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Center for ADVANCED NON-FERROUS STRUCTURAL ALLOYS

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

Project 34: In-situ Observation of Phase and Texture Evolution Preceding Abnormal Grain Growth in Ni-based Aerospace Alloys

Fall 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
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Student: Byron McArthur (Mines)

Faculty: Amy Clarke, Kester Clarke, Michael Kaufman (Mines)

Industrial Mentors: Eric Payton, Adam Pilchak (AFRL), Kevin Severs (ATI)

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Project 34: In-situ Observation of Phase and Texture Evolution Preceding Abnormal Grain Growth in Ni-based Superalloys

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- Student: Byron McArthur (Mines)
- Advisor(s): Amy Clarke, Kester Clarke (Mines)

Project Duration

PhD: Nov. 2017 to Dec. 2020

- Problem: Abnormal grain growth in Ni-based superalloys (RR-1000) significantly reduces mechanical properties and occurs as a result of forging parameters.
- Objective: Determine the mechanism of abnormal grain growth in Ni-based superalloys using ex-situ and in-situ characterization techniques.
- Benefit: Improved mechanical properties for turbine disc alloys.

Recent Progress

- Characterized as-received material
- Forging & heat treating parameters refined to create abnormal grain growth
- Characterizing forging material
- Developing theory for abnormal grain growth

Metrics

Description	% Complete	Status
1. Literature review	50%	●
2. Explore abnormal grain growth forging parameters for RR1000	50%	●
3. Ex-situ and interrupted material testing and characterization	50%	●
4. Develop and test theory to explain abnormal grain growth phenomena	25%	●
5. Perform in-situ microscopy with a synchrotron source (HEDM) to demonstrate phenomena	0%	●

Industrial Relevance

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- Ni-based superalloys are used in turbine engine discs
  - Flight-critical components
- Forging parameters induce abnormal grain growth (AGG)
  - Reduction in fatigue life
- Phenomena observed to other superalloys and material systems

High pressure turbine disc

https://jetartaviationshop.co.uk/product/raf-sepecat-jaguar-aircraft-rolls-royce-adour-jet-engine-hp-turbine-disc-aviation-art/

Material: RR-1000, γ-γ'

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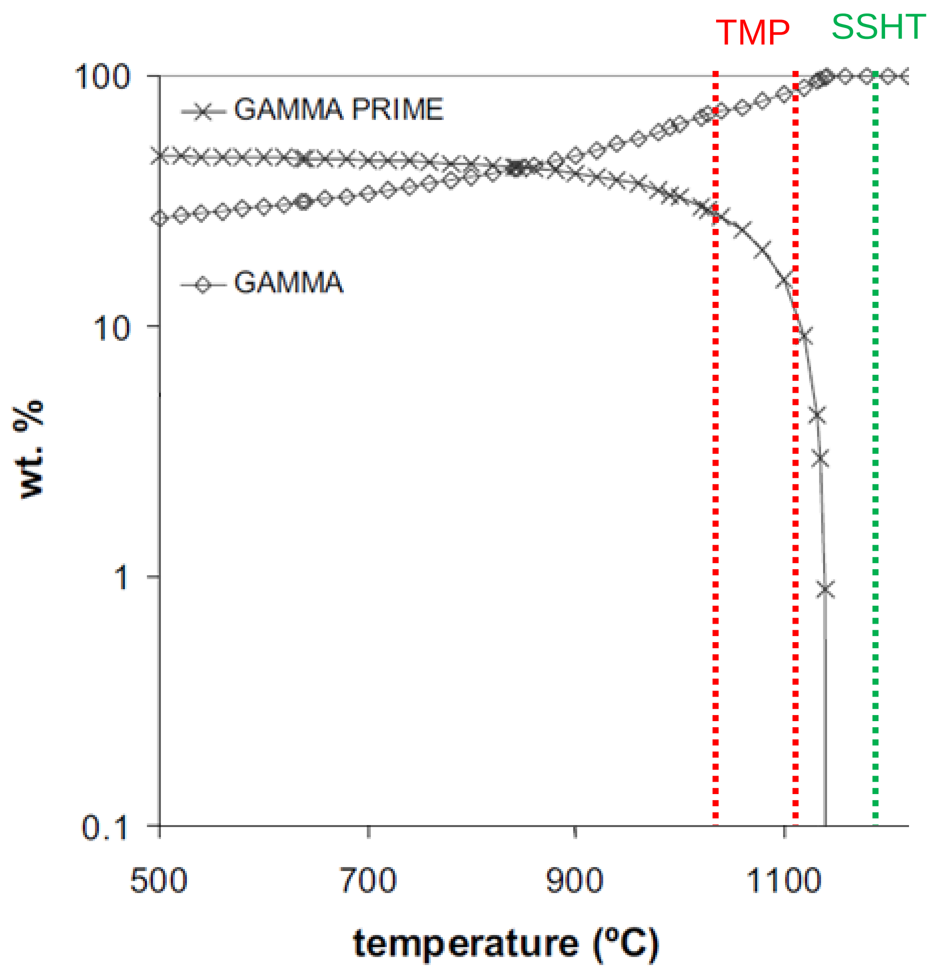
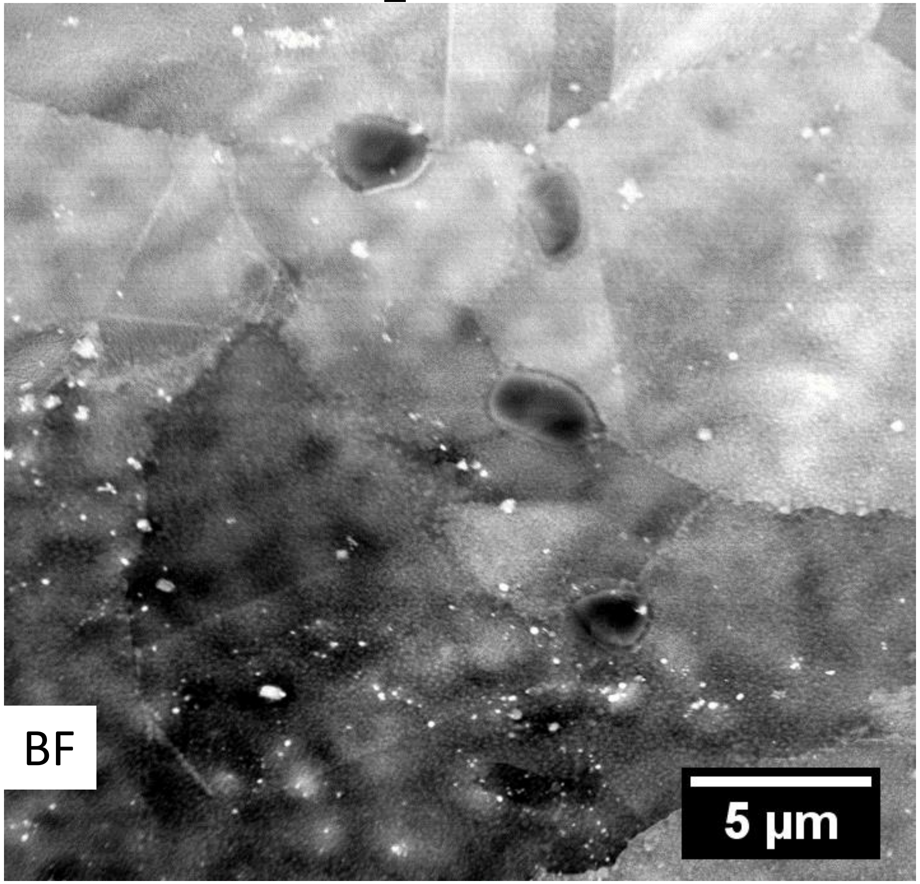
- Processing:
  - Powder metallurgy
  - Hot isostatic pressure compaction
  - Extruded at 5:1 ratio
  - Isothermal forging: 1035-1110°C
    - Performed in Gleeble®
    - Experienced thermal gradient
  - SSHT: 1150-1170°C
    - Performed in dilatometer
- Critical AGG parameters:
  - Strain rate
  - Heating rate to super solvus hold
  - Forging temperature

