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

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

Fall 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
October 2-4, 2018

Student: Brian Milligan (Mines)

Faculty: Amy Clarke (Mines)

Industrial Mentors: Amit Shyam (ORNL)

Other Participants: Dong Ma (ORNL), Lawrence Allard (ORNL), Francisco Coury (Mines)

OAK RIDGE National Laboratory

COLORADO SCHOOL OF MINES EARTH ENERGY ENVIRONMENT

IOWA STATE UNIVERSITY

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
PhD: 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
- User proposal to study phase transformations at Argonne National Laboratory using transmission X-ray microscopy (TXM) accepted.
- Initial TXM tomography (3-D) data collected.
- Applied quantitative modeling at a macro-scale to study strain hardening in 206 Al.
- Developed framework for quantification of strain hardening mechanisms from energetic standpoint

Metrics		
Description	**% Complete**	**Status**
1. Initial literature review	70%	●
2. In situ neutron diffraction, creep testing, and TXM	40%	●
3. Microstructural characterization pre- and post- creep and tension	50%	●
4. Qualitative assessment of neutron diffraction and mechanical test data	50%	●
5. Application and development of qualitative modelling to micro-scale diffraction data	30%	●

Industrial Relevance

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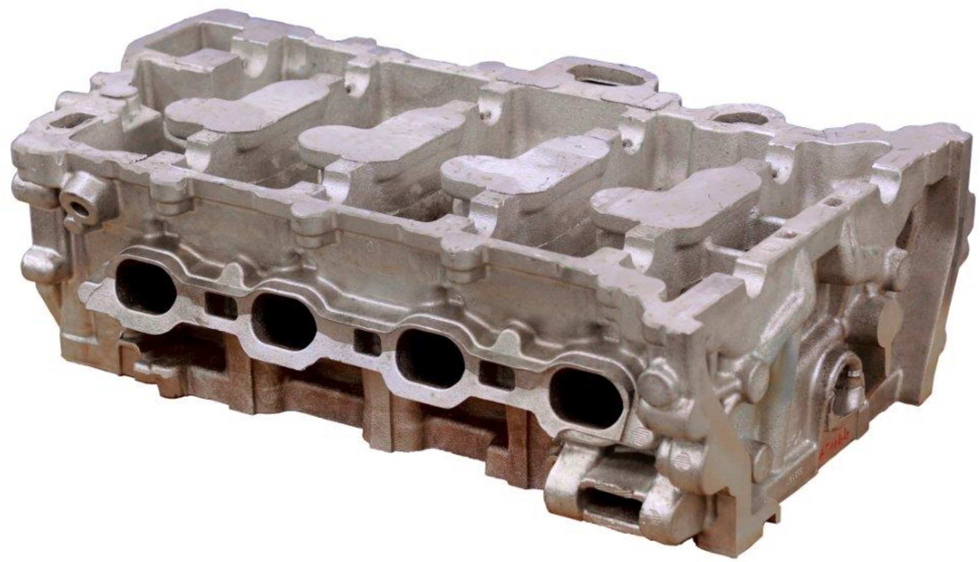
- Cast Al-Cu alloys have high strength, low density and are easy to manufacture
  - Used in various industries such as for cylinder heads in light-duty engines
- Understanding of mechanical behavior can be used to improve them
  - Grain-level mechanisms may be used in unique strengthening methods e.g. texture



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

Background in the model system 206 Al

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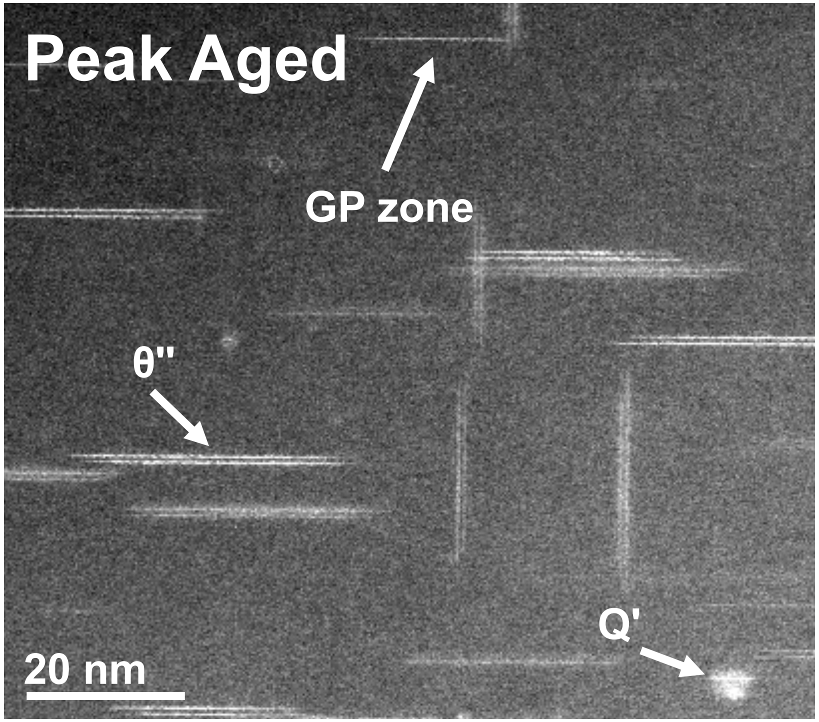
- Model Al-Cu system with a wide range of precipitates
- Simplifies many assumptions that would be required in other alloys
- All 206 experiments shown were performed at room temperature



