Project 31-L: Accumulative Roll Bonding of Al Sheets Toward Low Temperature Superplasticity

Fall Meeting

October 13th – 15th 2020

- Student: Brady McBride (Mines)
- Faculty: Kester Clarke (Mines)
- Industrial Mentors: Ravi Verma (Boeing), John Carpenter (LANL), Eric Payton (ARFL)

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- Student: Brady McBride (Mines)
- Advisor(s): Kester Clarke (Mines)

Project Duration

PhD: September 2017 to September 2021

- Problem: Superplastic forming requires high temperatures and very low strain rates.
- Objective: Develop an in-depth understanding of how accumulative roll bonding affects temperature dependent strength and superplastic properties of Al alloys.
- Benefit: Low temperature superplasticity could result in reduced cost and cycle time due to reduced deformation temperatures and increased strain rates.

Recent Progress

- Initial round of tensile testing for superplasticity based on literature review
- DSC and EBSD analysis on thermal stability of ARBed microstructure
- Initial XRD measurements for textural evolution and strain reduction during static annealing

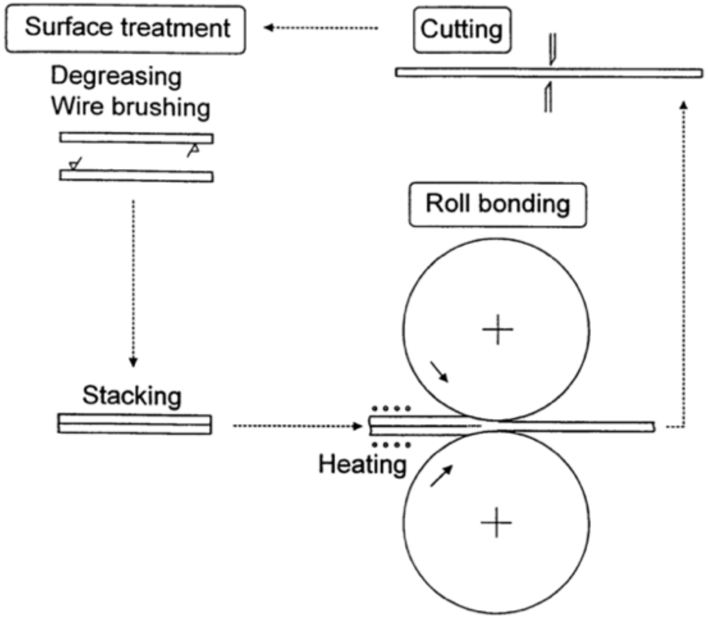
Metrics

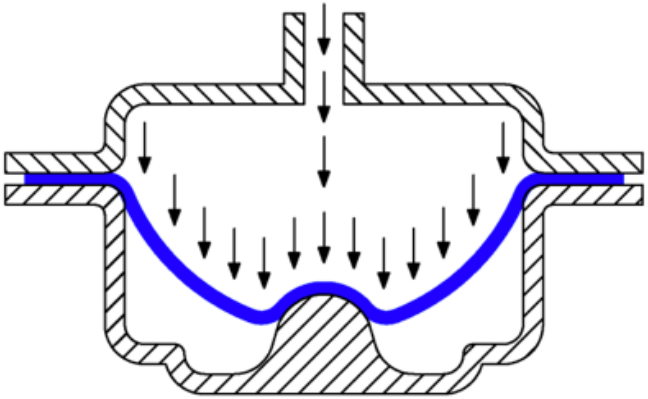
Description	% Complete	Status
1. Bulk production of samples with ARBed microstructure	100%	●
2. Static annealing trails on ARBed microstructure	75%	●
3. Tensile testing for superplasticity (1st round)	100%	●
4. Microstructural characterization after tensile testing (1st round)	0%	●
5. Process refinement for optimized superplasticity	0%	●

Outline

- Project overview
- Research questions
- Literature review
  - Strain rates & temperatures of interest
- 1st round of tensile tests
  - strain-to-failure, strain rate jump tests
- Thermal stability of ARBed microstructure
  - EBSD microstructural analysis
  - DSC analysis
- Next steps
- Challenges and opportunities

Industrial Relevance





Enhanced properties:

- Hall-Petch strengthening
- low temperature superplasticity

Applications:

- superplastic forming
- high strength sheet components

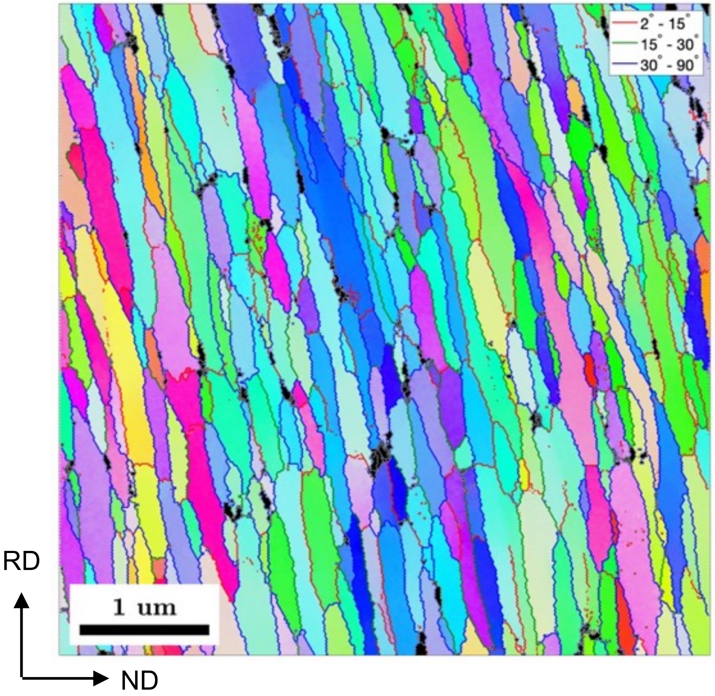
Benefits:

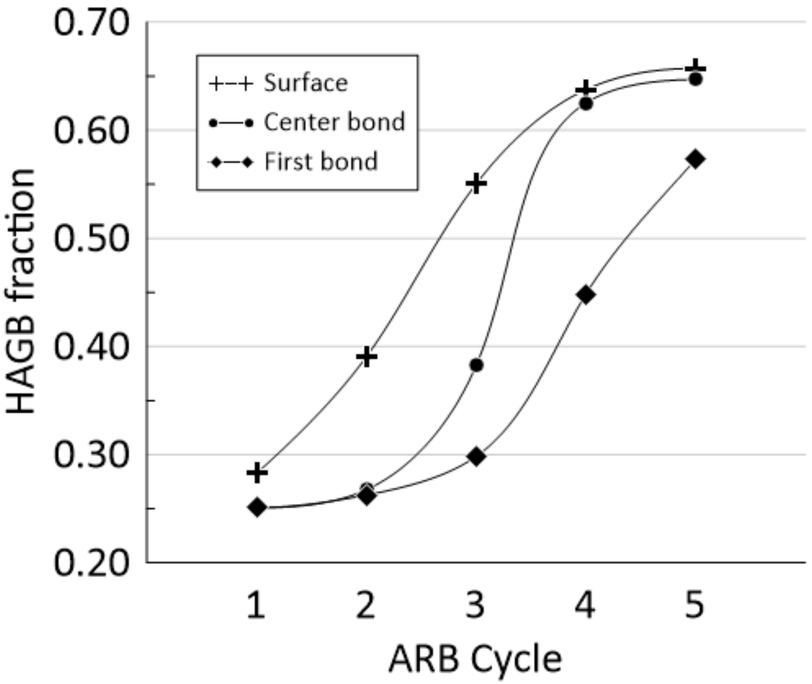
- reduced cycle time
- reduced die wear
- reduced processing cost

Saito et al., *Acta Materialia*, 1999.
Cleveland et al., *Materials Science and Engineering A*, 2003.

