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

Fall Meeting

October 13th-15th 2020

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

Oak Ridge National Laboratory

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

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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.

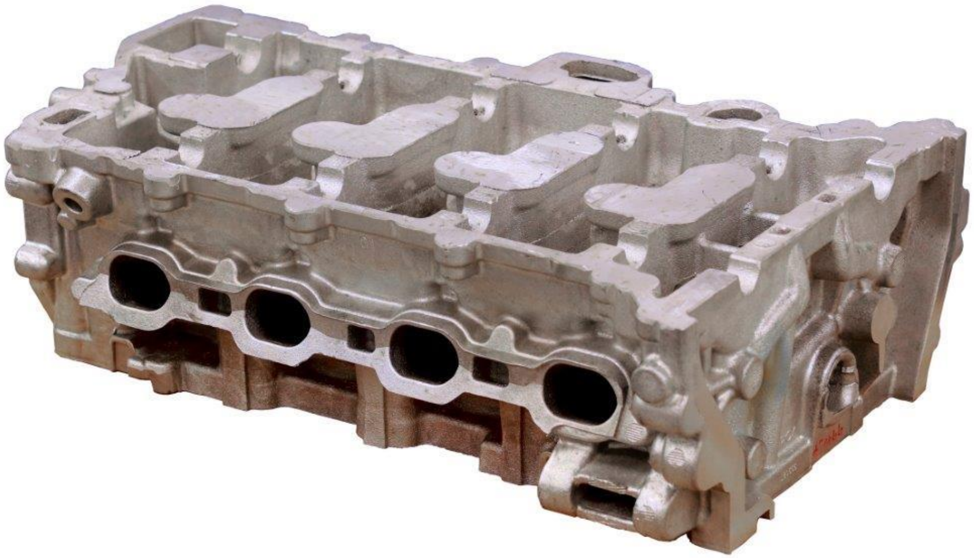
Recent Progress
- Submitted paper on alloy 206 neutron diffraction room temperature results to Acta Materialia
- Continued analysis of elevated temperature lattice strain results on alloy RR350
- Identified precipitate yielding at multiple temperatures in Alloy RR350 using lattice strain and peak width data
- Began microstructural analysis of Alloy RR350 post-mortem at room temperature at 300°C

Metrics

Description	% Complete	Status
1. Initial literature review	90%	●
2. In situ neutron diffraction, creep testing, and TXM	100%	●
3. Microstructural characterization pre- and post- creep and tension	80%	●
4. Qualitative assessment of neutron diffraction and mechanical test data	80%	●
5. Application and development of qualitative modelling to micro-scale diffraction data	80%	●

Industrial Relevance

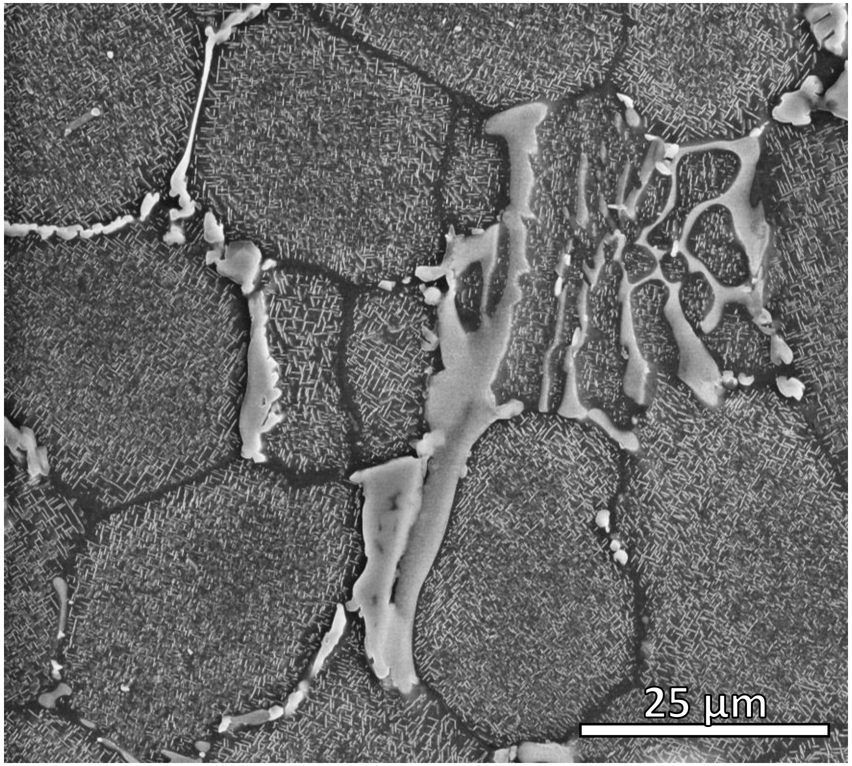
- Cast Al-Cu alloys have high strength, low density, and are very castable
  - Used in various industries such as for cylinder heads in light-duty engines
- Understanding of deformation mechanisms allow prediction of mechanical behavior
  - Strain hardening behavior commonly overlooked, but is relevant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

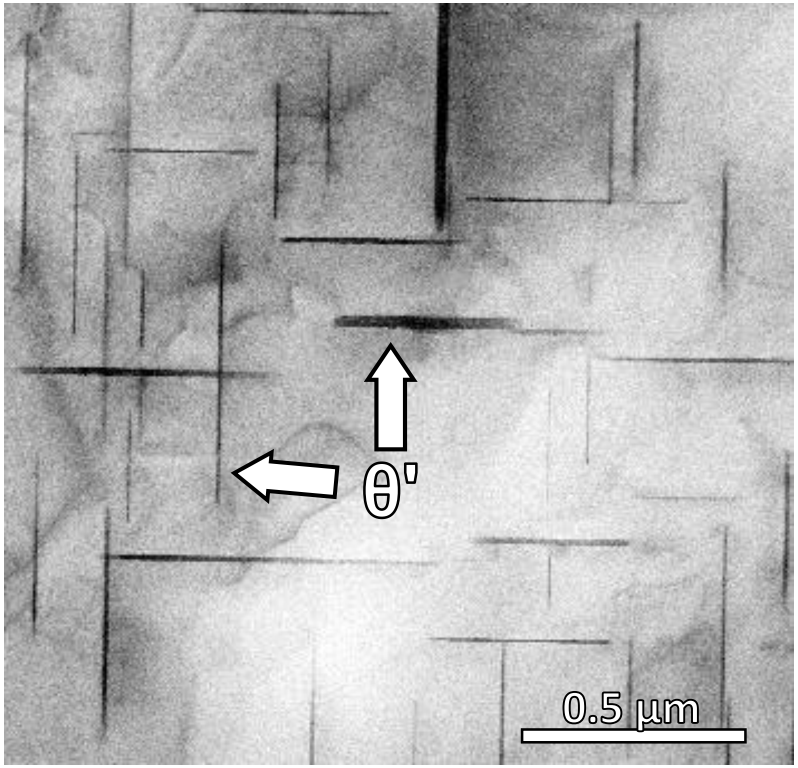


Cylinder head cast with ORNL ACMZ alloy.
Credit: Jason Richards (ORNL)

Alloy RR350 Used for Elevated Temperature Testing

Cu	Mn	Zr	Si	Zn	Fe	Ni	Co	Ti	Sb
4.8	0.19	0.17	0.05	0.01	0.09	1.2	0.26	0.21	0.17





Solutionize	Water Quench	Age	Overage
535°C for 12hr	80-90°C	240°C for 5hr	Test Temp. for 200hr

