Project 29-L: Identification of Deformation Mechanisms in Thermally Stable Cast Al-Cu Alloys via Neutron Diffraction

Spring Meeting

April 7th – 9th 2020

- Student: Brian Milligan (Mines)
- Faculty: Dr. Amy Clarke (Mines)
- Industrial Mentors: Amit Shyam (ORNL), John Carpenter (LANL)

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Acknowledgements

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- Student: Brian Milligan (Mines)
- Advisor(s): Amy Clarke (Mines), Amit Shyam (ORNL)

Project Duration
Ph.D.: August 2017 to May 2021

Problem
- Deformation and phase transformation behavior at a micro-scale in Al-Cu alloys is not well understood.

Objective
- Apply in-situ neutron diffraction, SEM, TEM, mechanical testing, and synchrotron X-ray imaging to better understand the mechanical behavior and phase transformations in these alloys.

Benefit
- Improvement of properties of thermally stable Al-Cu alloys (including new ORNL alloy), as well as furthering scientific understanding of precipitation strengthened Al alloys.

Recent Progress
- Paper to Materials Science and Engineering: A on creep at 300°C was accepted
- Created new model for anisotropic load transfer between matrix and precipitates
- Re-wrote publication for Acta Materialia on alloy 206 room temperature neutron diffraction
- Gave talk at TMS2020
- Passed qualifying exam

Metrics

Description	% Complete	Status
1. Initial literature review	90%	●
2. In situ neutron diffraction, creep testing, and TXM	65%	●
3. Microstructural characterization pre- and post- creep and tension	50%	●
4. Qualitative assessment of neutron diffraction and mechanical test data	80%	●
5. Application and development of qualitative modelling to micro-scale diffraction data	60%	●

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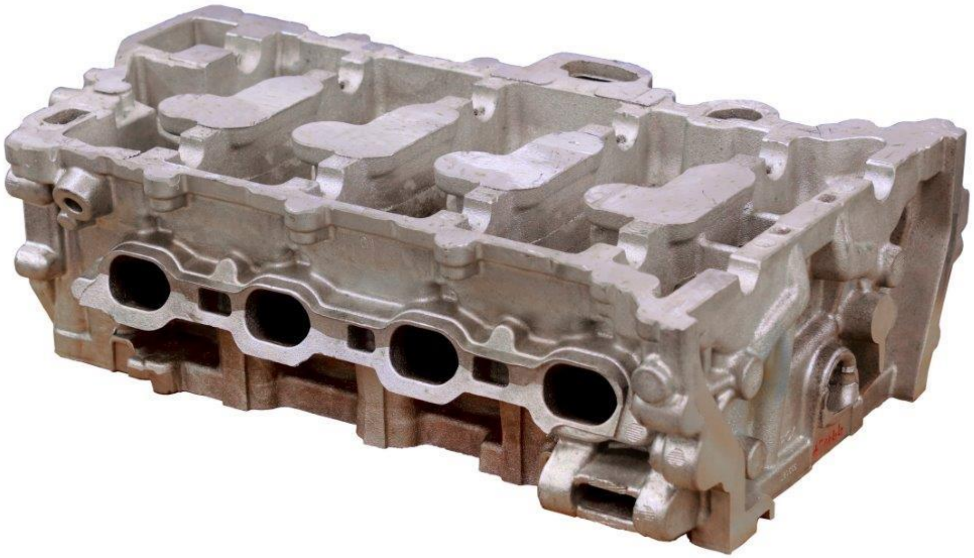
Industrial Relevance

- Cast Al-Cu alloys have high strength, low density, and are very castable
  - Used in various industries such as for cylinder heads in light-duty engines
- Understanding of deformation mechanisms allow prediction of mechanical behavior
  - Strain hardening behavior commonly overlooked, but is relevant for fatigue life



Cylinder head cast with ORNL ACMZ alloy.
Credit: Jason Richards (ORNL)

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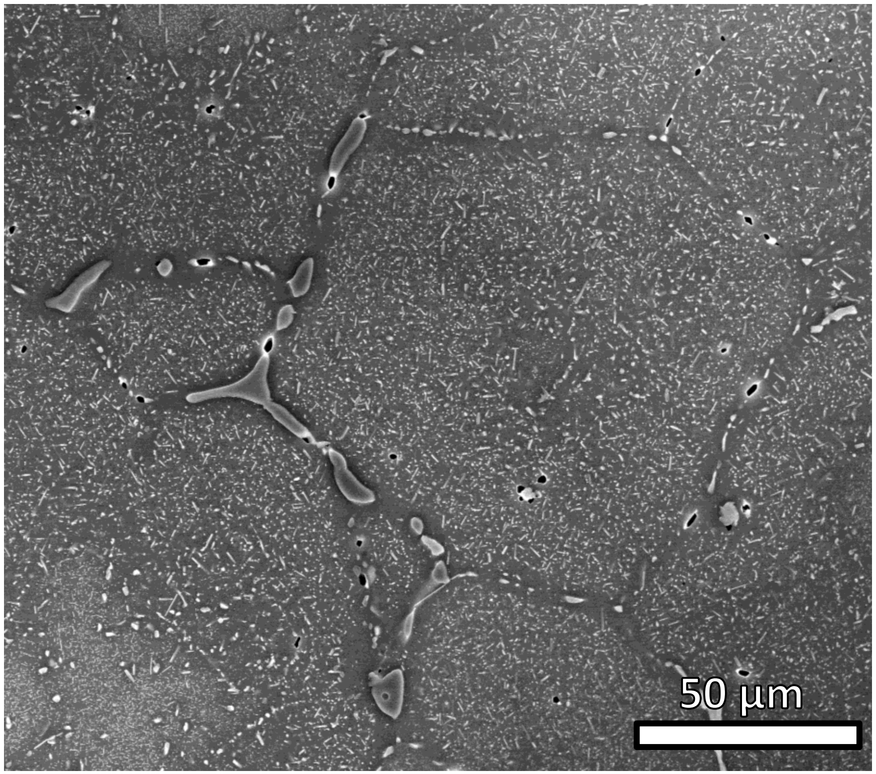
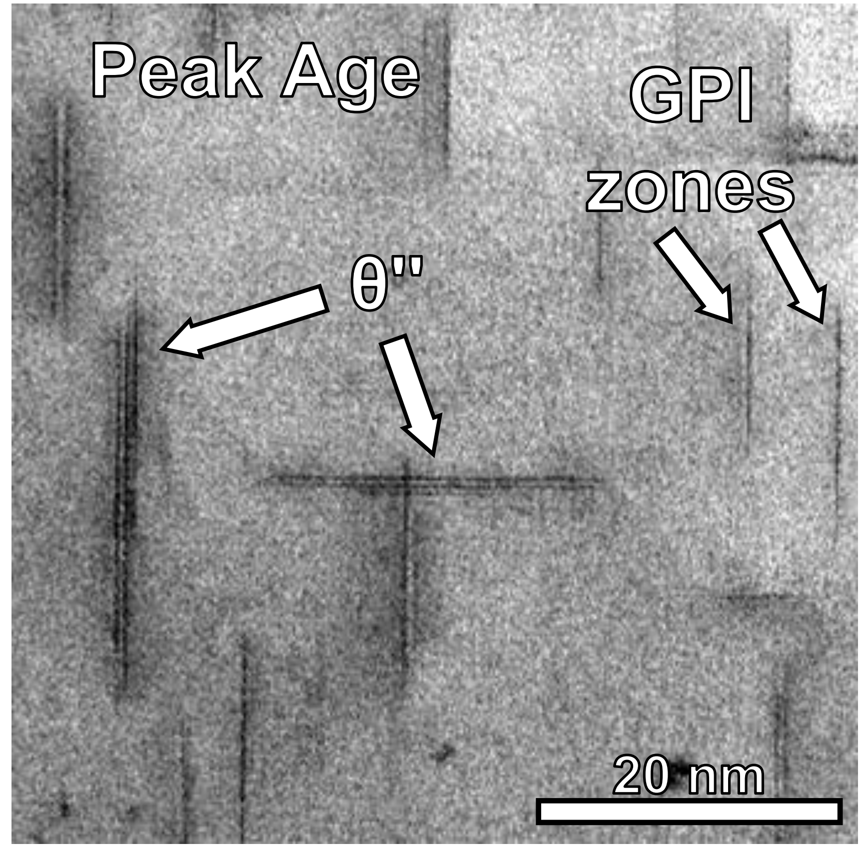
Al-Cu Alloy 206 Used in All Experiments





Composition of Alloy 206 (wt%)

Si	Cu	Mg	Fe	Mn	Ti	Al
0.12	4.5	0.30	0.14	0.23	0.02	bal.

STEM images courtesy of Lawrence Allard. Zone axis is [001].

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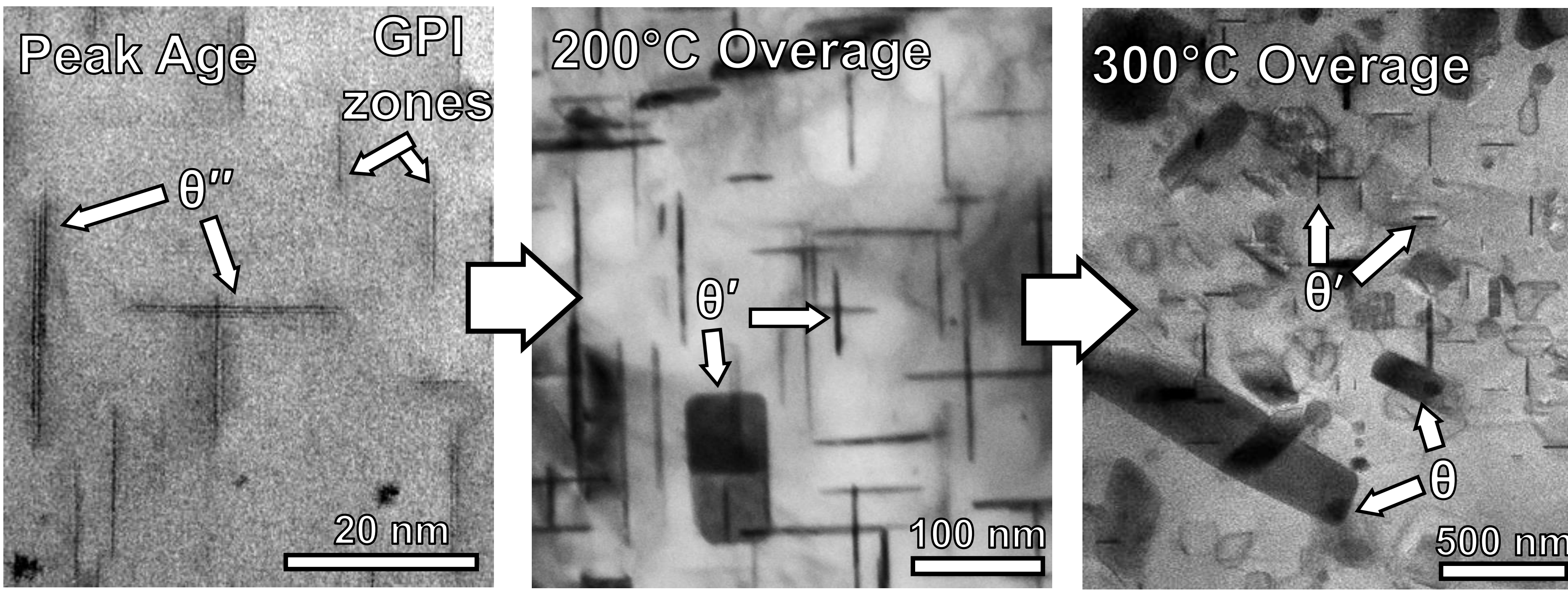
Heat Treatments → Microstructure

