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

Fall 2019 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
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Faculty: Amy Clarke (Mines)

Industrial Mentors: Amit Shyam (ORNL), John Carpenter (LANL)

Other Participants: Dong Ma, Lawrence Allard (ORNL); Francisco Coury, Chloe Johnson, Yaofeng Guo, Benjamin Ellyson, Alec Saville, Gus Becker (Mines)

Oak Ridge National Laboratory

NSF

Colorado School of Mines

Iowa State University

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

- 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

- Analyzed stresses in precipitates in alloy 206 room temperature tests
- Submitted paper to Materials Science and Engineering: A on creep at 300°C
- Wrote publication for Acta Materialia on alloy 206 room temperature neutron diffraction (revisions in progress)
- Gave poster at Gordon Conference

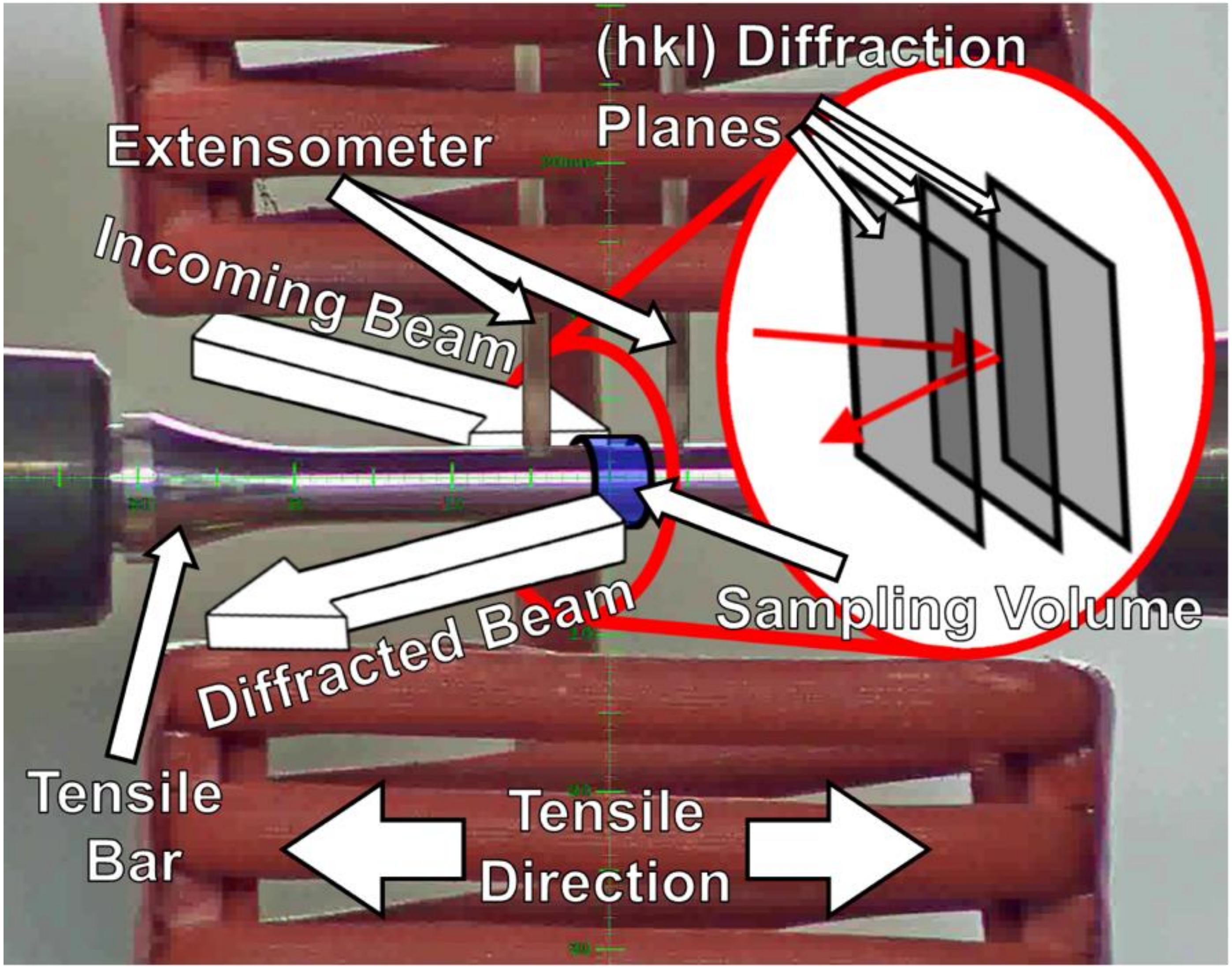
Metrics

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%	●

Project Motivation

- Al-Cu alloys are popular due to their low density and high strength
- Generally, the peak aged condition (which results in good ductility) is strengthened with GP zones
- However, high temperature stability requires thicker precipitates
- Precipitate-dislocation interaction with these thicker precipitates during strain hardening is still not fully understood
- This project aims to improve understanding in order to provide insight to alloy and heat treatment development to improve strain hardening behavior (and ductility, fatigue resistance by extension)

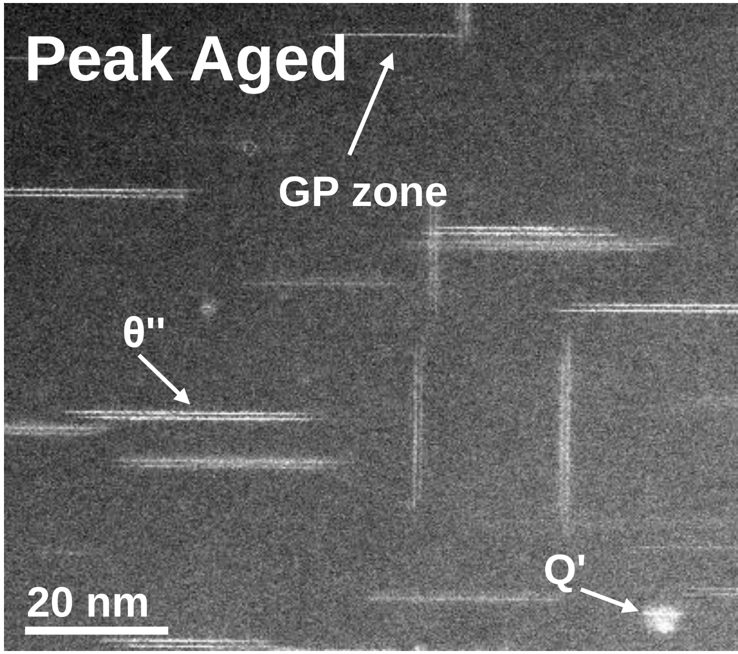
Background on Neutron Diffraction



Al Alloy 206

206 Al alloy composition

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



- Commonly used commercial cast Al-Cu alloy
- Possible to age and form multiple precipitate structures and sizes
- Precipitation sequence:

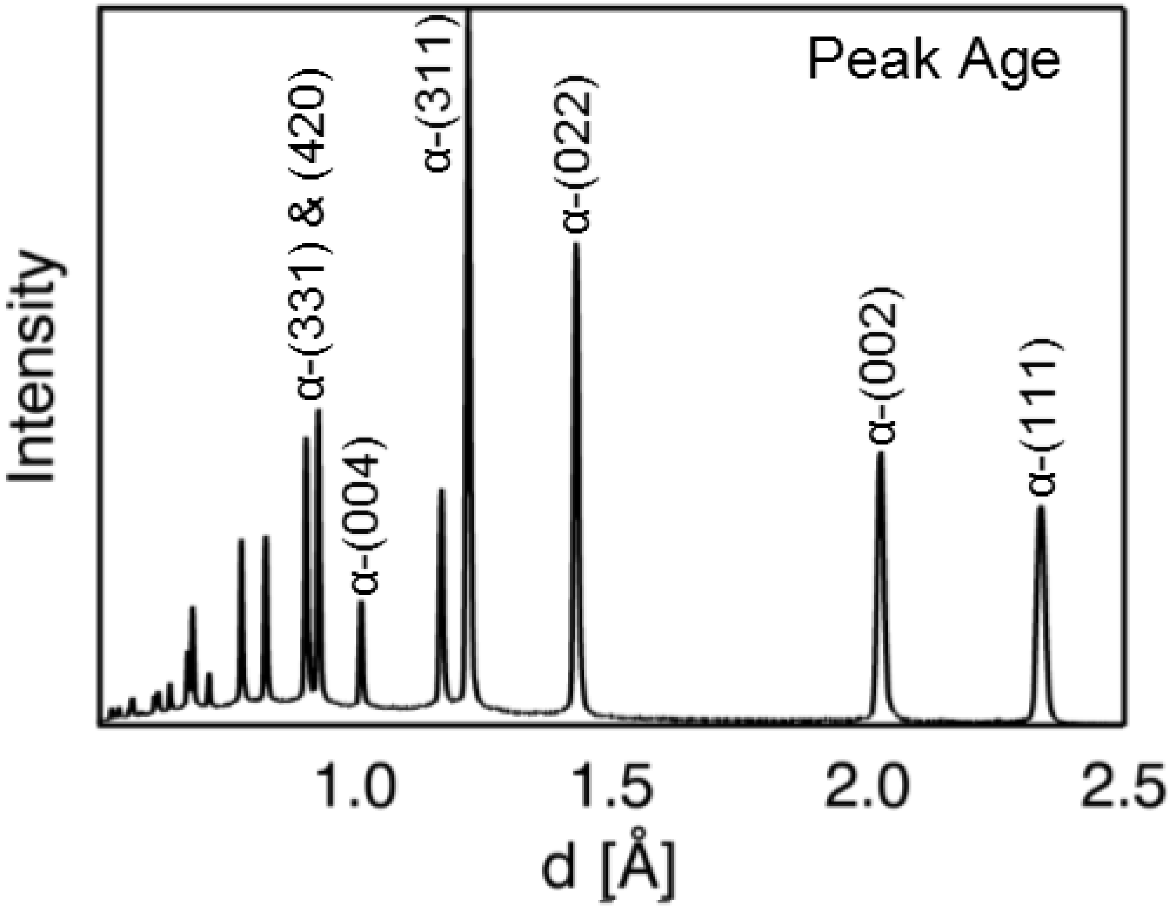
$$\text{GPI} \rightarrow \theta'' \rightarrow \theta' \rightarrow \boldsymbol{\theta}$$

Heat treatment schedule

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

Precipitate Diffraction

- Precipitates are low volume fraction, so we get little signal
- Improve signal with overlapping neutron collection windows
- Fortunately, lattice strains are large so information is still useful