ARBed Microstructure in Al 5083

Mid-thickness grain morphology after 5 ARB cycles





HABG fraction, grain size saturates after 5 cycles

Average grain size:	243 nm x 66 nm
Average aspect ratio:	3.7
High angle grain boundary:	≈60 %

Research Hypotheses

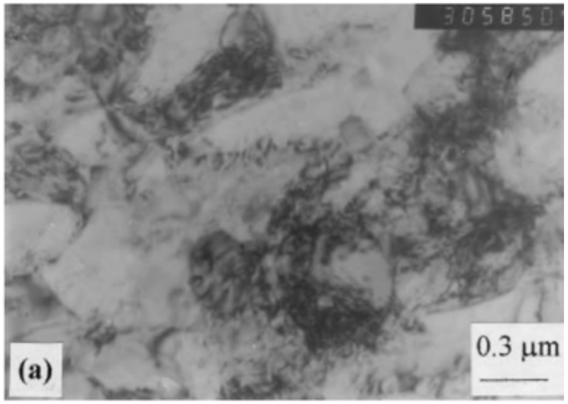
1. Thermomechanical processing by means of severe plastic deformation and static heat treatments can be used to produce a submicron grained microstructure conducive for superplasticity.

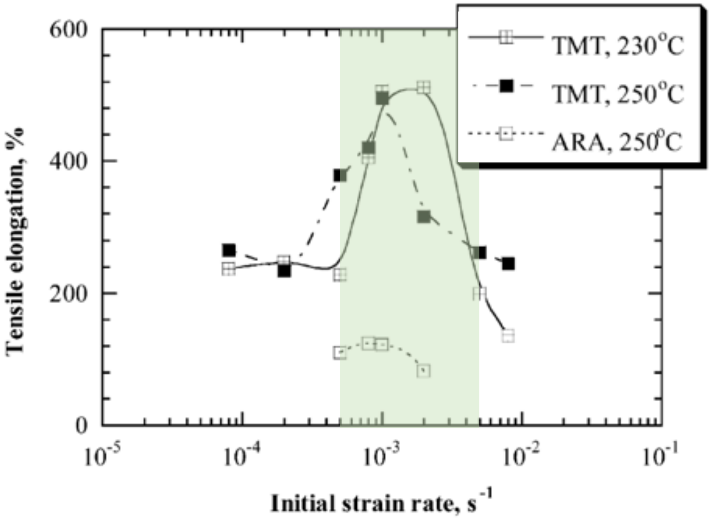
2. Deformation mechanisms (i.e. grain boundary sliding, dislocation creep) can be selectively activated in a submicron microstructure through proper selection of strain rate and deformation temperature to encourage superplastic flow.

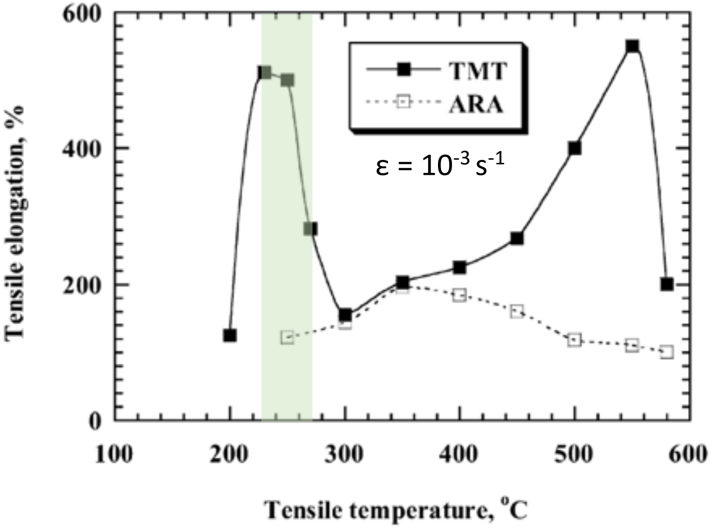
3. The combination of severe plastic deformation processing and deformation mechanism selection provides enhanced uniaxial superplastic behavior over conventionally processed material.

Literature Review

Severe warm rolling (ε=4)







200 – 300 °C
- 500 nm – 1 µm grains
- grain boundary sliding

300 – 400 °C
- 3 – 15 µm grains
- bi-modal grain size distribution
- solute drag / dislocation creep

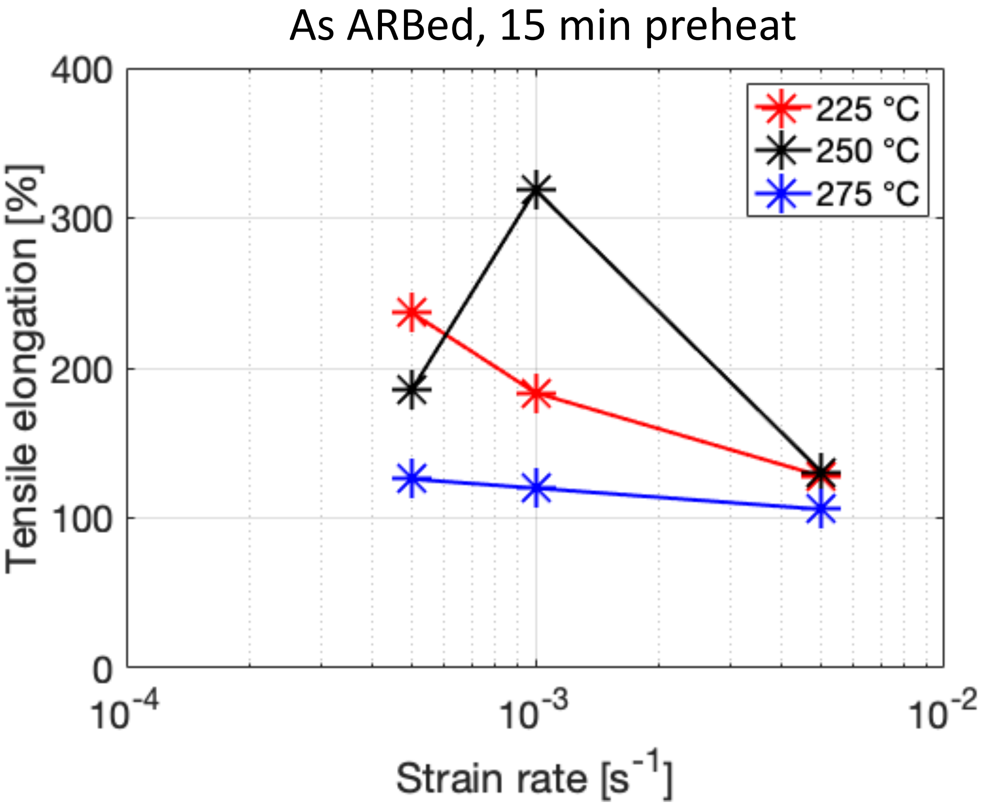
400 – 600 °C
- 8 µm grains
- grain boundary sliding