Step	Solutionize	Water Quench	Peak Age	Overage
Temp. (°C)	500	80-90	190	200, 300
Time (h)	5	<1	5	200



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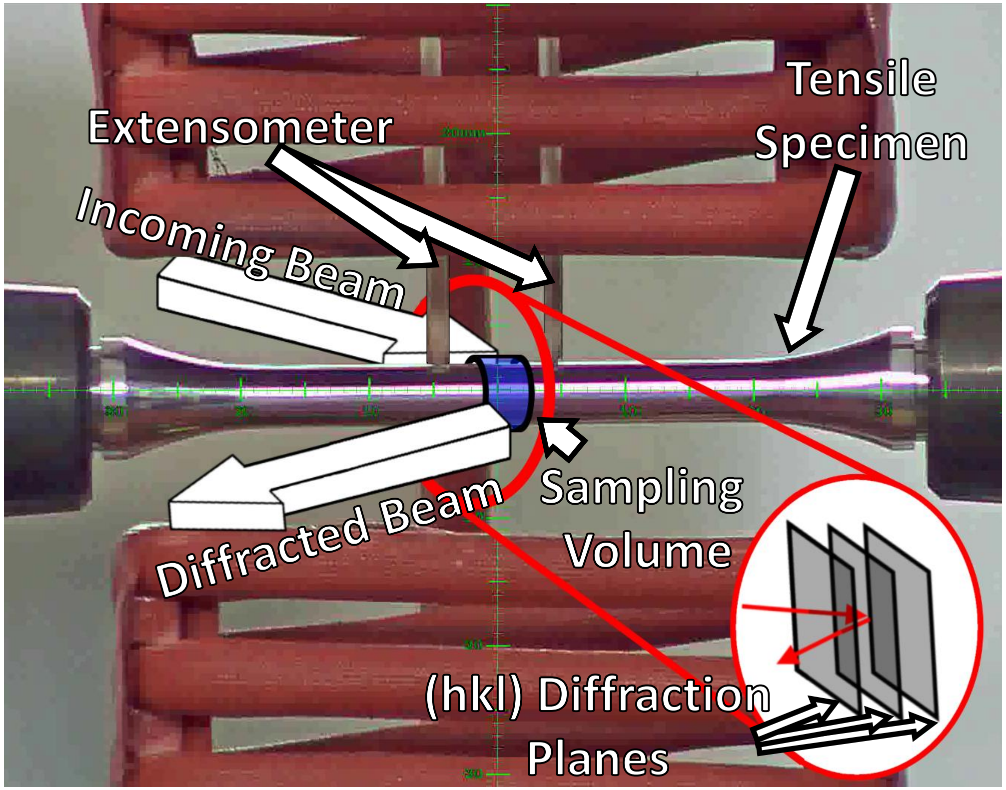
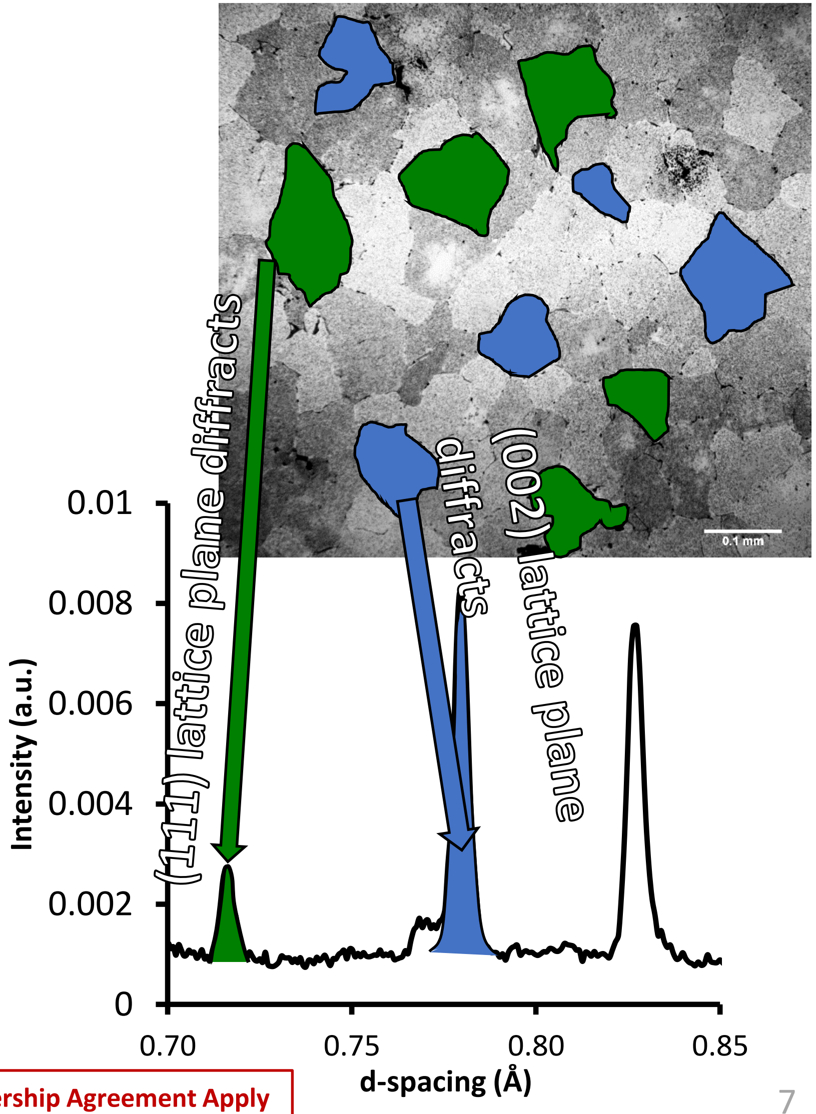
Neutron Diffraction Experiments at SNS VULCAN





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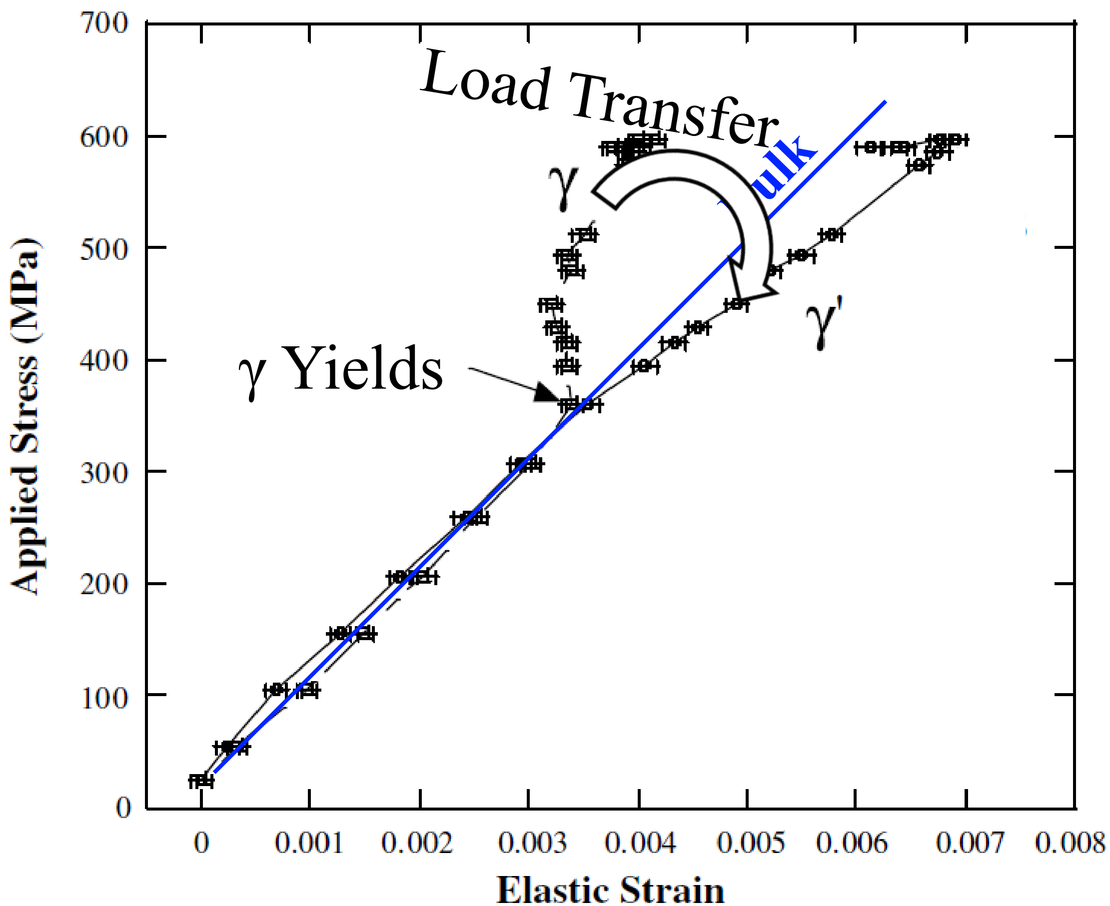
Y-plot Demonstrates Load Transfer Between Phases



PWA 1422 superalloy, reproduced from [1]

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Peak Age: θ″ Precipitates Shear Easily, No Load Transfer

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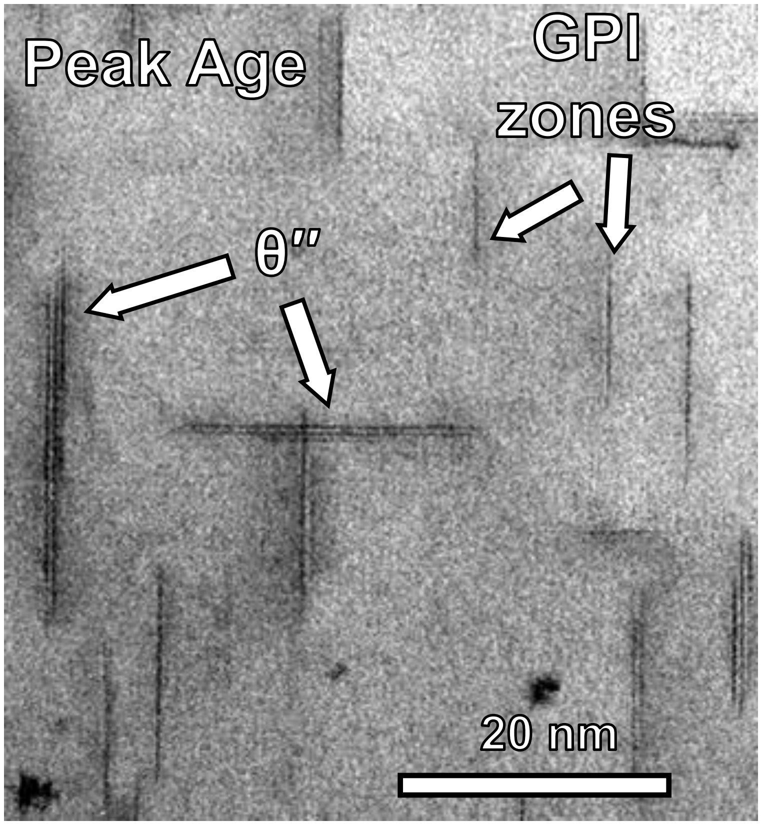