Microstructural Stability of Alloy RR350 up to 350°C

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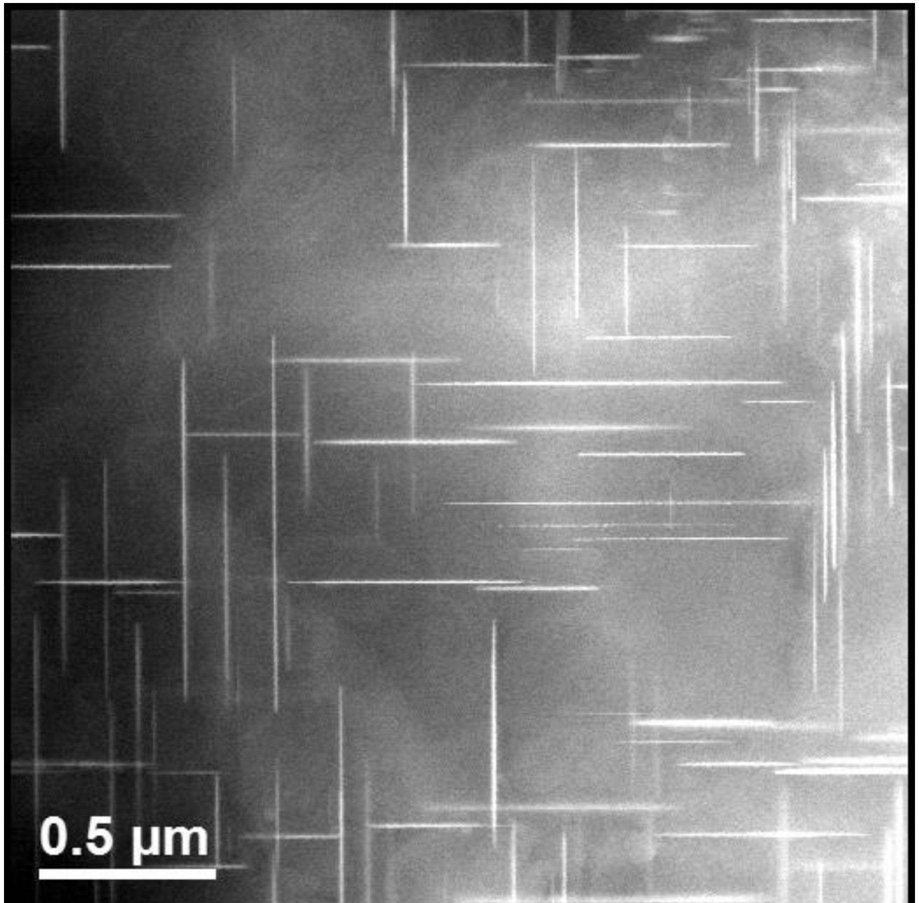
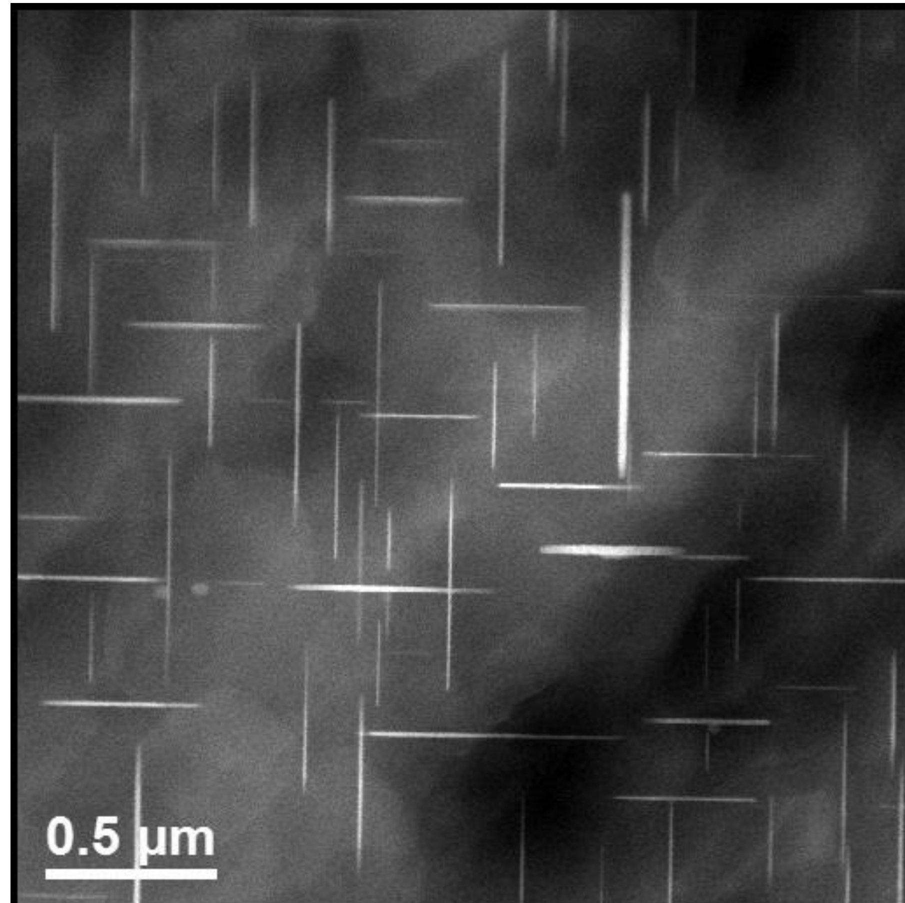
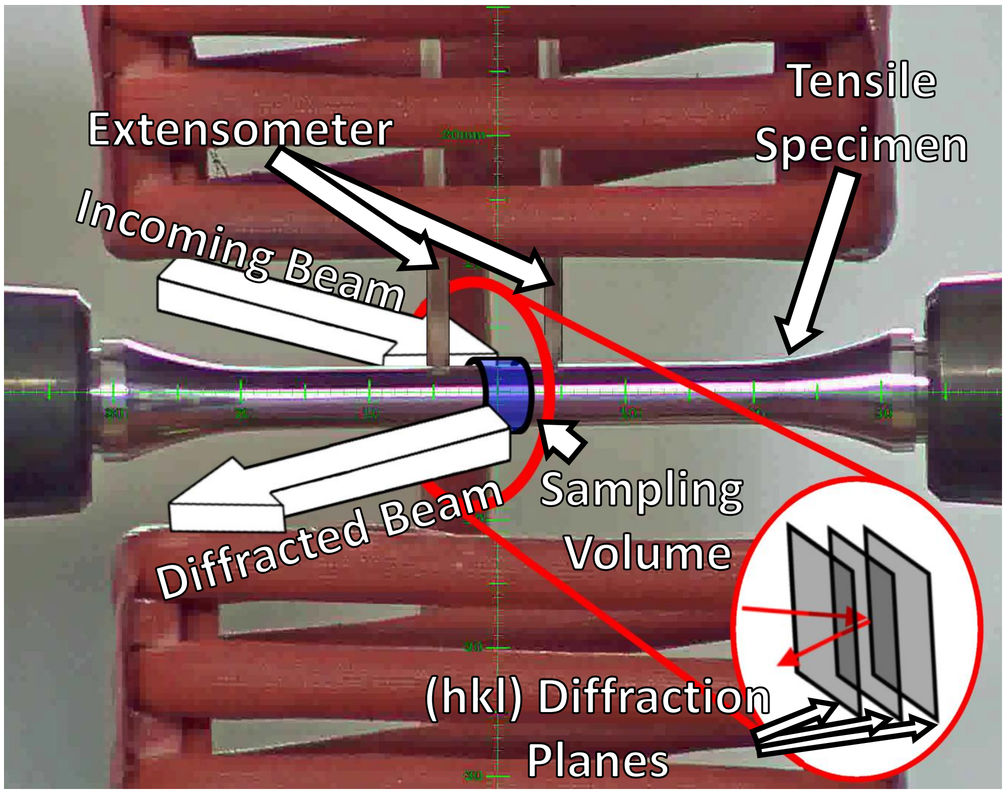
As Aged