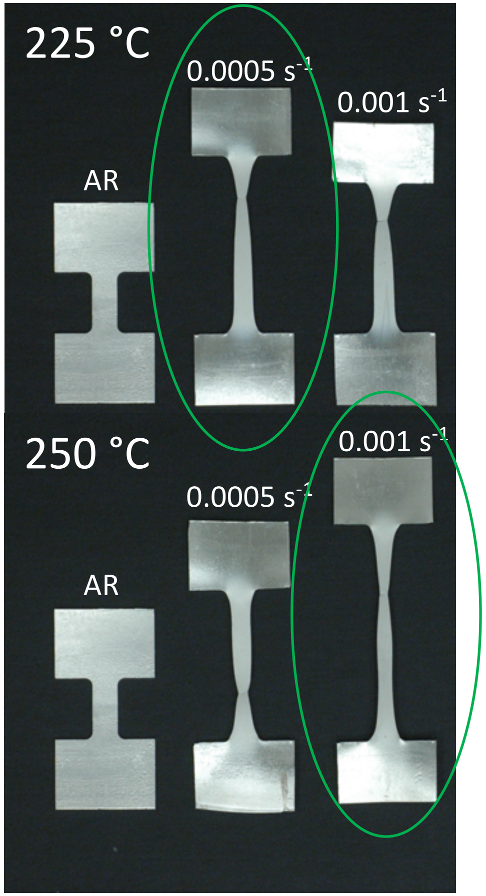
Hsiao & Huang, *Scripta Materialia*, 1999.

1st Round
of Tensile Tests

As ARBed Microstructure
15 minute Preheat

Preliminary Tensile Tests

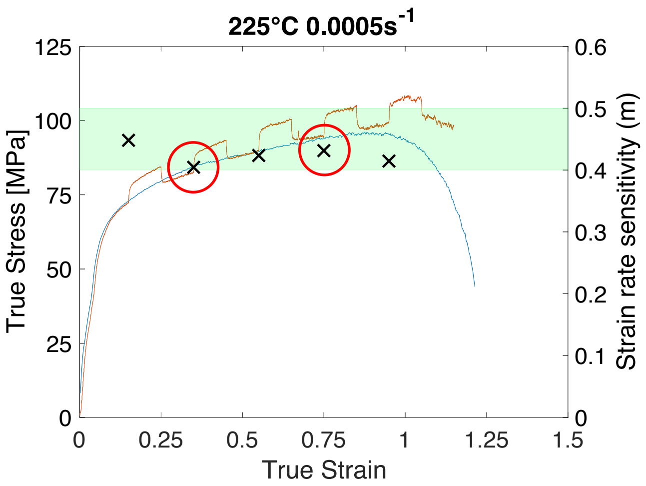


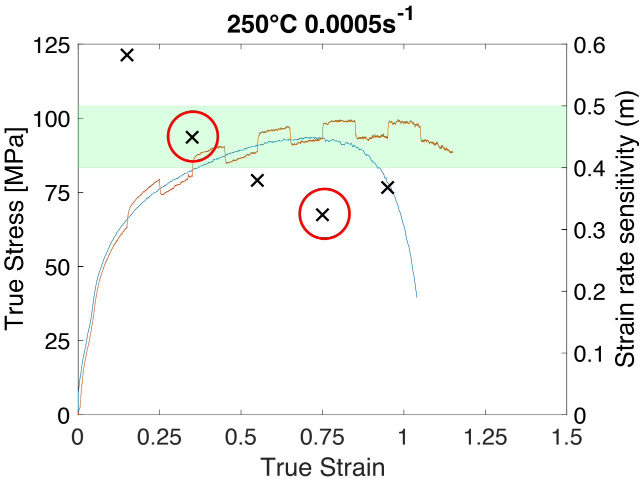


Temperatures > 250 °C, strain rates > 0.05 s^{-1} are not conducive for superplasticity

Possible competition between strain rate and microstructural evolution

Uniaxial Deformation ≤ 250 °C

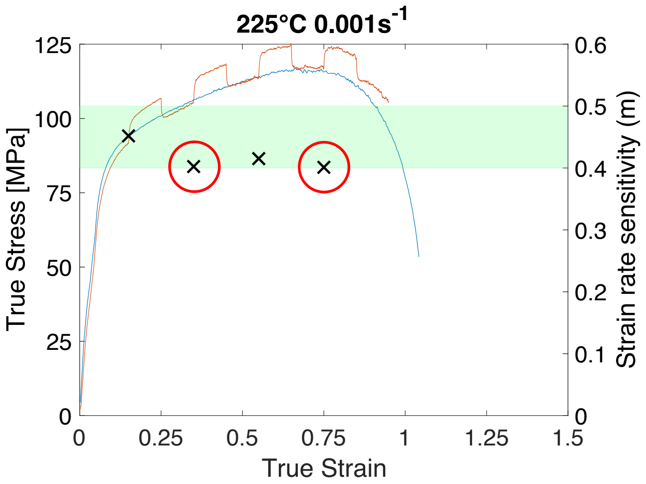


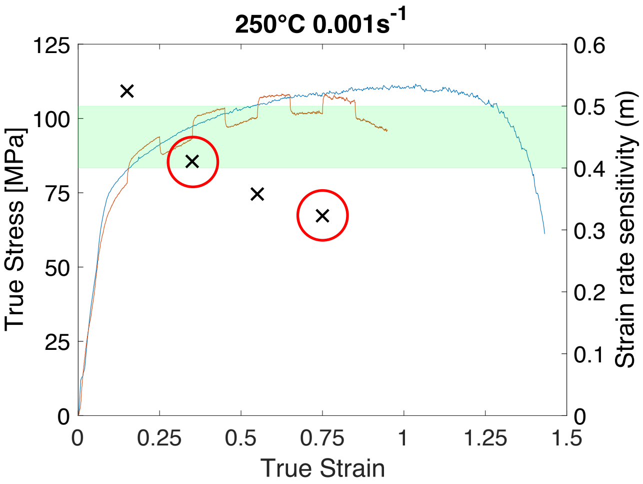


225 °C:

m ≈ 0.45

GBS stable through deformation





250 °C:

