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

Semi-annual Fall Meeting

October 2021

- Student: Brady McBride (Mines)
- Faculty: Dr. Kester Clarke (Mines)
- Industrial Mentors: John Carpenter (LANL), Eric Payton (AFRL)

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

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

Project Duration

PhD: September 2017 to December 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

- Identified temperature and strain rate limits for stable grain boundary sliding
- Quantified strain uniformity and cavitation damage during uniaxial superplasticity testing
- Completed biaxial bulge formability tests for two down-selected conditions based on uniaxial test results

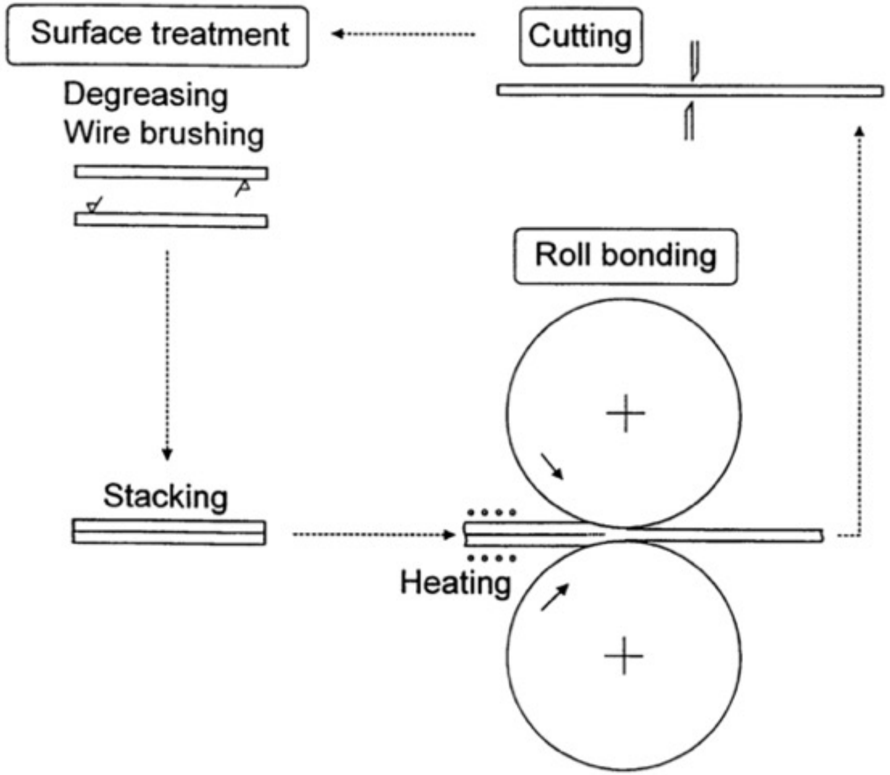
Metrics

Description	% Complete	Status
1. Develop ARB process with mitigated edge cracking	100%	●
2. Identify optimal conditions for low temperature superplasticity through tensile testing	100%	●
3. Characterize microstructure evolution with ARB processing and tensile deformation	100%	●
4. Formalize limits for low temperature superplasticity based on kinetics of deformation	75%	●
5. Characterize small-scale formability testing specimens	0%	●