206 Al composition

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

Heat treatment schedule

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

206 Al Microstructural Development

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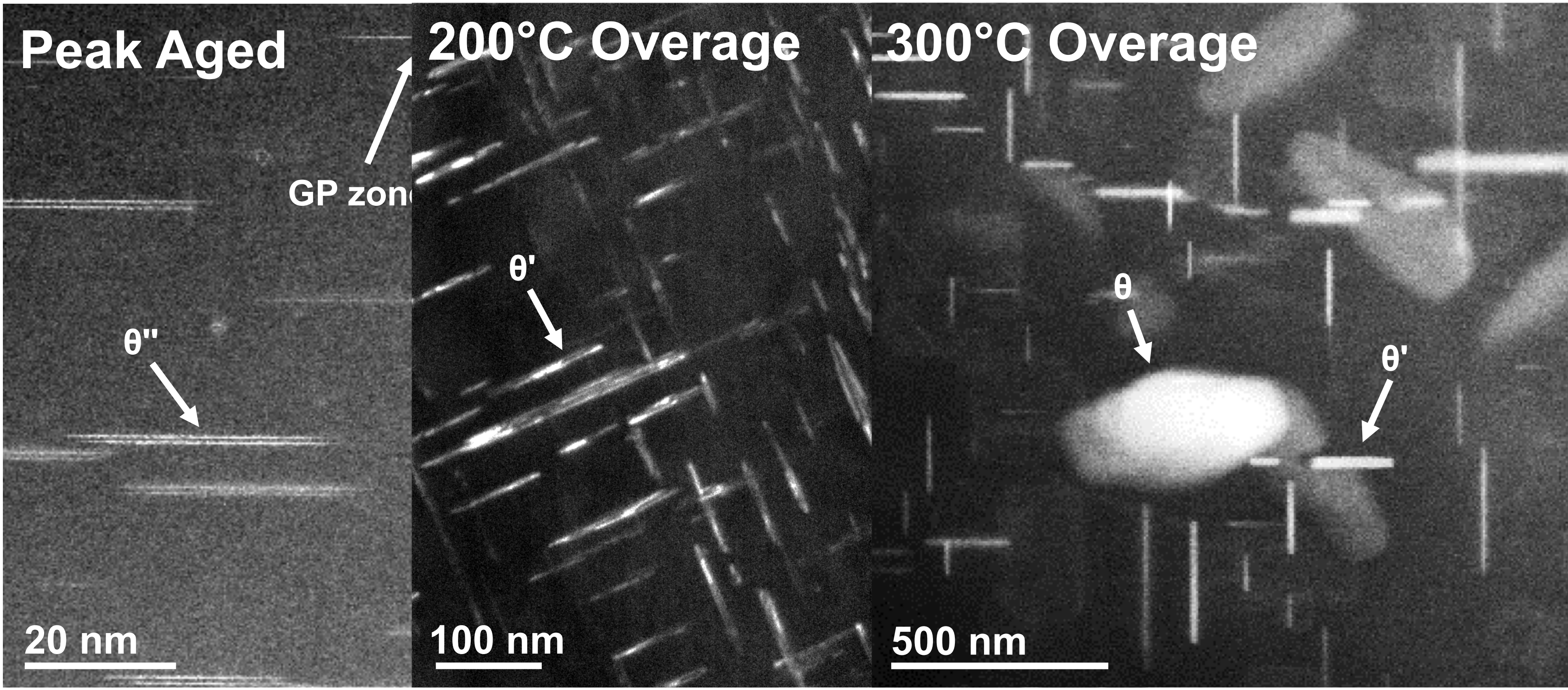
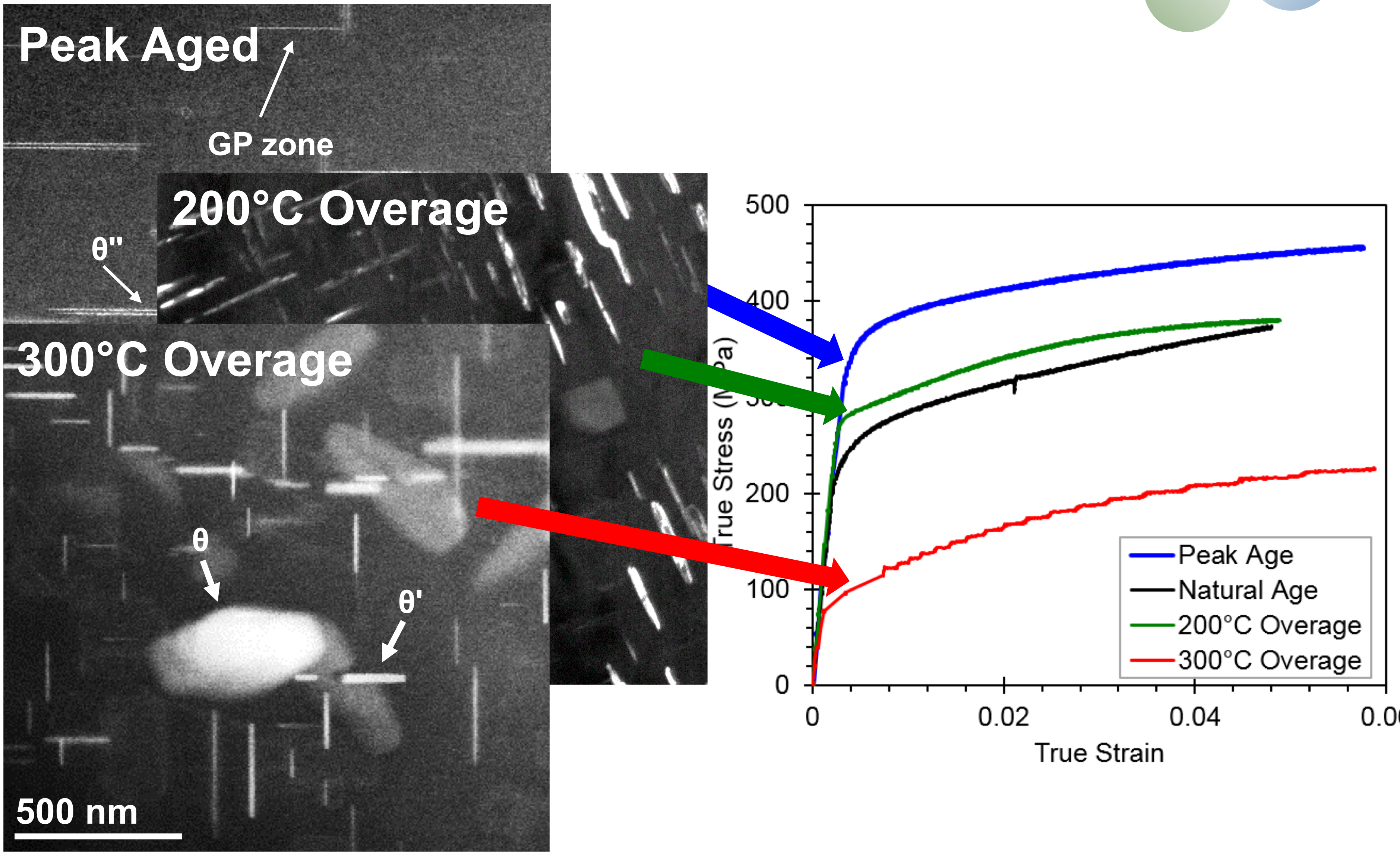
- Precipitates transform from shearable GP zones and θ'' to semi-shearable θ' and unshearable θ