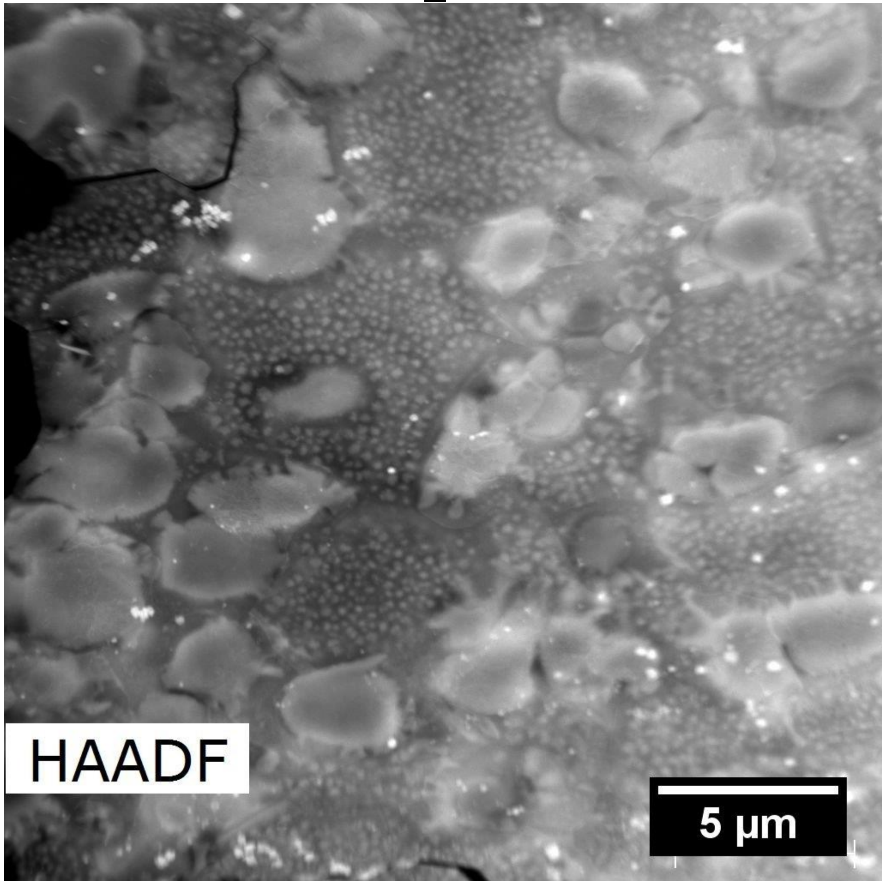


As-received Material

Low γ_1' Fraction



High γ_1' Fraction

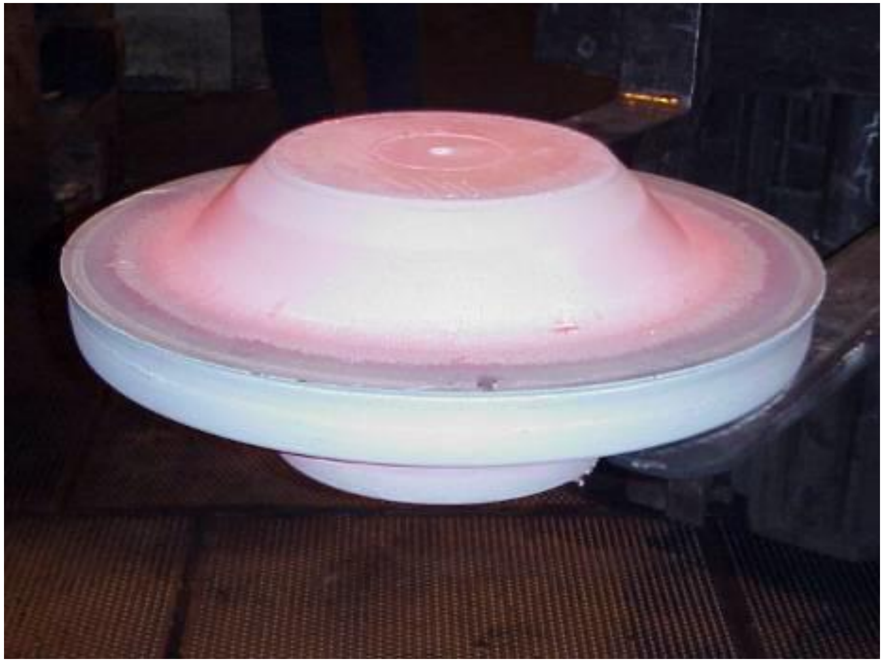


Note larger size of primary and secondary γ' as well as increased primary γ' fraction in Sample 2

Thanks to Yaofeng Guo for TEM imaging

Isothermal Forging

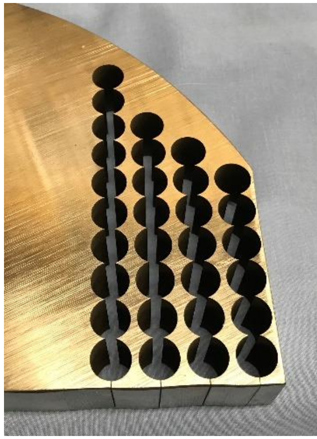
- Sub- γ' solvus temperature
- Low strain rate
- Maintain superplastic deformation for decreased forging loads
- Primary γ' pins γ grain boundaries
  - Secondary γ' less effective or dissolved
- Low stored energy accumulation
  - Grain boundary sliding (Coble creep)
  - Dynamic recovery
  - Dynamic recrystallization

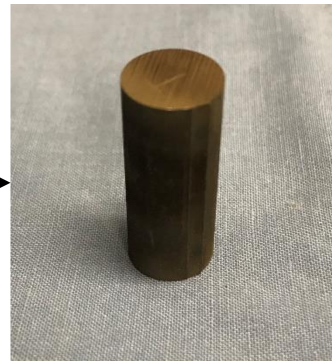


Mitchell, R. J., Lemsky, J. A., Ramanathan, R., Li, H. Y., Perkins, K. M., & Connor, L. D. *Superalloys 2008, pp.* 347–356.