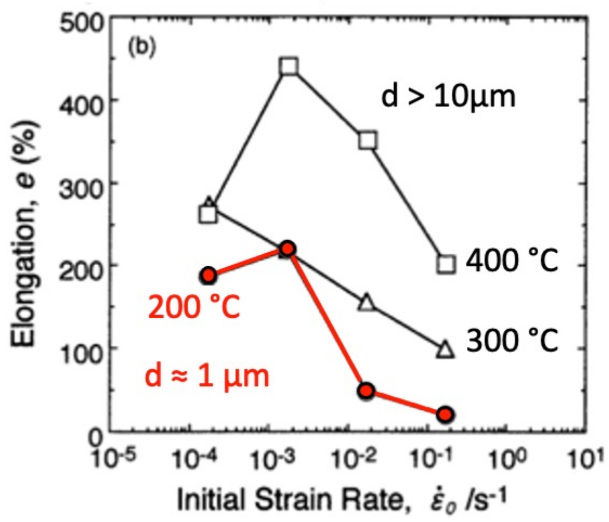
Agenda

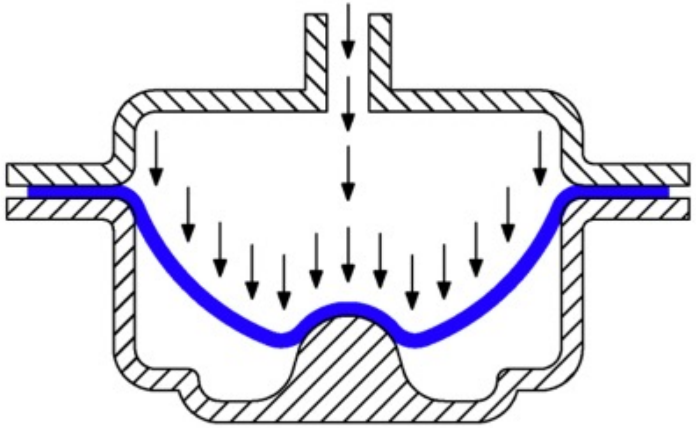
- Project introduction
- Microstructural evolution prior to tensile testing
  - Grain refinement
  - Continuous recrystallization
- Tensile testing for superplasticity
  - Identifying optimal parameters
- Characterization of optimal conditions (225 °C, $0.0005\ s^{-1}$ and 250 °C, $0.001\ s^{-1}$)
  - Microstructural evolution
  - Strain uniformity
  - Cavitation damage
- Biaxial formability testing
- Future work

Industrial Relevance



After 5 ARB cycles of AA 5083:





Enhanced properties:

- Hall-Petch strengthening
- low temperature superplasticity for sheet forming operations

Potential forming benefits:

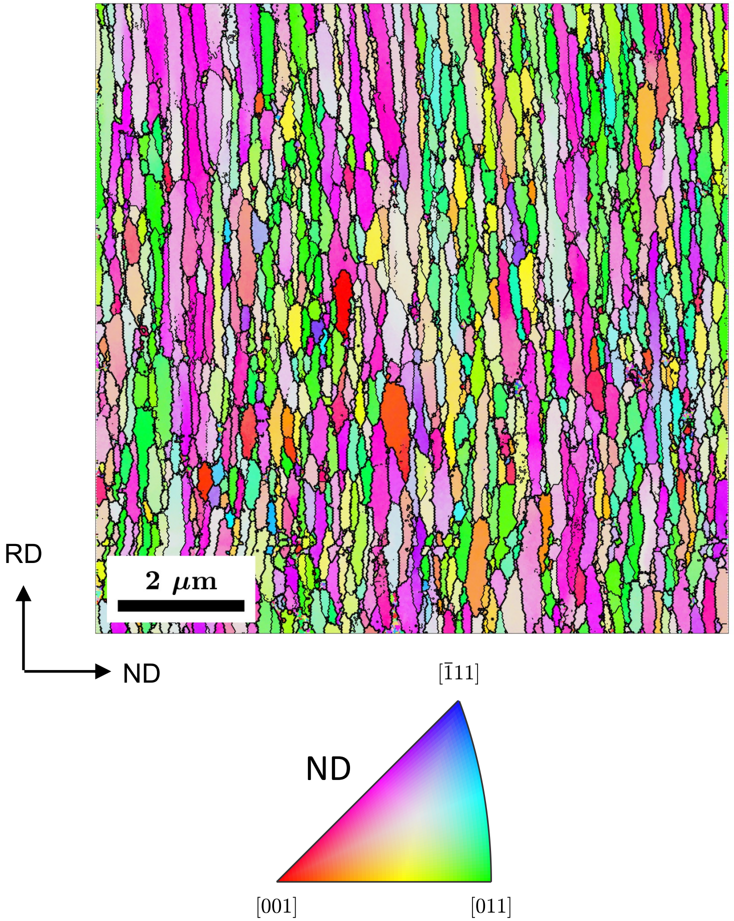
- reduced operating temperature
- reduced cycle time
- reduced operating costs
- increased final part strength