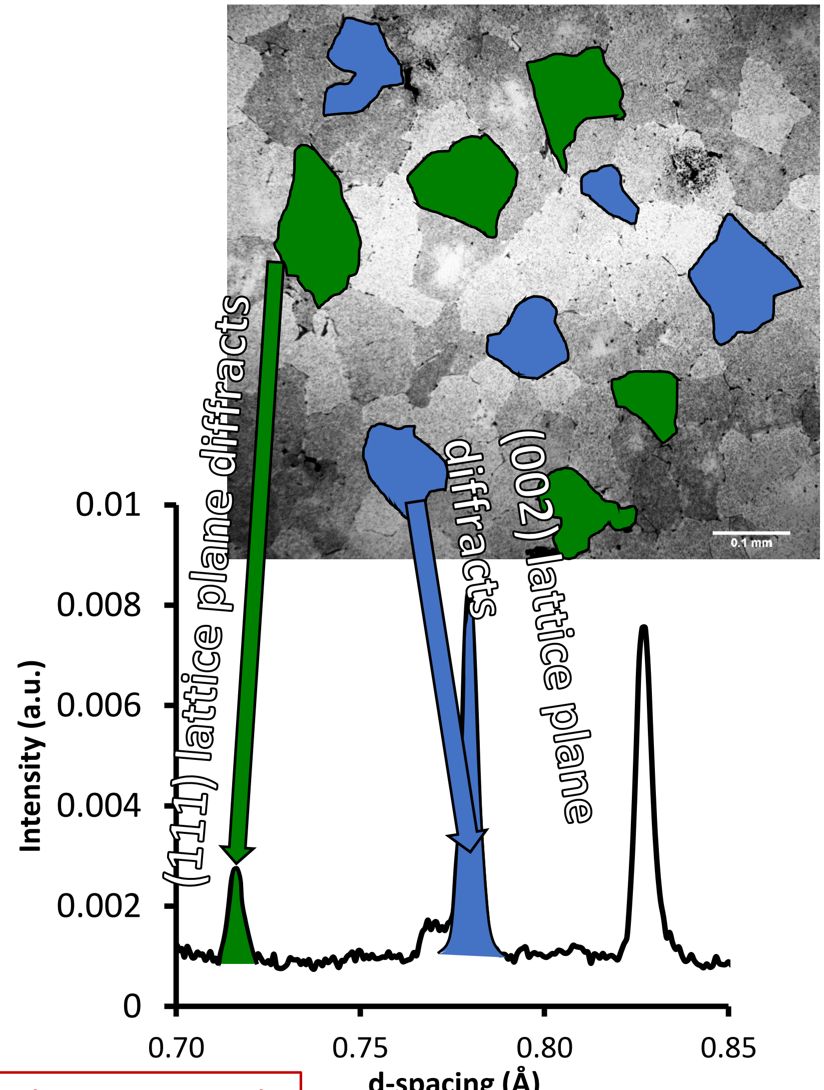


300°C overaged

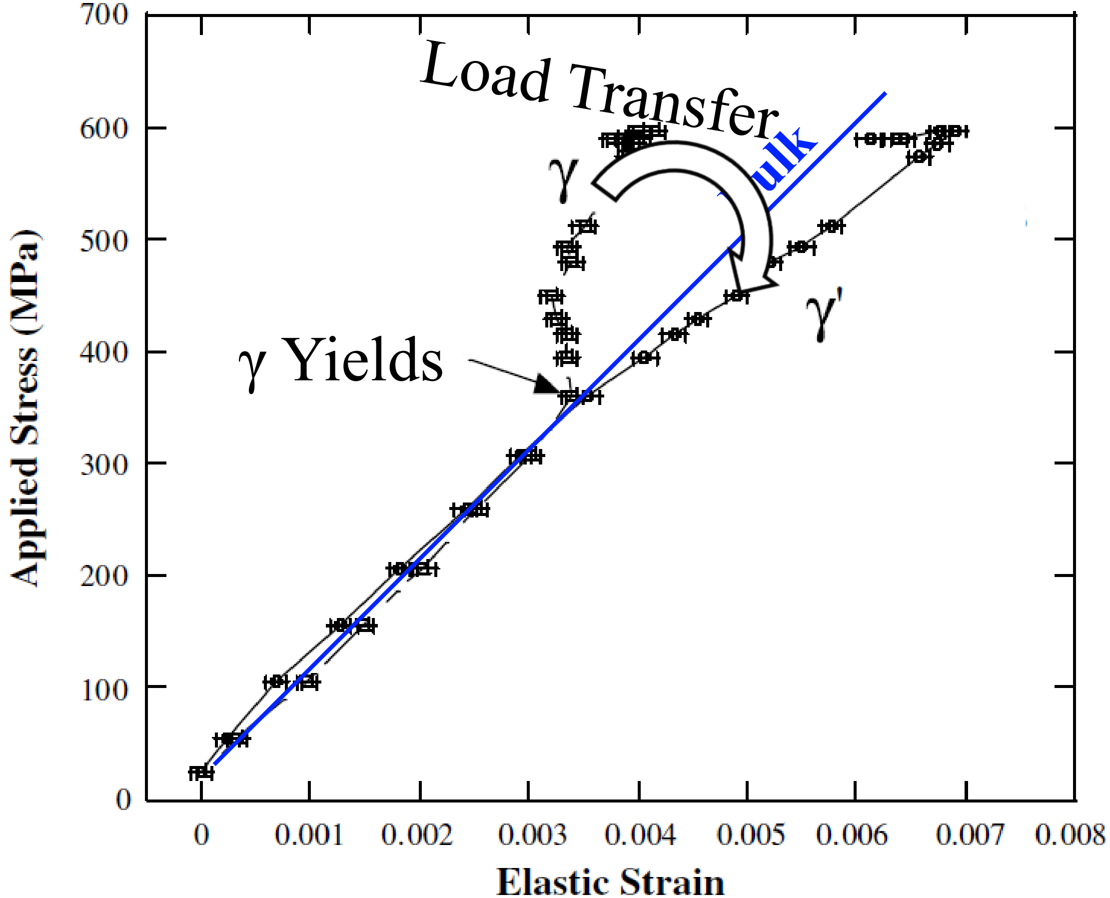


Neutron Diffraction Experiments at SNS VULCAN





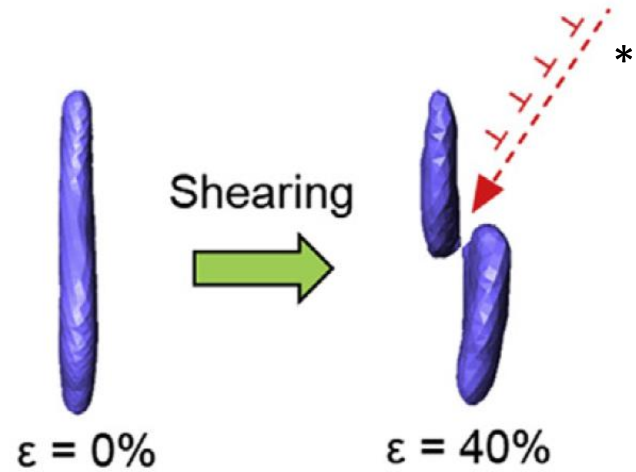
Y-plot Demonstrates Load Transfer Between Phases

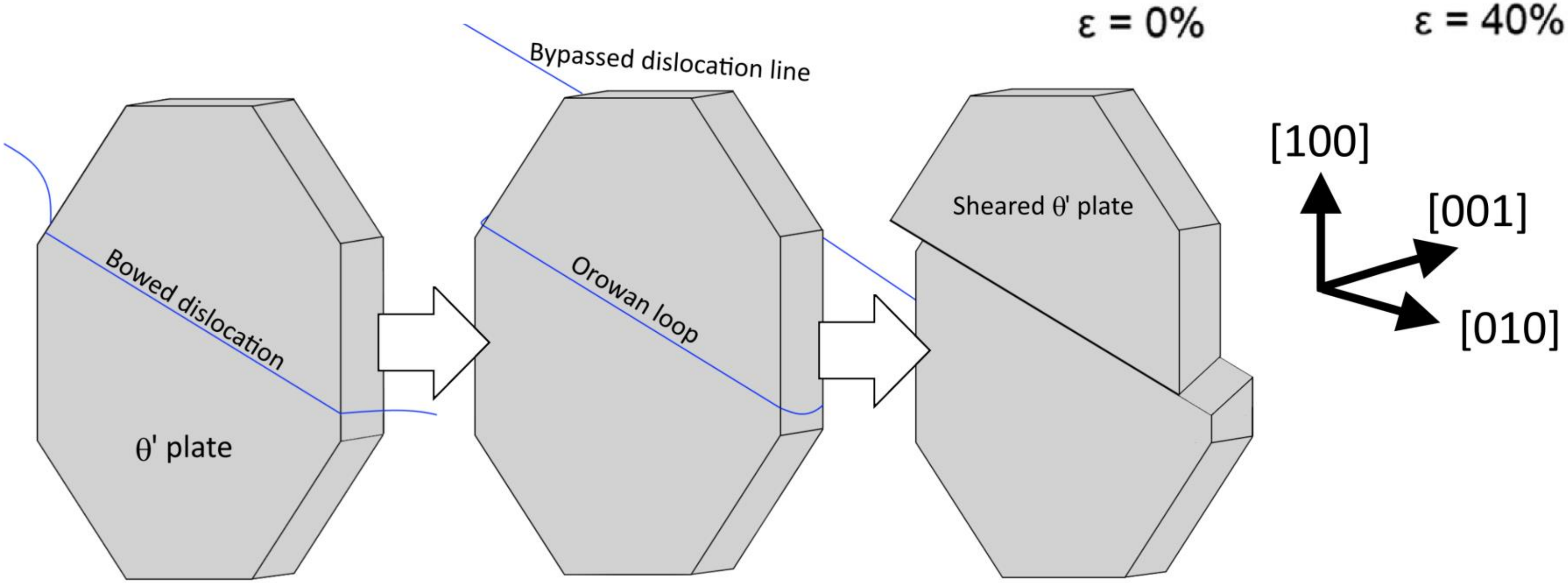


PWA 1422 superalloy, reproduced from [1]

Concept Re-Introduction: Delayed Shearing

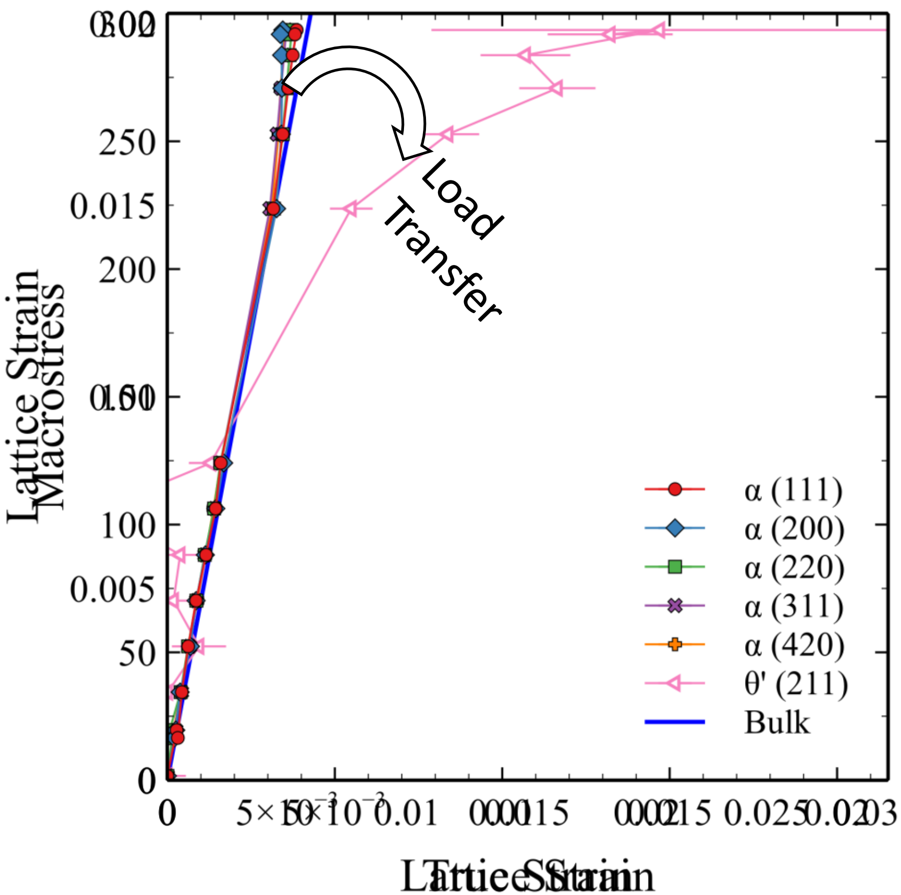
- Orowan looping at onset of yielding, load transfer occurs during plastic deformation
- Load transfer causes high stress in precipitates → yielding