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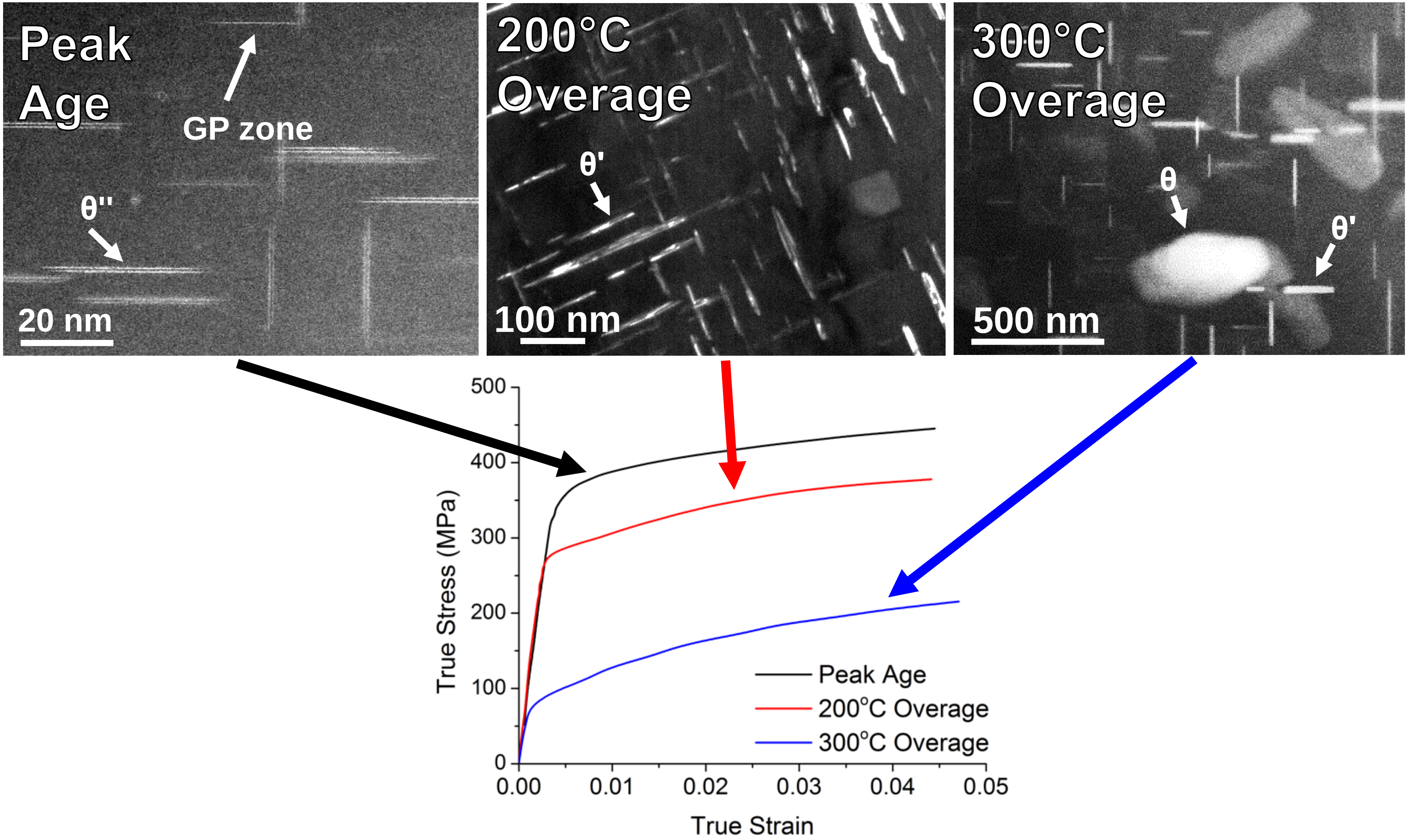
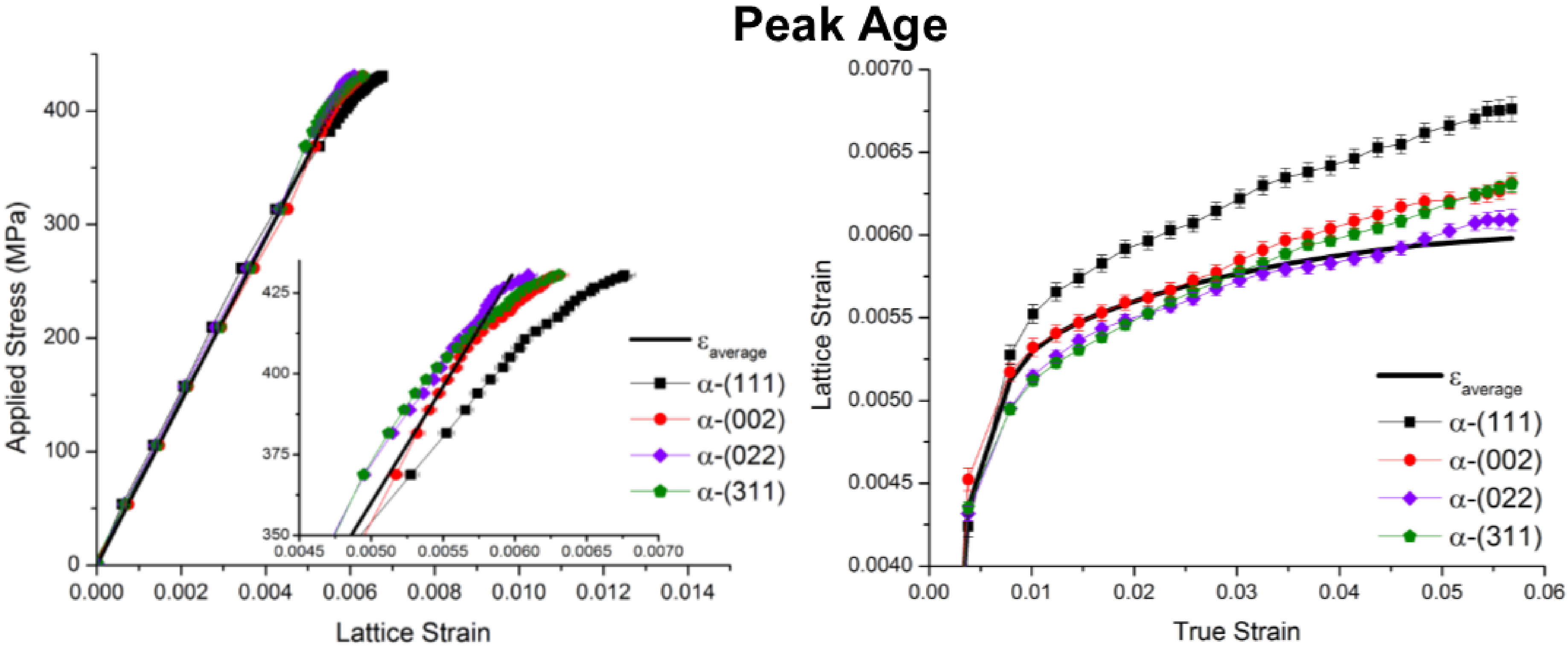
Microstructure → Properties

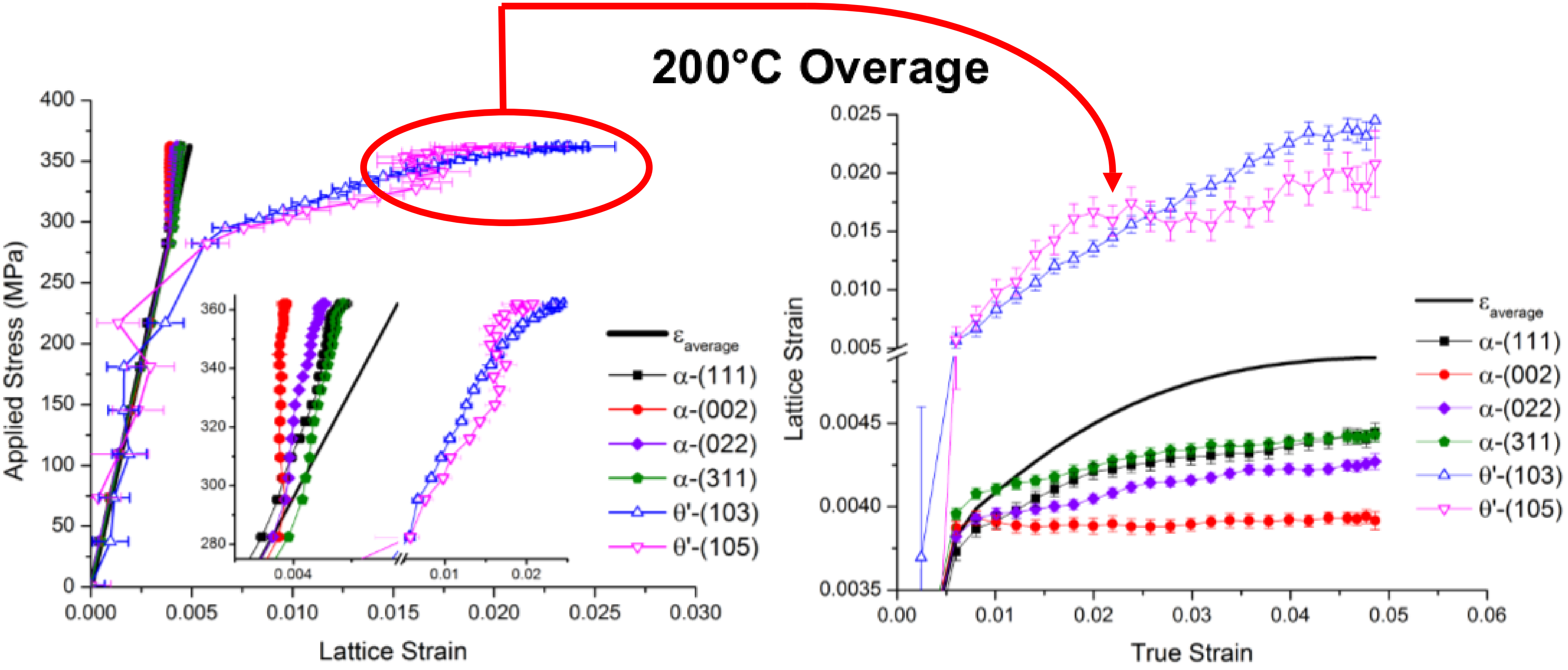


Peak Age Neutron Results



200°C Overage Neutron Results

Massive anisotropy!