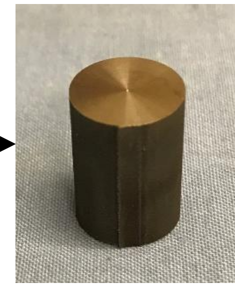
Experimental Procedure

Wire-EDM

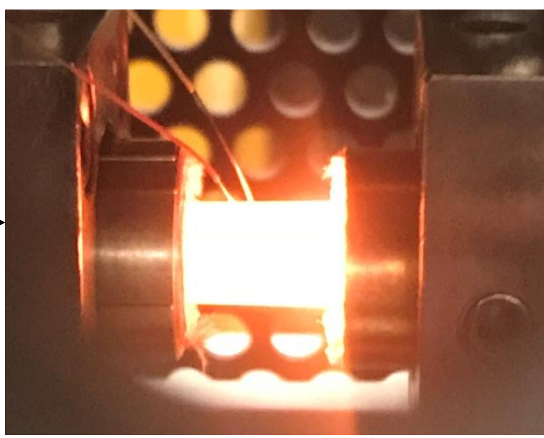




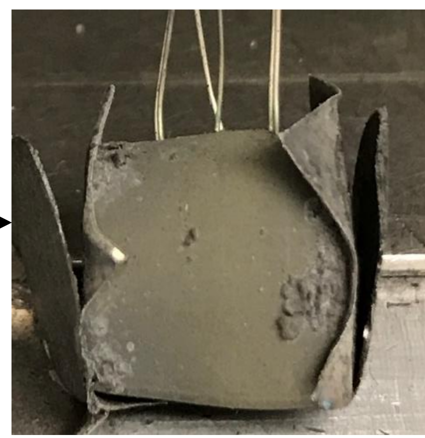
Machine to length with parallel faces

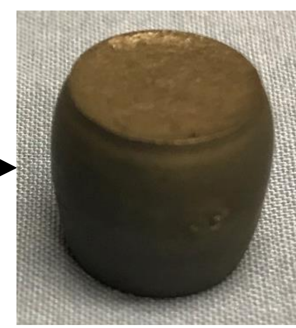


Isothermal forging in Gleeble®



Thermocouple locations



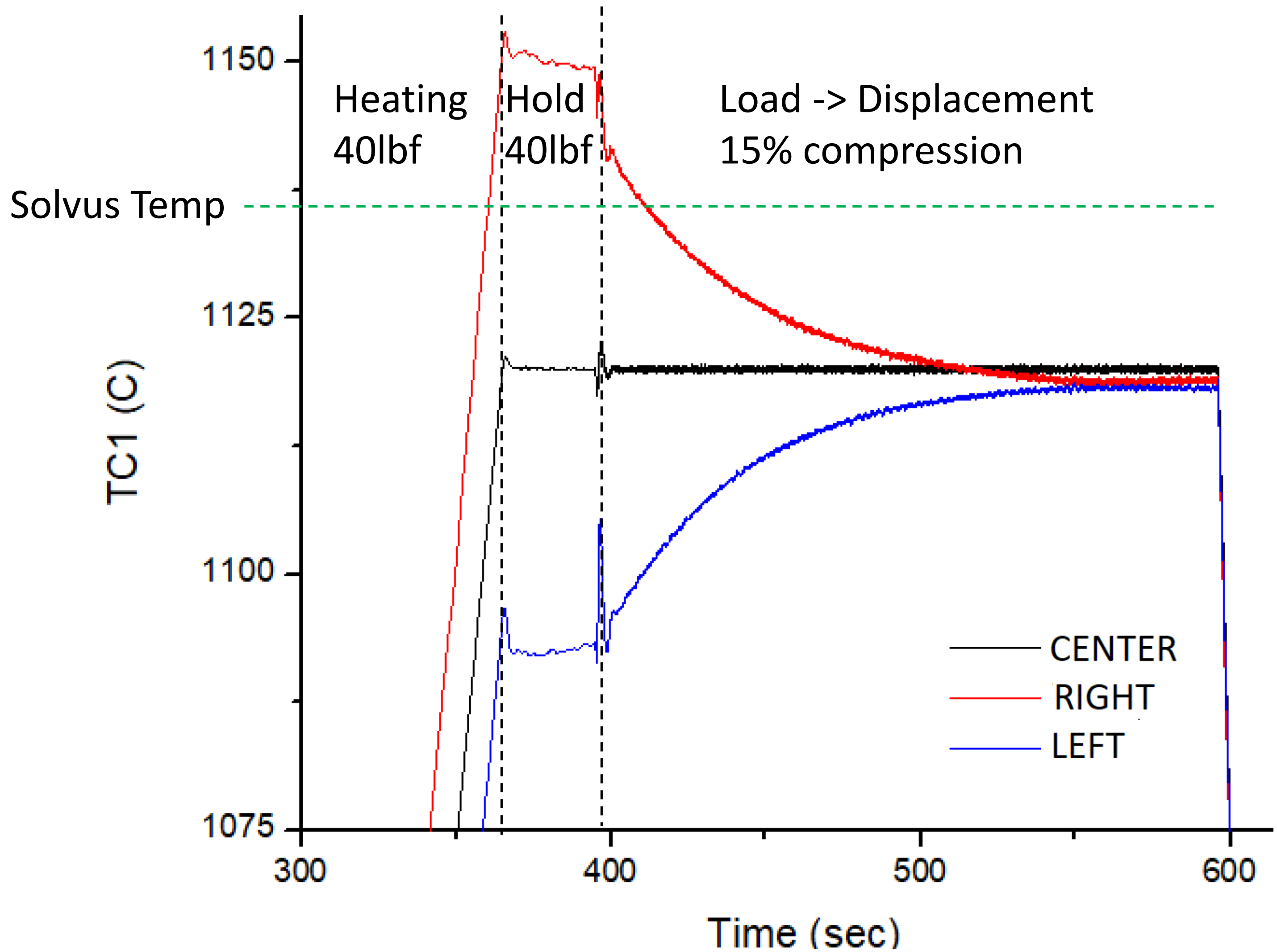


As-deformed Specimen