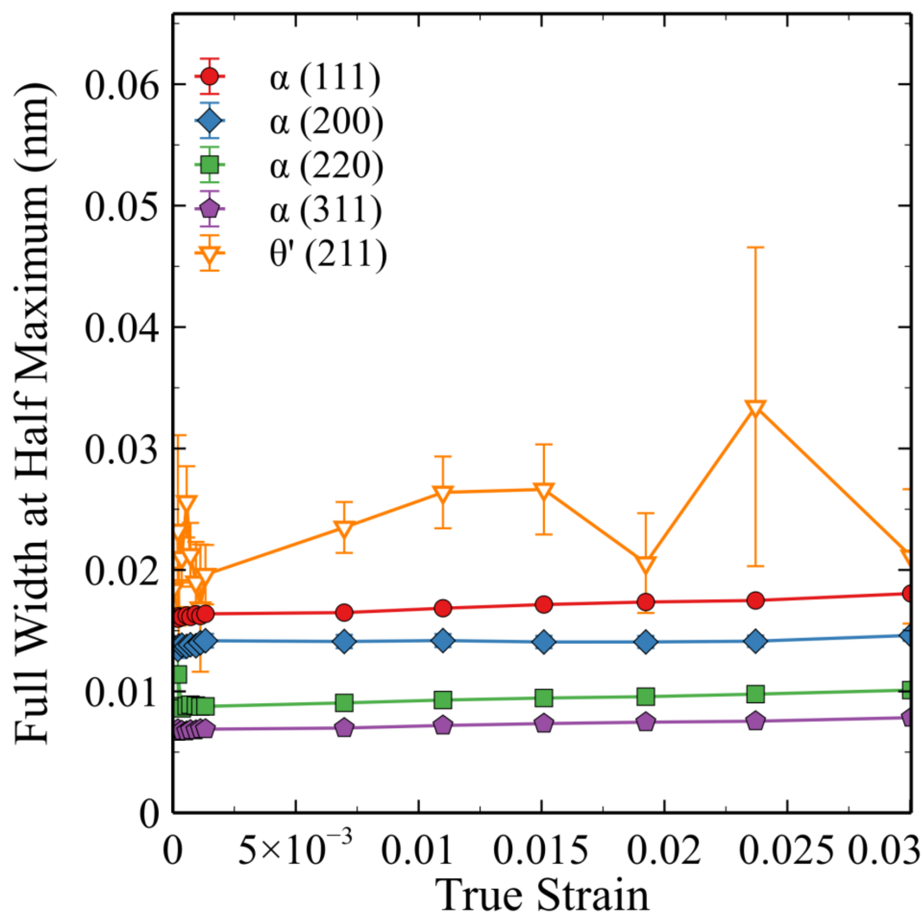




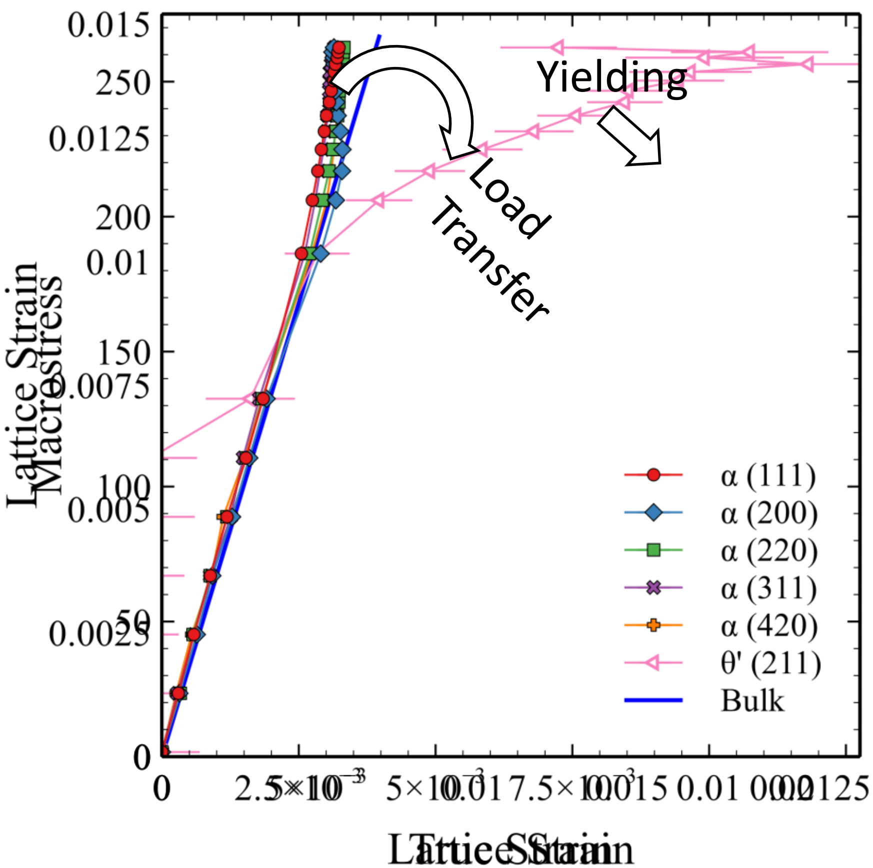
*C. S. Kaira *et al*, Acta Materialia 176 (2019) p242-249

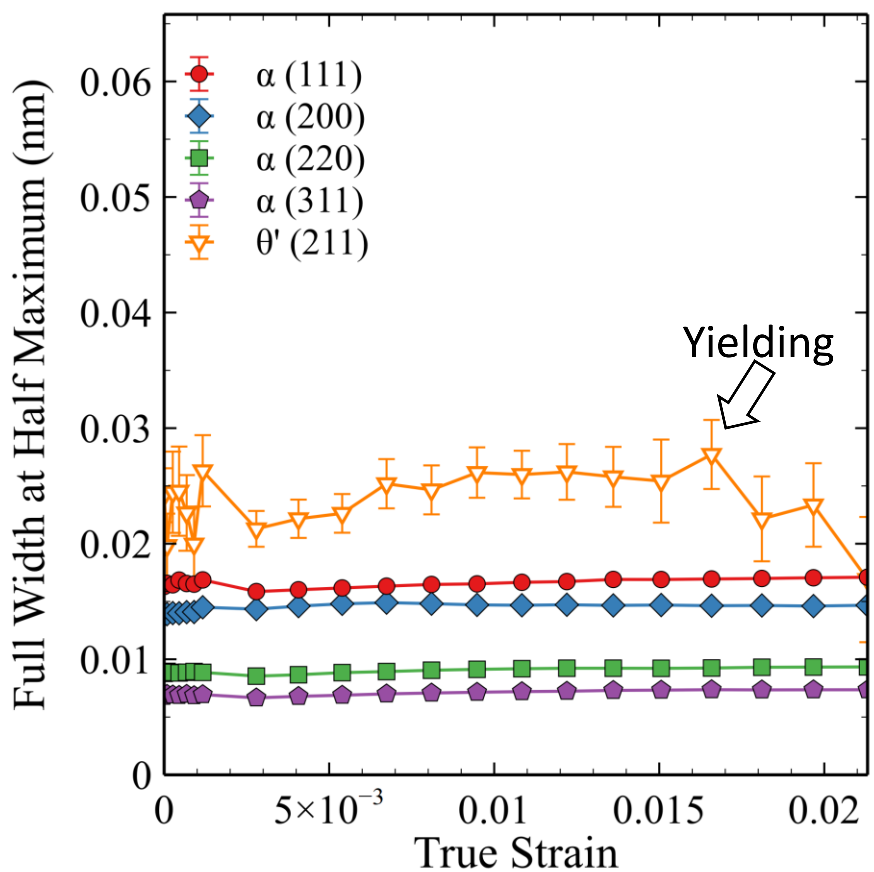
Room Temperature Test Displays Load Transfer