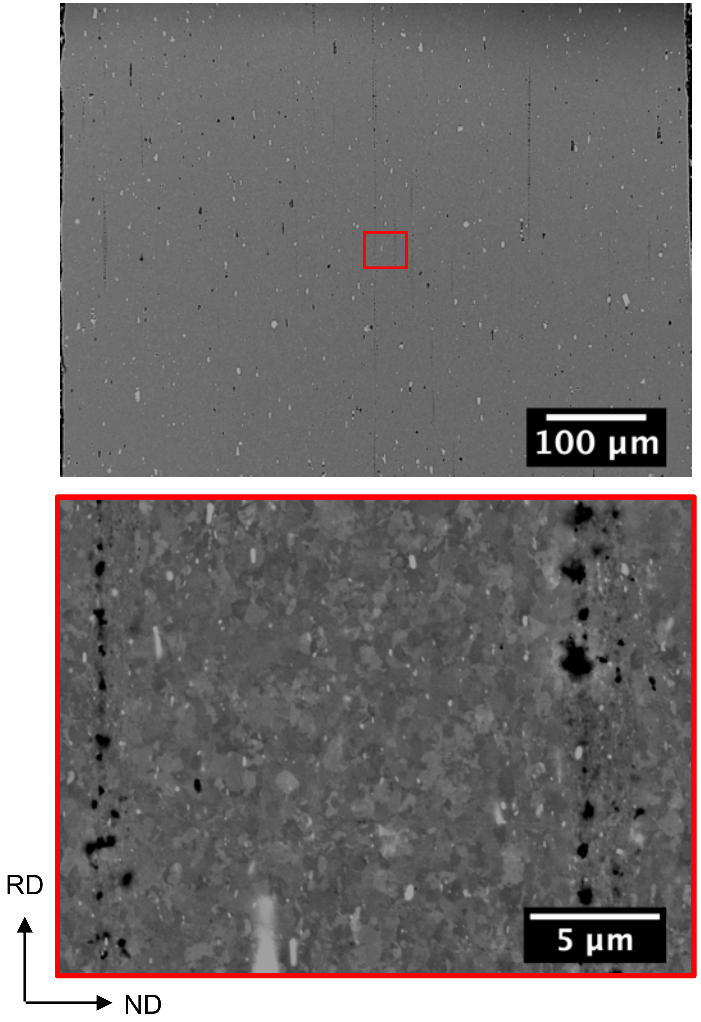
m ≈ 0.5 → 0.3

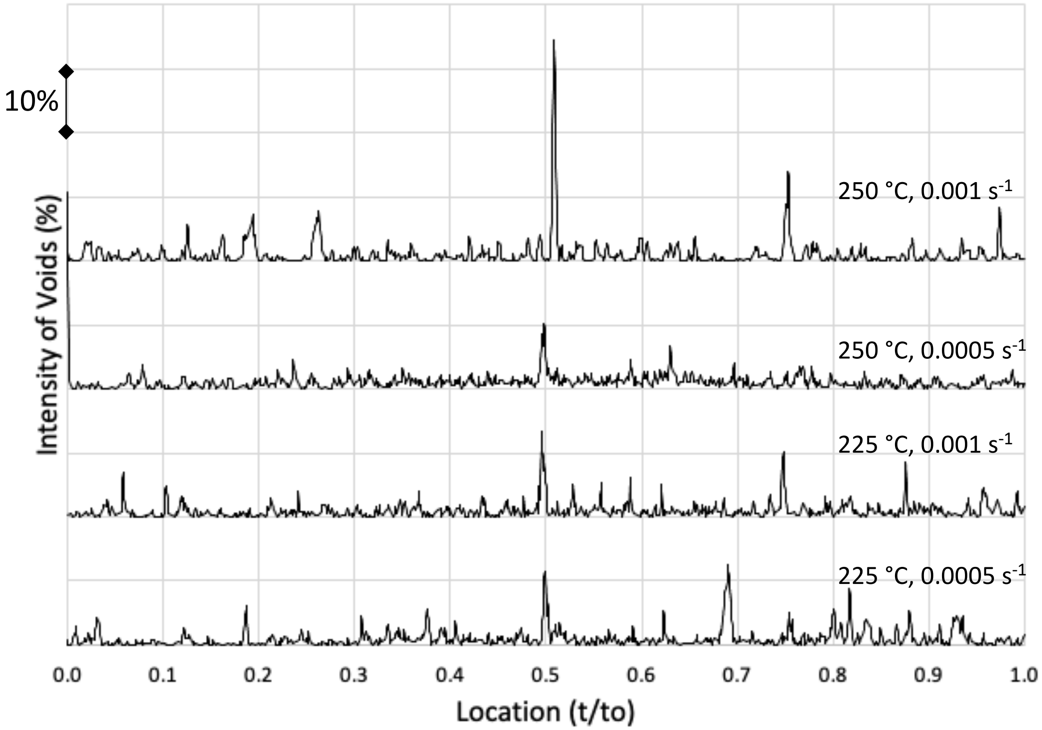
GBS transitions to dislocation creep

Pilling & Ridley, *Superplasticity in Crystalline Solids*, 1984.

Consequence of Bonding Interfaces

225 °C, 0.001 s^{-1}, strain-to-failure



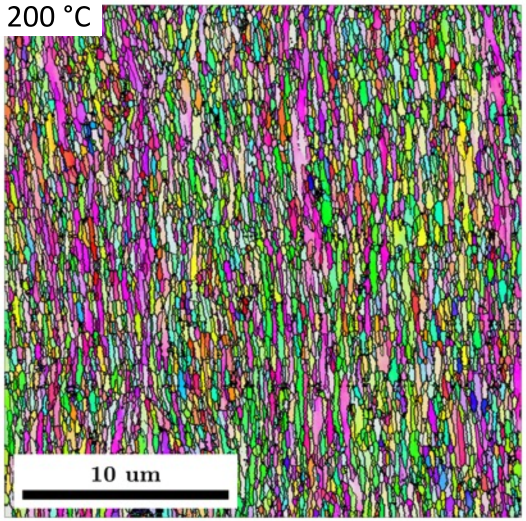


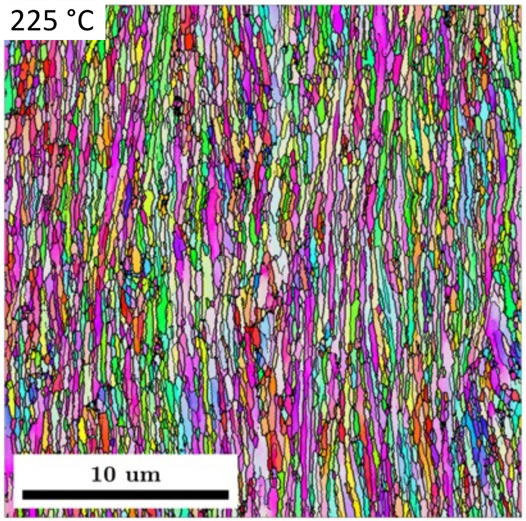
Is delamination via cavity coalesce the cause of failure?