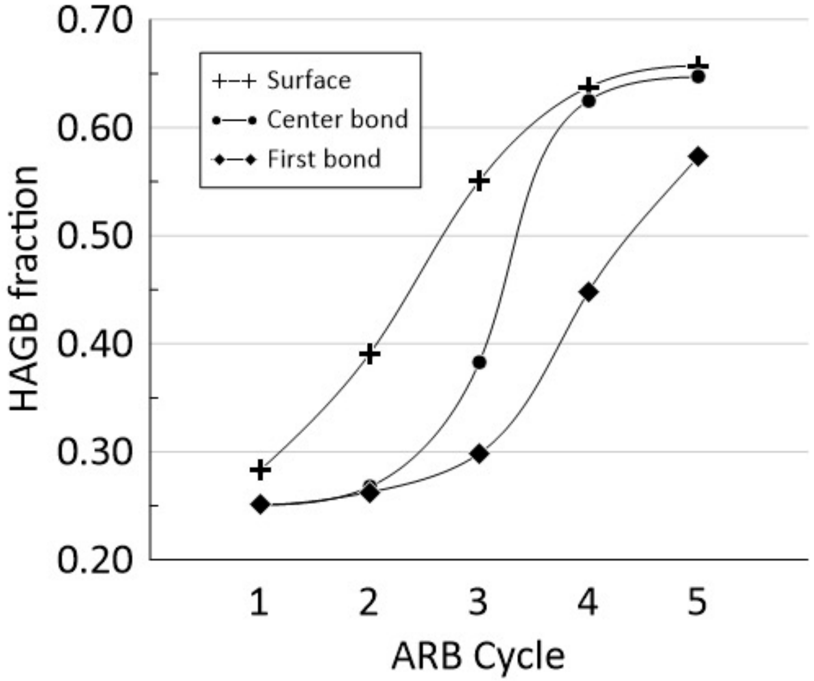
Tsuji et al., *Acta Materialia*, 1999.
Abu-Farha et al., *Int'l Journal of Sustainable Manufacturing, 2008*.

Microstructural Evolution Prior to Tensile Testing

Grain Refinement through Accumulative Roll Bonding

Mid-thickness grain morphology
after 5 ARB cycles





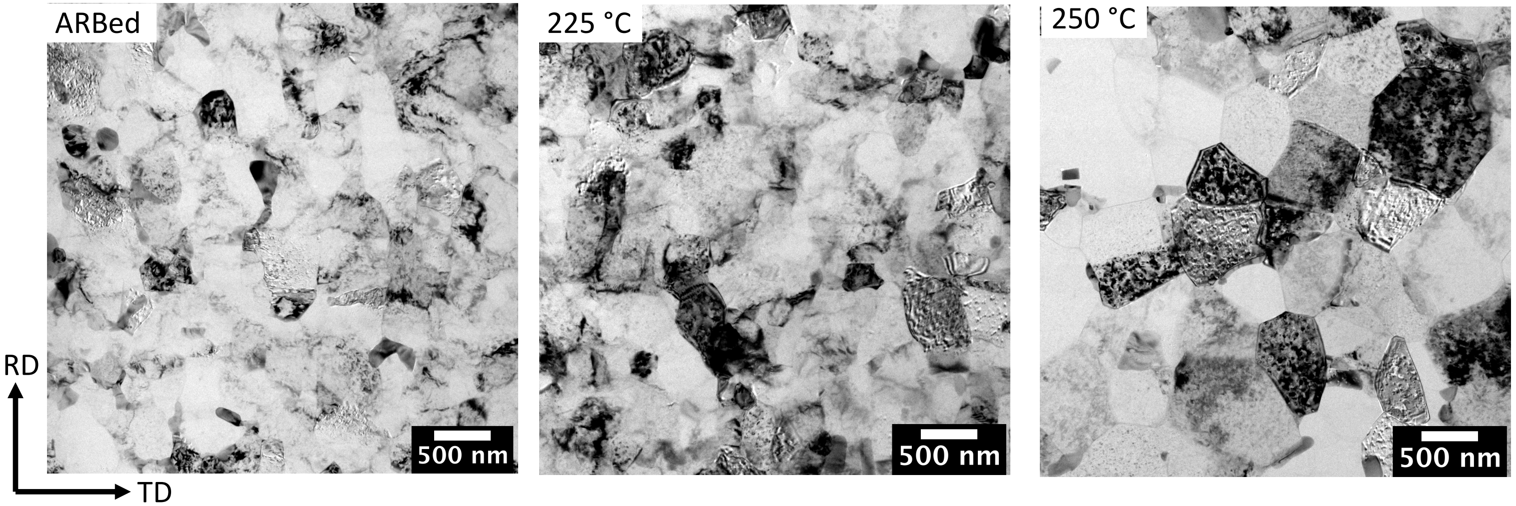
HABG fraction, grain size saturates after 5 cycles

