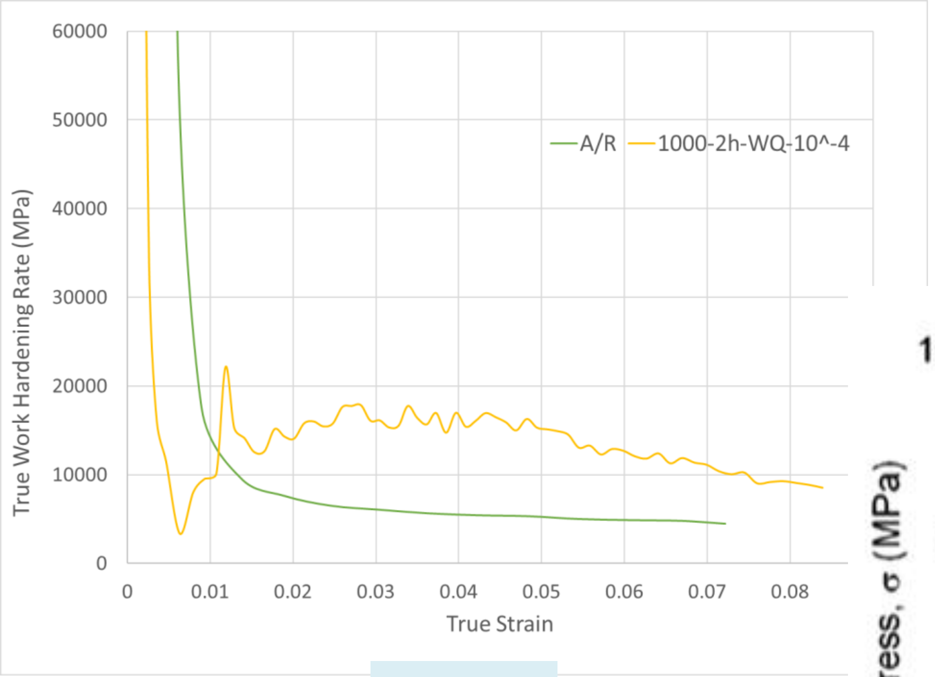
Multiple Variants Can Be Present in a Single Grain