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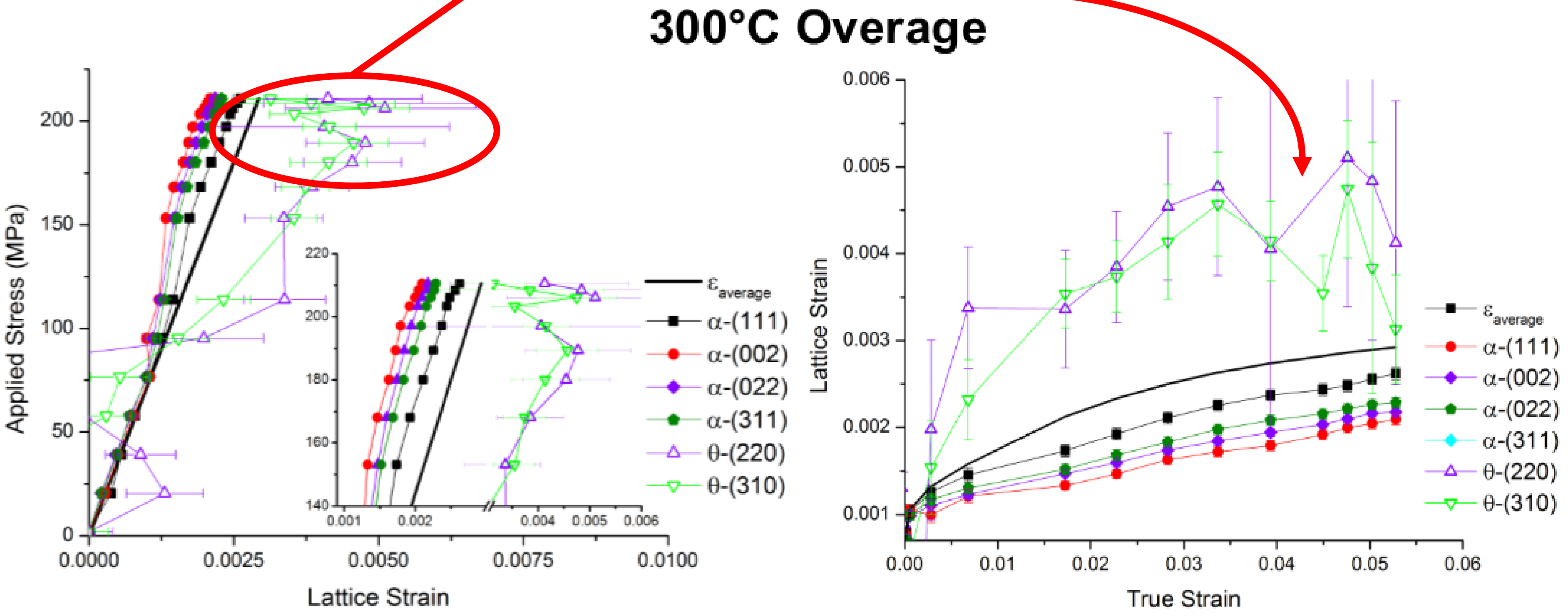
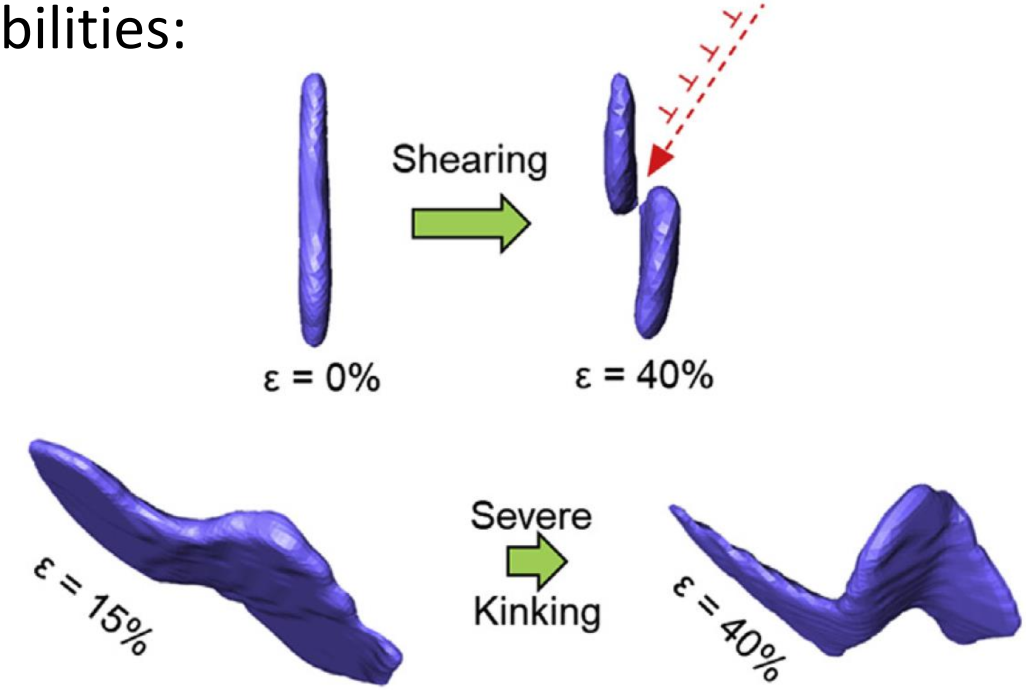
300°C Overage Neutron Results

Little anisotropy!



What's Happening to our Precipitates?