Dilatometer Specimen for SSHT

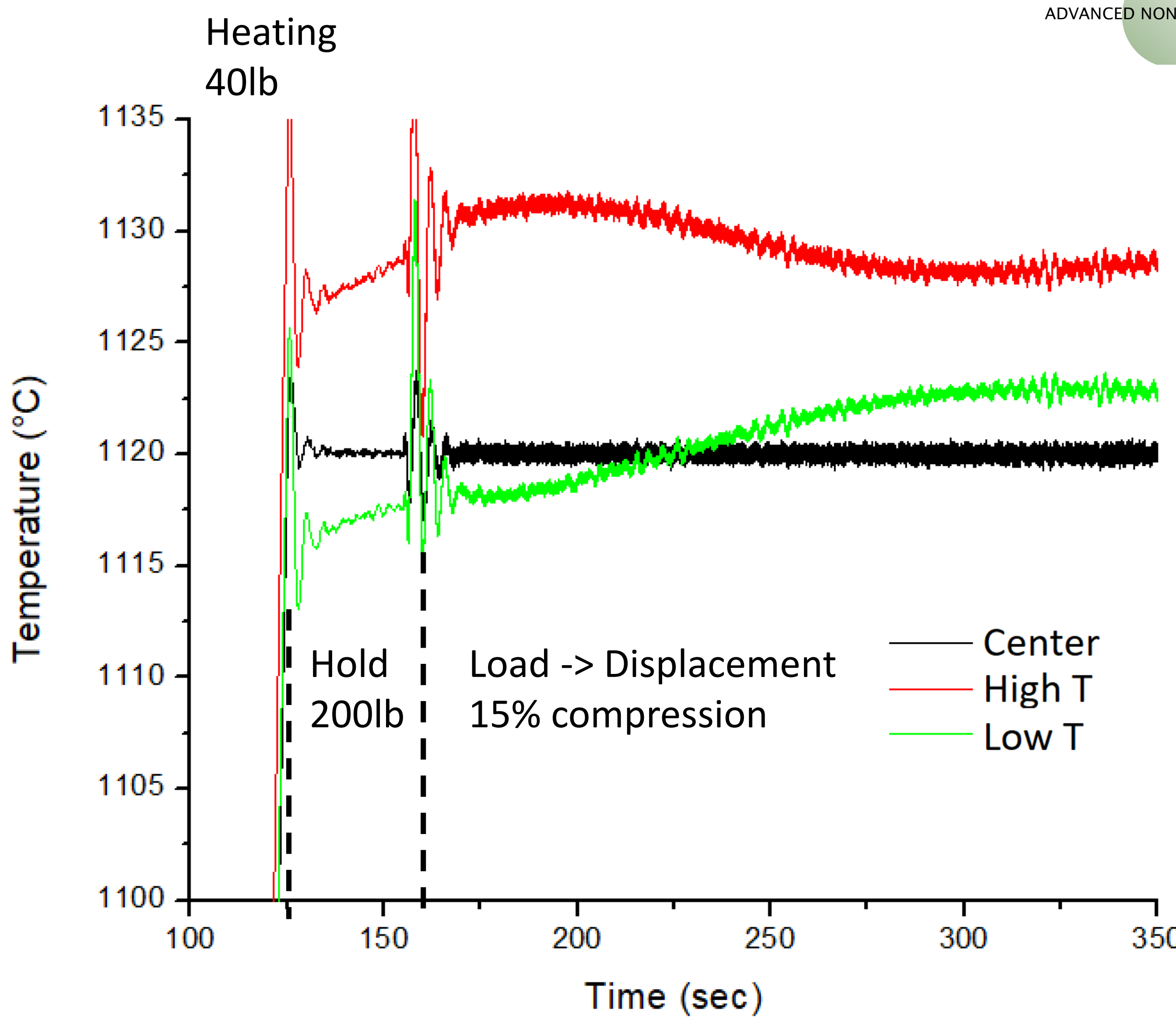
SSHT Specimen

Thermal Gradient Issues
Isothermal Forging in Gleeble®

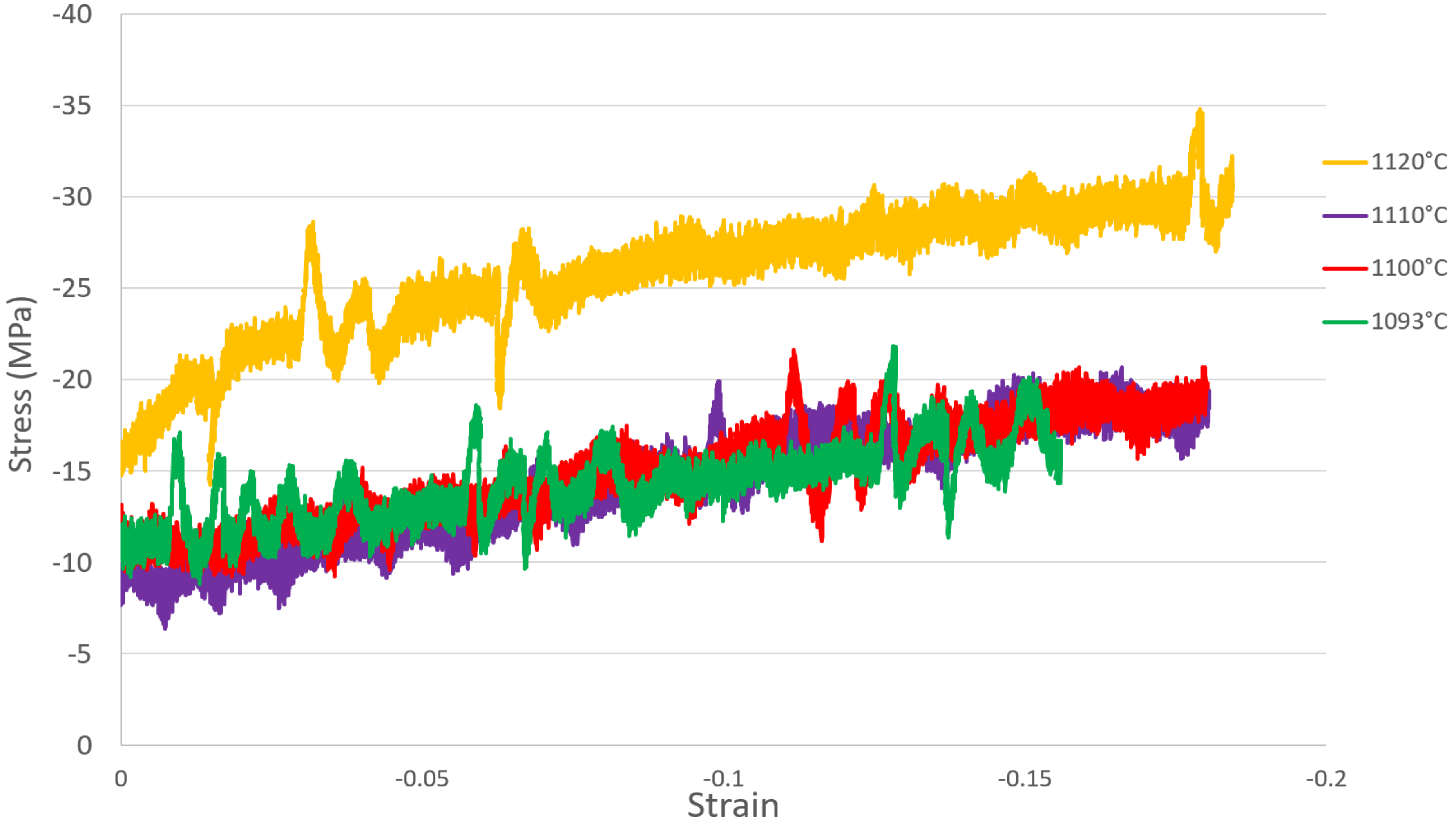


Reducing Thermal Gradients

Isothermal Forging in Gleeble®

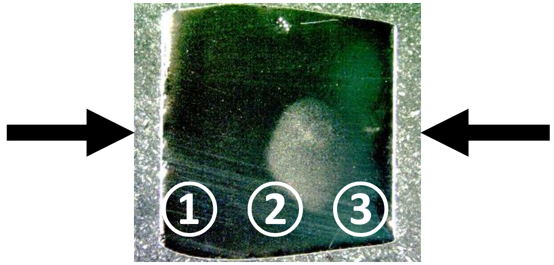


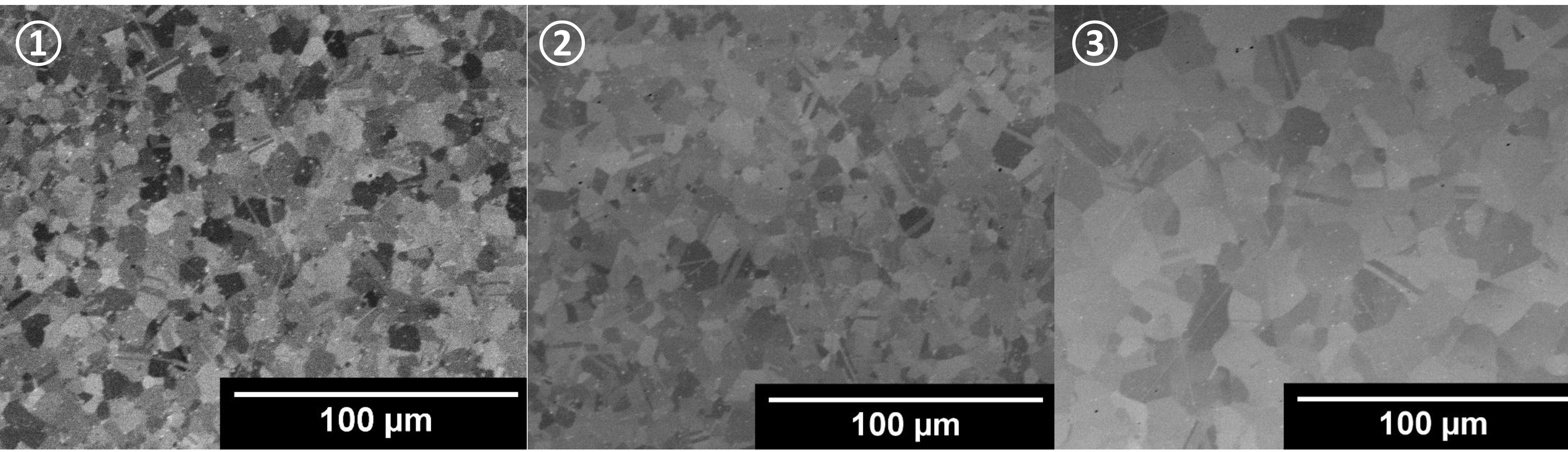
Flow-stress (RR-1000, 0.0008 /s)
Sample 1