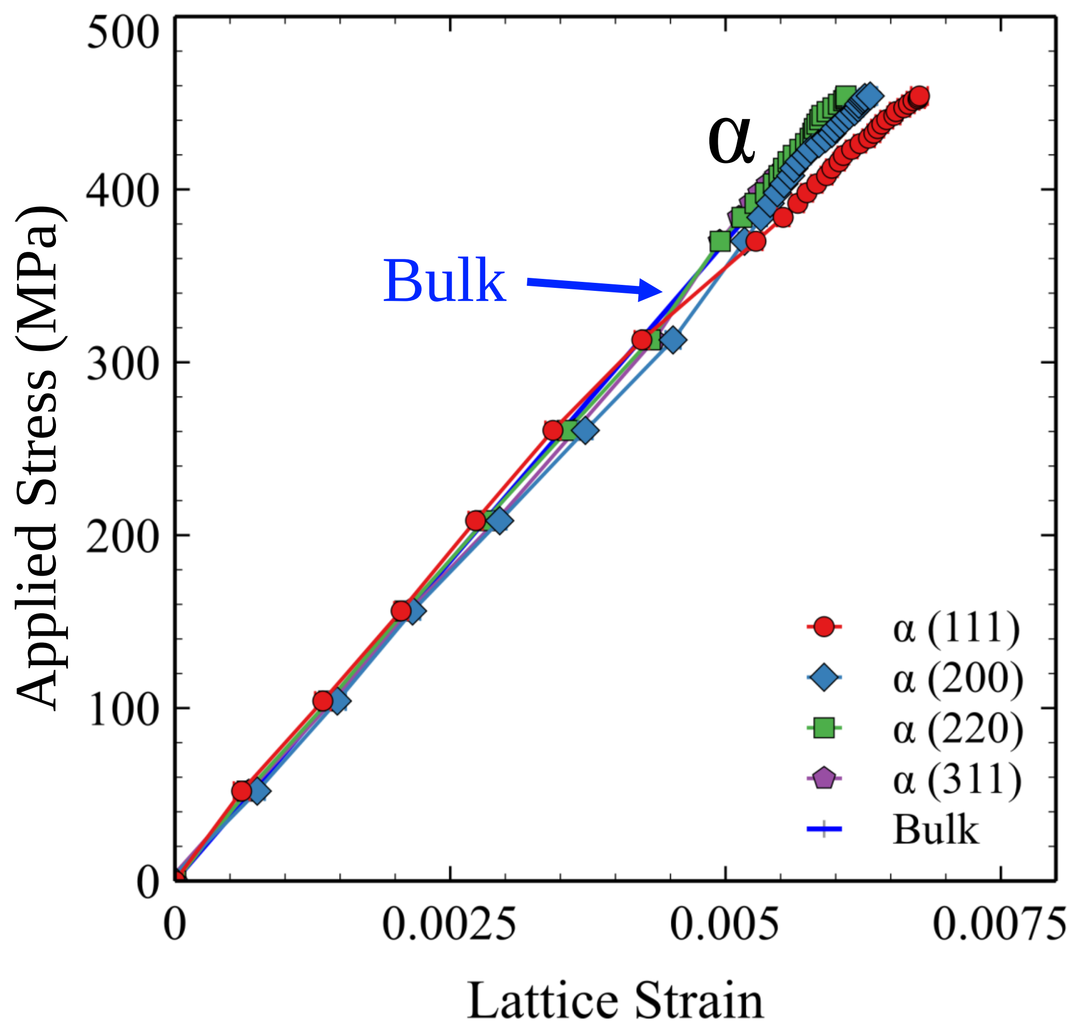

- θ″ precipitates easily sheared by dislocations [2]

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300°C Overage: Orowan Looping, Load Transfer and Precipitate Fracture

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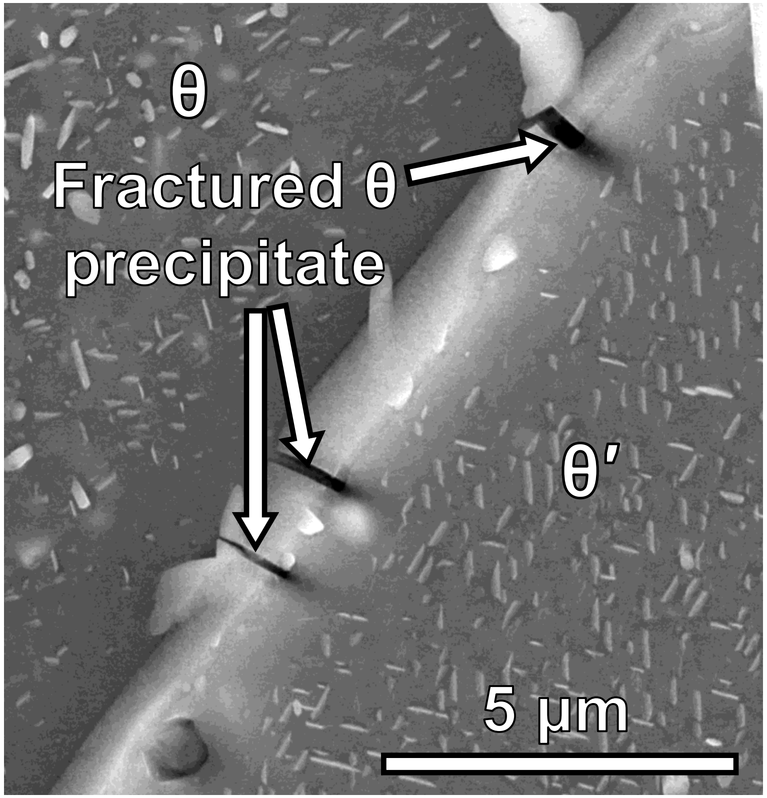

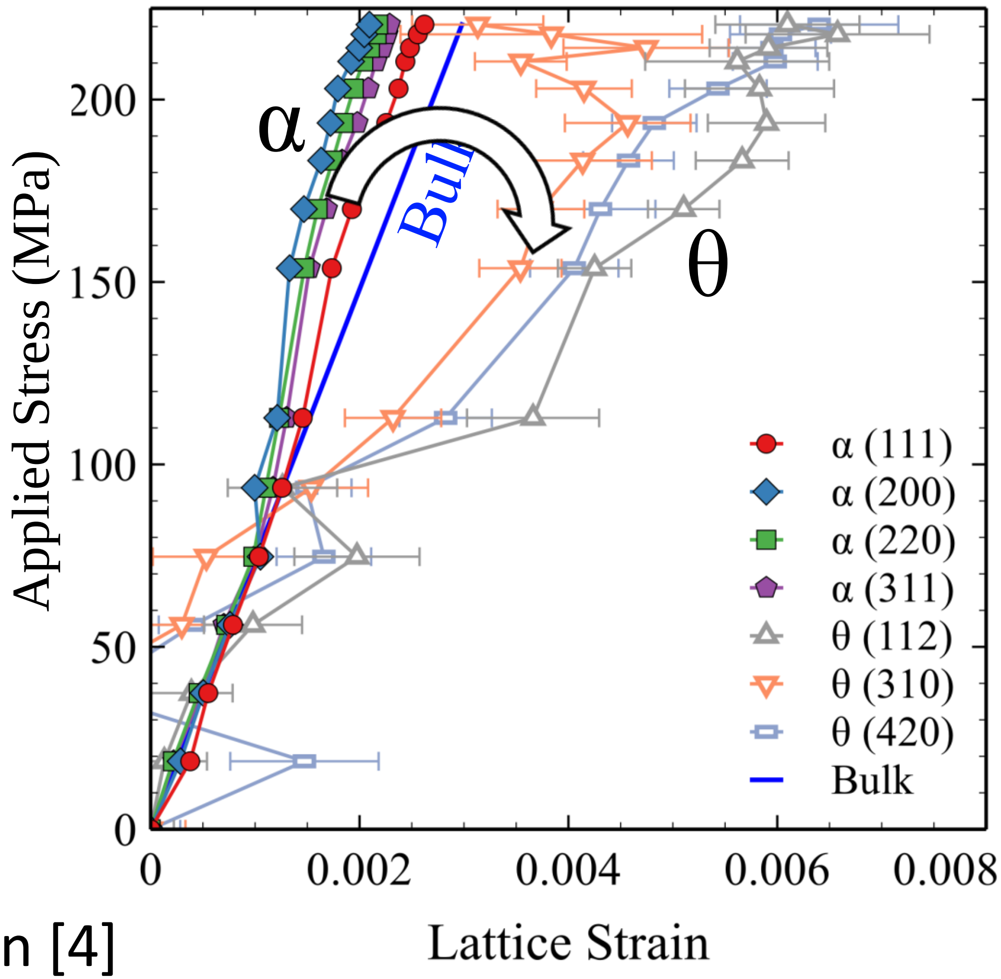

- θ precipitates un-shearable [3]
- Precipitate fracture at high strain [4]

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200°C Overage: Orowan Looping, Load Transfer, and Anisotropy

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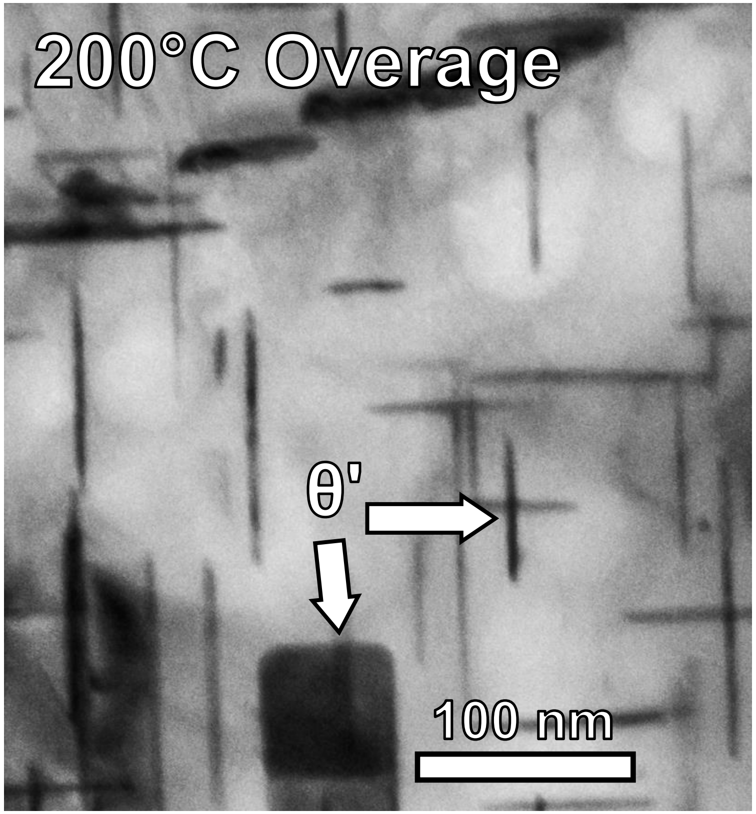