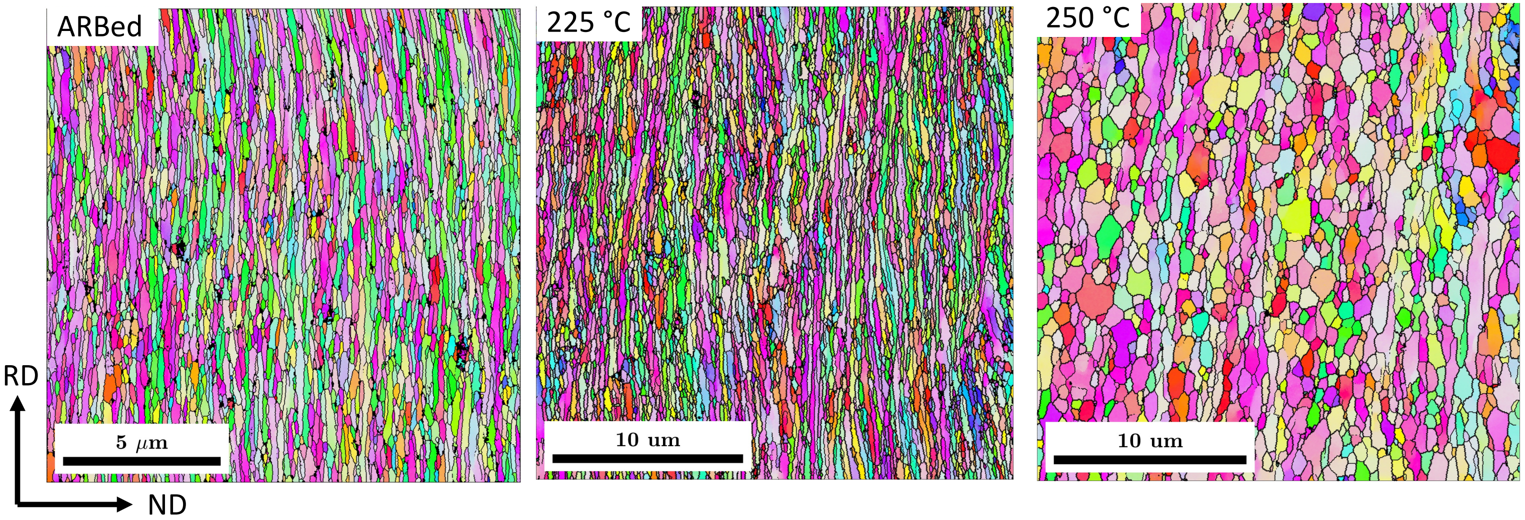
Average grain size:	243 nm x 66 nm
Average aspect ratio:	3.7
High angle grain boundary:	≈60 %

in-situ recrystallization during processing leads to refined microstructure with with high HAGB fraction