Hierarchy of Deformation Product

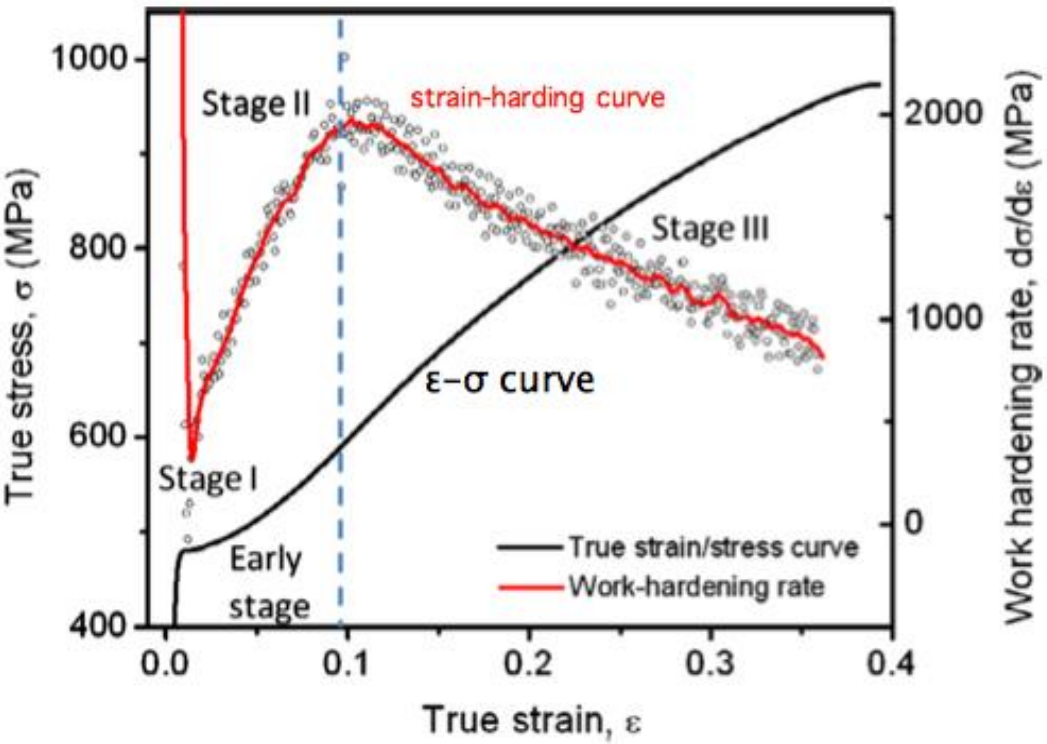


Work Hardening Rate and TRIP/TWIP Effect



Ti-1023

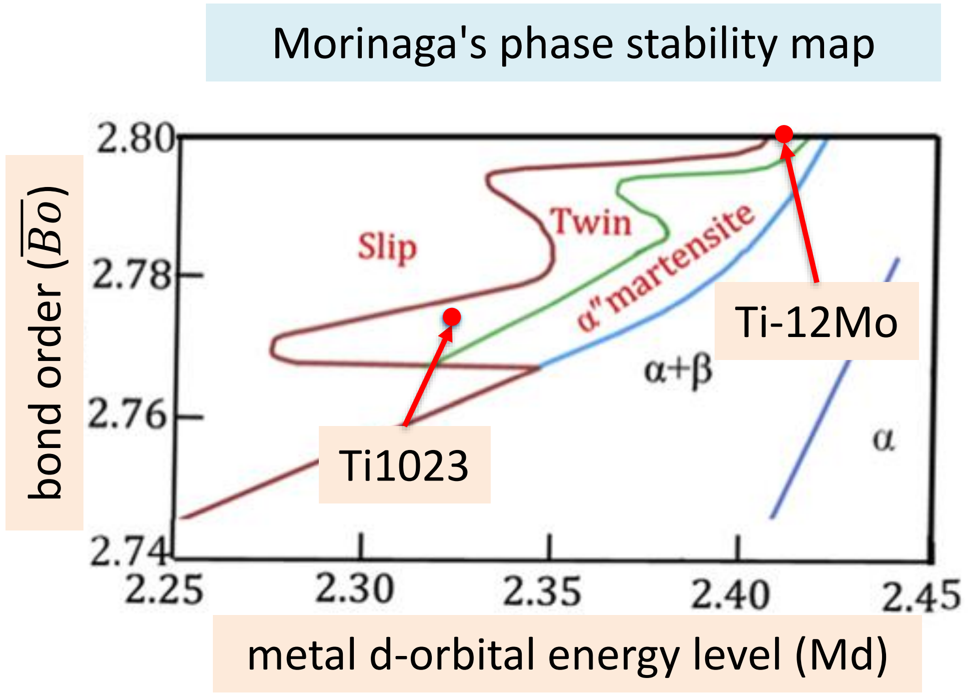
Ti-12Mo (wt.%)



Sun, F. et al. 61 Acta Materialia (2013): 6406-6417

Deformation Modes in β-Ti Alloys at Room Temperature

- Twinning
  - {112}<111> twinning
  - {332}<113> twinning
- Stress induced martensite
- Stress induced ω phase
- Slip