Micrographs courtesy of Lawrence Allard (ORNL) and Francisco Coury (Mines)

Mechanical Property Results



Neutron Diffraction used to Measure Internal Stress by Grain Orientation

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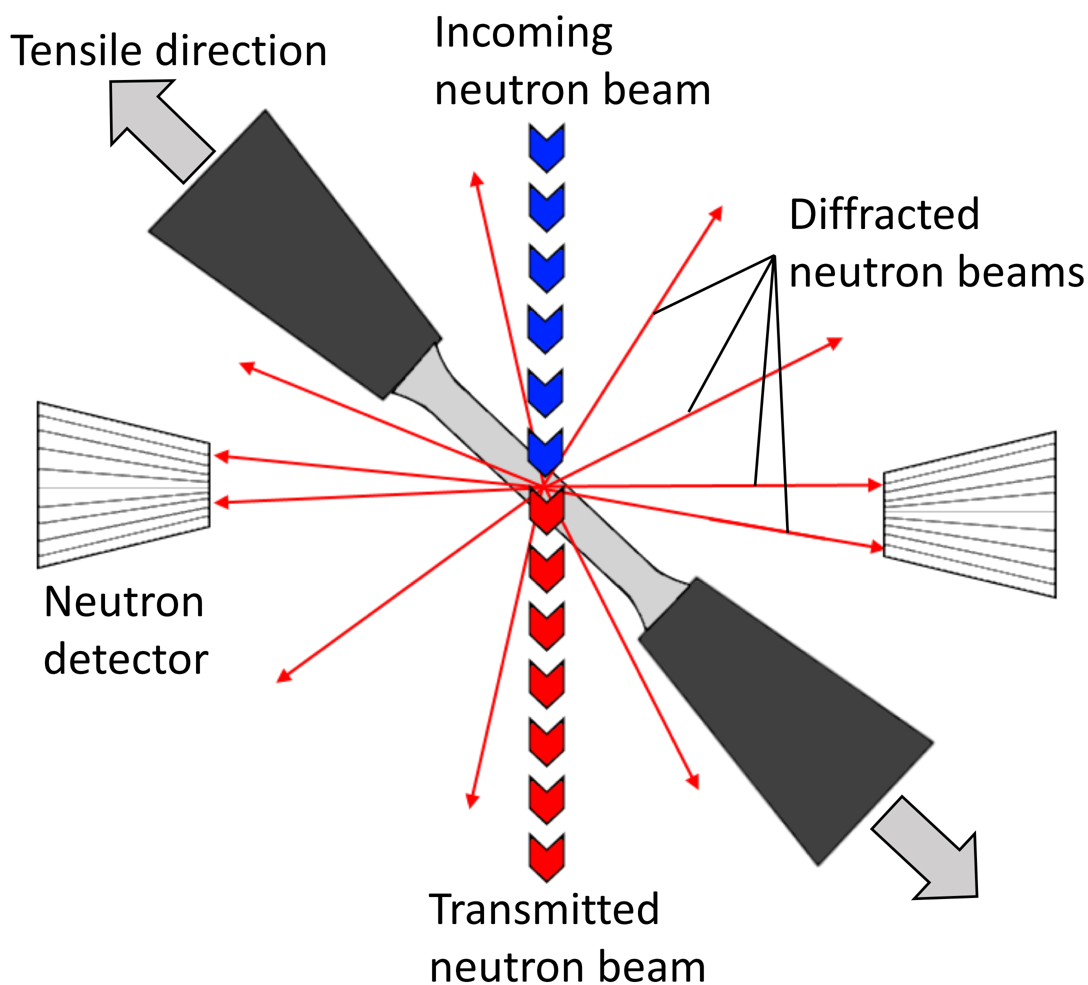
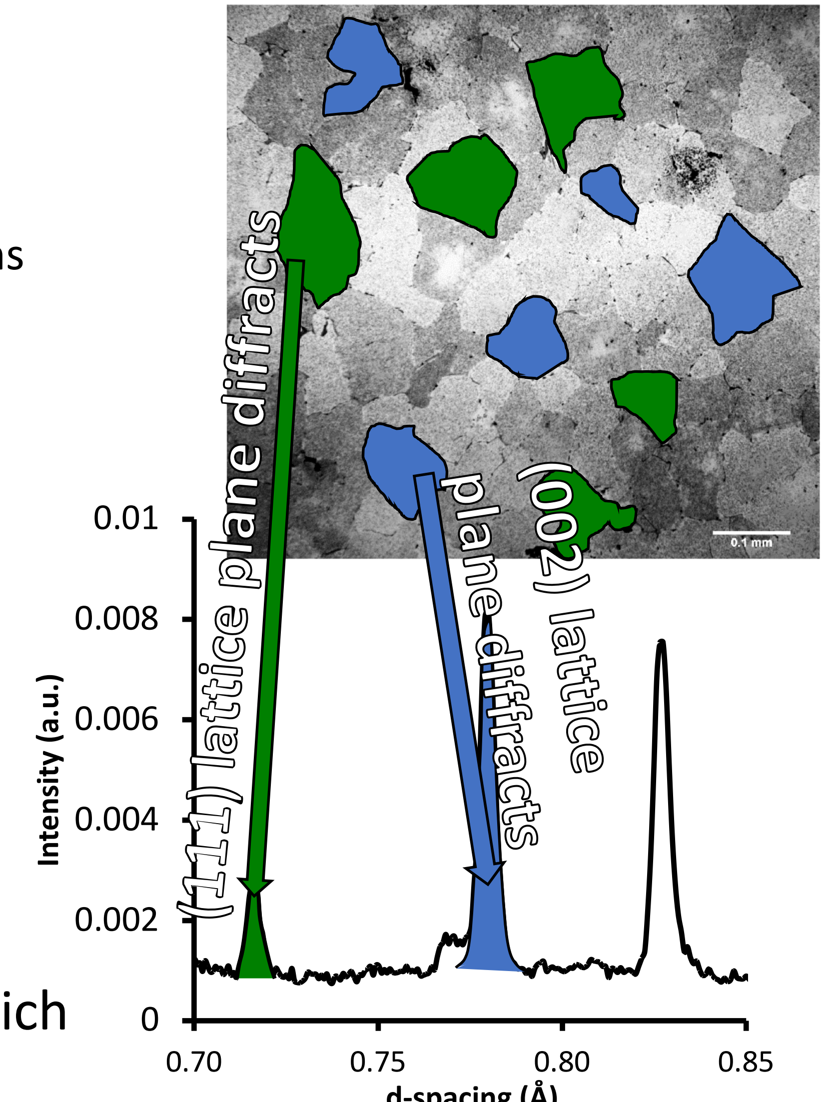
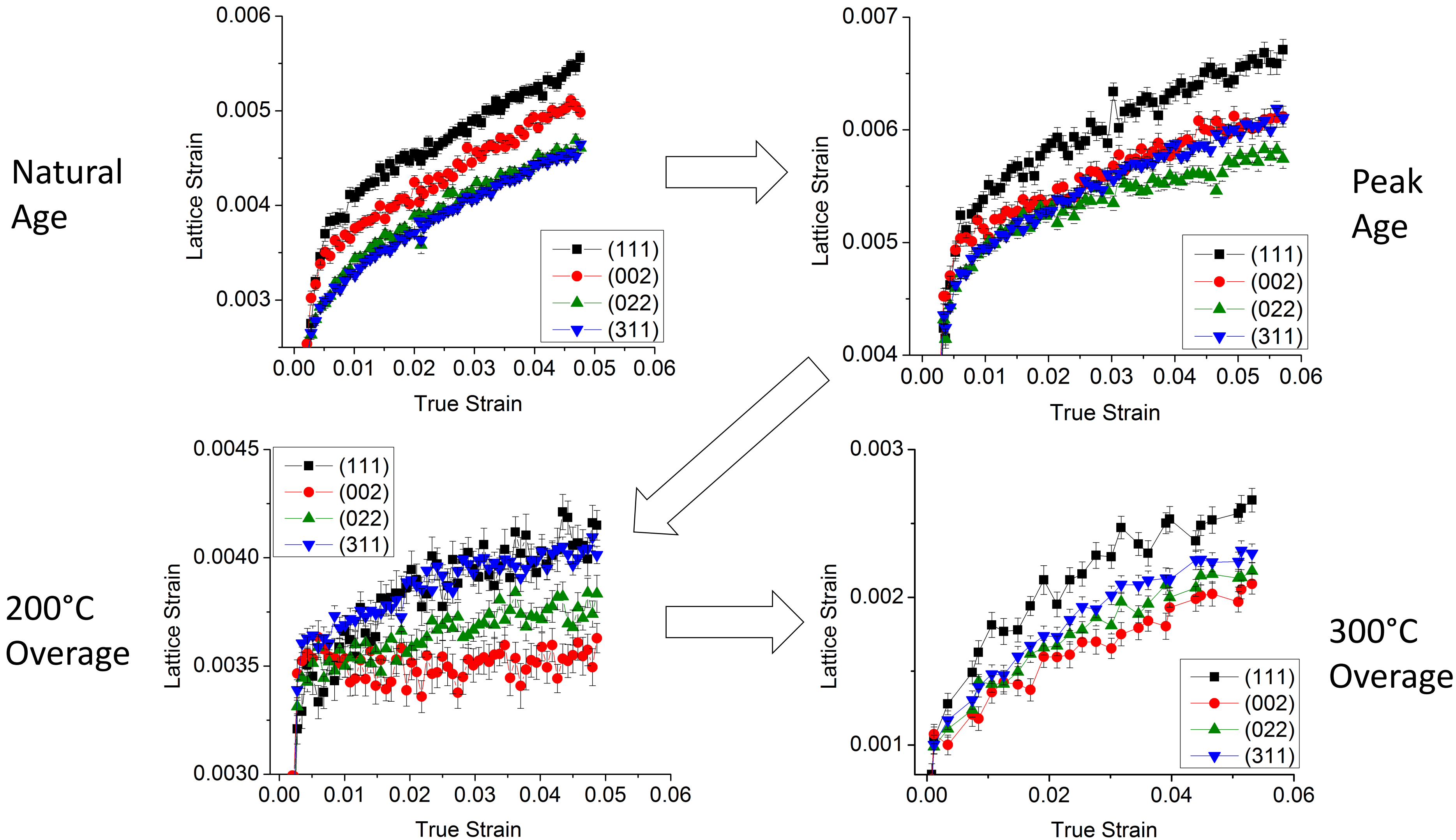