Continuous Static Recrystallization

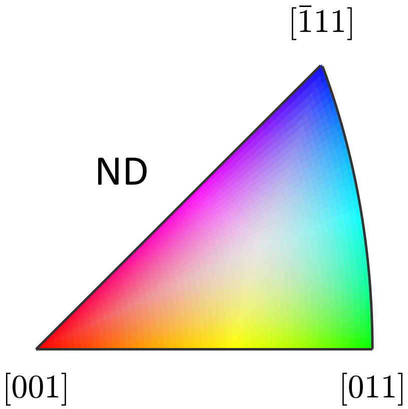
15 minute static anneal treatments





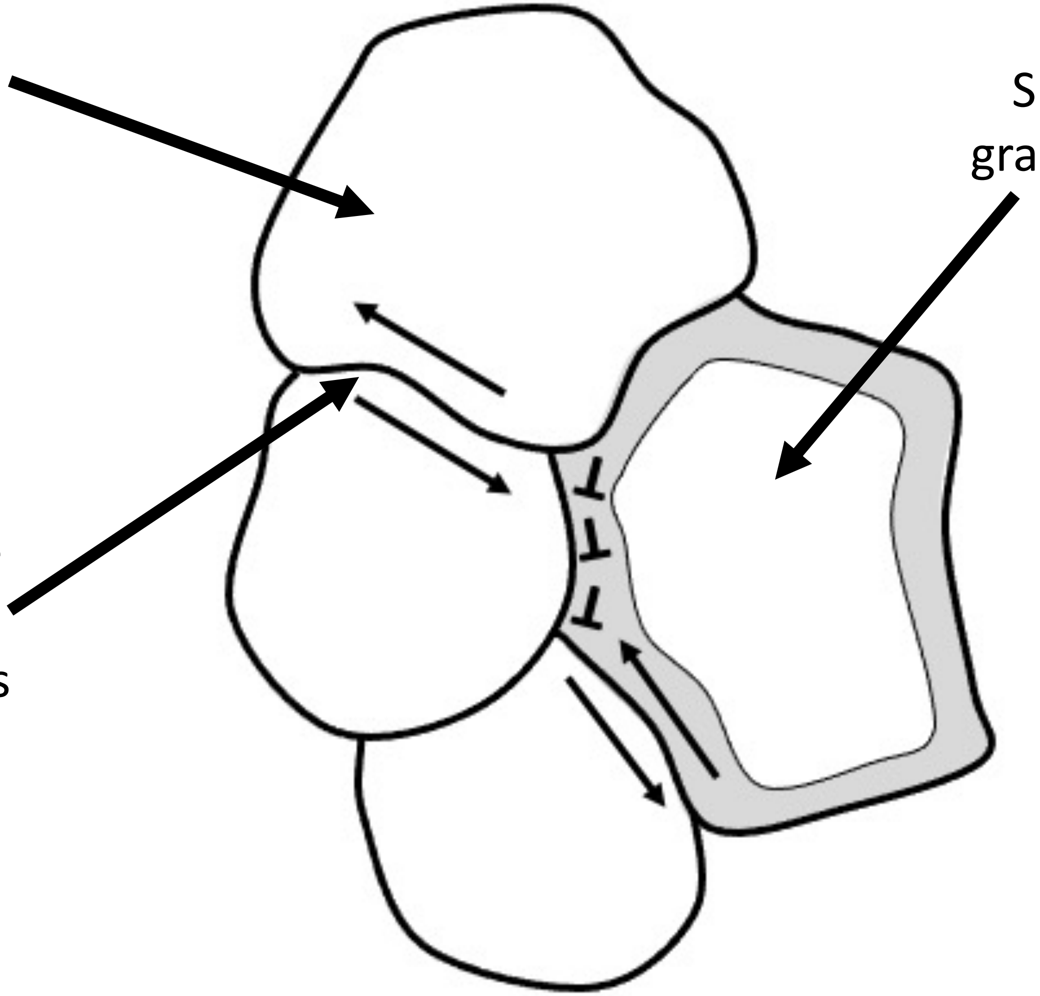
Continuous recrystallization between 225 and 250 °C