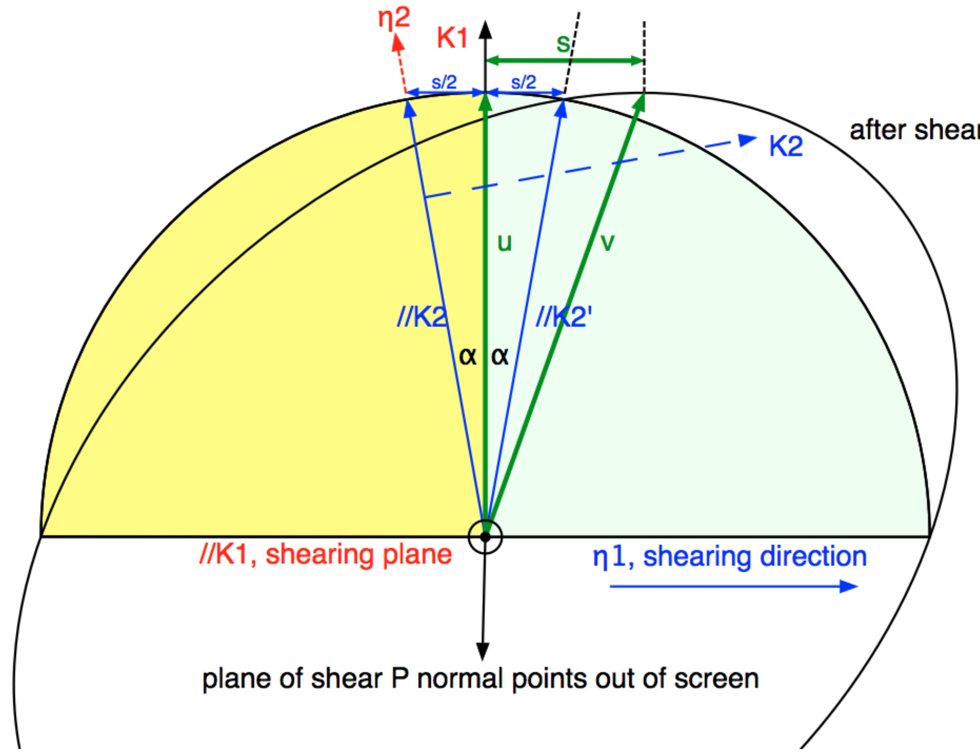


Ahmed, M., et al. 104 Acta Materialia (2016): 190-200

Two Twinning Systems

{112}<111> twinning	{332}<113> twinning
$(112)[\bar{1}\bar{1}1]$	$(332)[11\bar{3}]$
$(121)[\bar{1}1\bar{1}]$	$(323)[1\bar{3}1]$
$(211)[1\bar{1}\bar{1}]$	$(233)[\bar{3}11]$
$(\bar{1}12)[1\bar{1}1]$	$(3\bar{3}2)[1\bar{1}\bar{3}]$
$(\bar{1}21)[11\bar{1}]$	$(3\bar{2}3)[131]$
$(\bar{2}11)[\bar{1}\bar{1}\bar{1}]$	$(2\bar{3}3)[\bar{3}\bar{1}1]$
$(1\bar{1}2)[\bar{1}11]$	$(\bar{3}32)[\bar{1}1\bar{3}]$
$(1\bar{2}1)[\bar{1}\bar{1}\bar{1}]$	$(\bar{3}23)[\bar{1}\bar{3}1]$
$(2\bar{1}1)[11\bar{1}]$	$(\bar{2}33)[311]$
$(11\bar{2})[\bar{1}\bar{1}\bar{1}]$	$(33\bar{2})[113]$
$(12\bar{1})[\bar{1}11]$	$(32\bar{3})[1\bar{3}\bar{1}]$
$(21\bar{1})[1\bar{1}1]$	$(23\bar{3})[\bar{3}1\bar{1}]$