- Allows measurement of lattice strain, which is related to elastic internal stress

Anisotropy Observed in Neutron Results

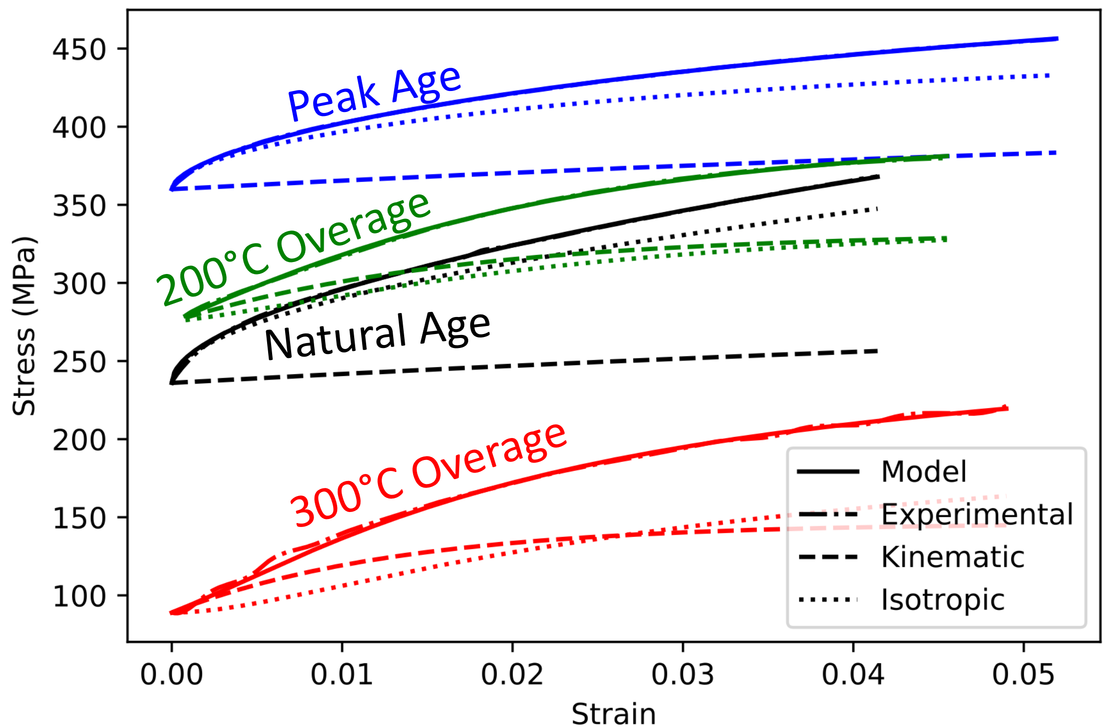


Macroscopic strain hardening model

- da Costa Teixiera *et al.* model for Al-Cu strain hardening

$$\sigma_f = \sigma_0 + \sigma_{ss} + \left(\sigma_p^n + \sigma_d(\epsilon_p)^n\right)^{1/n} + \langle\sigma\rangle(\epsilon_p)$$