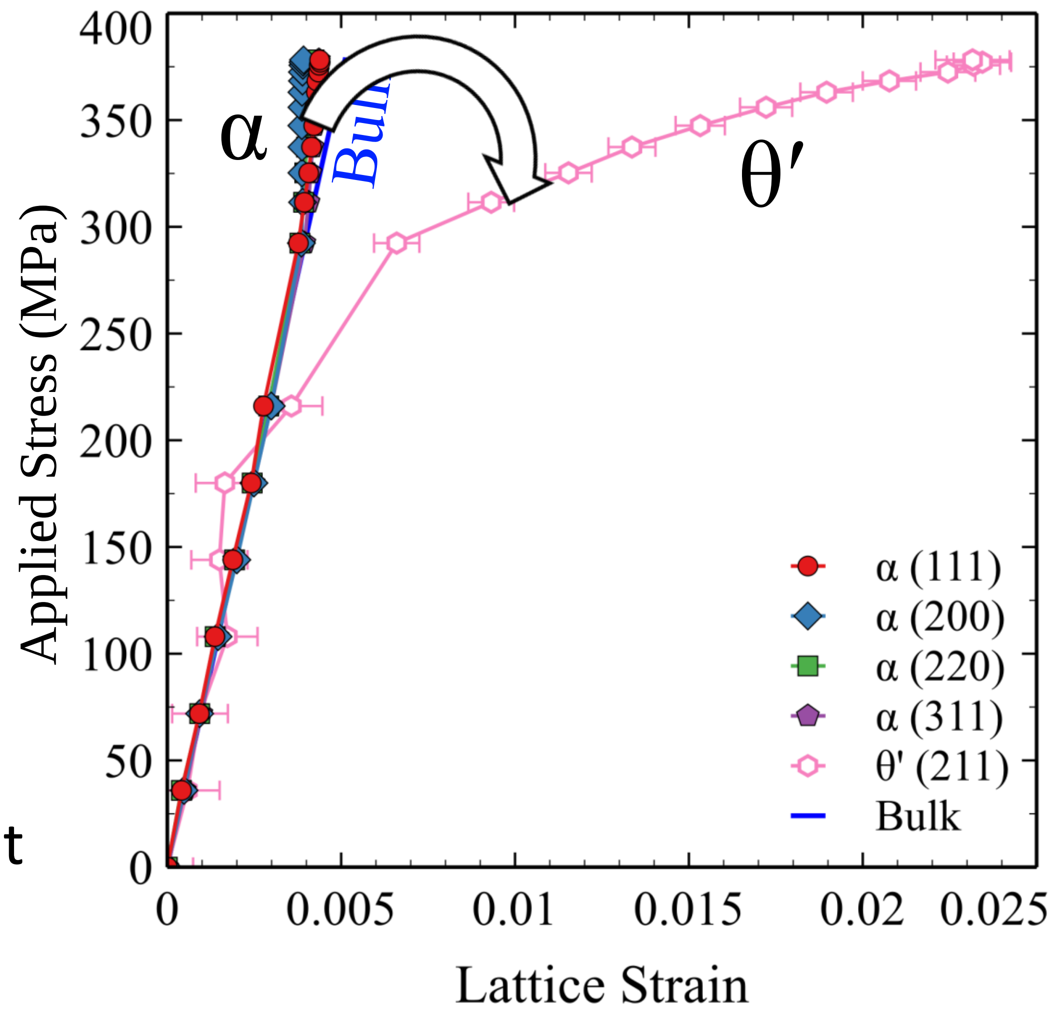

- θ′ precipitates un-shearable at bulk yield point [3]

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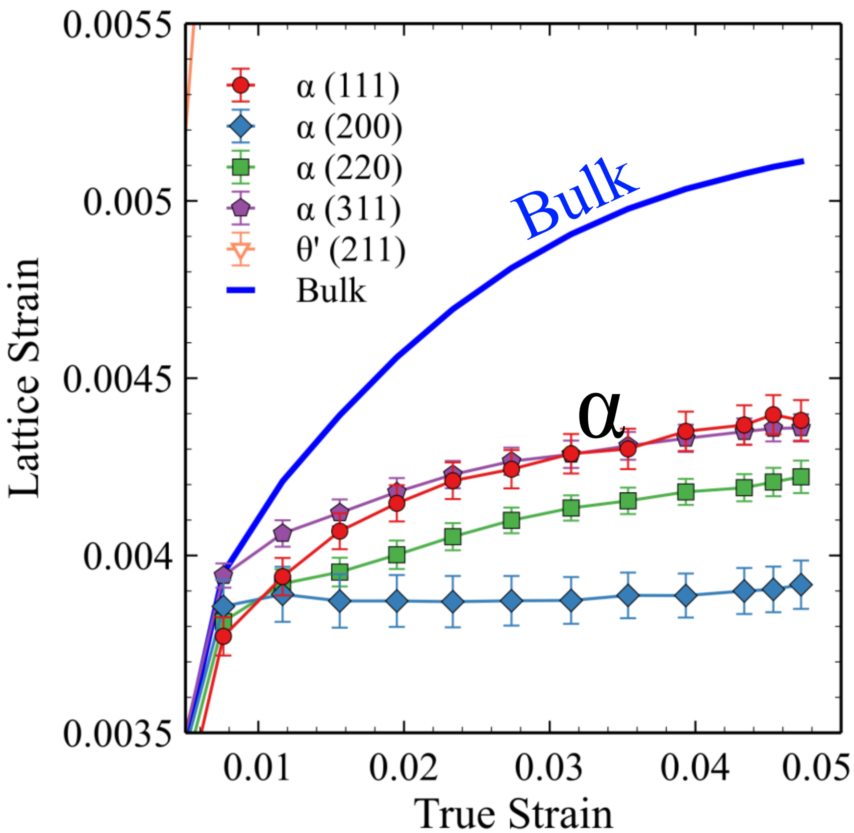
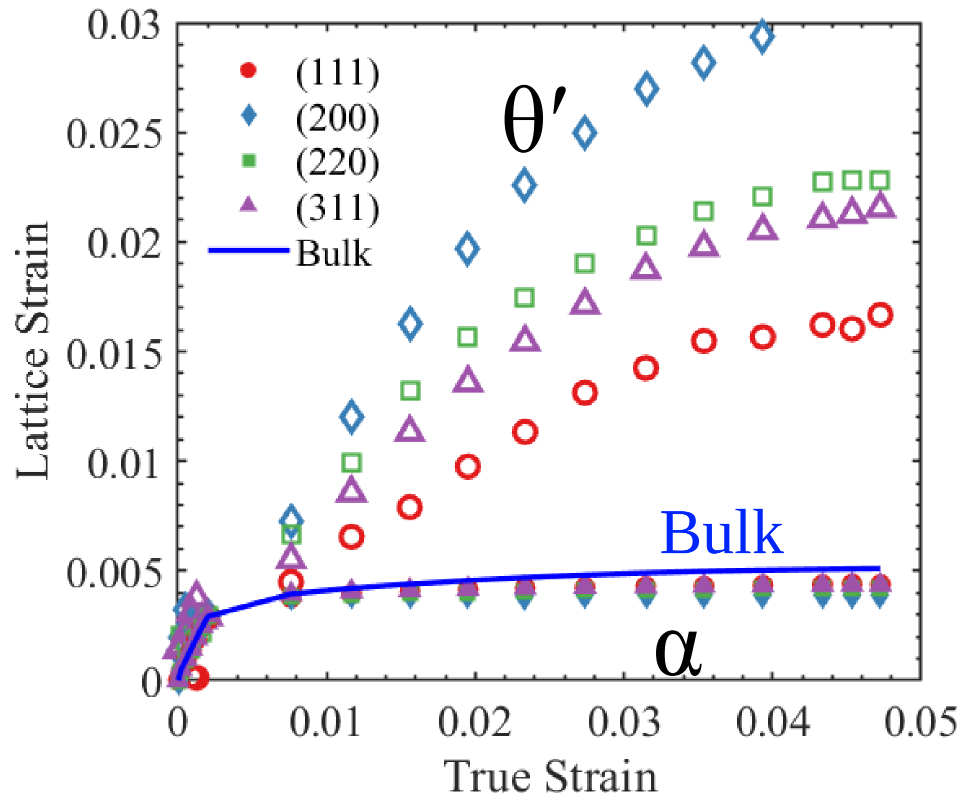
Hypothesis: Anisotropic Strain Hardening Caused by Anisotropic Load Transfer