100°C Test Shows Load Transfer → Yielding





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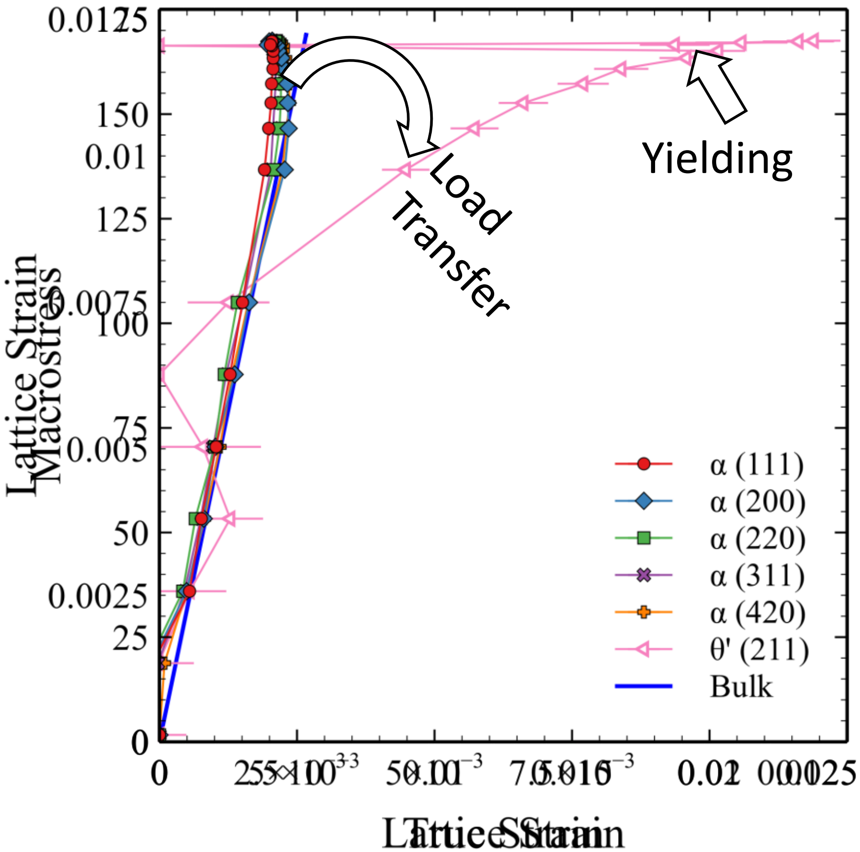
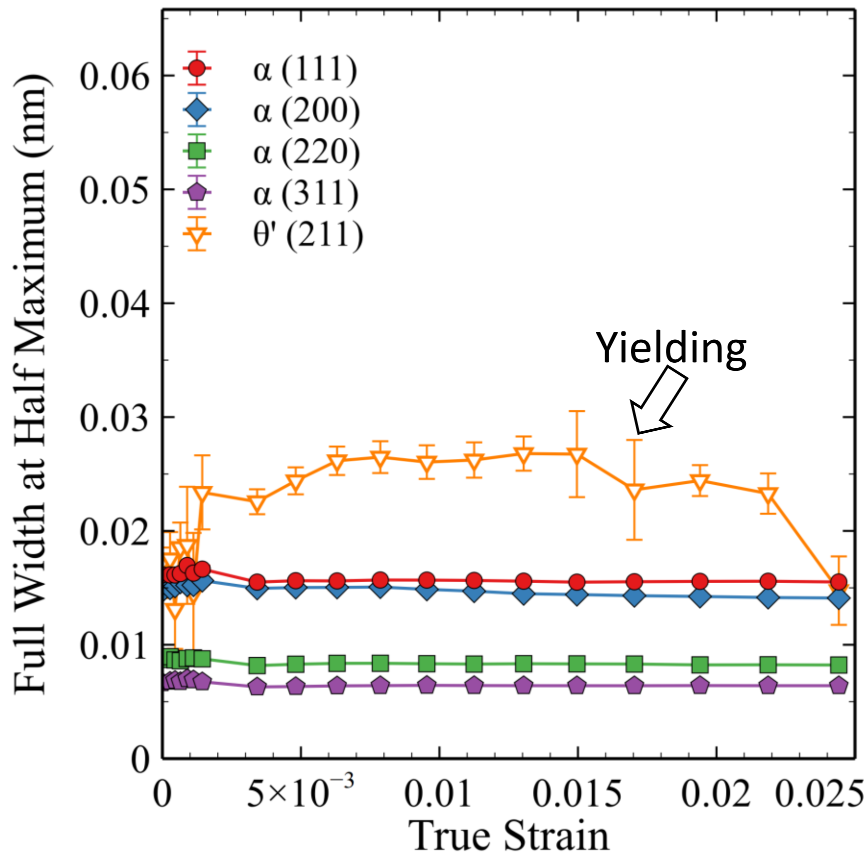
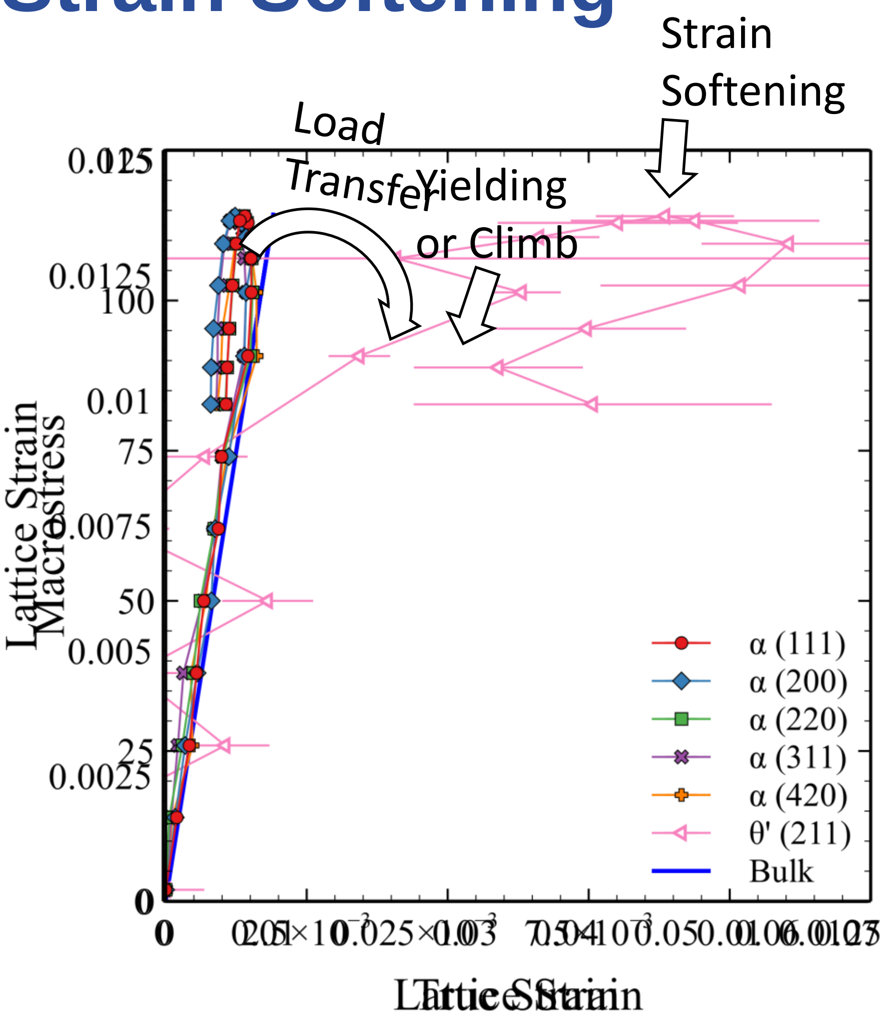
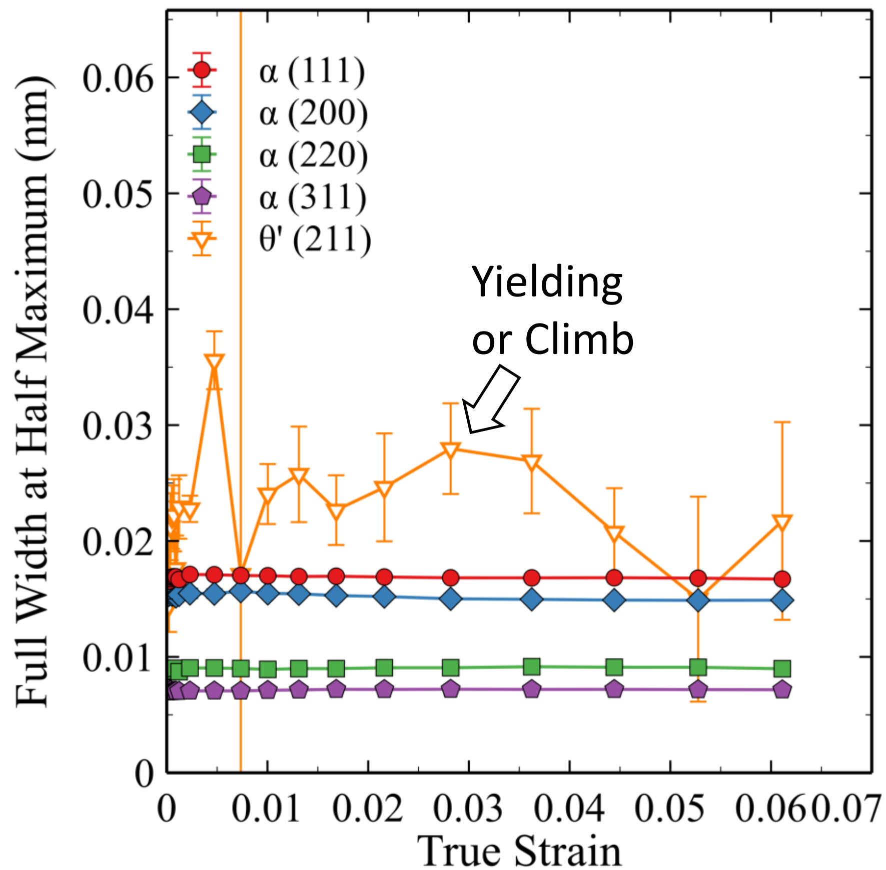
200°C Test Shows Load Transfer → Yielding