σ_f	Flow stress
σ_0	Pure Al yield strength
σ_{ss}	Solid solution strength
σ_p	Static precipitation strength
σ_d	Strain hardening due to isotropic mechanisms
$\langle\sigma\rangle$	Strain hardening due kinematic mechanisms
ϵ_p	Plastic strain
n	Addition coefficient



J. da Costa Teixiera *et al*, Acta Mater. 57 (2009) p.6075

Changing deformation mechanisms due to growing precipitates

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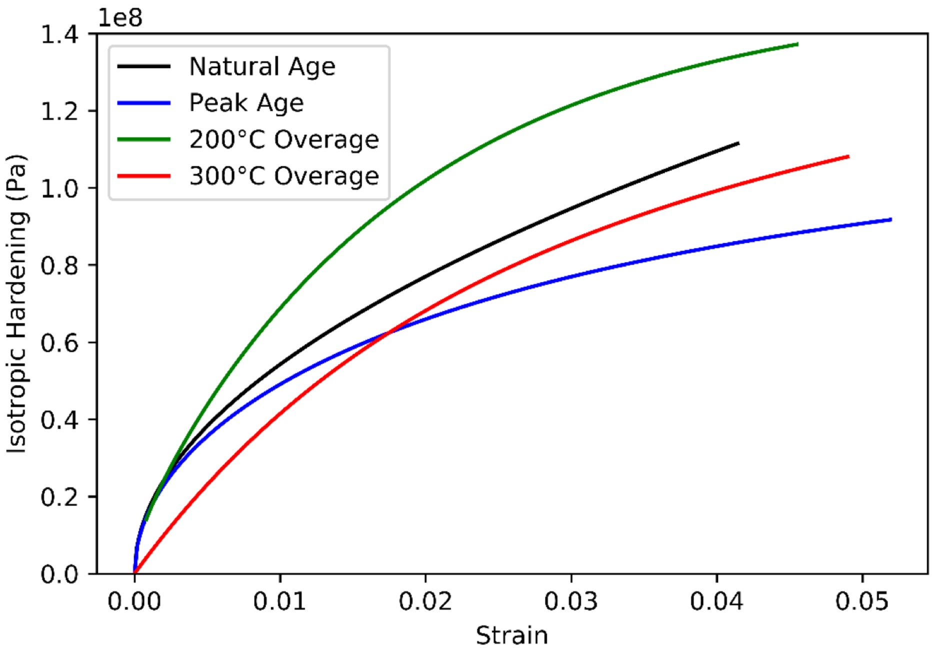
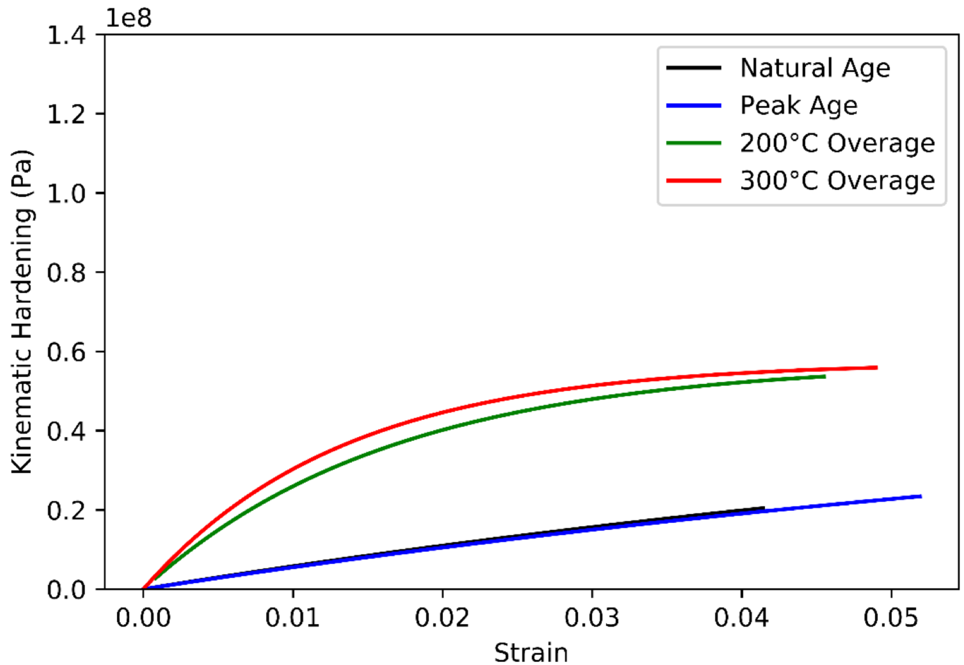
- As precipitates grow, Orowan looping becomes active and kinematic hardening increases
- Even relatively thick θ′ precipitates may be sheared through *delayed shearing*