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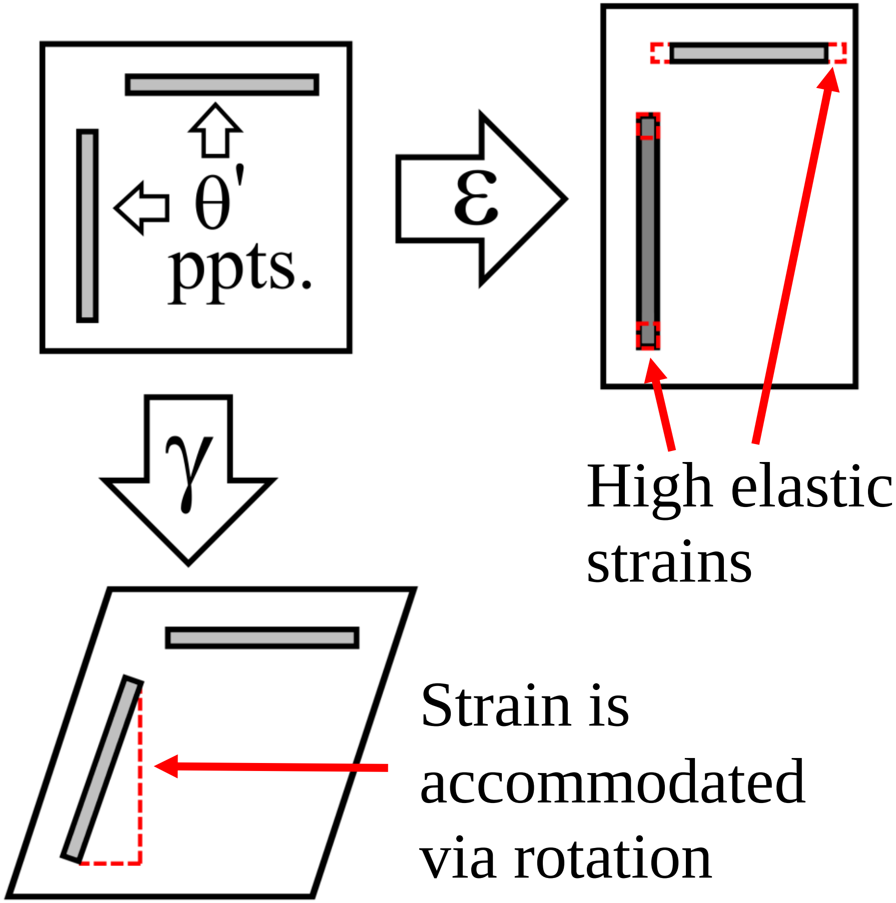
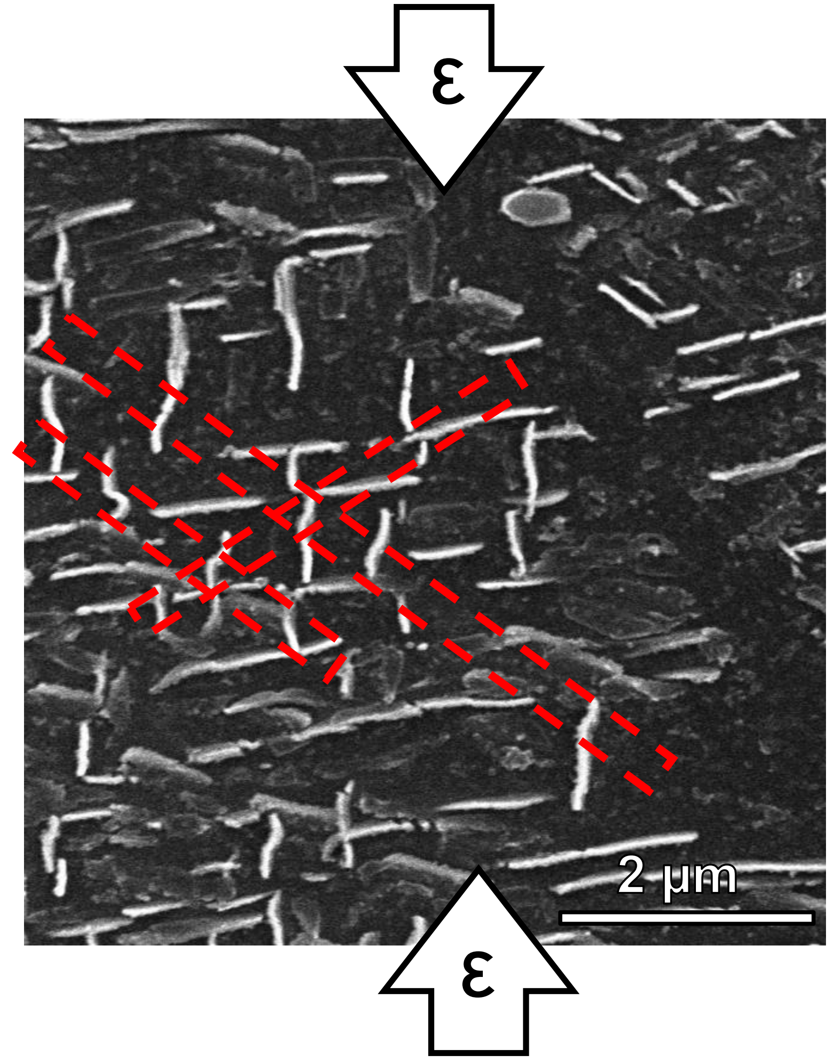
Anisotropic Load Transfer Caused by Precipitate Rotation





Post-compression Al-Cu alloy RR350 reproduced from [5]

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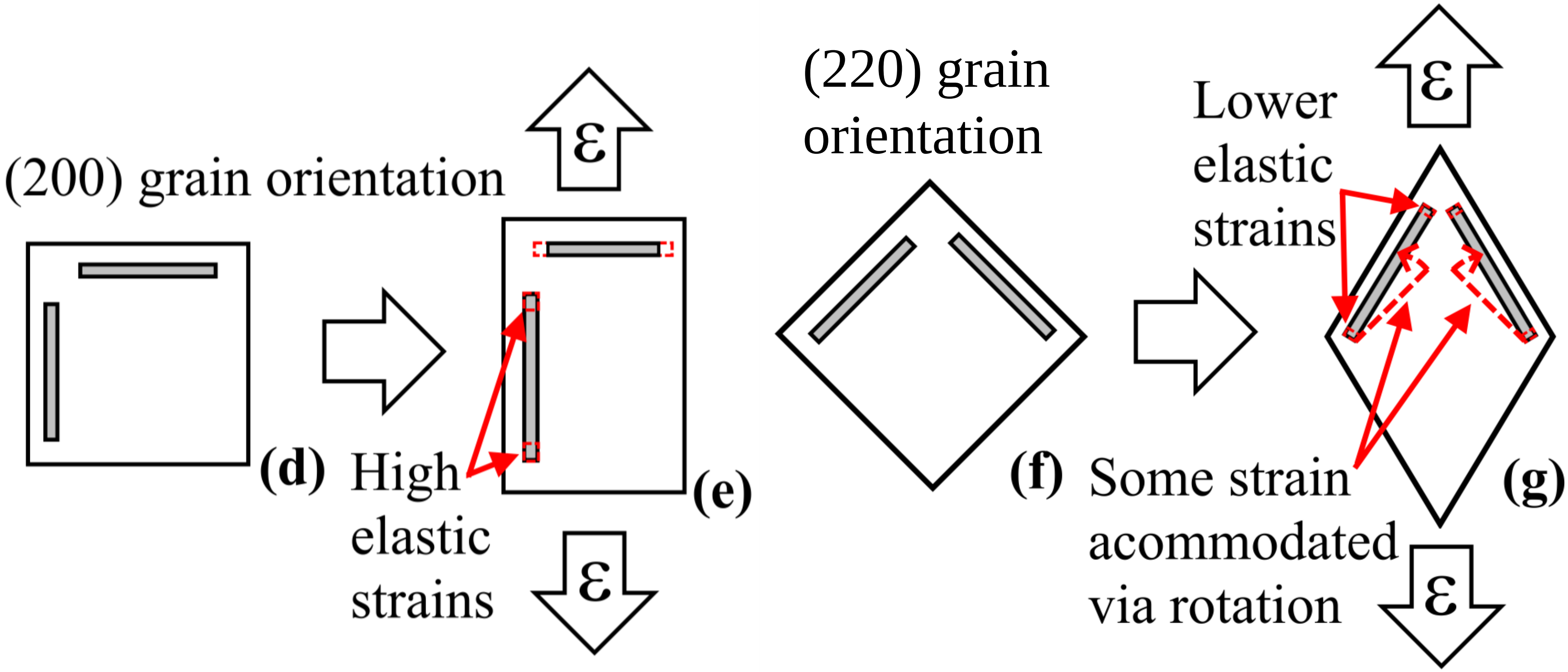
(200) Grain Orientation has Highest Load Transfer



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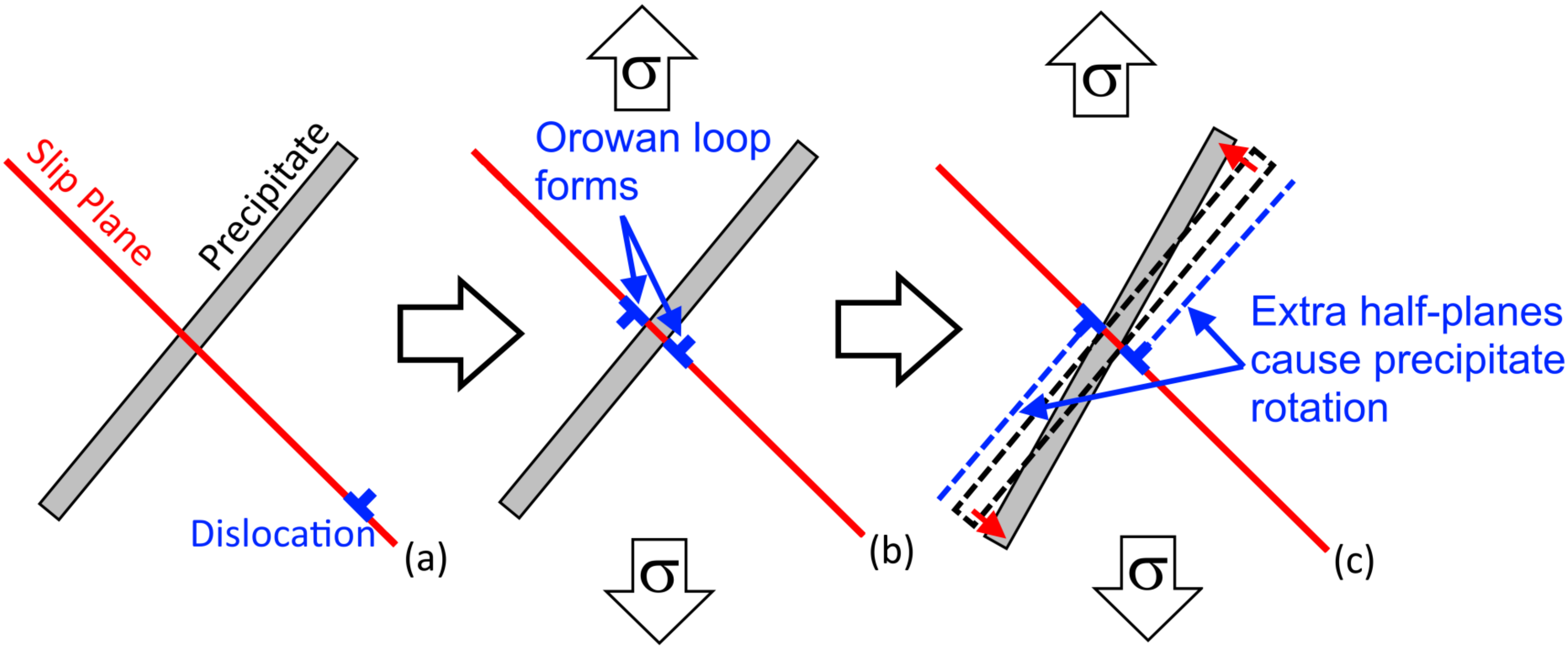
Dislocation Mechanism for Precipitate Rotation