Post-deformation Microstructure

Sample 1

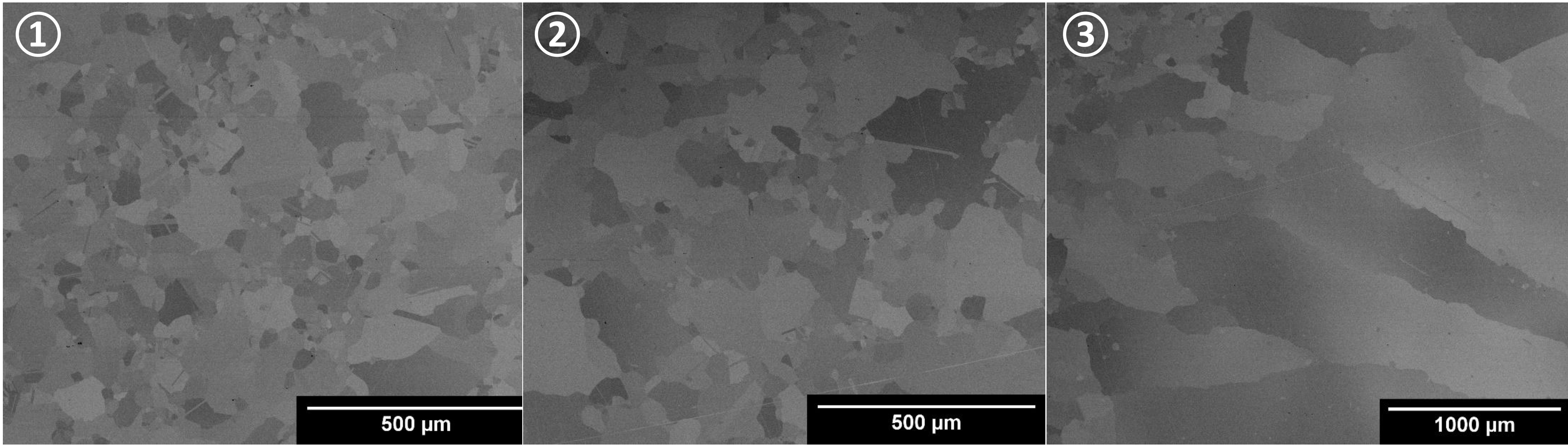




Decreasing γ’ phase fraction

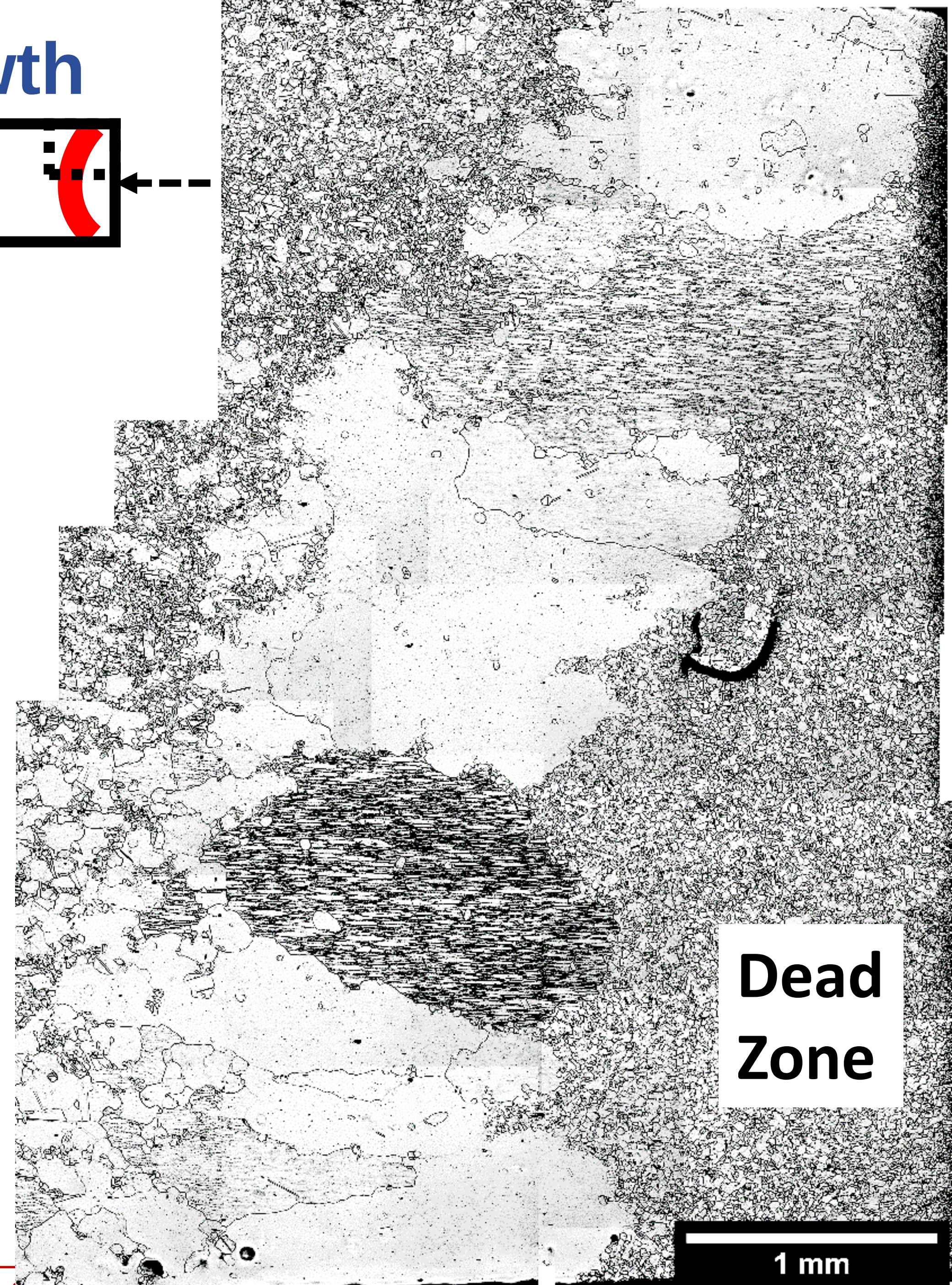
Deformation + SSHT Microstructure

1160°C



Abnormal Grain Growth

- AGG region follows ε and $\dot{\varepsilon}$ bands
- Occurs at high deformation temperatures
  - Requires low ε and $\dot{\varepsilon}$
- Prior powder structure observed via etching
  - Reveals oxides in grains of certain orientations