Mechanism of delayed precipitate shearing

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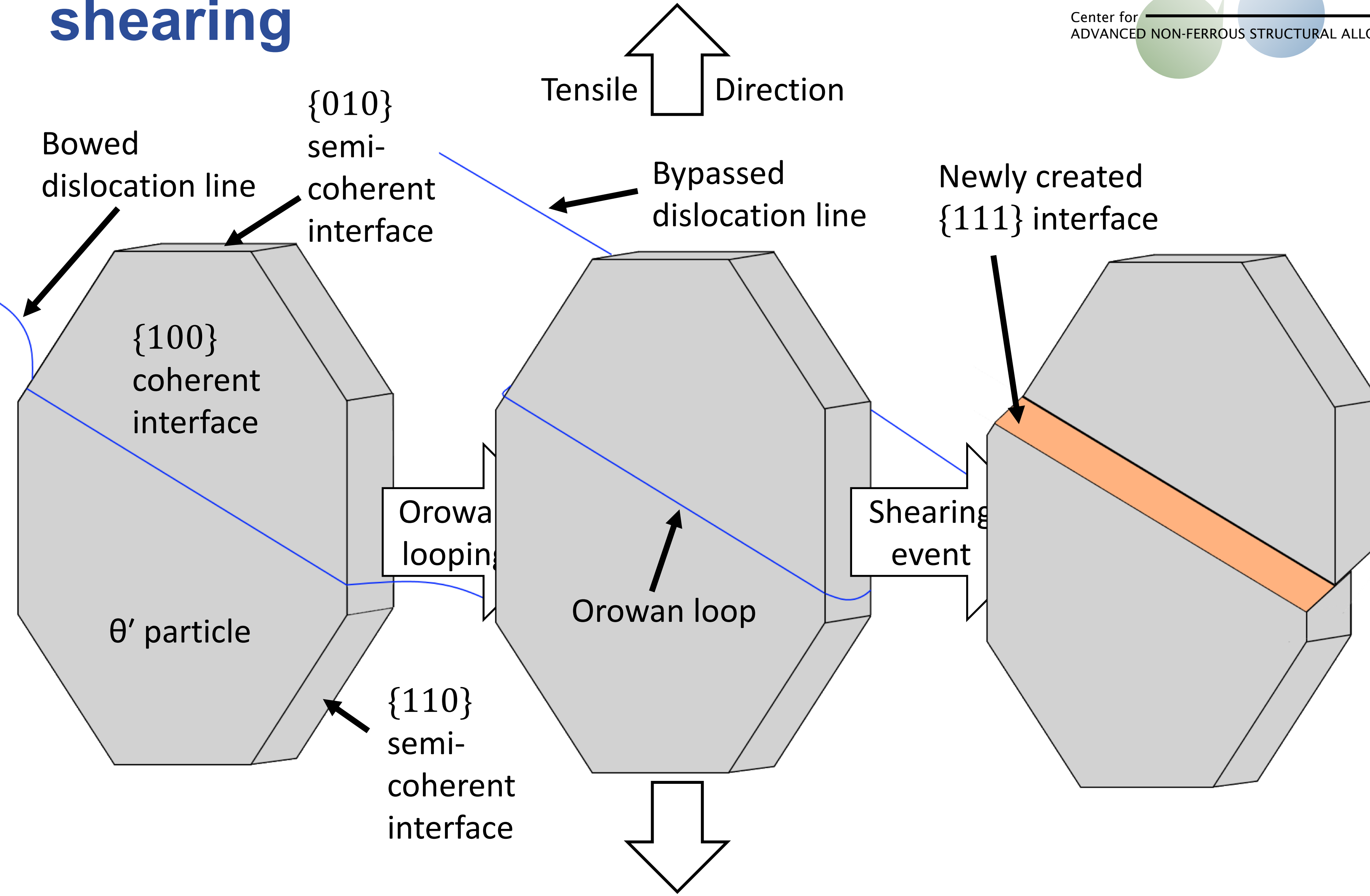
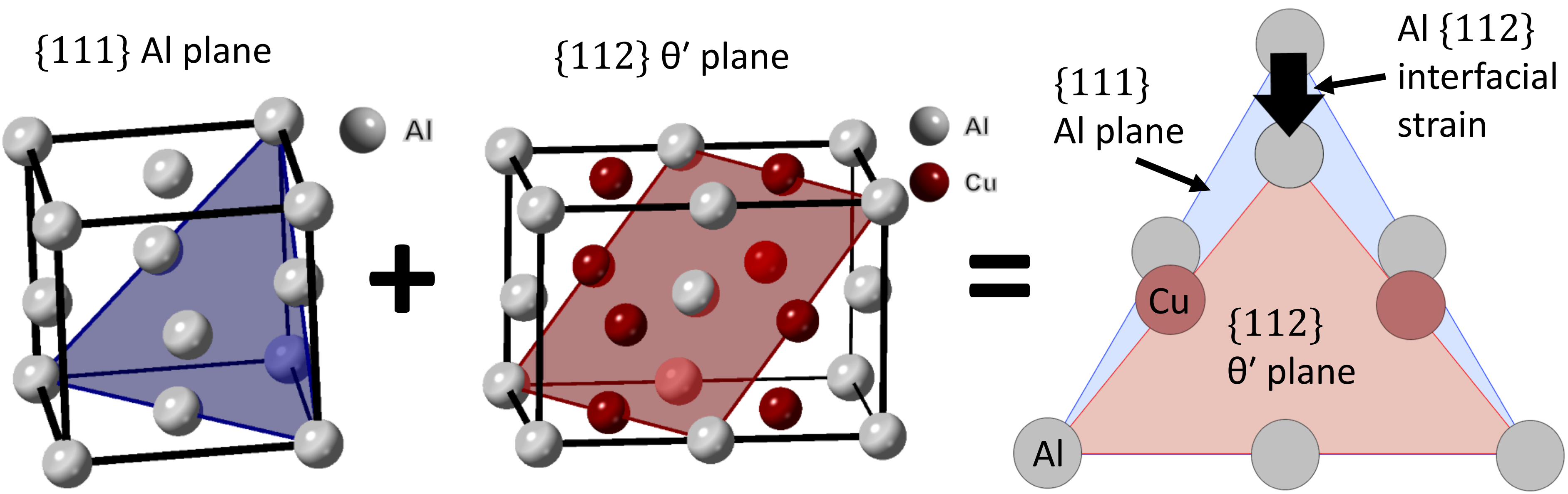


Interfacial matchup on newly-created interface from θ' shearing

- 2 contributions to interfacial energy: chemical and lattice mismatch
- Both terms are normally isotropic
- Lattice mismatch strain may be counteracted or aggravated by applied stress, if there is also a mismatch in Young's modulus
  - This effect would be anisotropic based on applied stress direction