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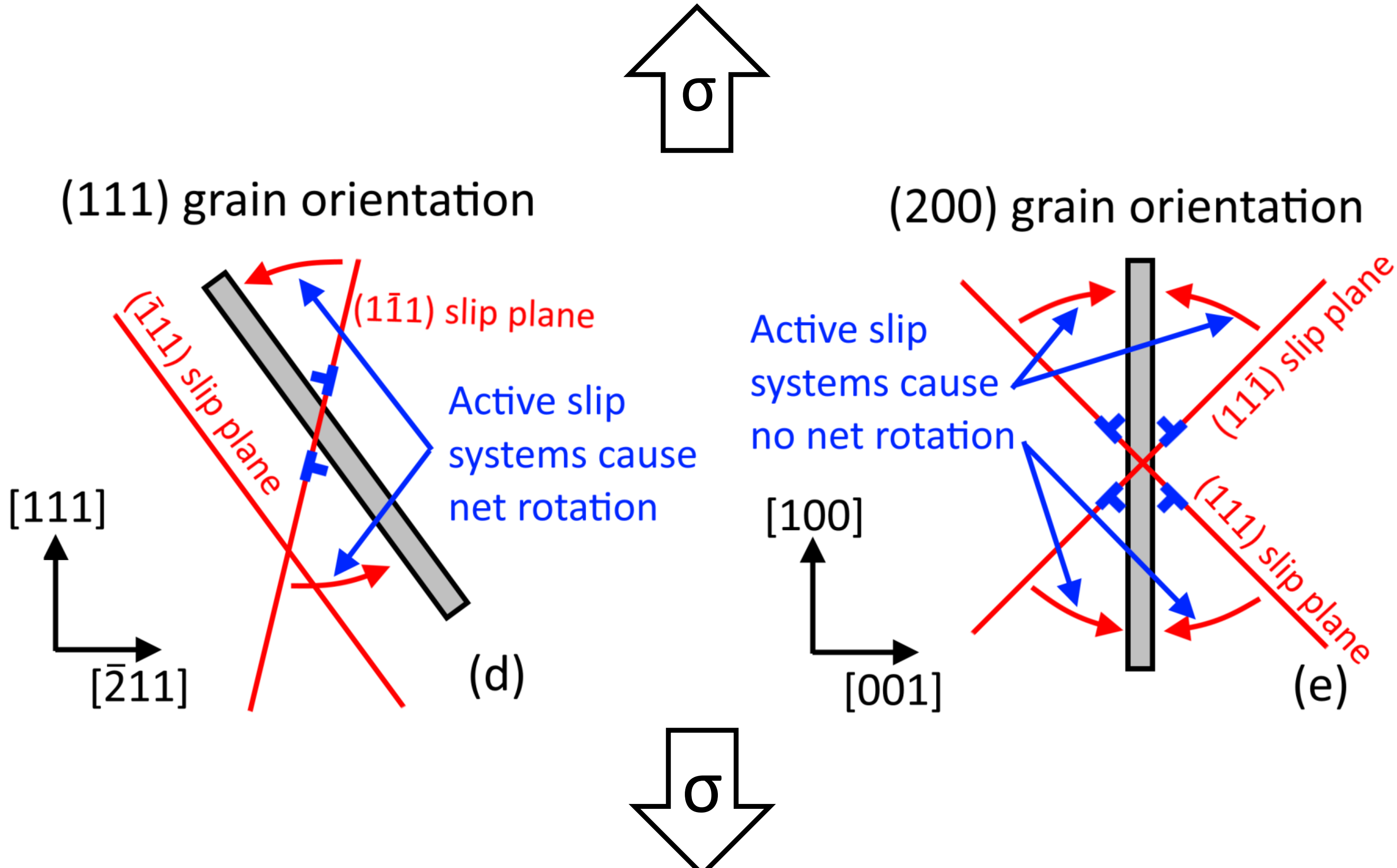
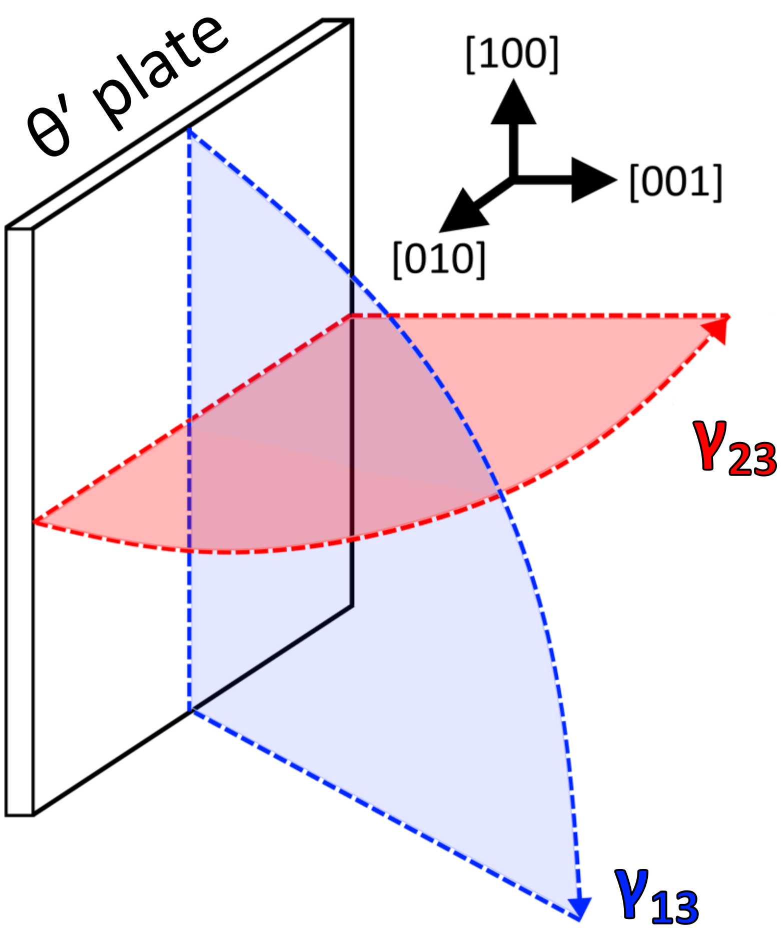
Anisotropic Rotation Dislocation Mechanism



Modeling Precipitate Rotation: Assumptions

- Uniaxial bulk strain
- Iso-strain conditions
- Precipitates deform elastically
- γ_{13} and γ_{23} are accommodated *via* rotation [6]
- Applied stress and stress from load transfer do not interact



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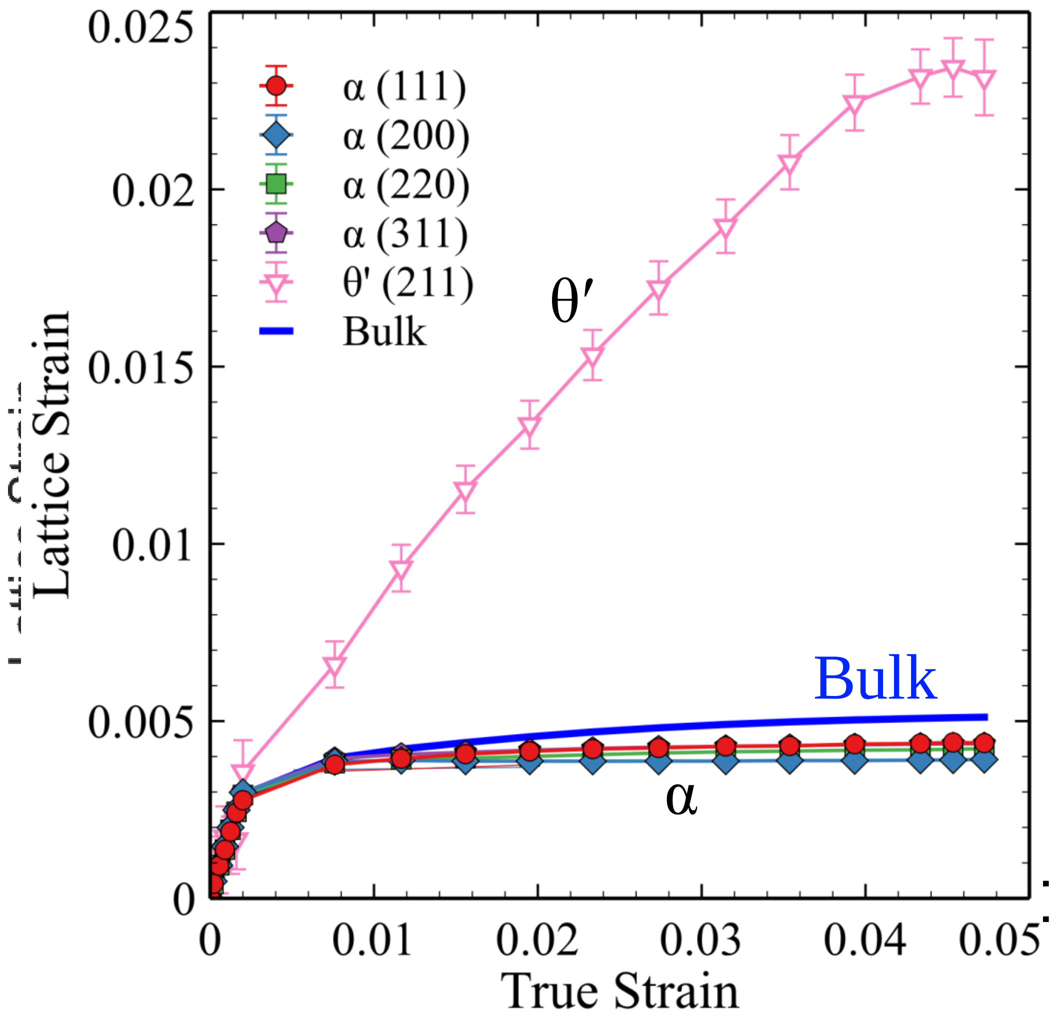
Modeling Precipitate Rotation: Total Lattice Strain



$$\sigma_{total}^{hkl} = \sigma_{app} + \sigma_{transfer}$$

$$\epsilon_{lattice}^{hkl} = \frac{\sigma_{total}^{hkl}}{E^{hkl}}$$

*Assuming precipitate does not yield

$$\sigma_{transfer} = \epsilon_{transfer} * E^{hkl}$$

$$\epsilon_{lattice}^{hkl} = \frac{\sigma_{app}}{E^{hkl}} + \epsilon_{transfer}$$