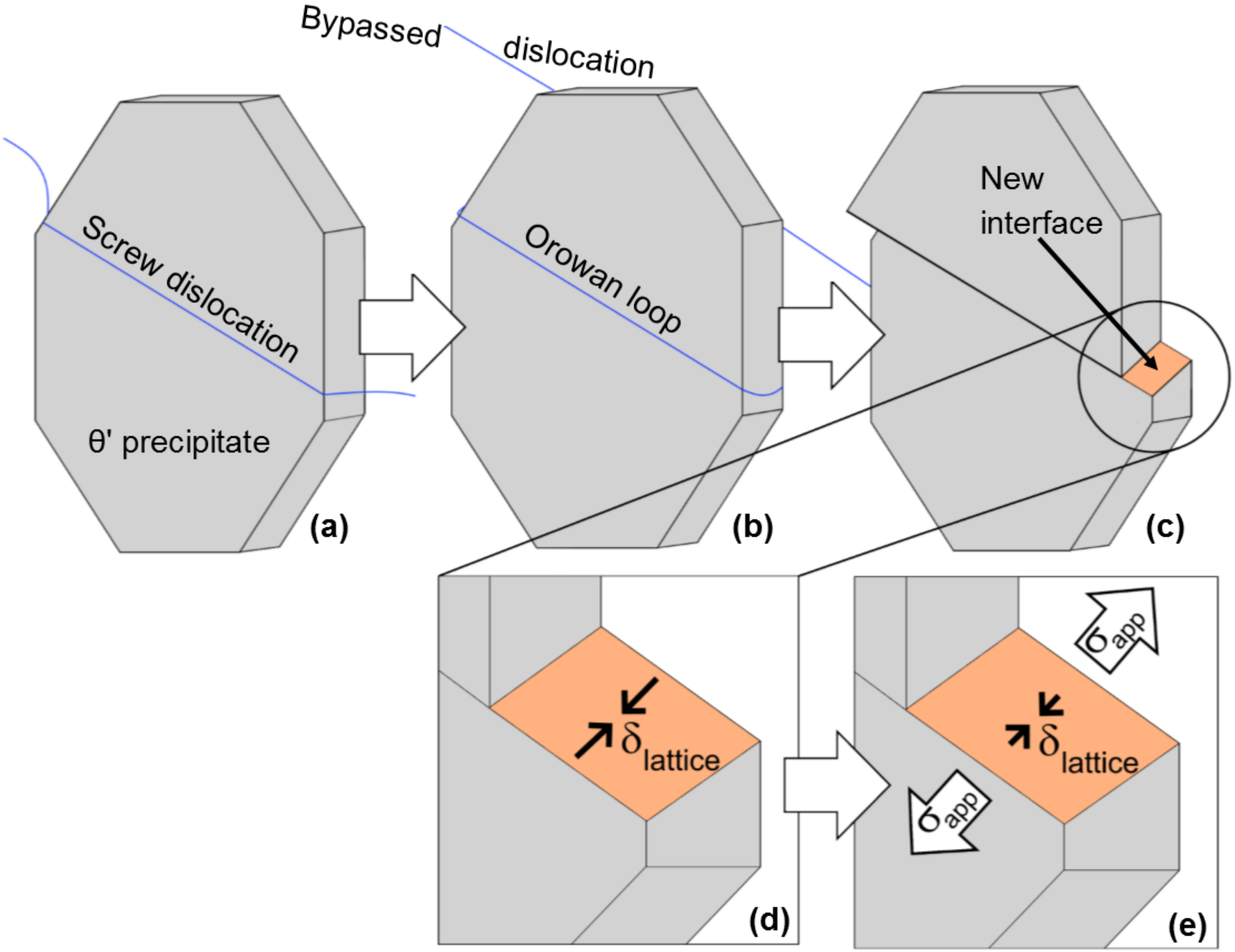
- Several possibilities:



- Precipitates can also crack and fracture, leaving voids
- Shearing and kinking likely anisotropic on a precipitate scale due to the orientation relationship of these precipitates with the matrix

From: Kaira *et al*, Acta Mat. 176 (2019) p.242

Where Does the Anisotropy Come From?



Modeling the Anisotropy

- Described the effect of applied stress on interfacial energy with a simple, 1-D model
- Interfacial energy determines propensity for precipitates to shear
- Precipitate shearing will result in a lower strain hardening rate than Orowan looping

$$d_{\sigma}^{\alpha-Al} = d_{0}^{\alpha-Al}\left(1 + \sigma_{app} * f(\theta)\right)$$

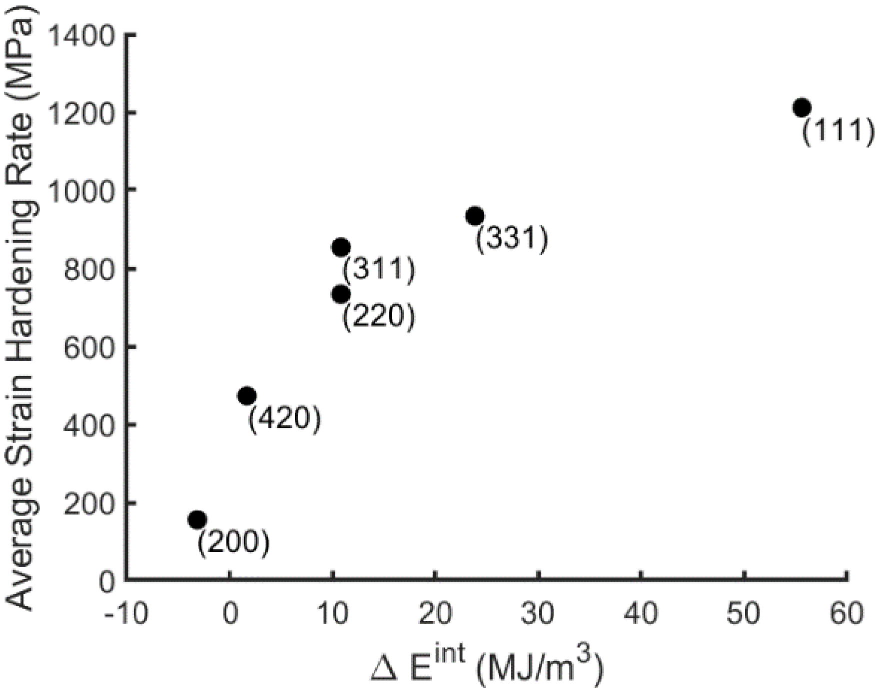
$$d_{\sigma}^{\theta'} = d_{0}^{\theta'}\left(1 + \sigma_{app} * f(\theta)\right)$$