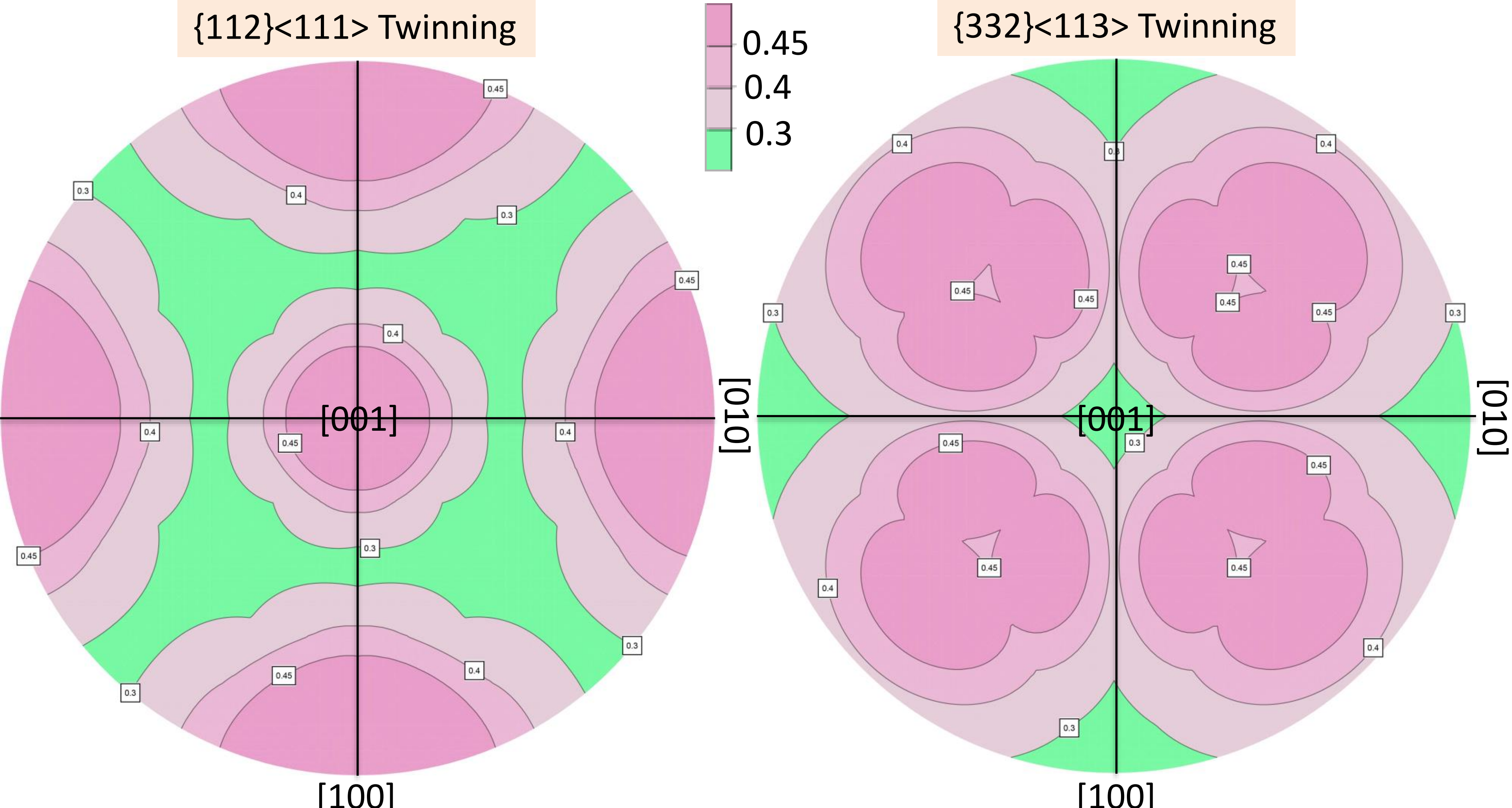
- **Polarization of twinning and operative twinning**