Influence of SSHT Temperature

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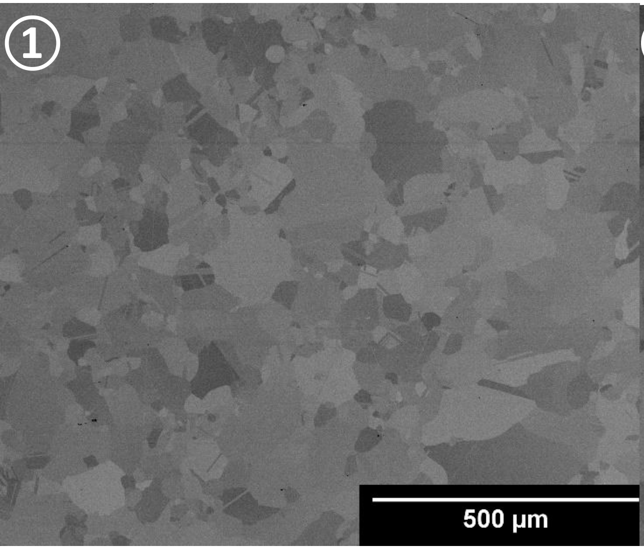
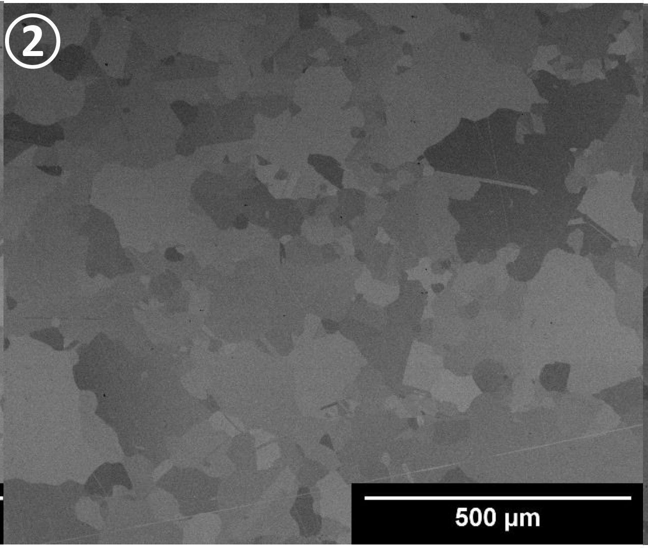
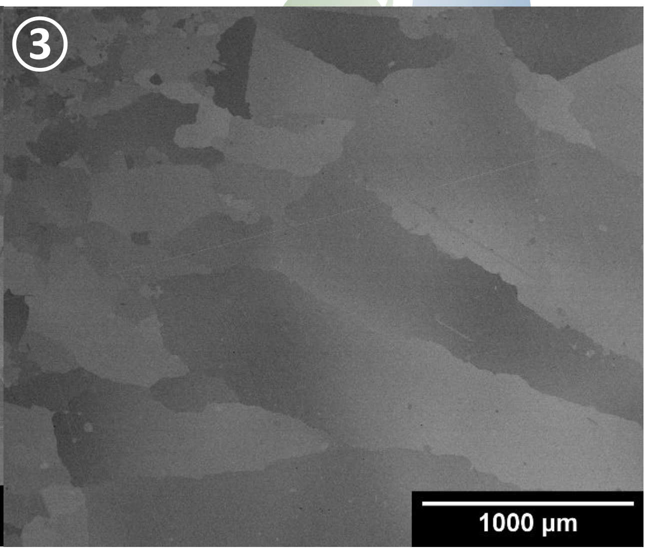
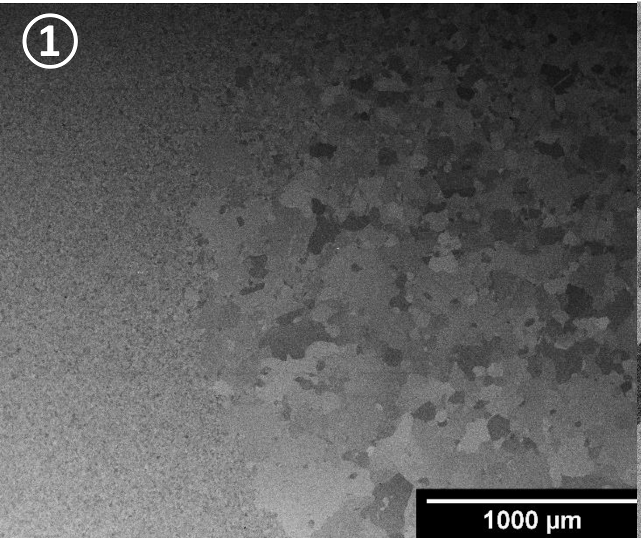
1160°C