Applied stress effects on precipitate shearing energy

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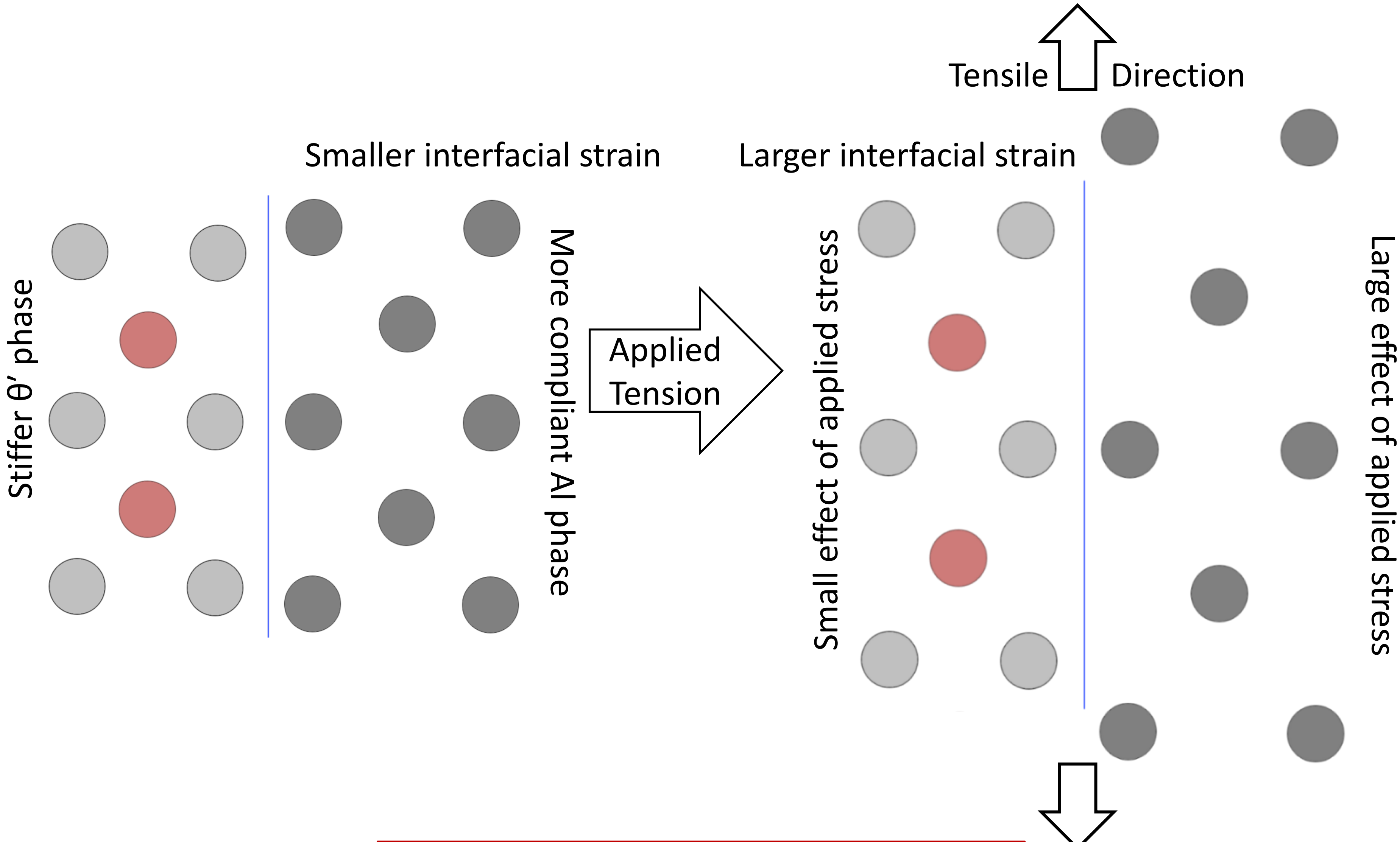

Energetics of New Interface Formation during Shearing

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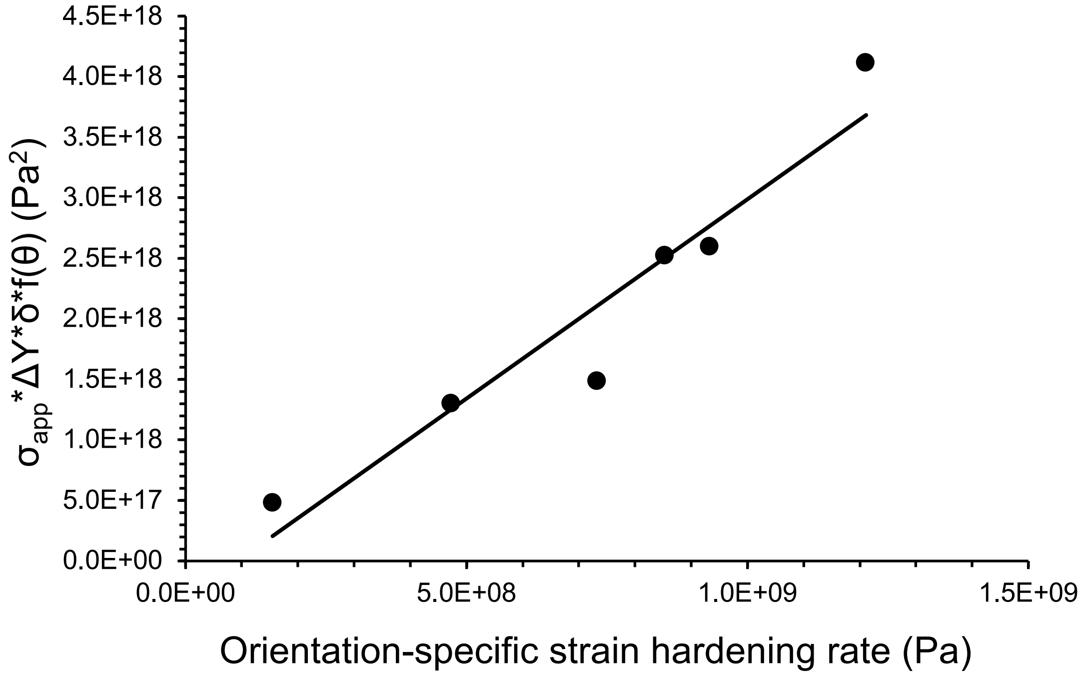
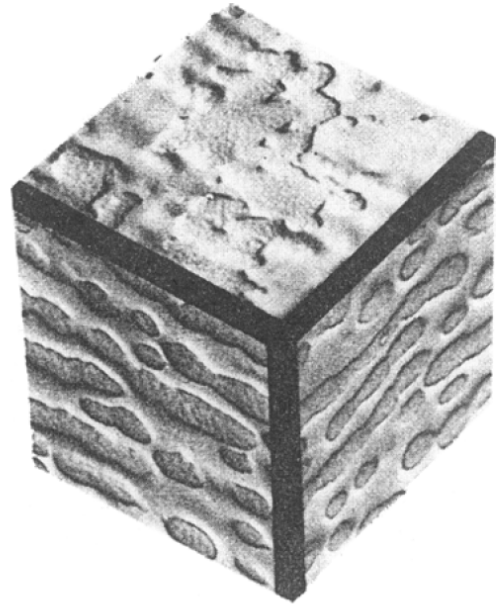
- $\Delta\gamma_{shear} \propto \sigma_{app} * \Delta Y * \delta * \sum_n \frac{(\cos(\theta) - \nu \sin(\theta))}{n}$
  - $\Delta\gamma_{shear}$ = difference in shearing energy due to applied stress
  - σ_{app} = applied stress
  - ΔY = modulus mismatch
  - δ = lattice mismatch
  - θ = angle between lattice mismatch & applied stress
  - ν = Poisson's ratio
- Sum over full multiplicity of both directions
- Good correlation is taken as evidence for importance of mechanism