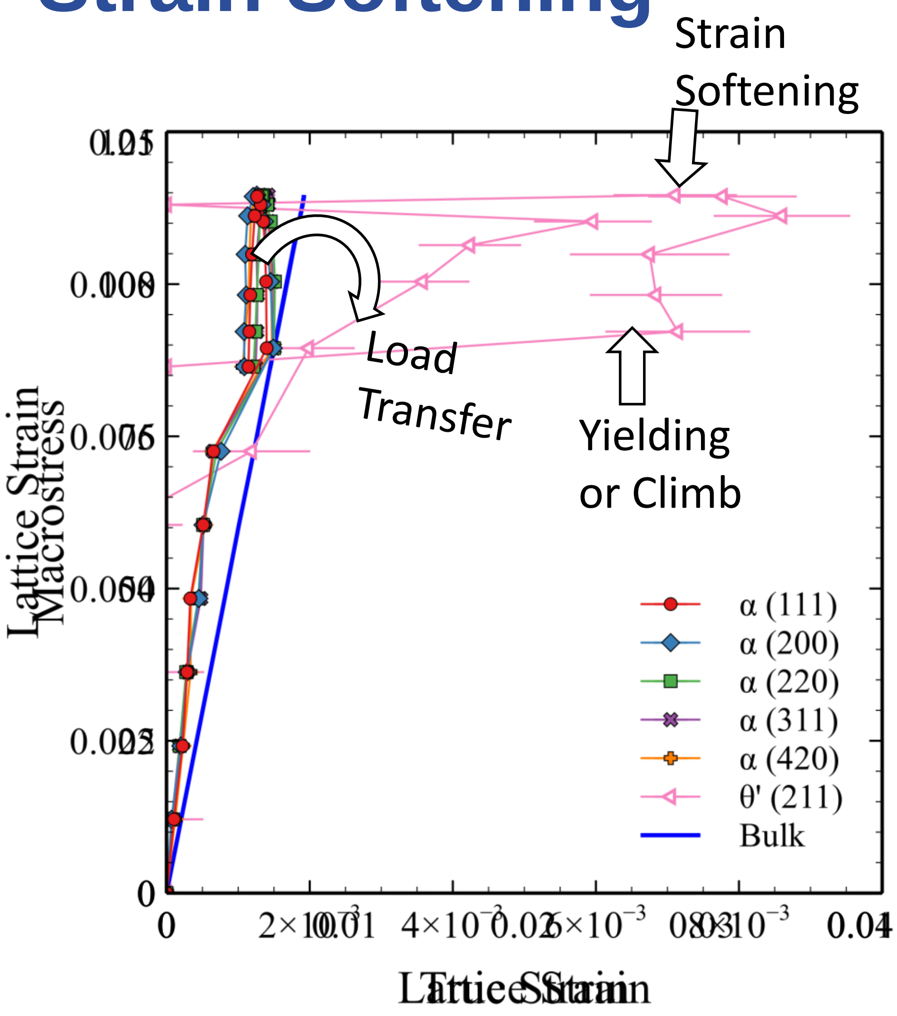


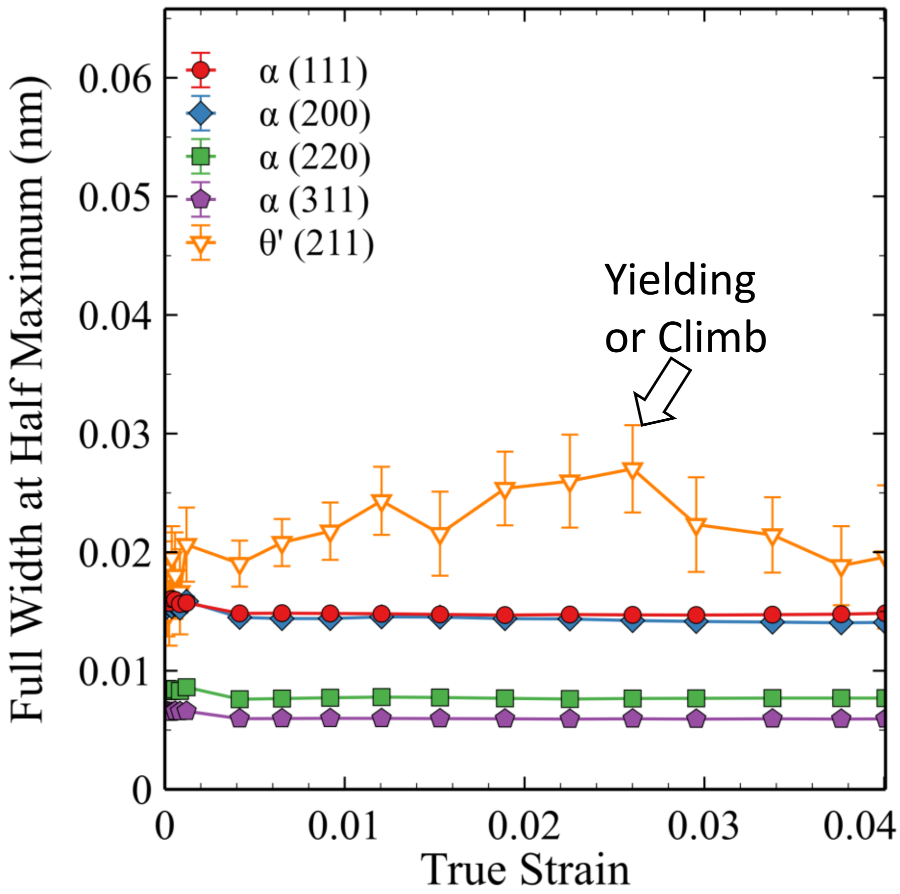
300°C Test shows Yielding and Strain Softening





350°C Test shows Yielding and Strain Softening





STEM Reveals Low Dislocation Density in As-Aged Conditions

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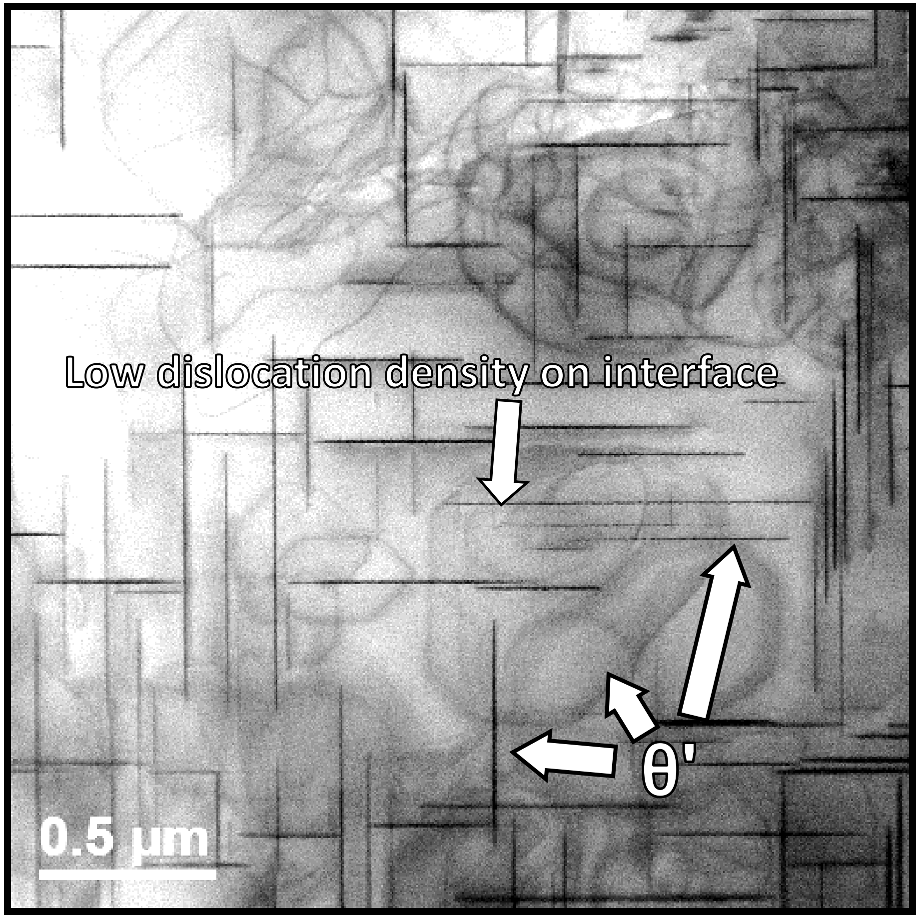
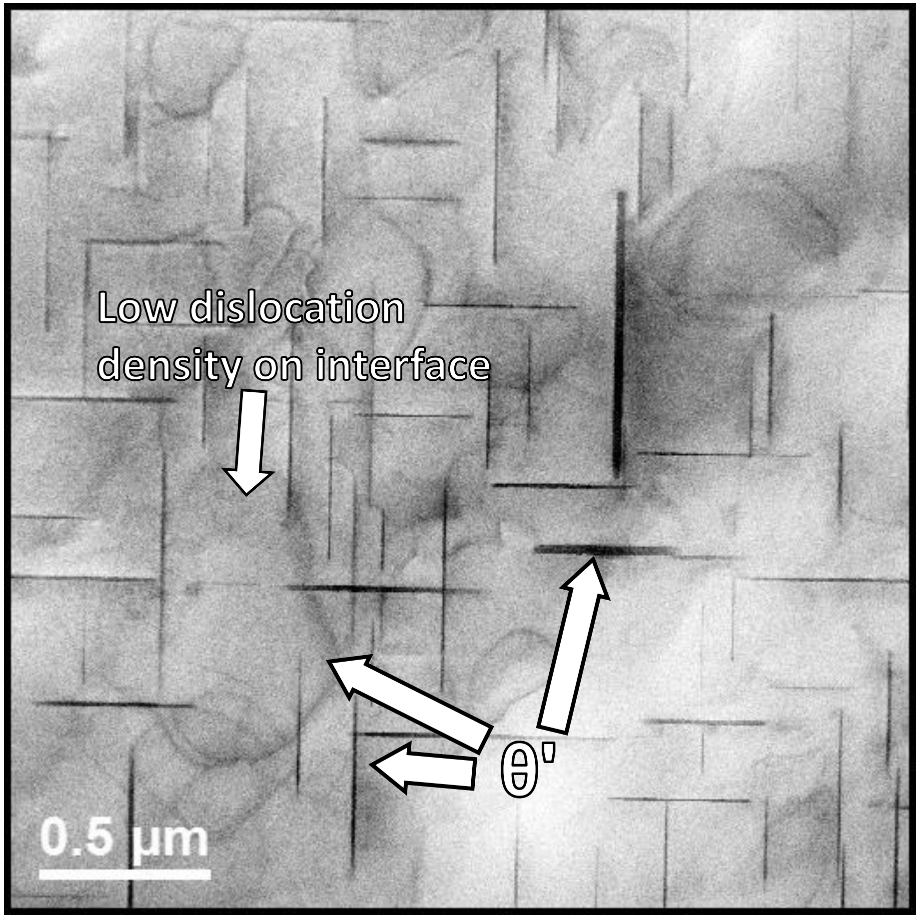
Peak Aged