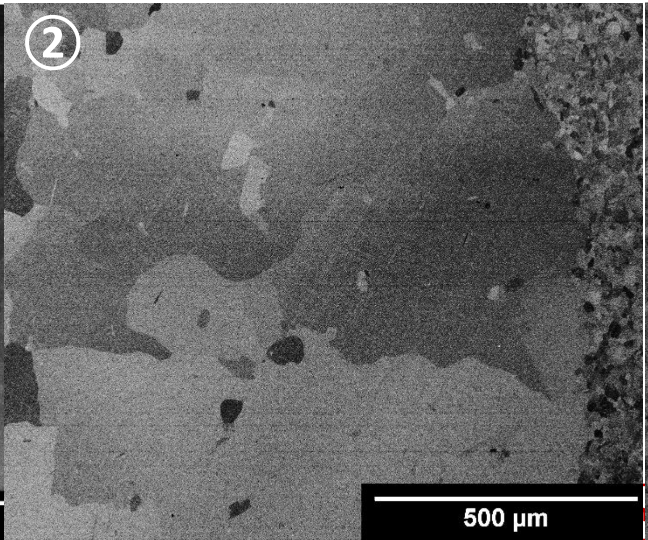


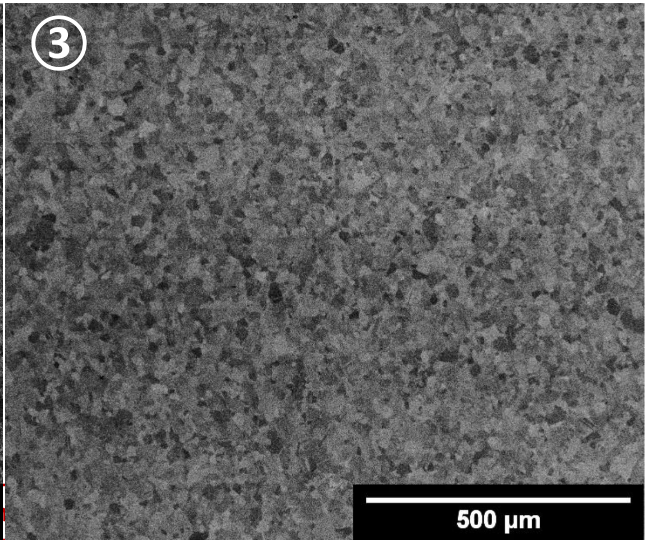




1140°C







Influence of SSHT Heating Rate

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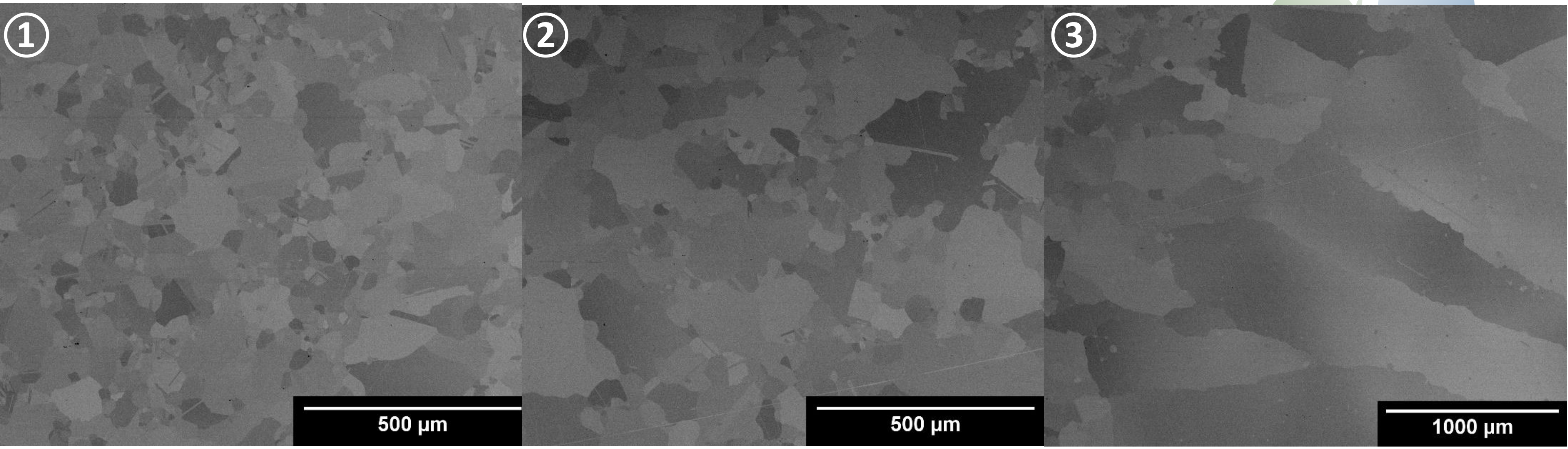
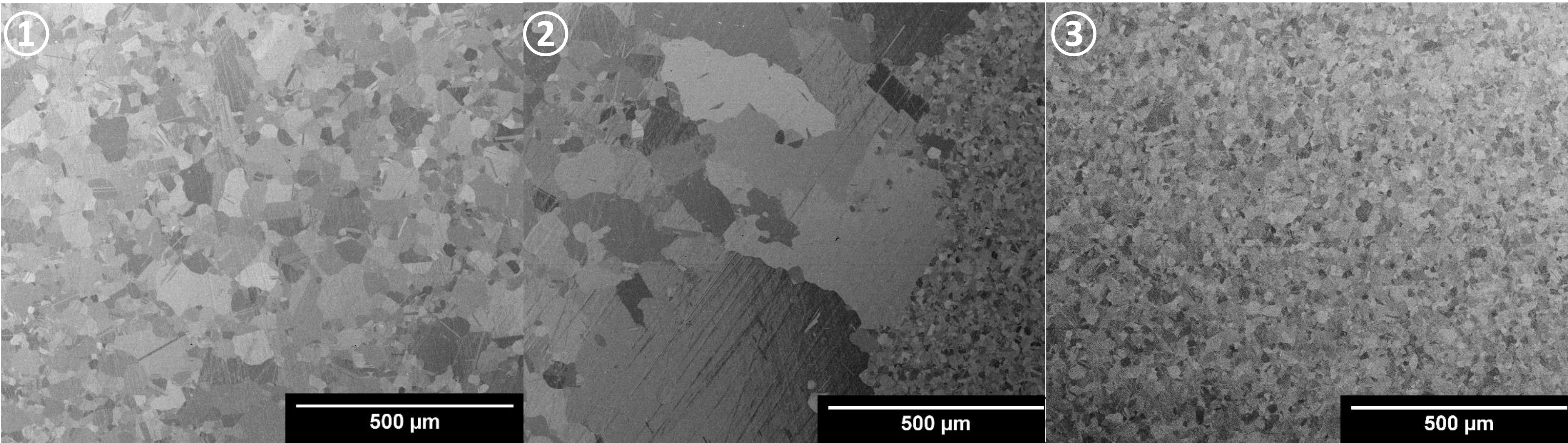
0.12°C/s to 1160°C



0.02°C/s to 1160°C



Influence of SSHT Time @ 1160°C

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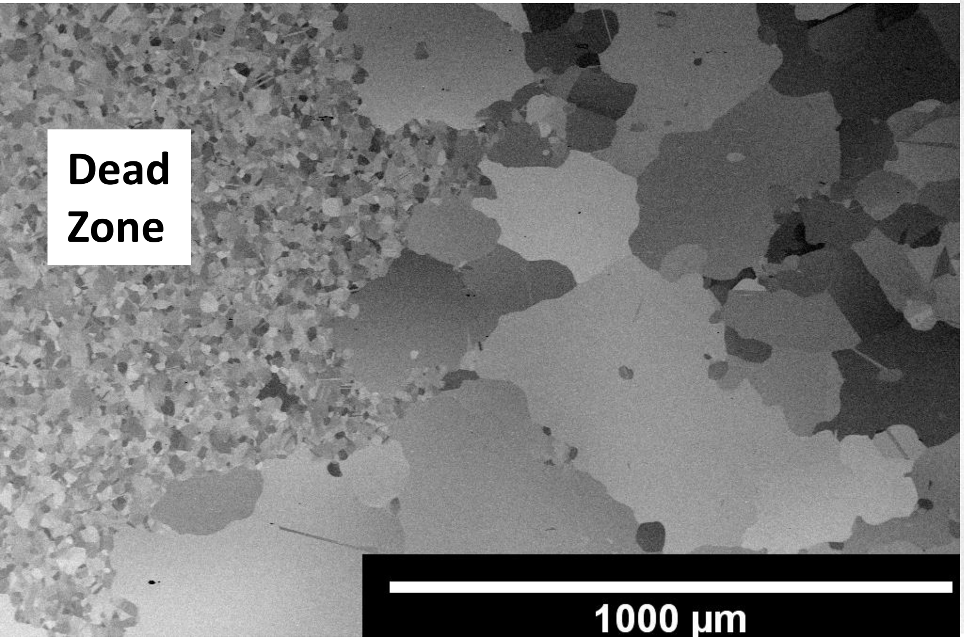
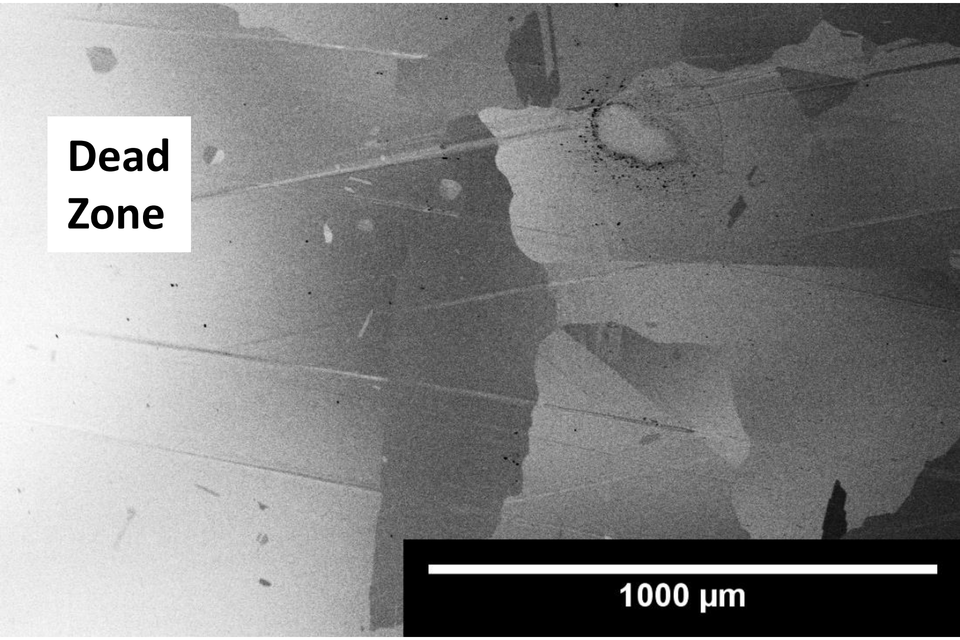
5 minutes