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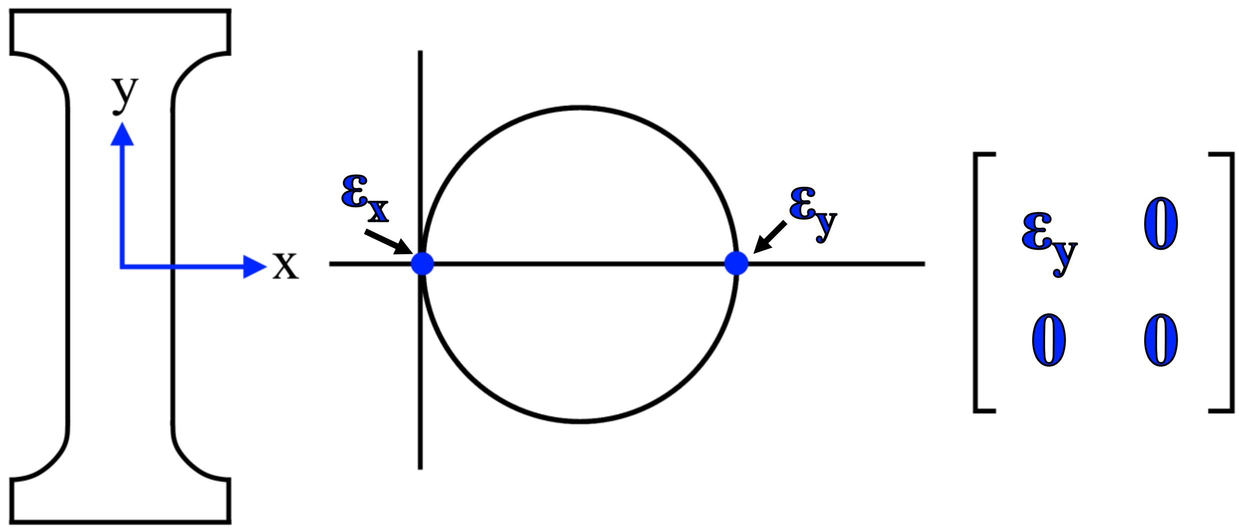
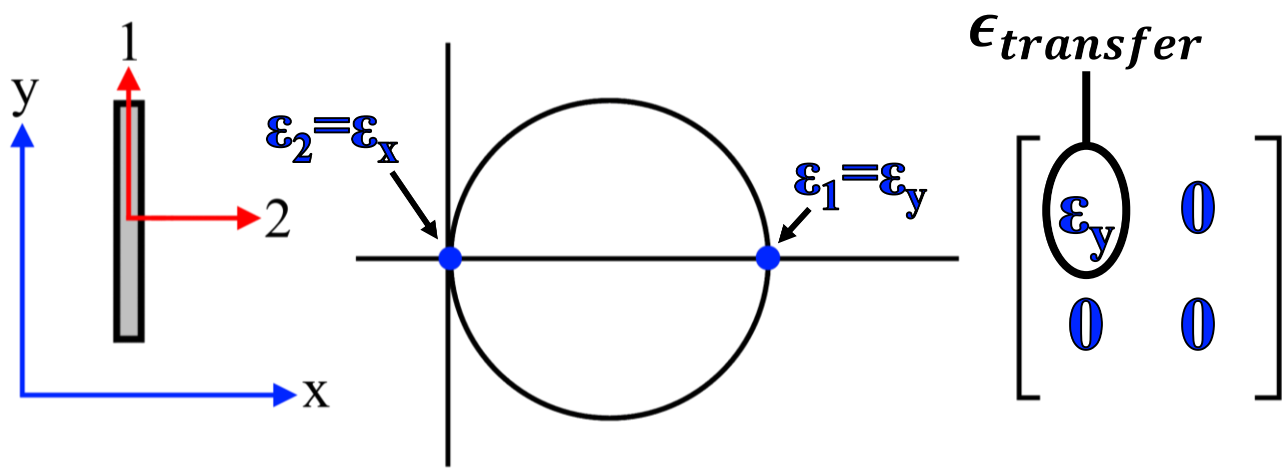
Transfer Strain 1. Calculate Specimen Strain State



(200) type precipitate



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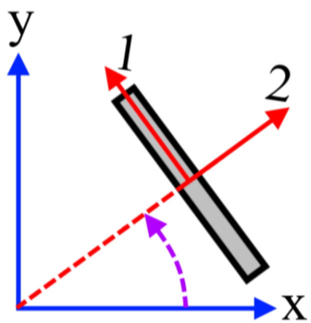
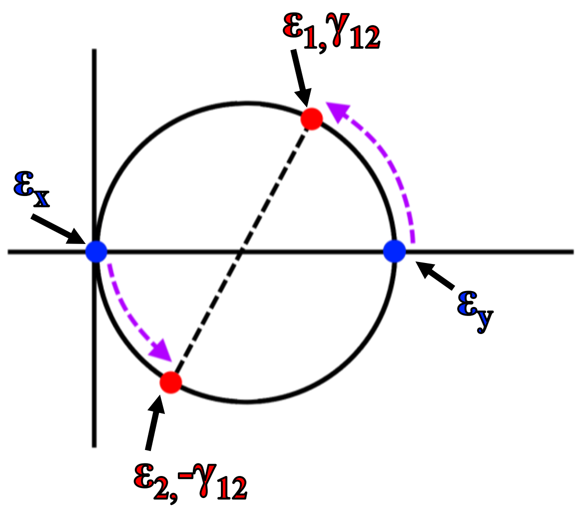
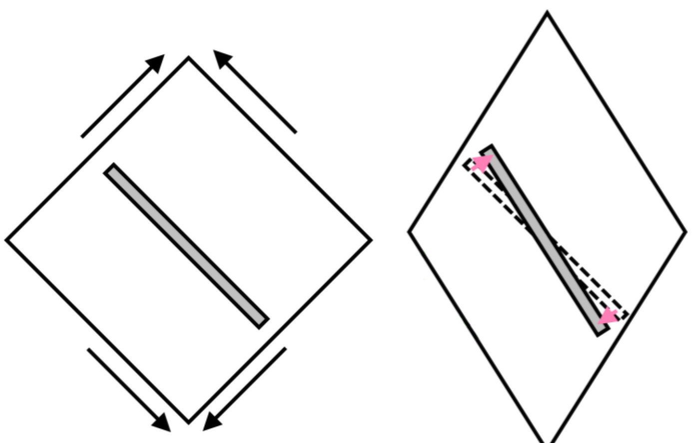
Transfer Strain 2. Rotate Strain State to Precipitate Axes

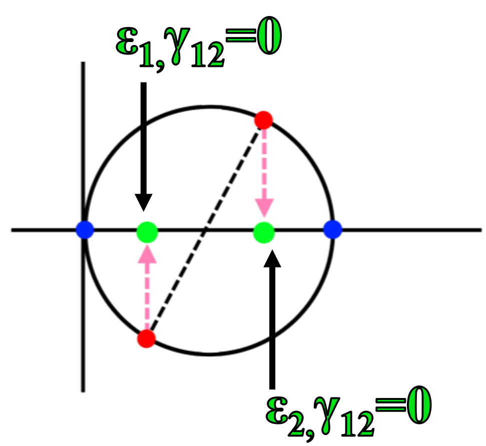
(111) type precipitate





$$\begin{bmatrix} \varepsilon_y & 0 \\ 0 & 0 \end{bmatrix} \Rightarrow \begin{bmatrix} .9\varepsilon_y & .3\varepsilon_y \\ -.3\varepsilon_y & .1\varepsilon_y \end{bmatrix}$$





$$\begin{bmatrix} .9\varepsilon_y & .3\varepsilon_y \\ -.3\varepsilon_y & .1\varepsilon_y \end{bmatrix} \Rightarrow \begin{bmatrix} .9\varepsilon_y & 0 \\ 0 & .1\varepsilon_y \end{bmatrix}$$

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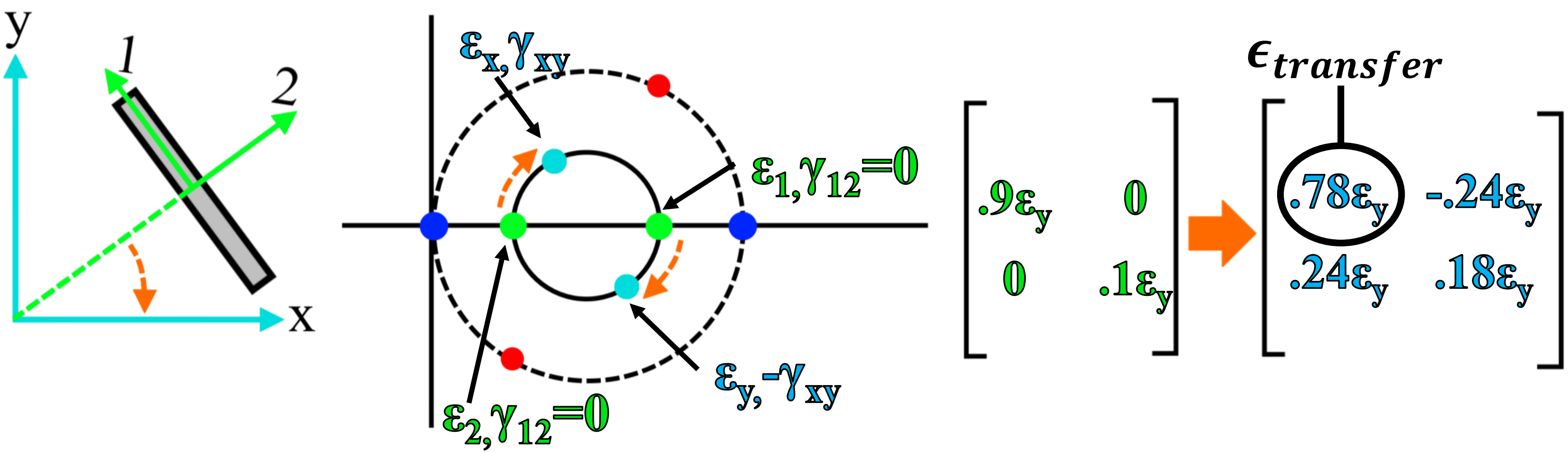
Transfer Strain 3. Rotate Back to Sample Axes



Precipitate	Rotation	$\epsilon_{transfer}$
(200)	0°	ε_y
(111)	36°	$0.78\varepsilon_y$

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Modeling Precipitate Rotation: Comparison to Experiments

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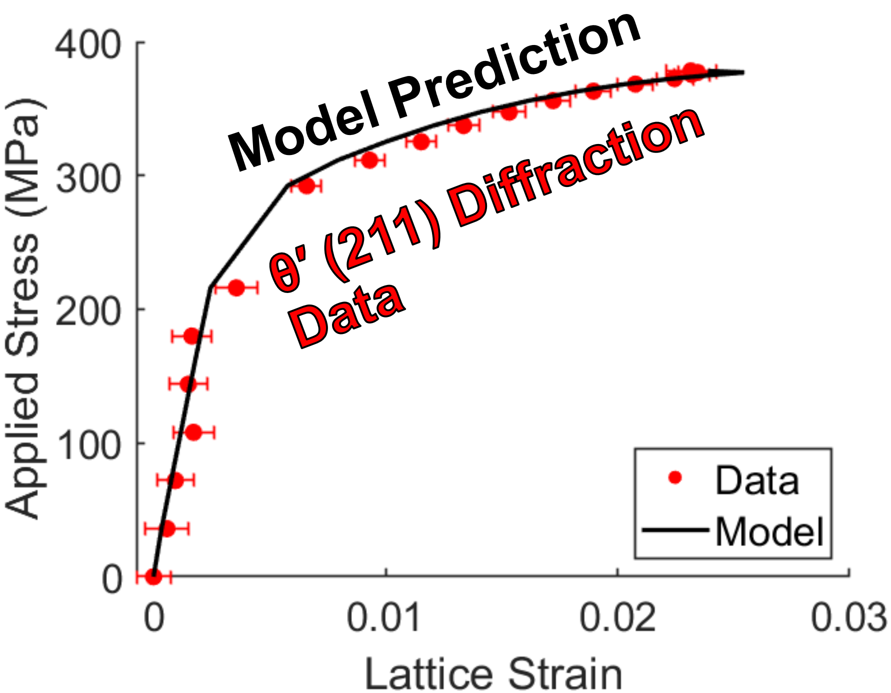
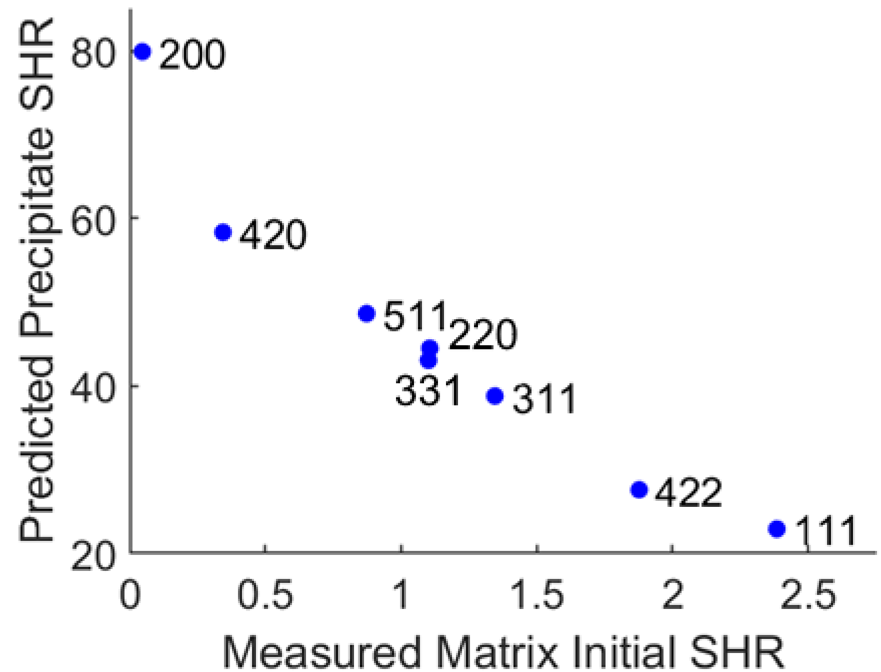
Precipitate Comparison