Significant grain growth above 250 °C



Identifying Optimal Parameters for Low Temperature Superplasticity

Requirements for Superplasticity: Grain Boundary Sliding



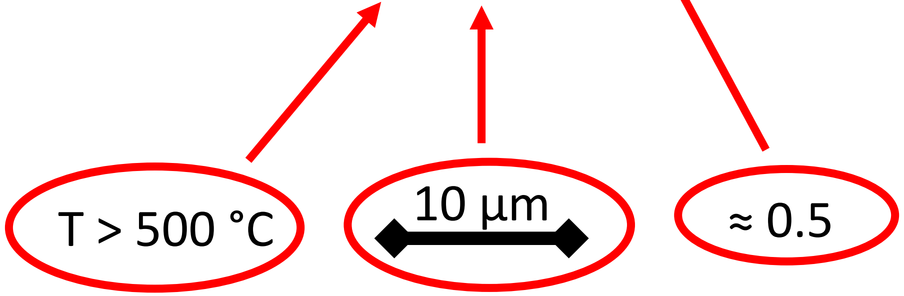
Near equiaxed grains

Small grain size

High angle grain boundaries

Convention superplasticity in AA 5083

$$\dot{\varepsilon} = A\frac{DGb}{kT}\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{\frac{1}{m}}$$