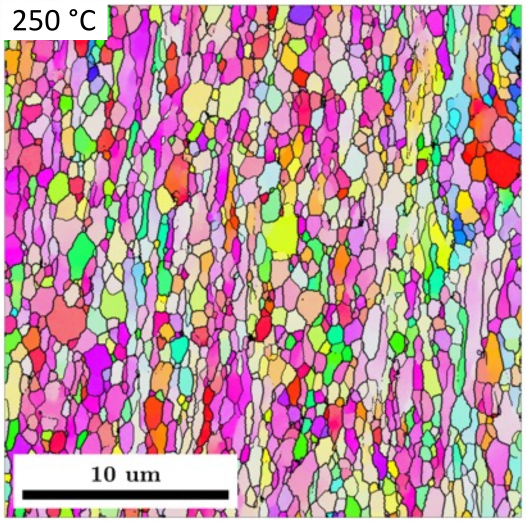
Thermal Stability of ARBed Microstructure

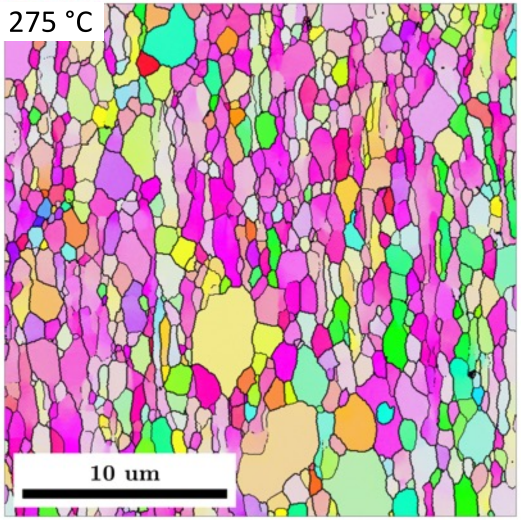
Thermal Stability

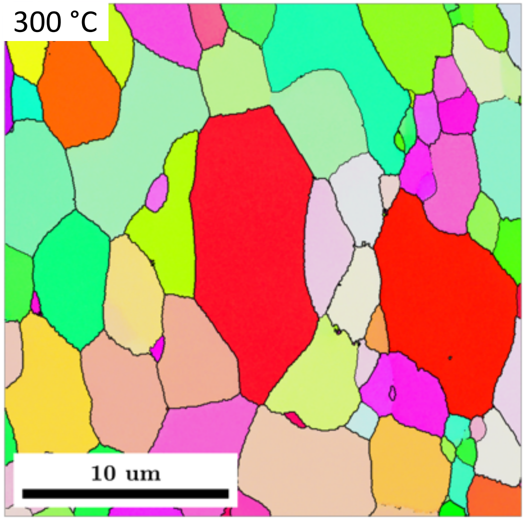
15 minute static anneal



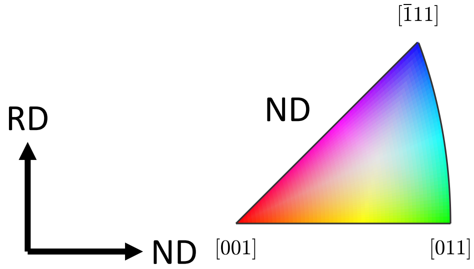






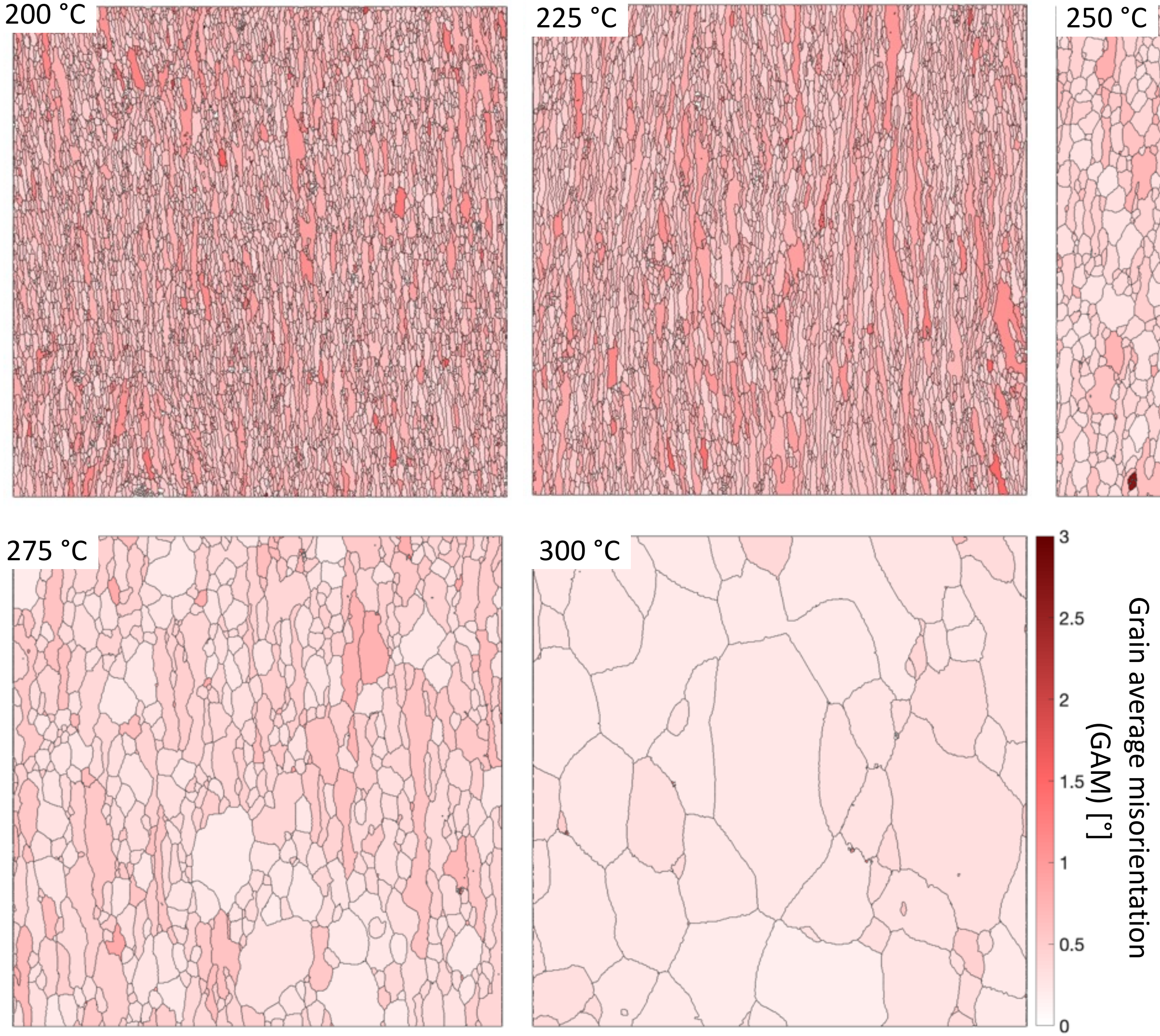


Formation of near-equiaxed grains around 250 °C

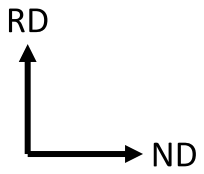


Thermal Stability

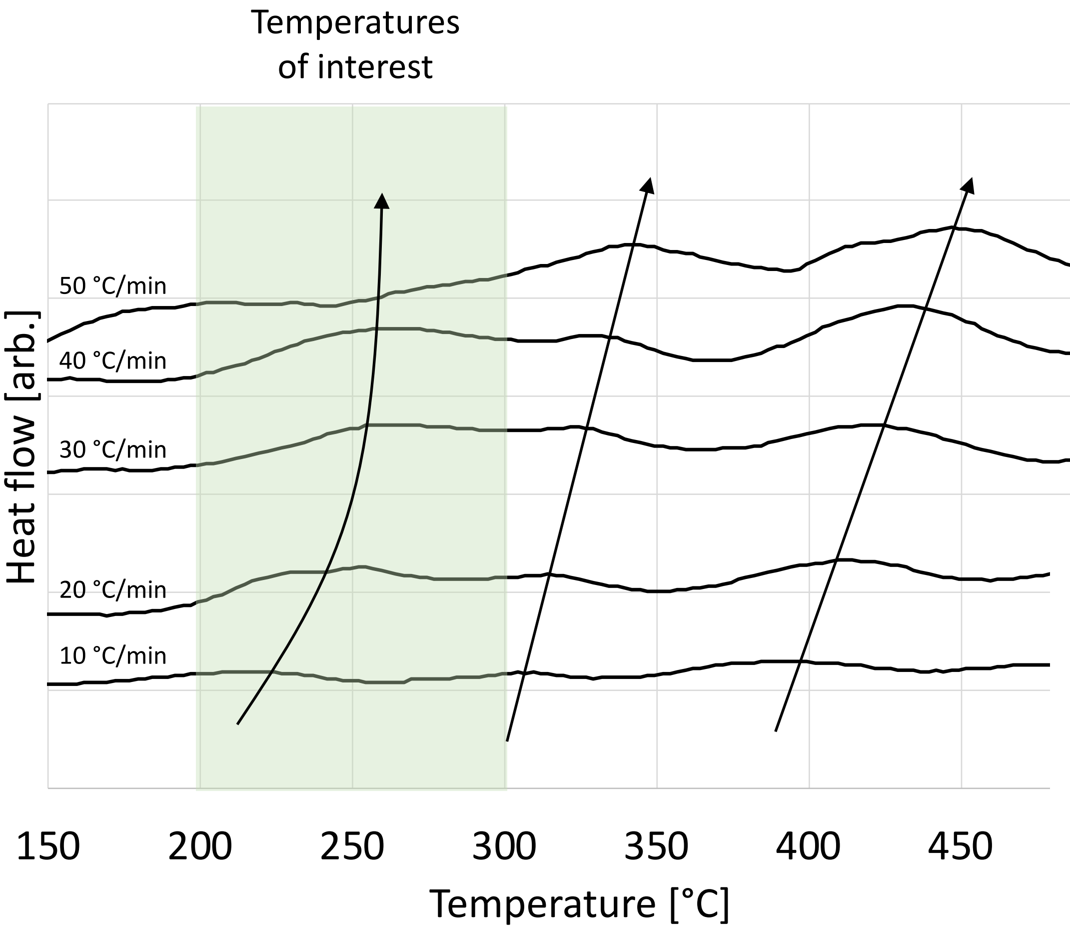
15 minute static anneal



Growth of grains
with minimal GAM
(strain energy)



Differential Scanning Calorimetry (DSC)