Matrix Comparison



Model attempted to predict behavior of precipitates in (422) grain orientation, data is for (211) θ′ precipitates

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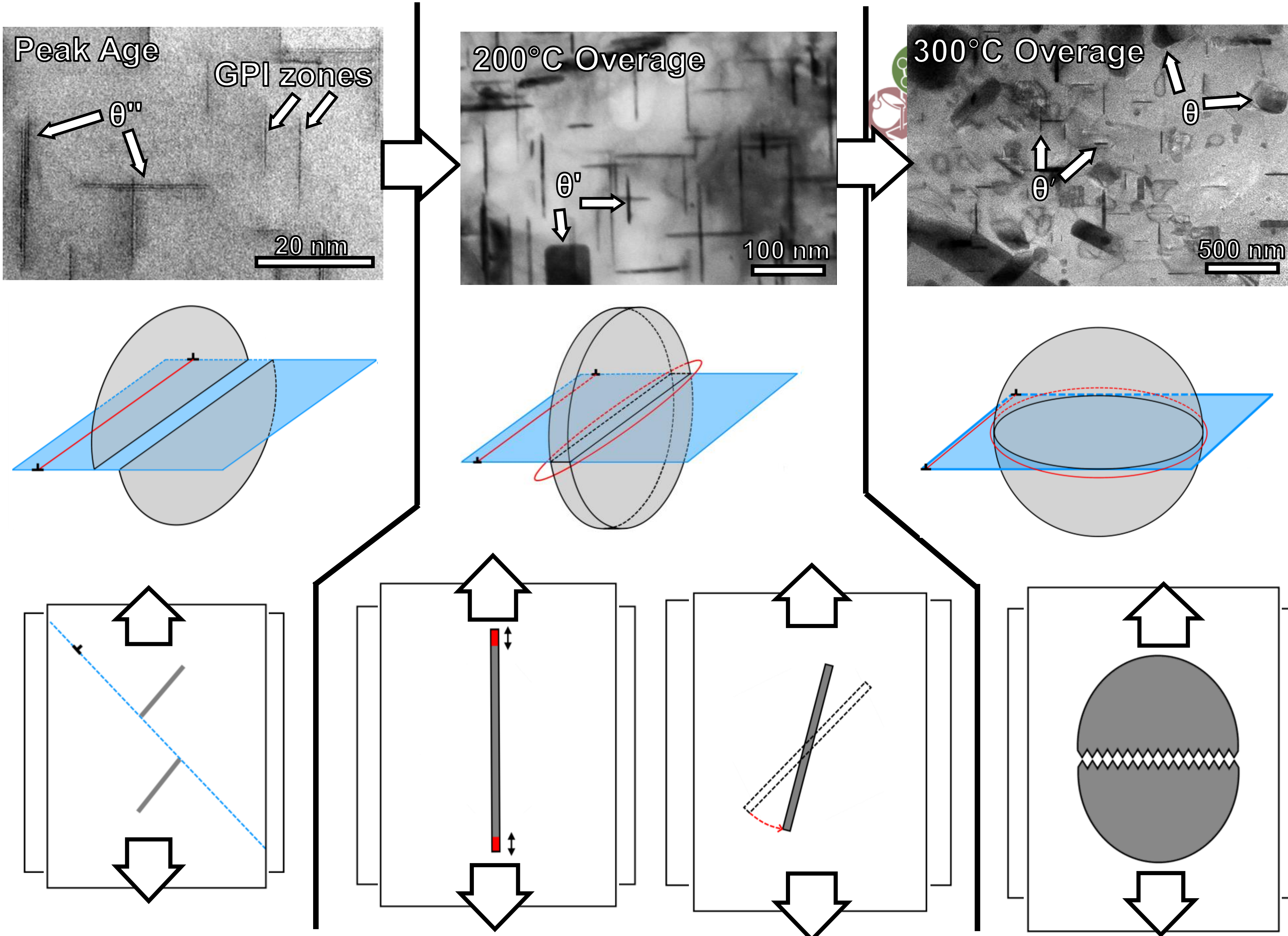

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Progress

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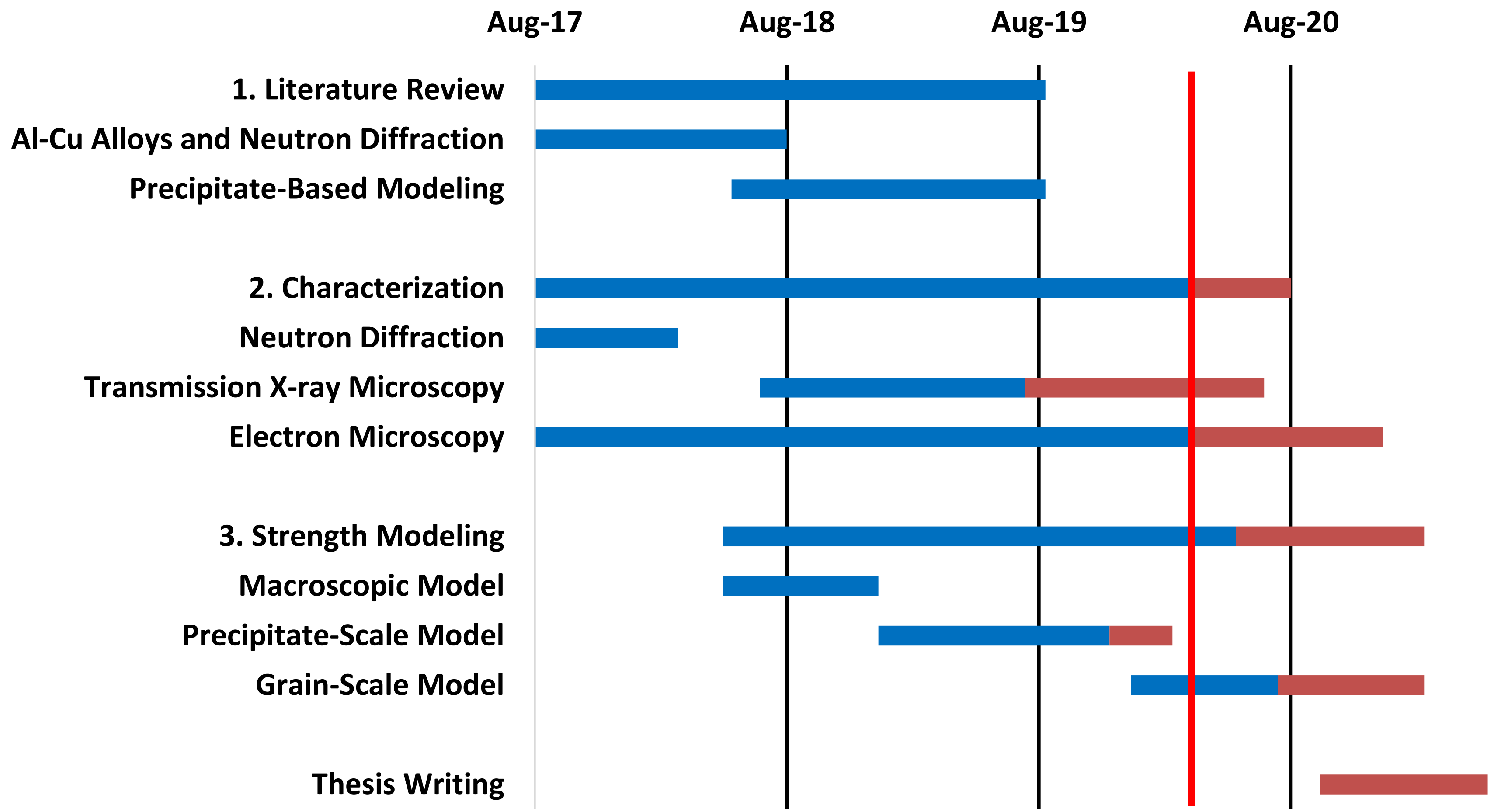

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References

[1] S. Ma *et al*, CRSS of γ-γ′ phases from in situ neutron diffraction of a directionally solidified superalloy tension tested at 900°C, Acta Materialia 56 (2008) 4102-4113

[2] S. D. Dahlgren, Coherency Stresses, Composition and Dislocation Interactions for θ" Precipitates in Age-Hardened Al-Cu, Metallurgical and Materials Transactions A 7 (1976) 1401-1405

[3] I. Adlakha *et al*, Revealing the atomistic nature of dislocation-precipitate interactions in Al-Cu alloys, Journal of Alloys and Compounds 797 (2019) 325-333

[4] S. Bahl *et al*, Effect of copper content on the tensile elongation of Al–Cu–Mn–Zr alloys: Experiments and finite element simulations, Materials Science and Engineering A (2020) 138801

[5] P. Shower *et al*, The effects of microstructural stability on the compressive response of two cast aluminum alloys up to 300 °C, Materials Science and Engineering A 700 (2017) 519-527

[6] W. F. Hosford, R. H. Zeisloft, The anisotropy of age-hardened Al-4 pct Cu single crystals during plane-strain compression, Metallurgical Transactions 3 (1972) 113-121

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Challenges & Opportunities

- Only one precipitate orientation in the 200°C overaged condition is measurable with high confidence
  - Other conditions with higher volume fractions of θ′ precipitates may be worth looking at
- Delayed shearing may be interesting as a function of load transfer (and orientation)
- Load transfer during creep is another area of study
  - Will load transfer still happen during climb?
  - Will the precipitates still be measurable at high temperature?

Thank you!

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