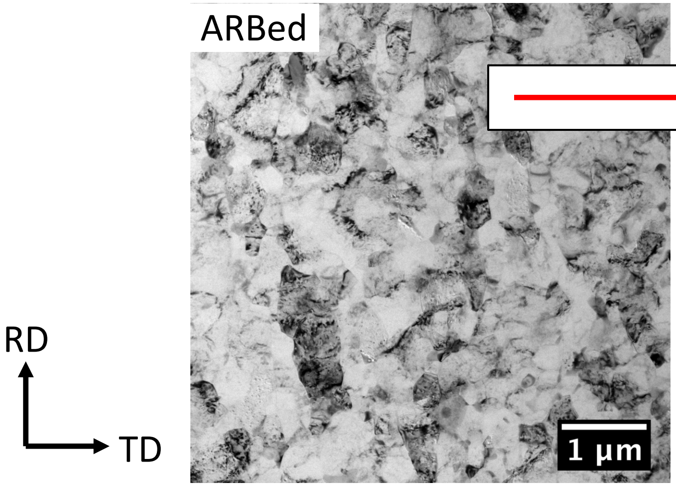


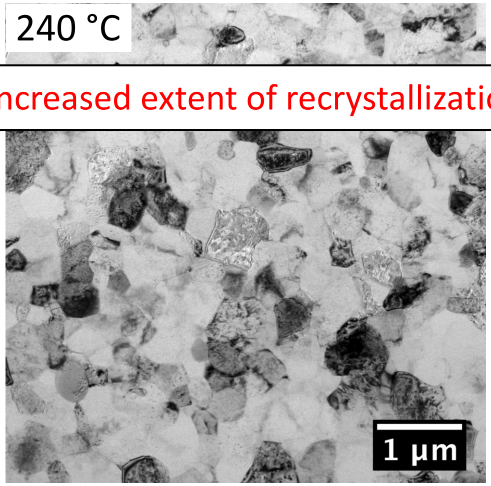
T > 500 °C

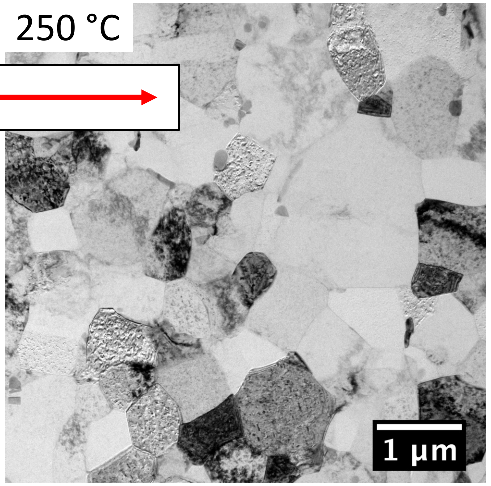
10 µm

≈ 0.5

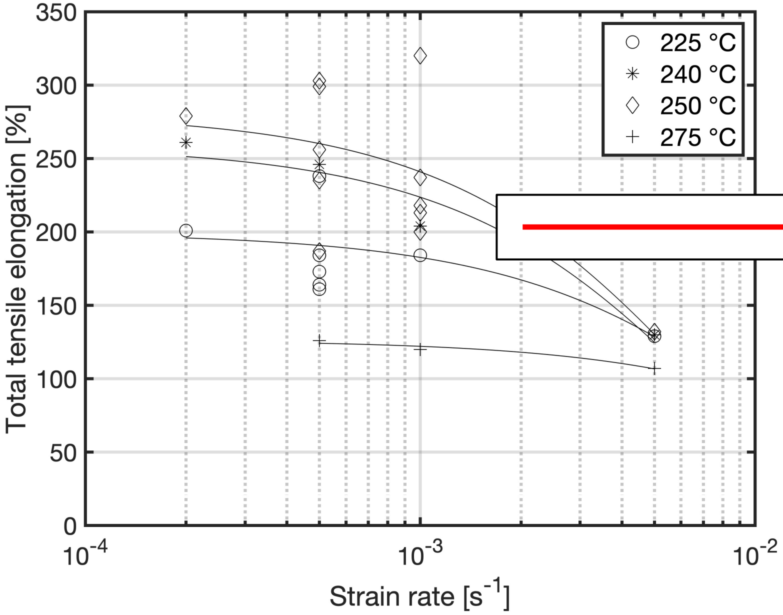
Effect of Partial Recrystallization on Low Temperature Superplasticity