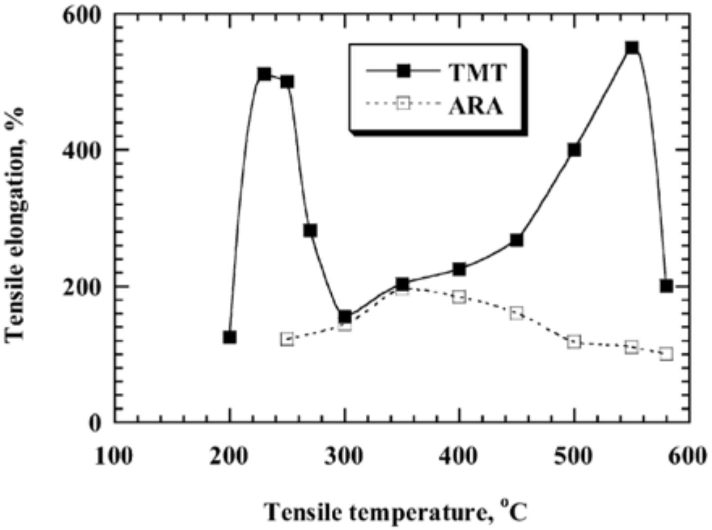
Potentially 3 peaks

≈ 250 °C

≈ 325 °C

≈ 400 °C

Separate recrystallization events?



Future Work

1. TEM investigation on interrupted strain tests ($\varepsilon = 0.35, 0.75$)
   - investigate microstructure evolution with different tensile parameters

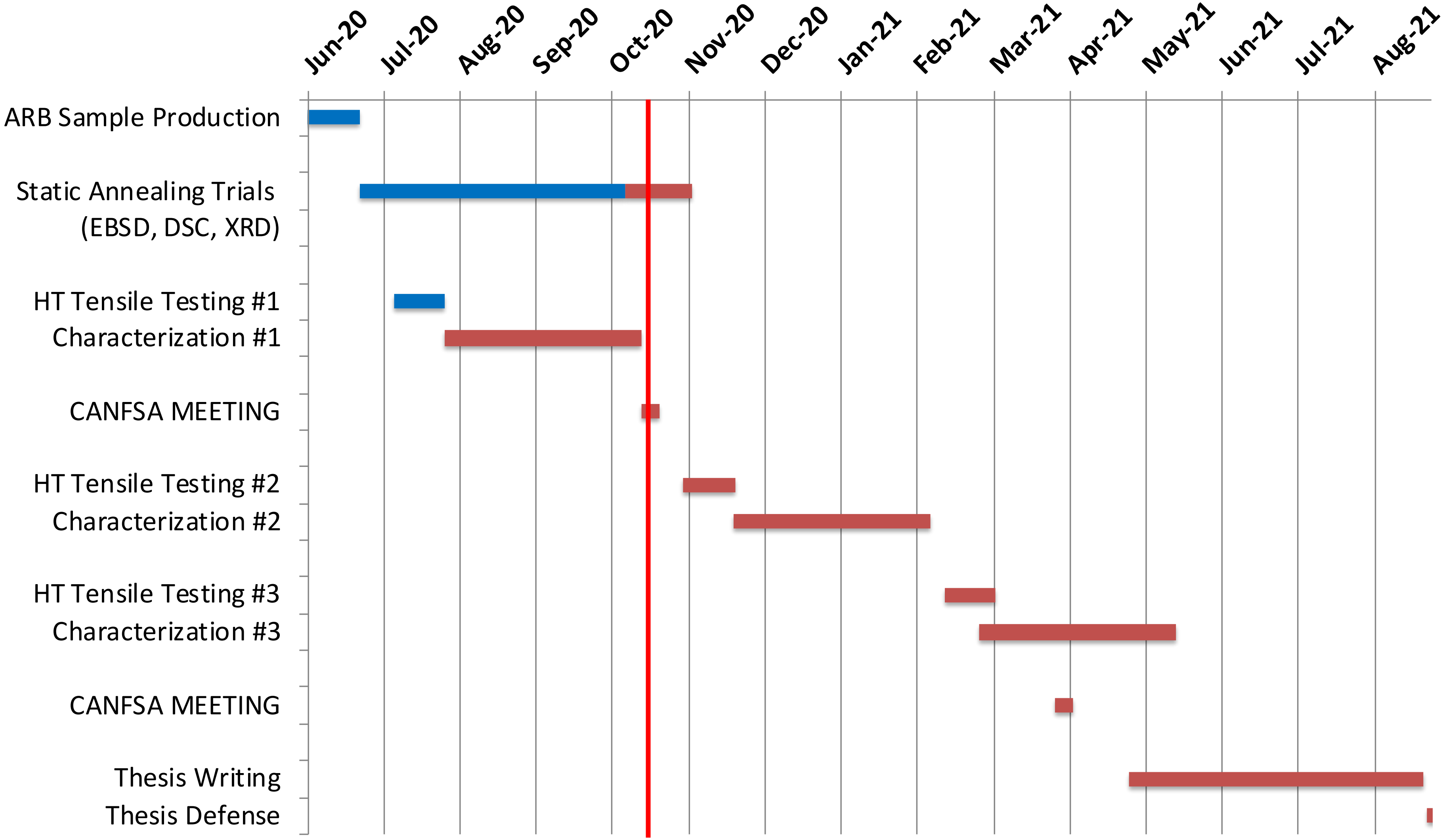
2. Continue DSC analysis
   - identify activation energies associated with exothermic peaks
   - conduct constant temperature experiments to see if peaks are associated with transport-limited or thermodynamic activation