$$\delta_0 = (d_0^{\alpha-Al} - d_0^{\theta\prime})/d_0^{\alpha-Al}$$

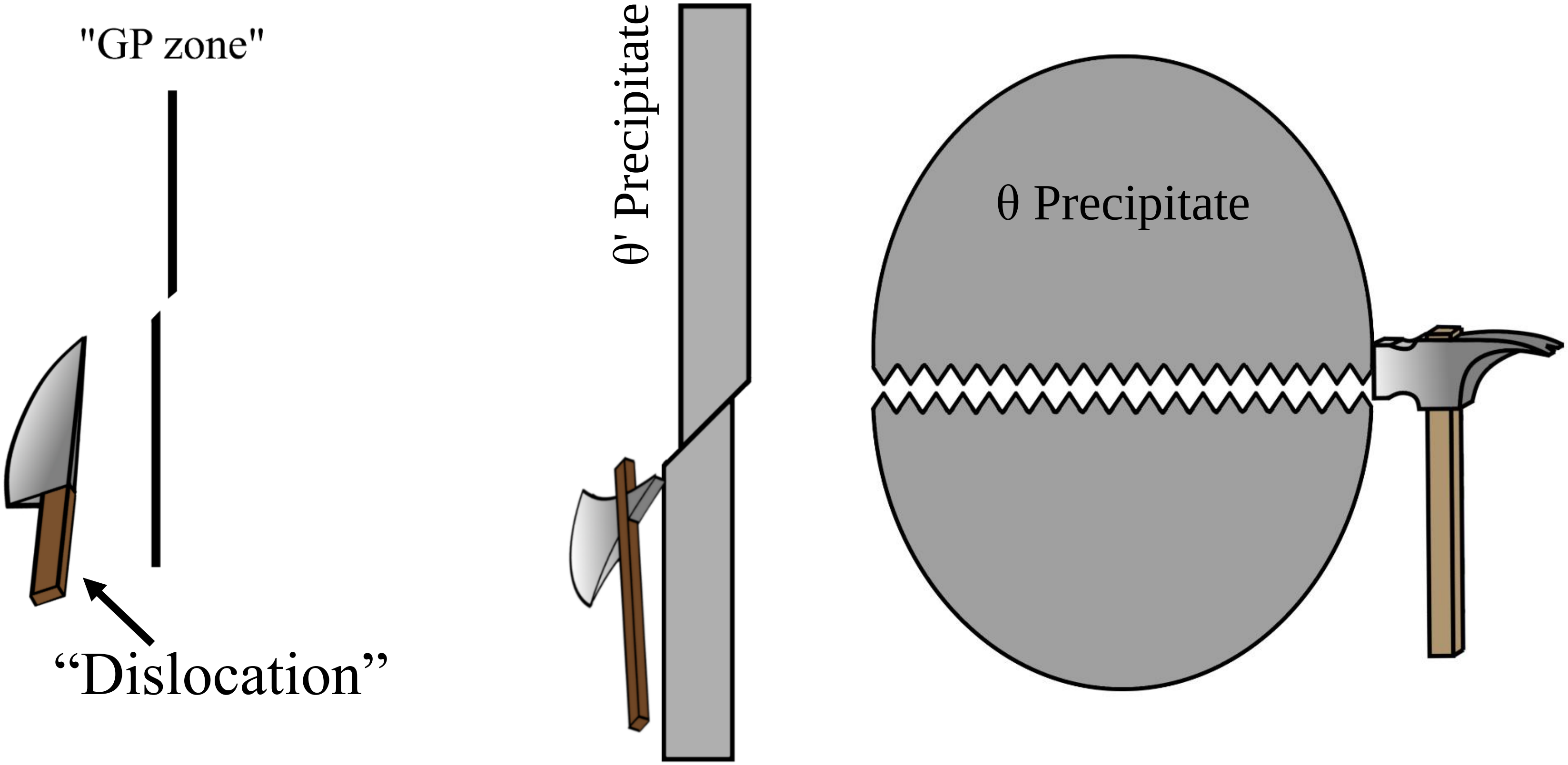
$$\delta_\sigma = (d_\sigma^{\alpha-Al} - d_\sigma^{\theta\prime})/d_\sigma^{\alpha-Al}$$

$$E^{int} = \delta_\sigma^2 * C^{int}$$

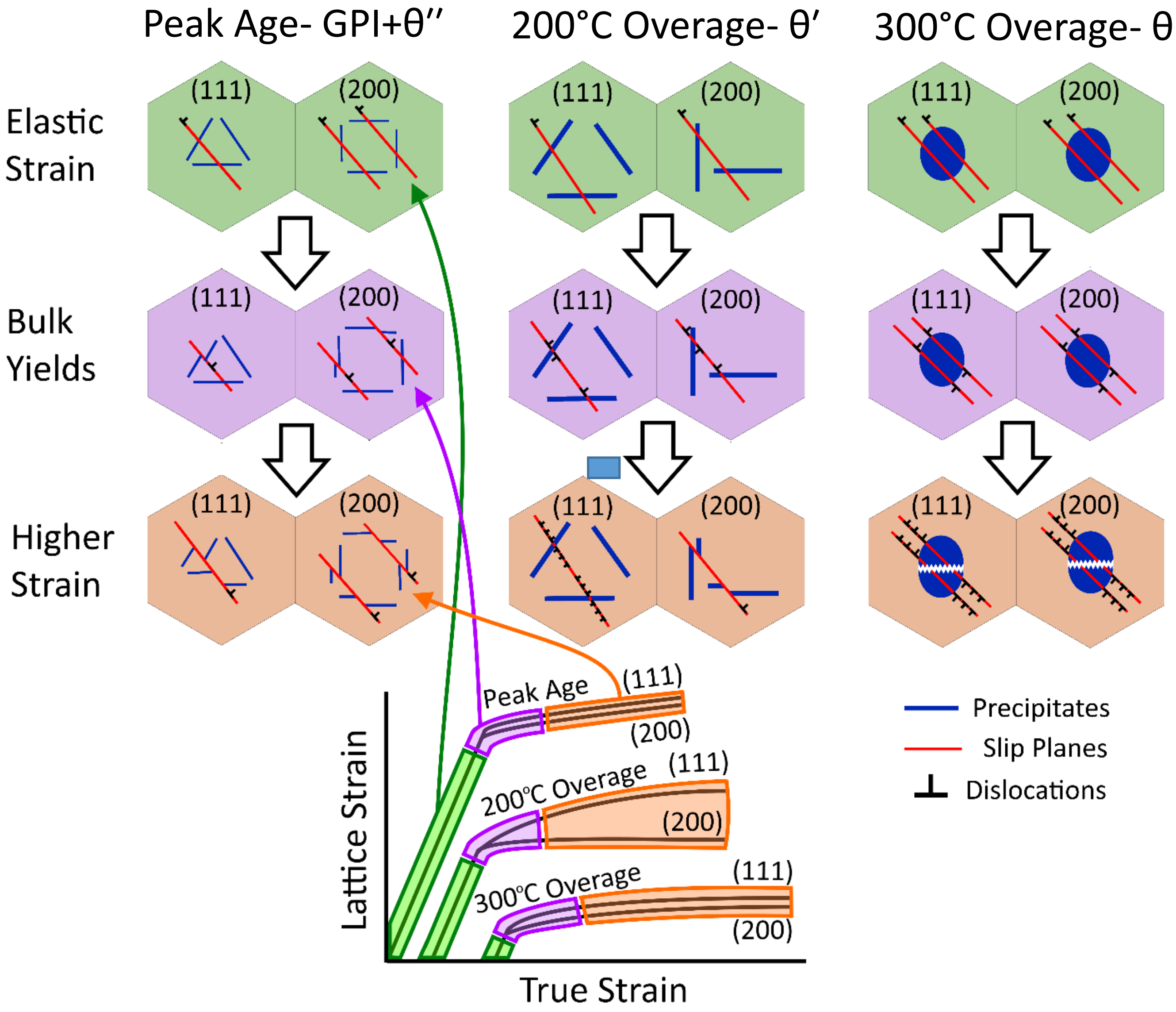
$$\Delta E^{int} = E^{int} - \delta_0^2 * C^{int}$$