For the 200°C overaged state

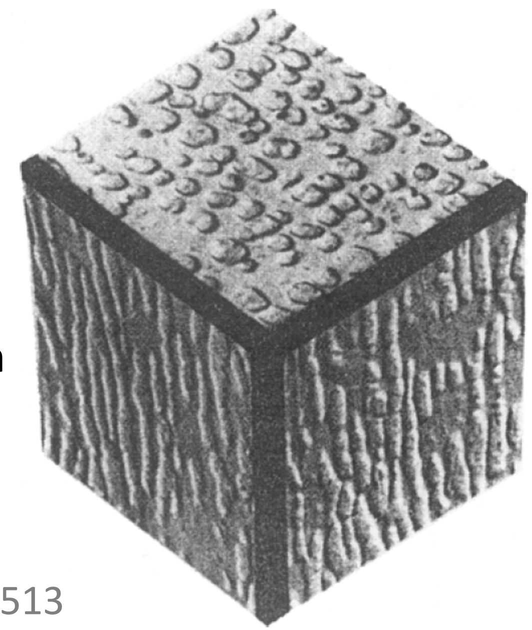


Existing case: Rafting of γ-γ' structures in Ni superalloys

- Morphology of γ′ is changed in tension or compression
- Energy for precipitate growth is affected by external stress
  - Applied stress causes less strain in stiffer phase
  - This can change strain energy in particular interface orientations
- $\gamma_{shear} \propto \sigma_{app} * \delta_{misfit} * \Delta Y$
- Hypothesis: Same effect can increase/decrease likelihood of precipitate shearing
  - Strain energy of newly created interface can be changed



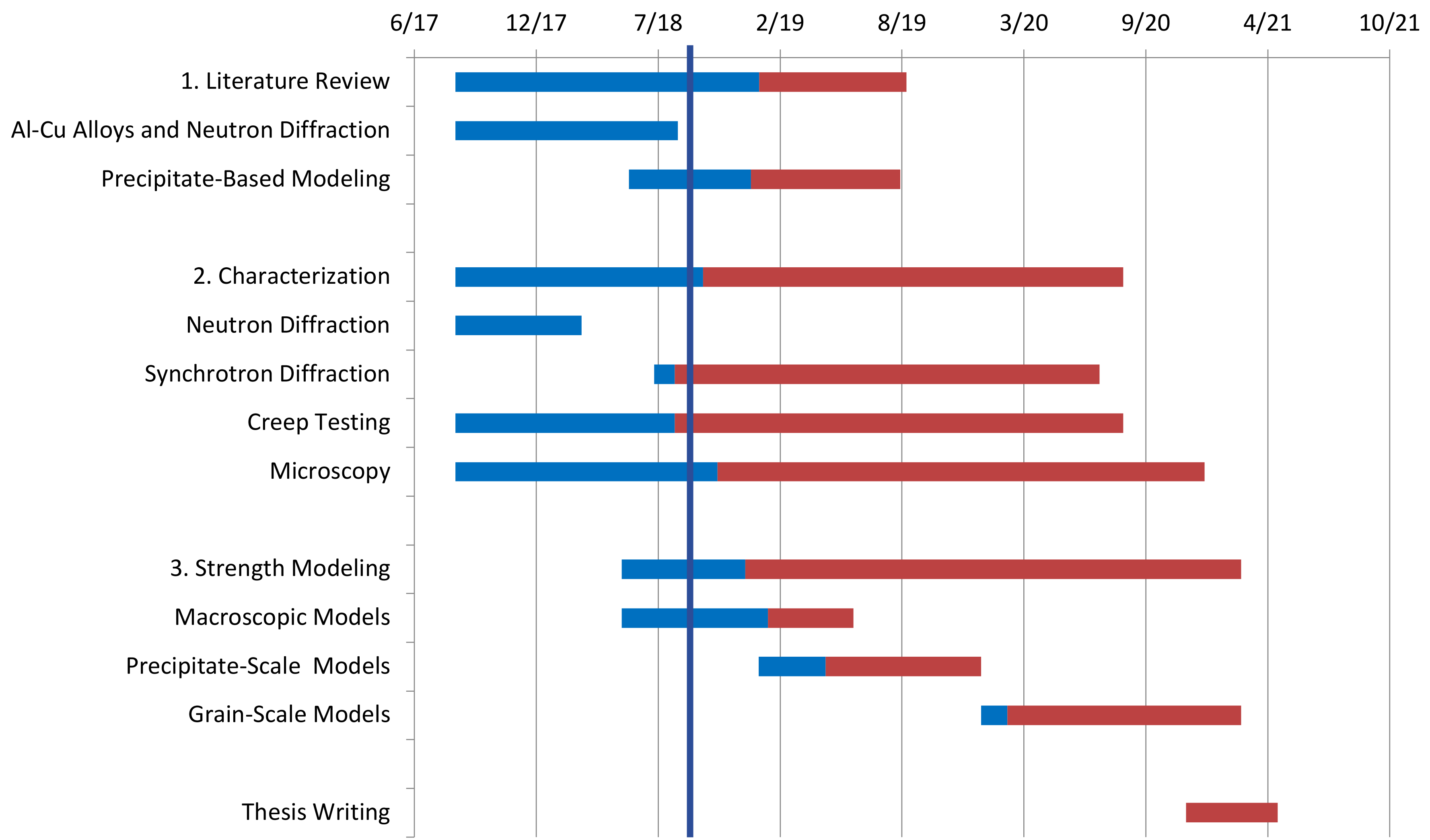
Tension



Compression

F.R.N. Nabarro, Metall. Mater. Trans. A 27 (1996) p.513

Progress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1. Literature Review
Al-Cu Alloys and Neutron Diffraction
Precipitate-Based Modeling
2. Characterization
Neutron Diffraction
Synchrotron Diffraction
Creep Testing
Microscopy
3. Strength Modeling
Macroscopic Models
Precipitate-Scale Models
Grain-Scale Models
Thesis Writing

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Thanks for your attention.

Questions?