Schmid Factor of Two Twinning Systems

{112}<111> Twinning

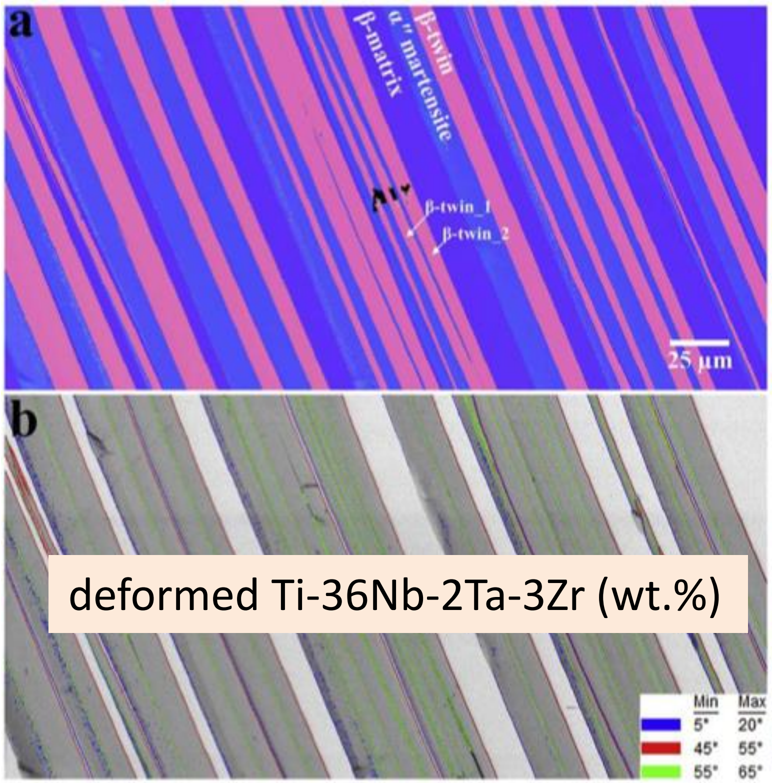
{332}<113> Twinning



Coupled {332} Twinning and Stress Induced Martensitic Transformation

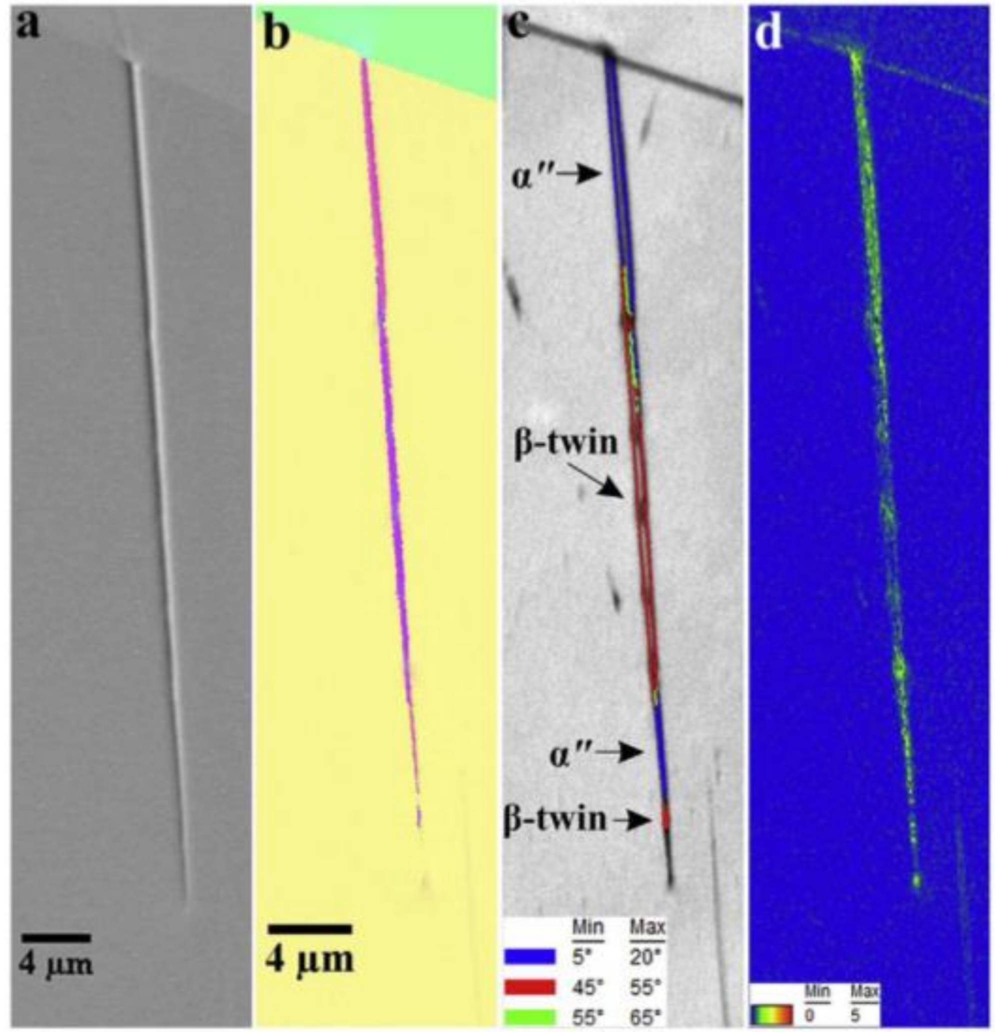
Misorientation

- {112} twinning: ∑3, **60° - <111>**
- {332} twinning: ∑11, **50.57° - <110>**



deformed Ti-36Nb-2Ta-3Zr (wt.%)