3. XRD analysis on static annealed specimens
   - characterize textural evolution, strain and crystallize size

4. 2nd round of tensile tests
   - static anneal specimens at 250 °C, test at temperatures < 250 °C to avoid grain growth

5. Investigate cause of failure (cavitation coalescence)

Progress


Jun-20
Jul-20
Aug-20
Sep-20
Oct-20
Nov-20
Dec-20
Jan-21
Feb-21
Mar-21
Apr-21
May-21
Jun-21
Jul-21
Aug-21
ARB Sample Production
Static Annealing Trials (EBSD, DSC, XRD)
HT Tensile Testing #1
Characterization #1
CANFSA MEETING
HT Tensile Testing #2
Characterization #2
HT Tensile Testing #3
Characterization #3
CANFSA MEETING
Thesis Writing
Thesis Defense

Challenges and Opportunities

- Analysis of DSC data
  - Additional work needed to understand (3) exothermic events
- Strain measurement and necking behavior
  - Quantify accuracy of strain measurement (ASTM E2448)
  - Investigate affect of interface in void coalescence

Thank you!
Brady McBride
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References

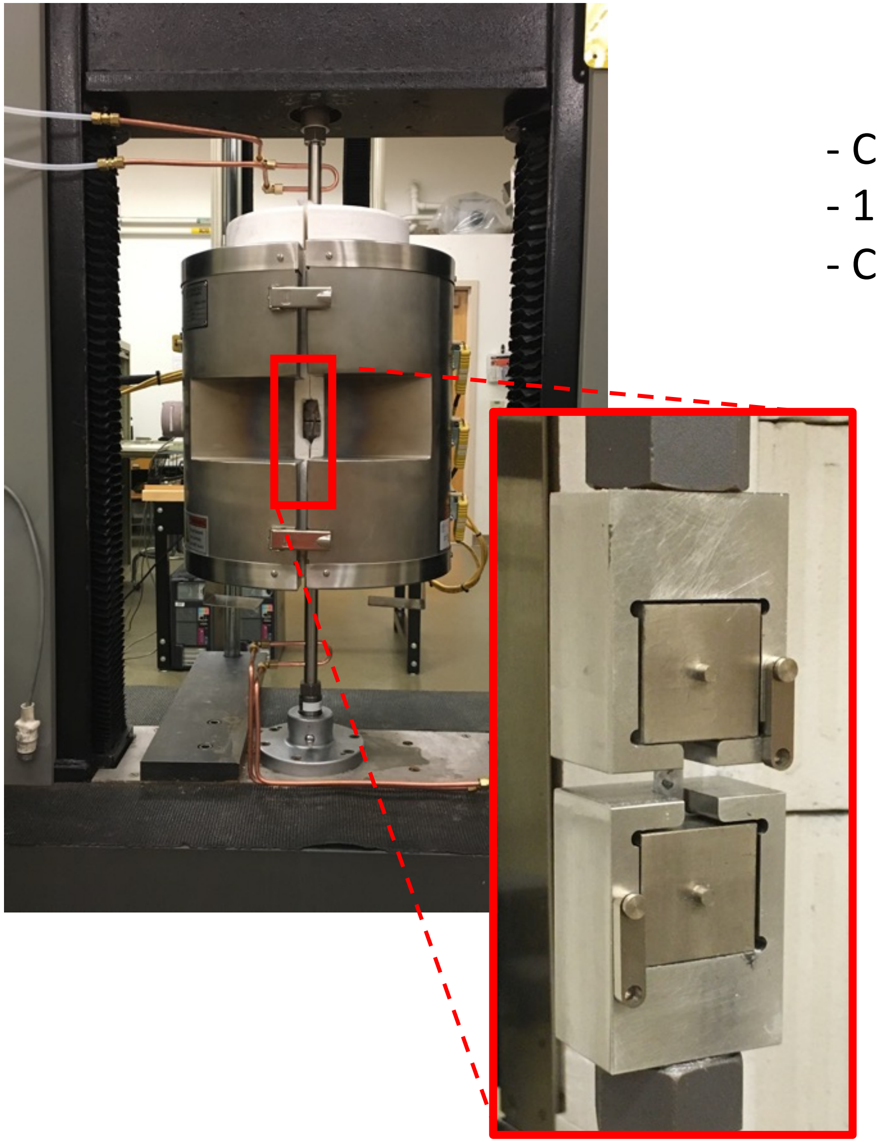
[1] Saito, Y., Utsunomiya, H., Tsuji, N. and Sakai, T., “Novel ultra-high straining process for bulk materials—development of the accumulative roll-bonding (ARB) process,” *Acta Materialia*, vol. 47, no. 2, pp. 579–583, 1999.

[2] Cleveland, R. M., Ghosh, A. K. , and Bradley, J. R., “Comparison of superplastic behavior in two 5083 aluminum alloys,” *Materials Science and Engineering A*, vol. 351, no. 1-2, pp. 228–236, 2003.