30 minutes



Microstructure Summary

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Post Deformation

- γ' pins GB
- γ size gradient across specimen
  - Due to thermal gradient

Post-SSHT

- AGG occurs extensively in ↑T side, following ε and $\dot{\varepsilon}$ bands

Influence of SSHT Temperature

- ↓T shifts AGG to ↑ ε region

Influence of SSHT Heating Rate

- ↓$\dot{T}$ shifts AGG to ↑ ε region

Influence of SSHT Time

- Initial γ growth followed by consumption of neighboring grains

Anomalous Flow Stress

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Low Temperature Side

- Higher γ' phase fraction
  - Primary and Secondary
- Primary γ' precipitates pin γ grain boundaries
- Secondary γ' precipitates interact with dislocations
- Dynamic recrystallization (DRX) in low T side
  - $\downarrow$GS causes $\downarrow T_{DRX}$
  - Localized flow softening
    - $\uparrow$ ε and $\dot{\varepsilon}$
    - Continued DRX

High Temperature Side

- Gradient towards dynamic recovery or superplasticity
  - Both result in lower stored energy

Proposed AGG Mechanism:
Stored Energy Driven Static Recrystallization

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- Dislocation interactions with remaining γ'
  - Increase dislocation density and prevent dynamic recovery
  - Dynamic recrystallization occurs in ↓T region
- Dynamic recovery occurs within ↑T region
  - Low stored energy
- ↑ ε and $\dot{\varepsilon}$ regions promote dynamic recrystallization
- Locally inhomogeneous strain post-deformation
  - Remaining un-recrystallized grains
- SSHT static recrystallization
  - Nucleation site limited
    - Low SSHT temperature and heating rate promote AGG in ↑ ε and $\dot{\varepsilon}$ regions
  - Recrystallized grains impinge upon each other
    - High nucleation sites limit AGG extent
    - Consumes un-recrystallized regions

Future Work

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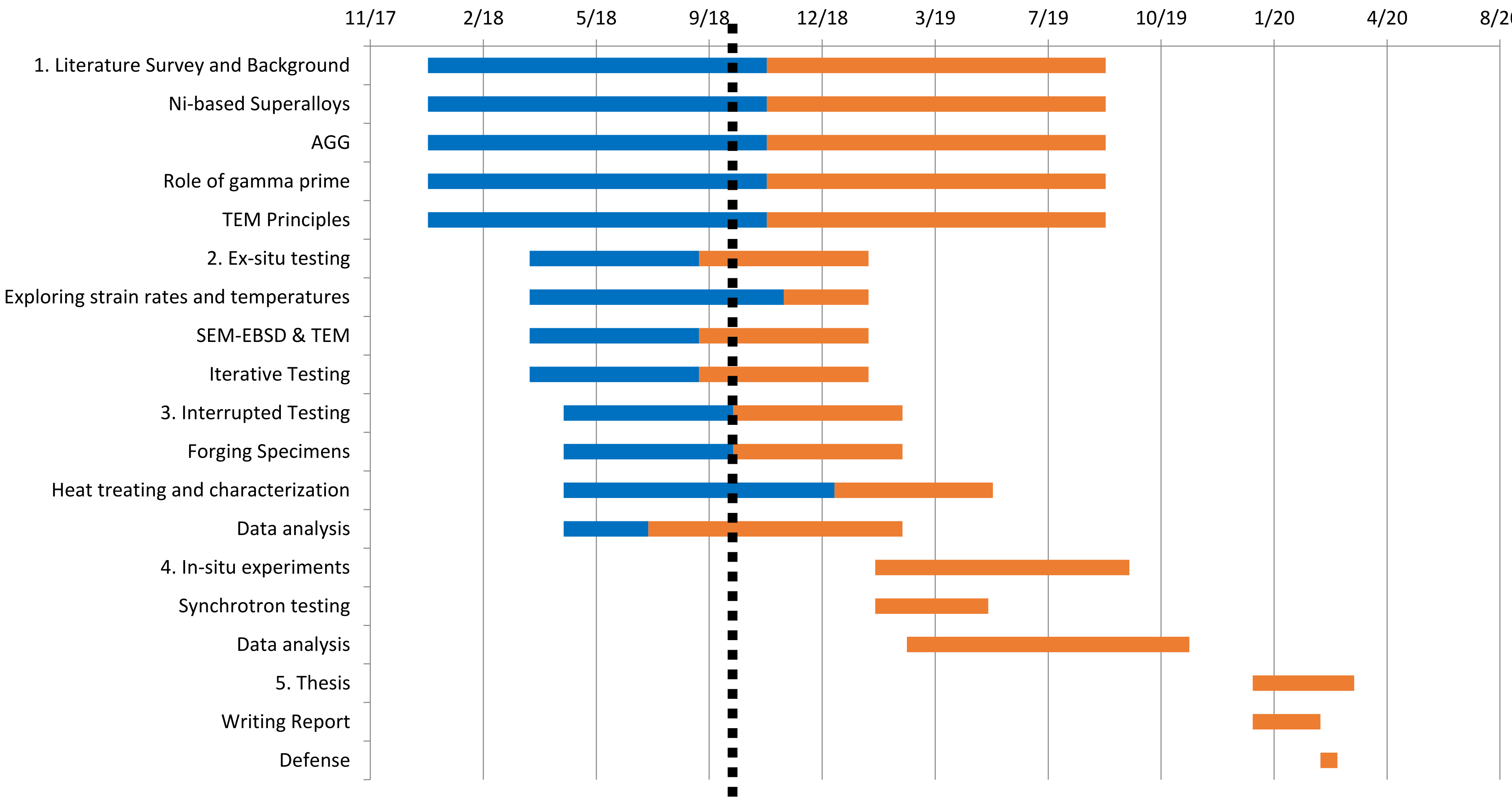
- Reduce/control gradients and variations in isothermal forging
  - Larger specimen
  - Work with DSI (Gleeble® manufacturer)
- Further characterize stored energy
  - GND's via SEM-EBSD
  - SSD's via Micro-XRD
  - Dislocation sub structures via TEM
- Utilize high primary γ' material to determine effects of primary γ' fraction
- Literature review on high energy diffraction techniques

Progress



11/17
2/18
5/18
9/18
12/18
3/19
7/19
10/19
1/20
4/20
8/20
1. Literature Survey and Background
Ni-based Superalloys
AGG
Role of gamma prime
TEM Principles
2. Ex-situ testing
Exploring strain rates and temperatures
SEM-EBSD & TEM
Iterative Testing
3. Interrupted Testing
Forging Specimens
Heat treating and characterization
Data analysis
4. In-situ experiments
Synchrotron testing
Data analysis
5. Thesis
Writing Report
Defense

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Thank you very much!

Byron McArthur

bmcarthu@mines.edu