Lai, M.J., et al. 111 Acta Materialia (2016): 173-186



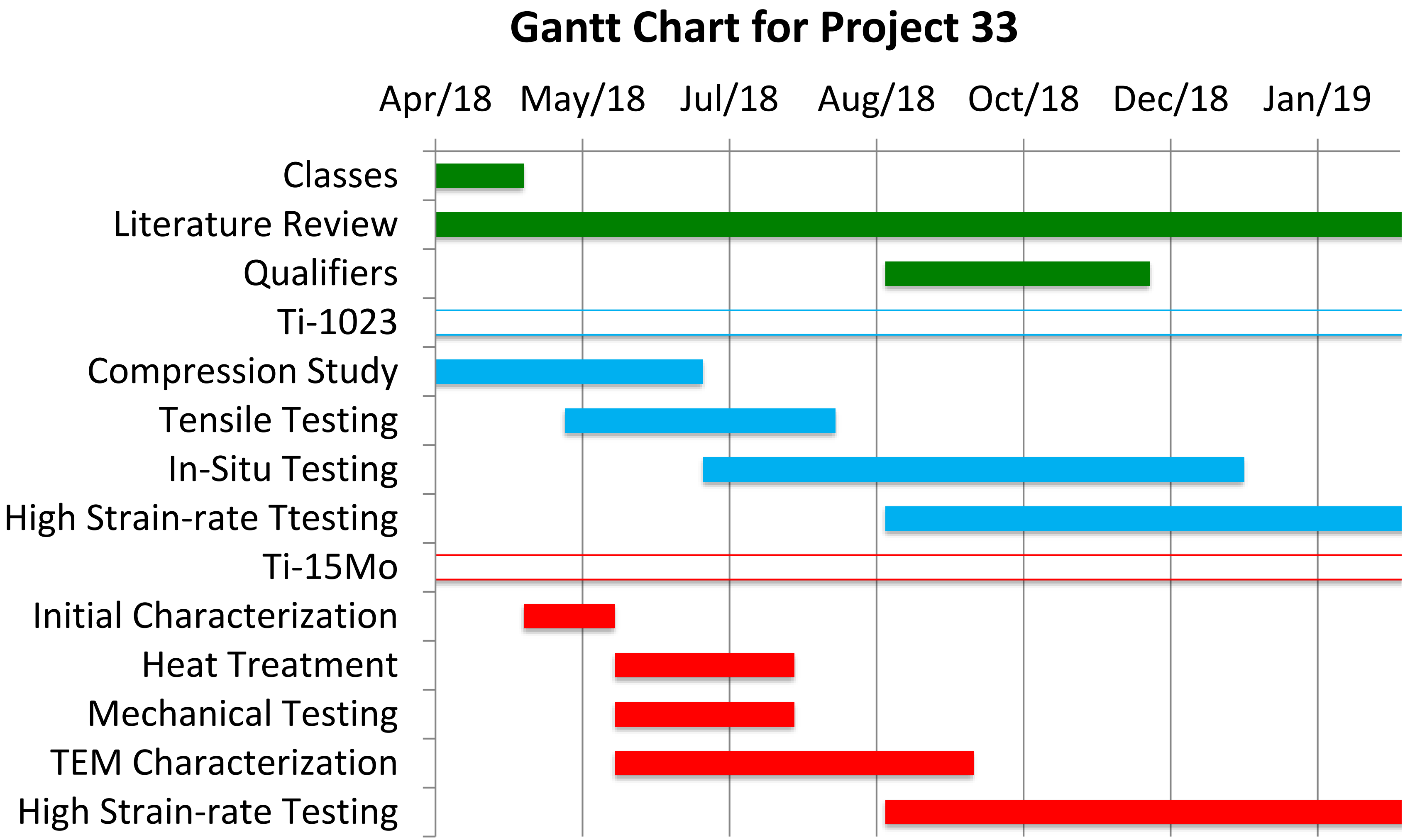
Ongoing EBSD Characterization

- Post-mortem EBSD of deformed samples
- In situ EBSD during deformation
- Understanding the coupling of mechanisms in Ti-1023 will inform future Ti-alloy experiments

Summary

- Compression study nearly complete:
  - Fully equiaxed β microstructure with little/no martensite
  - Evidence of TRIP/TWIP behavior
- EBSD and TEM microstructural characterization is underway
- Tensile testing of Ti-1023 based upon compression testing results
- Ti-15Mo from ATI available

Progress


Gantt Chart for Project 33
Apr/18
May/18
Jul/18
Aug/18
Oct/18
Dec/18
Jan/19
Classes
Literature Review
Qualifiers
Ti-1023
Compression Study
Tensile Testing
In-Situ Testing
High Strain-rate Ttesting
Ti-15Mo
Initial Characterization
Heat Treatment
Mechanical Testing
TEM Characterization
High Strain-rate Testing

Thank you very much!

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References

[1] Brozek, C., et al. "A β-titanium alloy with extra high strain-hardening rate: design and mechanical properties." Scripta Materialia 114 (2016): 60-64.