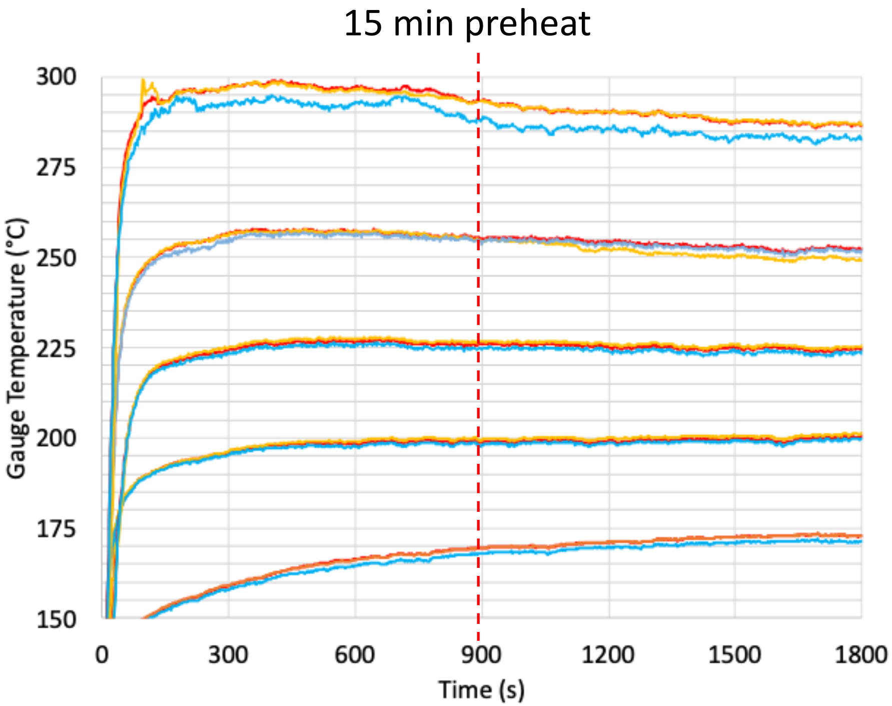
[3] Hsiao, I. C., and Huang, J.C., "Development of low temperature superplasticity in commercial 5083 Al-Mg alloys." *Scripta Materialia,* vol. 40, no. 6, pp. 697-703, 1999.

[4] Pilling, J. and Ridley, N., *Superplasticity in crystalline solids*, The Institute of Materials, London, 1984.

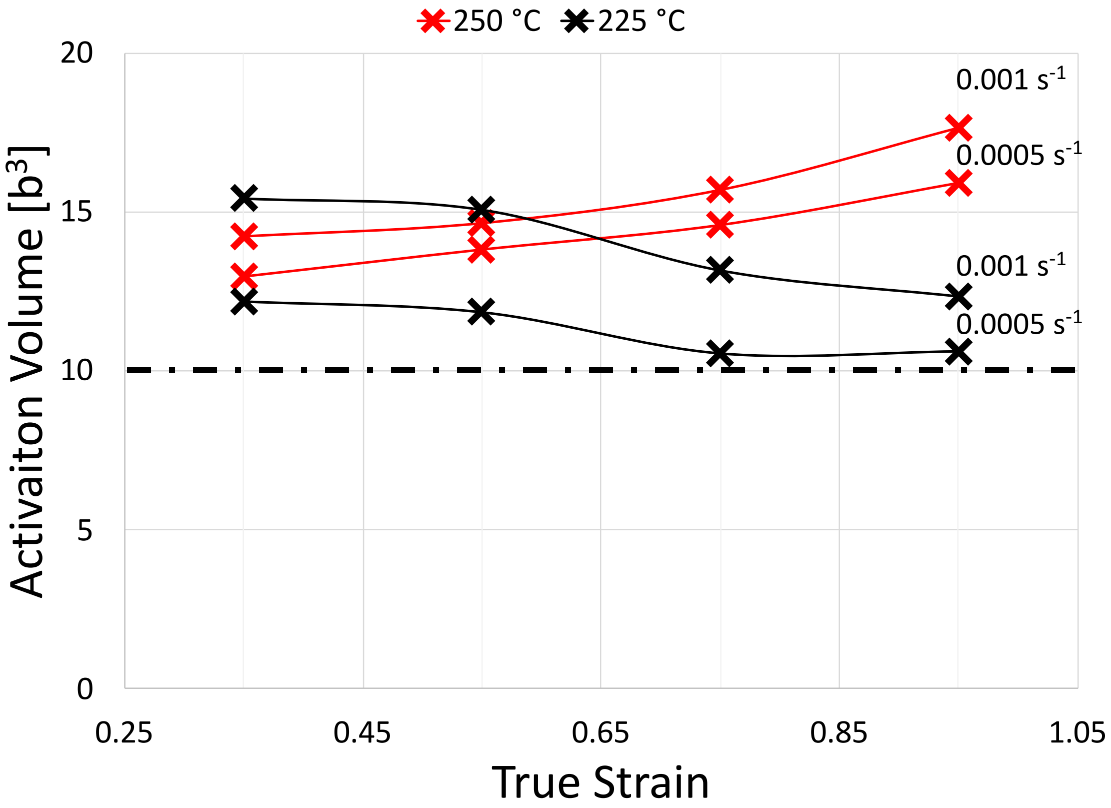
Tensile Testing Setup



- Constant strain rate (variable crosshead speed)
- 15 minute preheat prior to start
- Crosshead taken as elongation (ASTM E2448)



Uniaxial Deformation ≤ 250 °C



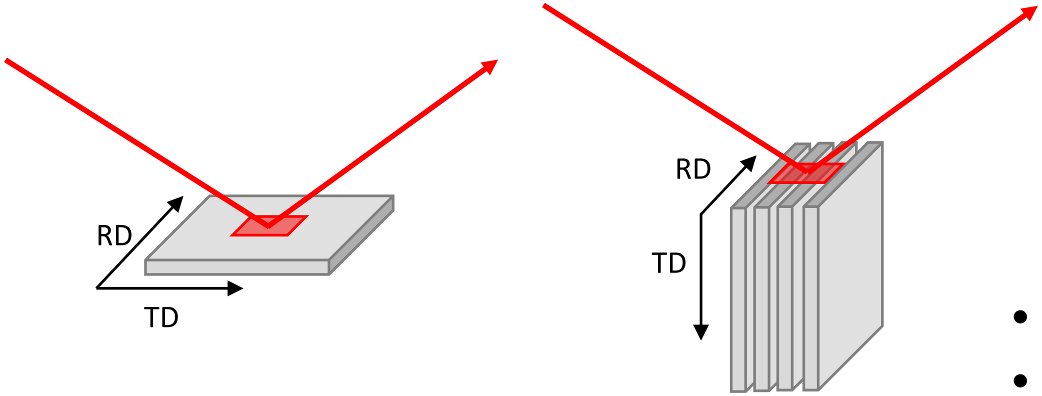
$$v = \frac{\sqrt{3}kT}{\sigma m}$$

<u>225 °C:</u>
m ≈ 0.45
GBS stable through deformation

<u>250 °C:</u>
m ≈ 0.5 → 0.3
GBS transitions to dislocation creep

Pilling & Ridley, *Superplasticity in Crystalline Solids*, 1984.

X-ray Diffraction Analysis



Difficulties analyzing through-thickness variation.

<u>Proposed characterization</u>

Static annealing (200 – 300 °C):

- texture evolution
- Williamson-Hall (strain vs crystallite)