Fun Representation



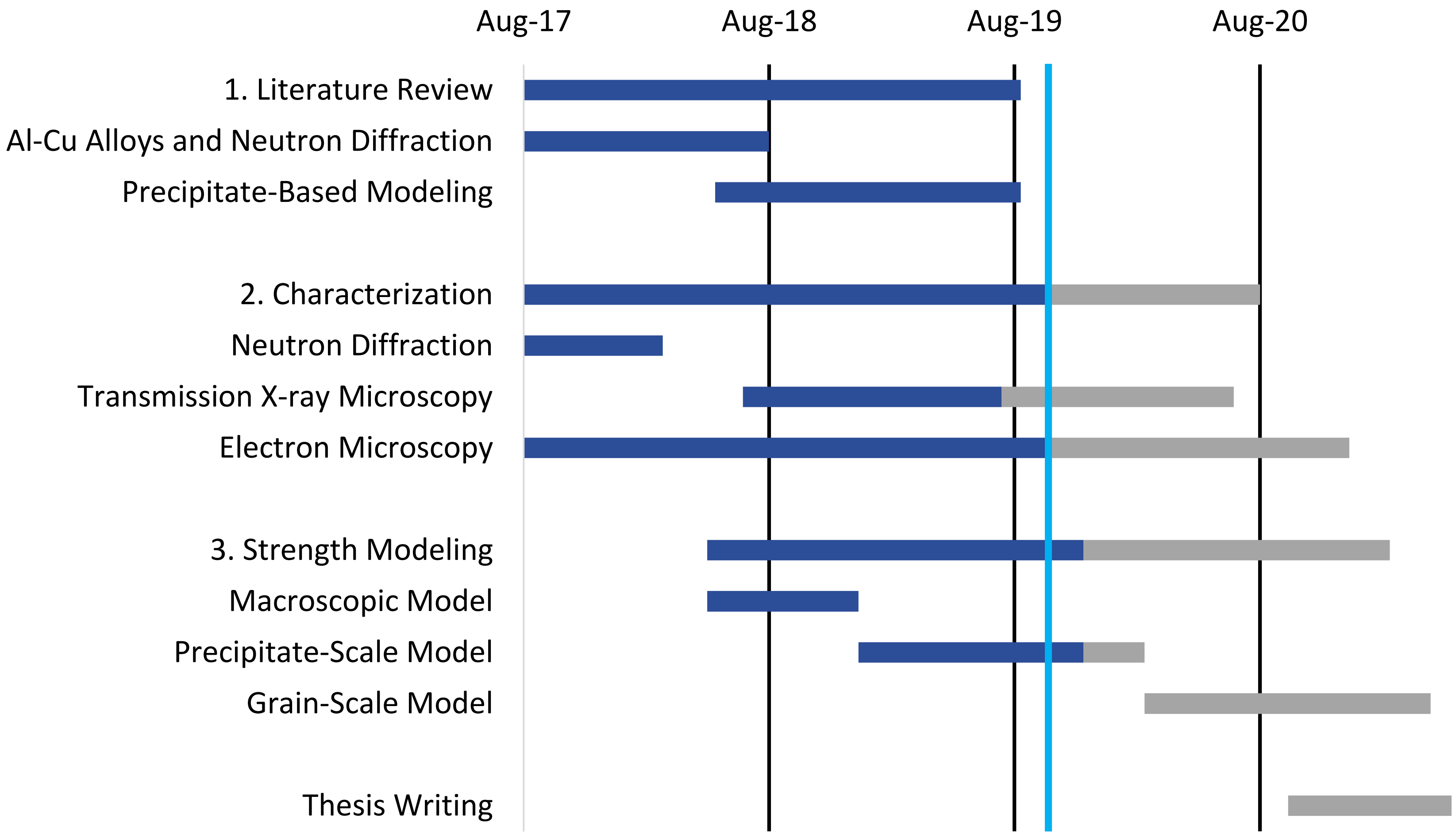
What Did We Learn?



Challenges & Opportunities

- Challenge: Very difficult to observe early stages of precipitate shearing in TEM
  - Will most likely collaborate with ORNL microscopists
- Challenge: Creep data is very noisy
  - Will use similar strategy to precipitate stress analysis
- Opportunity: Can optimize precipitate thickness using modeling, traditional heat treating, and alloying
  - Trade-offs between mechanical properties and thermal stability
- Opportunity: Can test precipitate-scale anisotropy with stress + temperature aging
  - Creates precipitates of only selected orientations; can use to develop interesting microstructures to test my ideas
- Opportunity: Textured materials
  - May also be used to test my ideas and is in line with real-world applications

Progress



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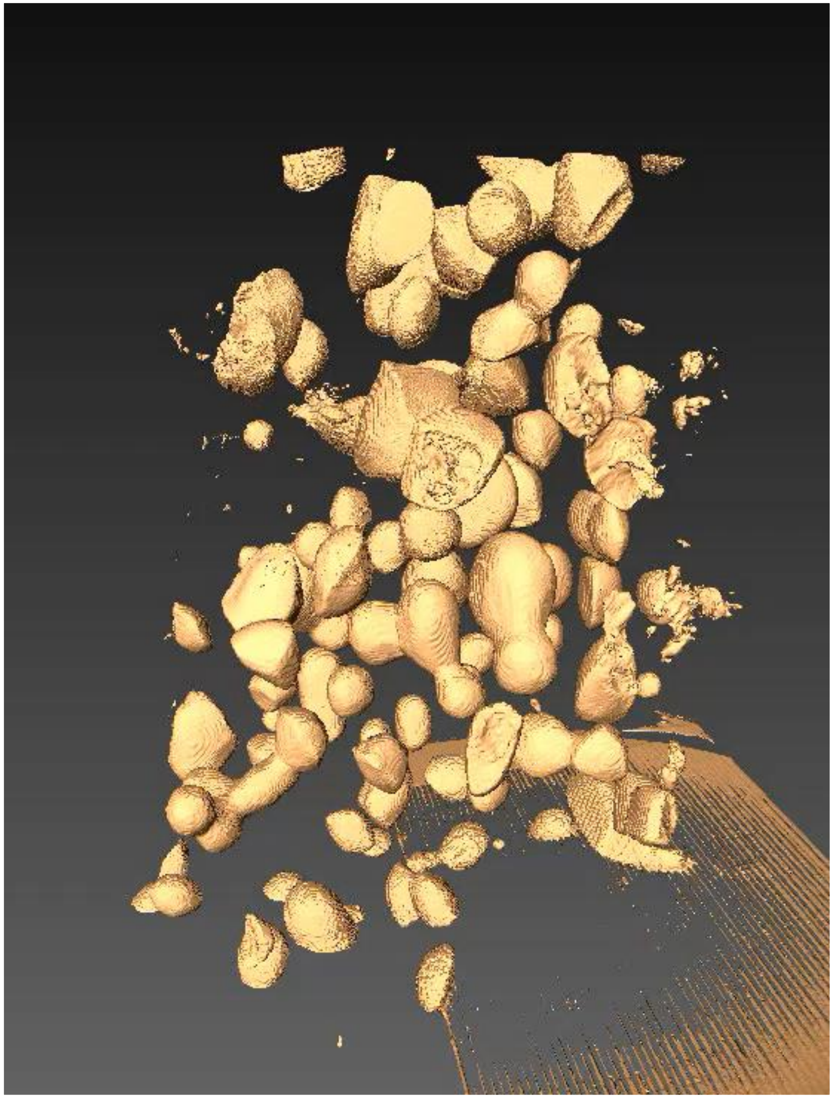
Transmission X-ray Microscopy

- Performed preliminary aging experiments at Argonne National Lab in December 2018
- Plans to install in-situ aging capabilities on beamline are underway
- Will return and perform true in-situ 4-D (3-D plus time) aging experiments once equipment is working



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Thanks for your attention!