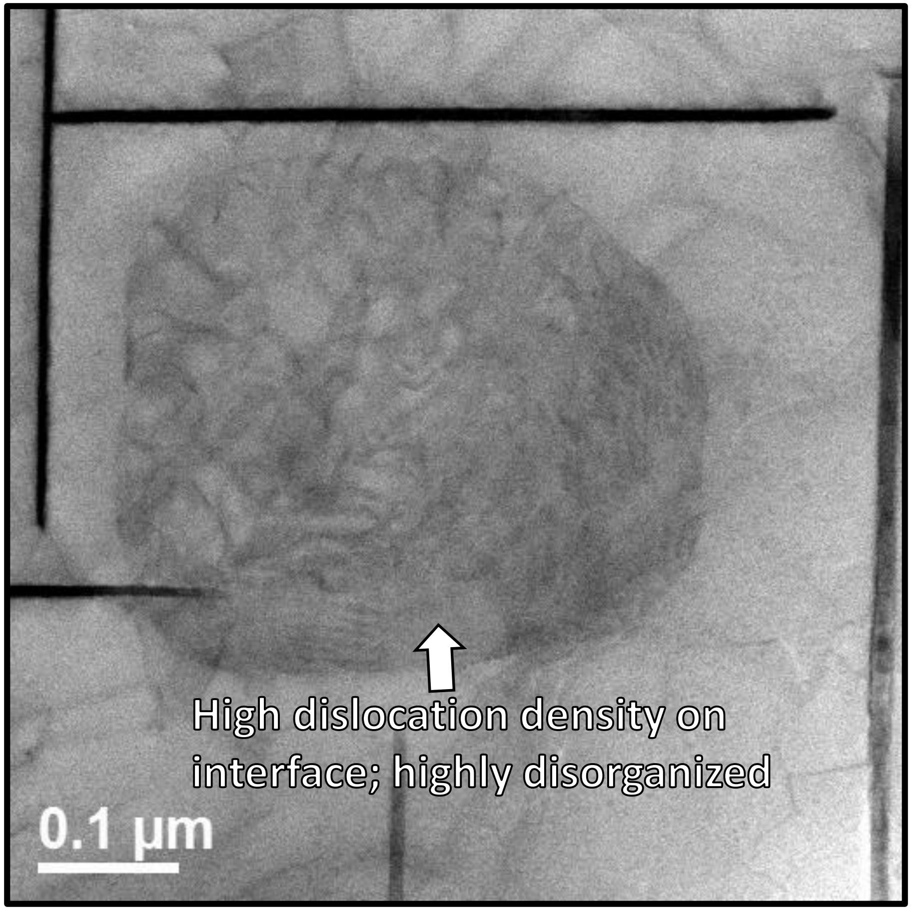


300°C Overaged

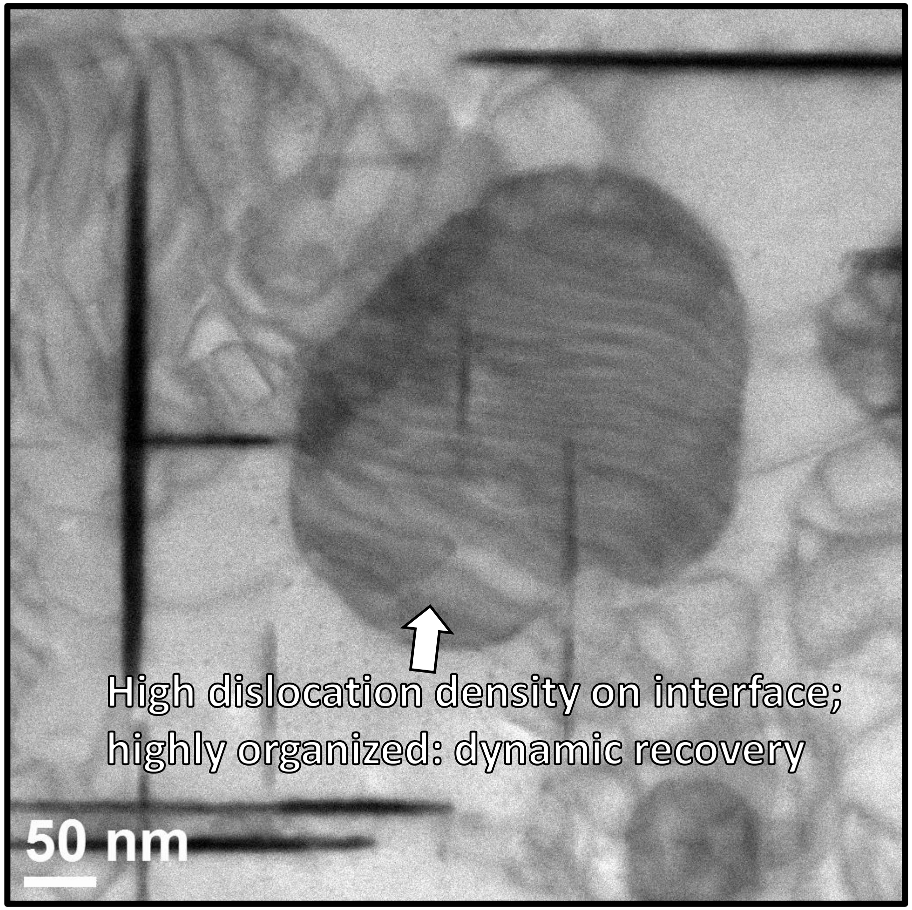


Orowan Loops on Precipitate Interfaces Post-Mortem

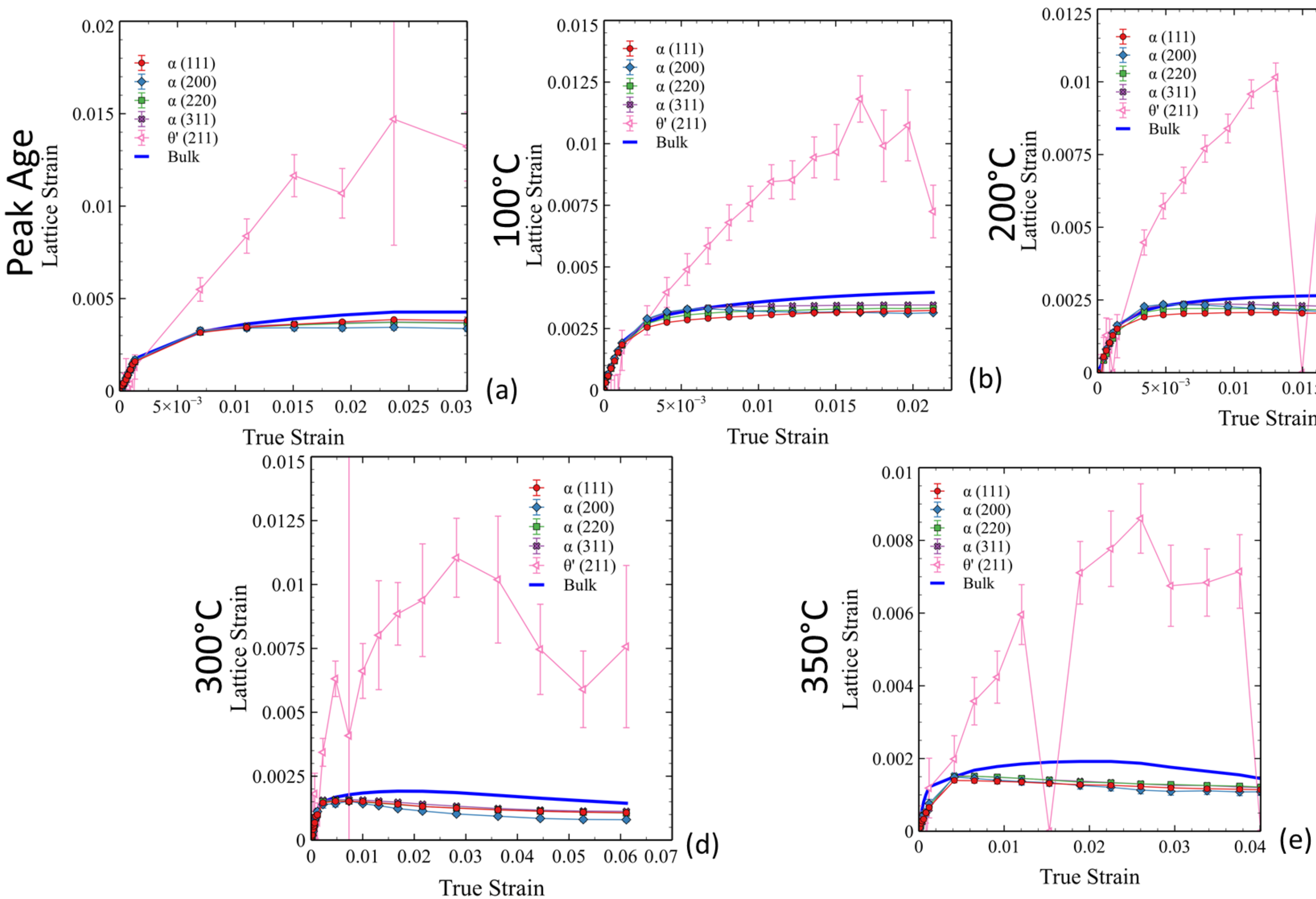
Room Temperature Post-Mortem



300°C Post-Mortem



Strength of the θ′ Precipitates



Strengthening Mechanisms in θ′ Precipitates

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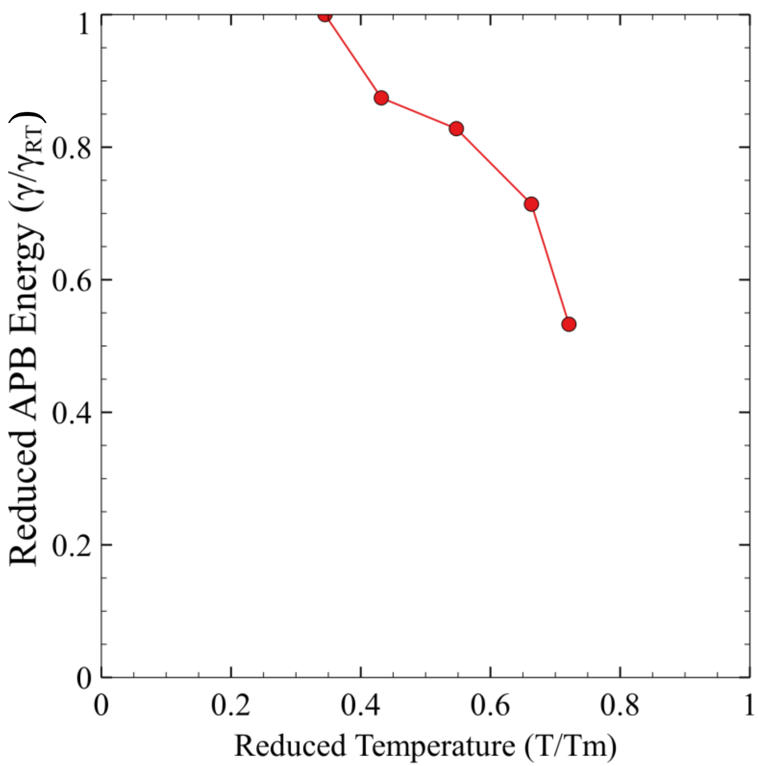
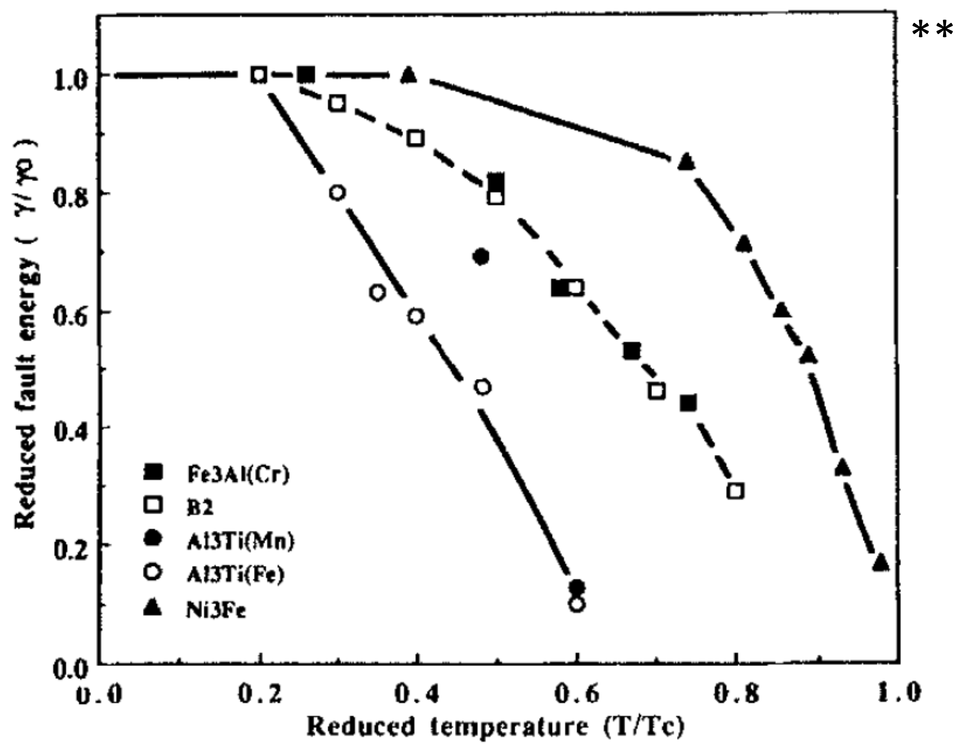
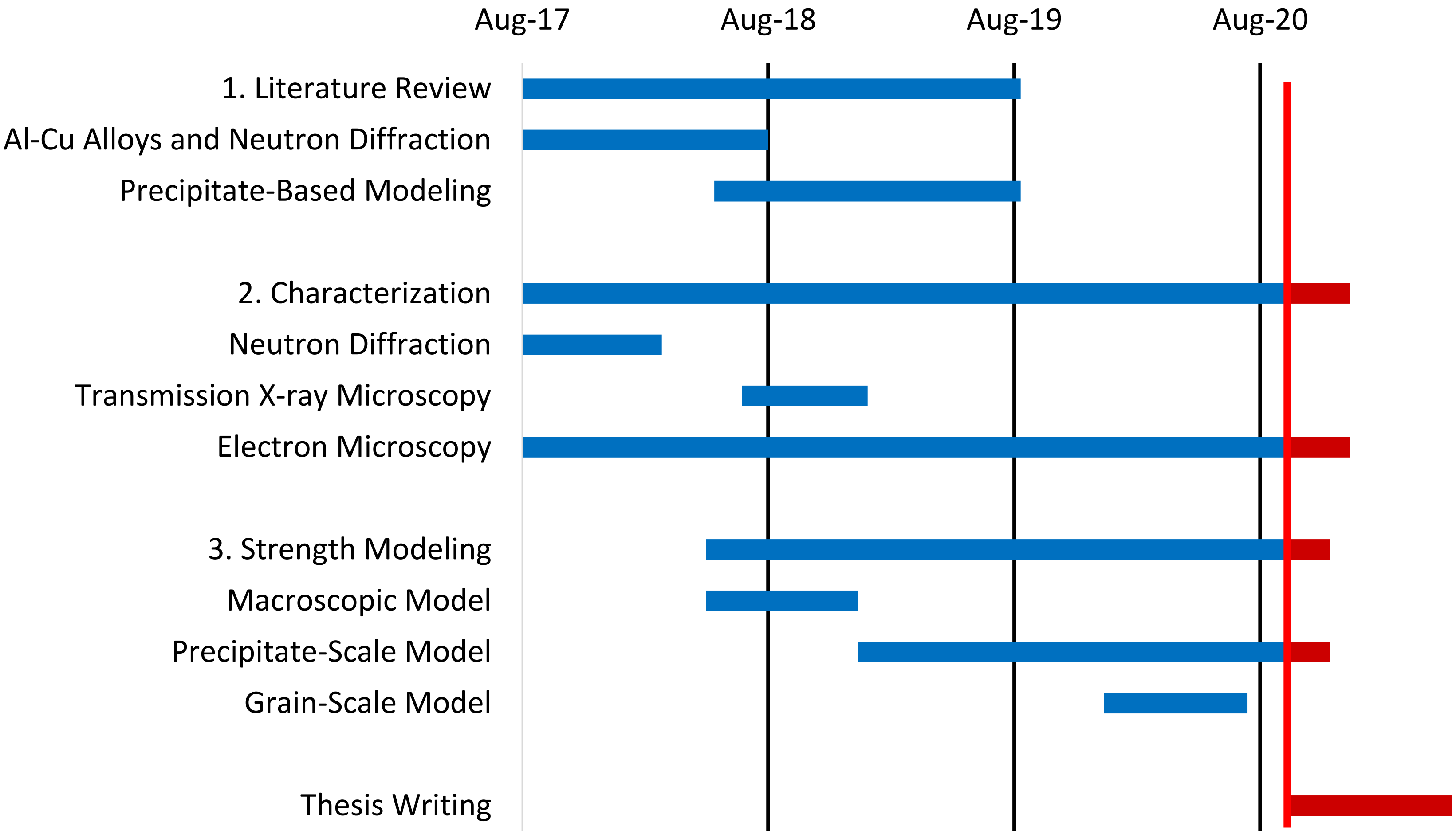
- Primary strengthening mechanism: Anti-Phase Boundary (APB)
- Strength-APB energy approximate relationship*: $\sigma^{rss} = \frac{E_{apb}}{b}$
- APB energy calculated 341-640 mJ/m^2; within a factor of 2 of literature





*H. Liu *et al,* Metall. Mater. Trans. 46A (2015) p3288-3301 **D. G. Morris, M. Leboeuf, Phil. Mag. Letters 70:1 (1994), p.29-39

Progress


Aug-17
Aug-18
Aug-19
Aug-20
1. Literature Review
Al-Cu Alloys and Neutron Diffraction
Precipitate-Based Modeling
2. Characterization
Neutron Diffraction
Transmission X-ray Microscopy
Electron Microscopy
3. Strength Modeling
Macroscopic Model
Precipitate-Scale Model
Grain-Scale Model
Thesis Writing

Challenges & Opportunities

- Room temperature RR350 data may be unreliable; there is cross-over of two peaks in the diffraction data which makes analysis difficult
- Other strengthening mechanisms besides anti-phase boundary should be considered; could explain the over-estimation of literature values
- Still haven't ruled out climb of Orowan loops as an alternative mechanism for reducing precipitate stresses

Thank you!

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