[2] Li, C., et al. "Influence of α morphology and volume fraction on the stress-induced martensitic transformation in Ti–10V–2Fe–3Al." *Materials Science and Engineering: A* 528.18 (2011): 5854-5860.

[3] Bhattacharjee, A., et al. "Effect of β grain size on stress induced martensitic transformation in β solution treated Ti–10V–2Fe–3Al alloy." *Scripta materialia* 53.2 (2005): 195-200.

[4] Duerig, T. W., et al. "Formation and reversion of stress induced martensite in Ti-10V-2Fe-3Al." Acta Metallurgica30.12 (1982): 2161-2172.

[5] Neelakantan, S., et al. "Plasticity induced transformation in a metastable β Ti-1023 alloy by controlled heat treatments." Materials Science and Technology 25.11 (2009): 1351-1358.

[6] Sun, F., et al. "Investigation of early stage deformation mechanisms in a metastable b titanium alloy showing combined twinning-induced plasticity and transformation-induced plasticity effects." 61 Acta Materialia (2013): 6406-6417.

[7] Ahmed, M., et al. "Strain rate dependence of deformation-induced transformation and twinning in a metastable titanium alloy." 104 Acta Materialia (2016): 190-200.

[8] Lai, M.J., et al. "On the mechanism of {332} twinning in metastable β titanium alloys." 111 Acta Materialia (2016): 173-186.