Brian Milligan

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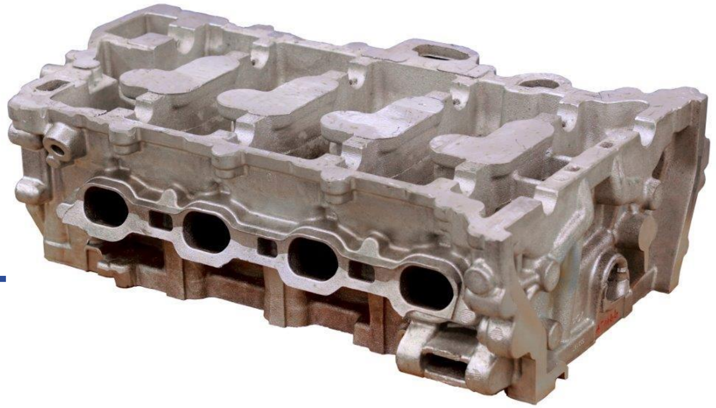
Project 29 - Identification of Deformation Mechanisms of Thermally Stable Cast Al-Cu Alloys via Neutron Diffraction and Creep Testing

Student: *Brian Milligan*

Faculty: *Amy Clarke*

Industrial Partners: *ORNL (Amit Shyam)*

Project Duration: *Sept. 2017 – May 2021*



Achievement

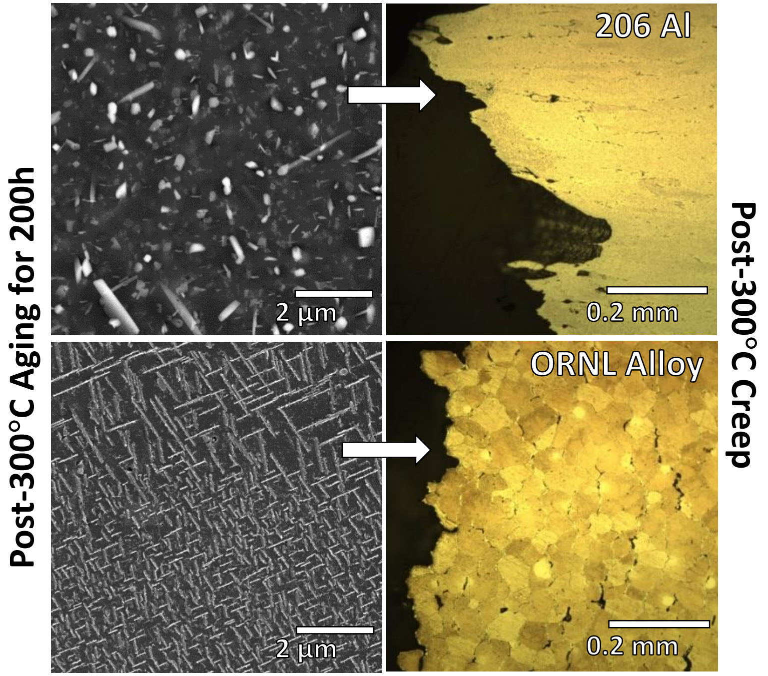
- Modeling of creep behavior in commercial and experimental Al-Cu alloys at high homologous temperature

Significance and Impact

- Thermally stable Al-Cu cylinder head alloys developed at ORNL outperform commercial alloys during creep loading, allowing for higher engine operating temperatures

Research Details

- Performed creep experiments and developed new low-stress microstructure-based creep model using results



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Project Duration: *Sept. 2017 – May 2021*

Program Goal

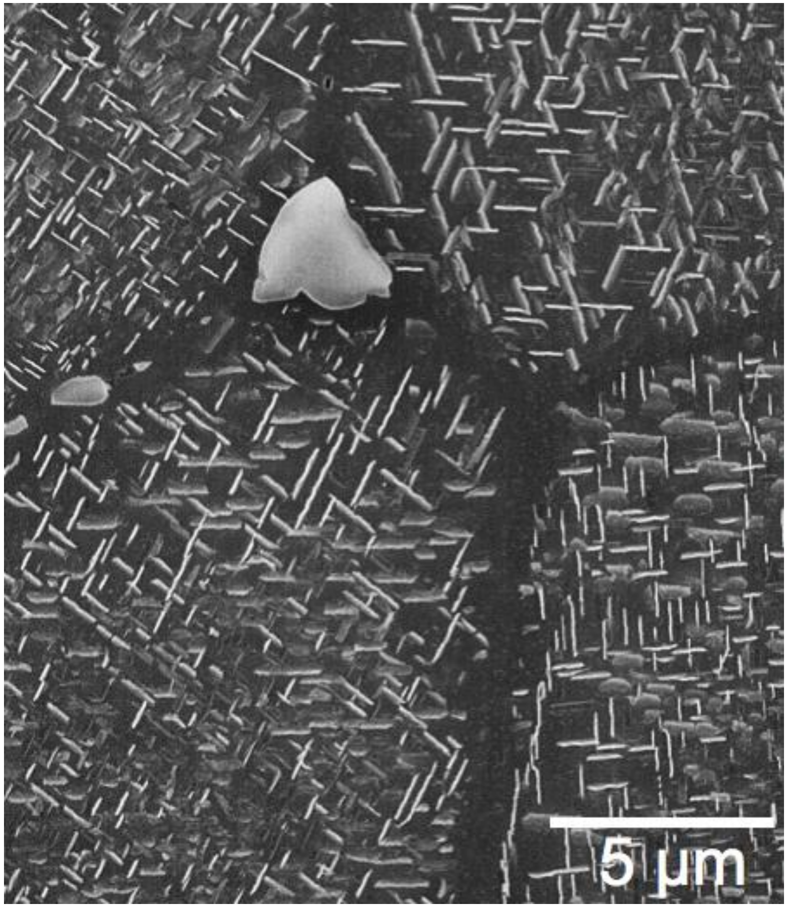
- Characterize the mechanical properties and microstructure of thermally stable Al-Cu alloys under various loading and aging conditions

Approach

- Utilize neutron diffraction, microscopy, and mechanical testing to identify deformation mechanisms ex-situ and in-situ

Benefits

- Improved scientific understanding of mechanical properties in Al-Cu alloys as well as insight into how to improve their performance at high temperature



Precipitation in RR350 aluminum alloy