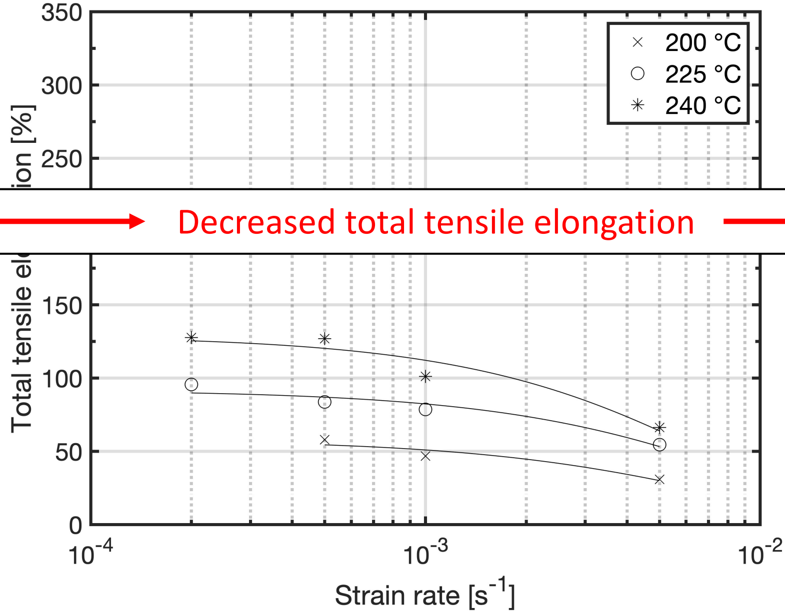


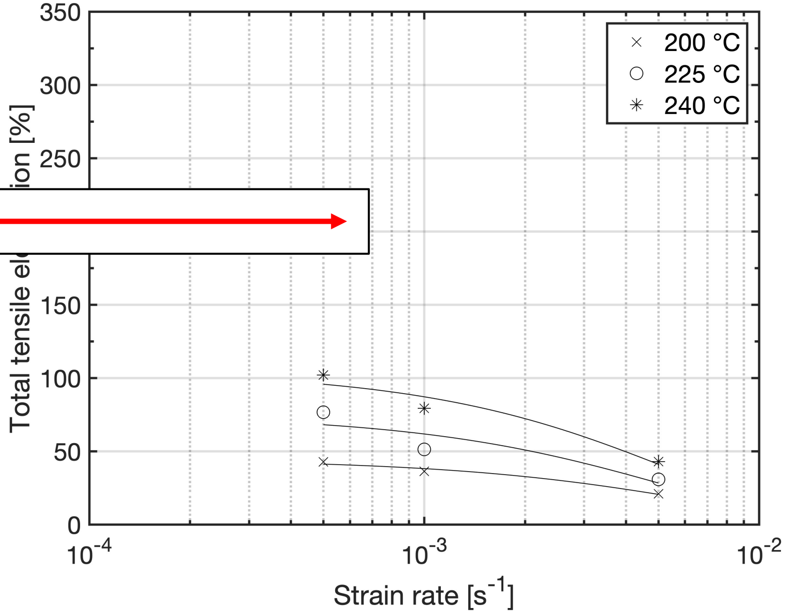




Increased extent of recrystallization

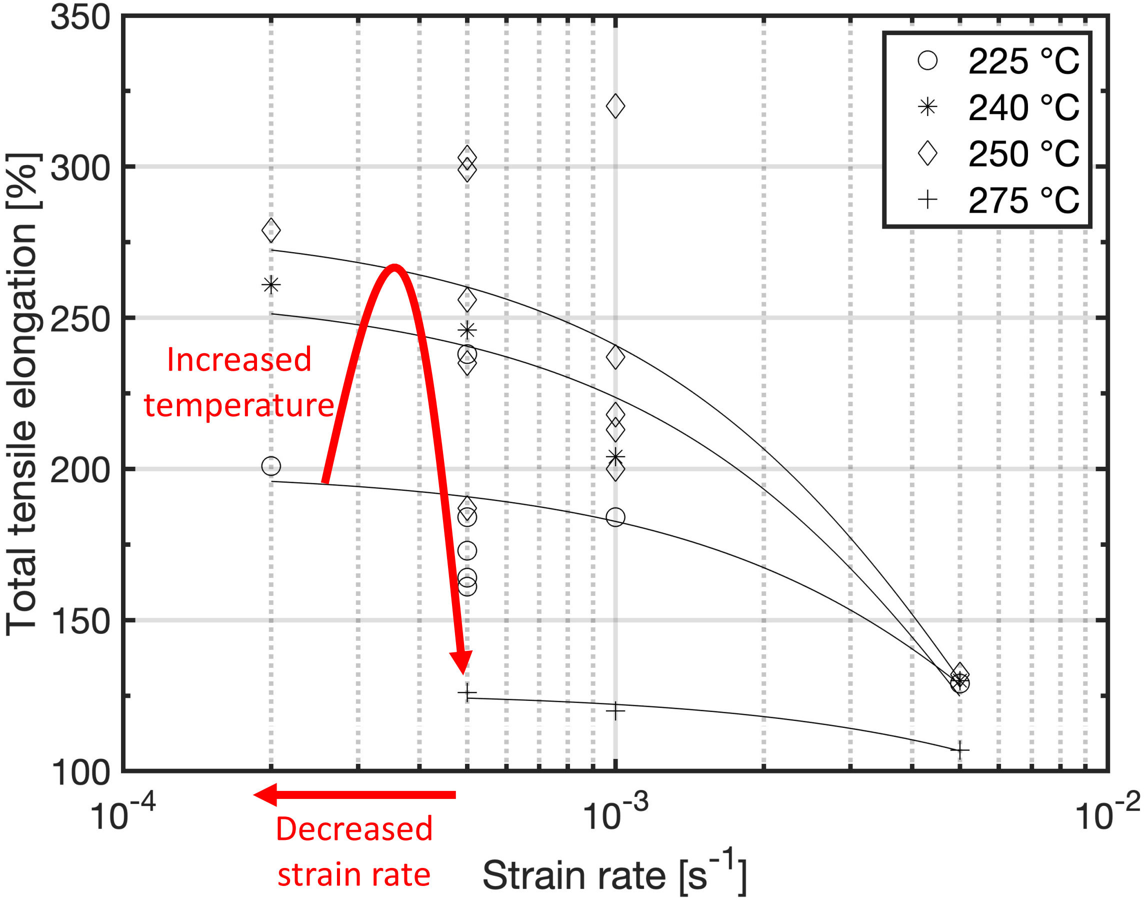


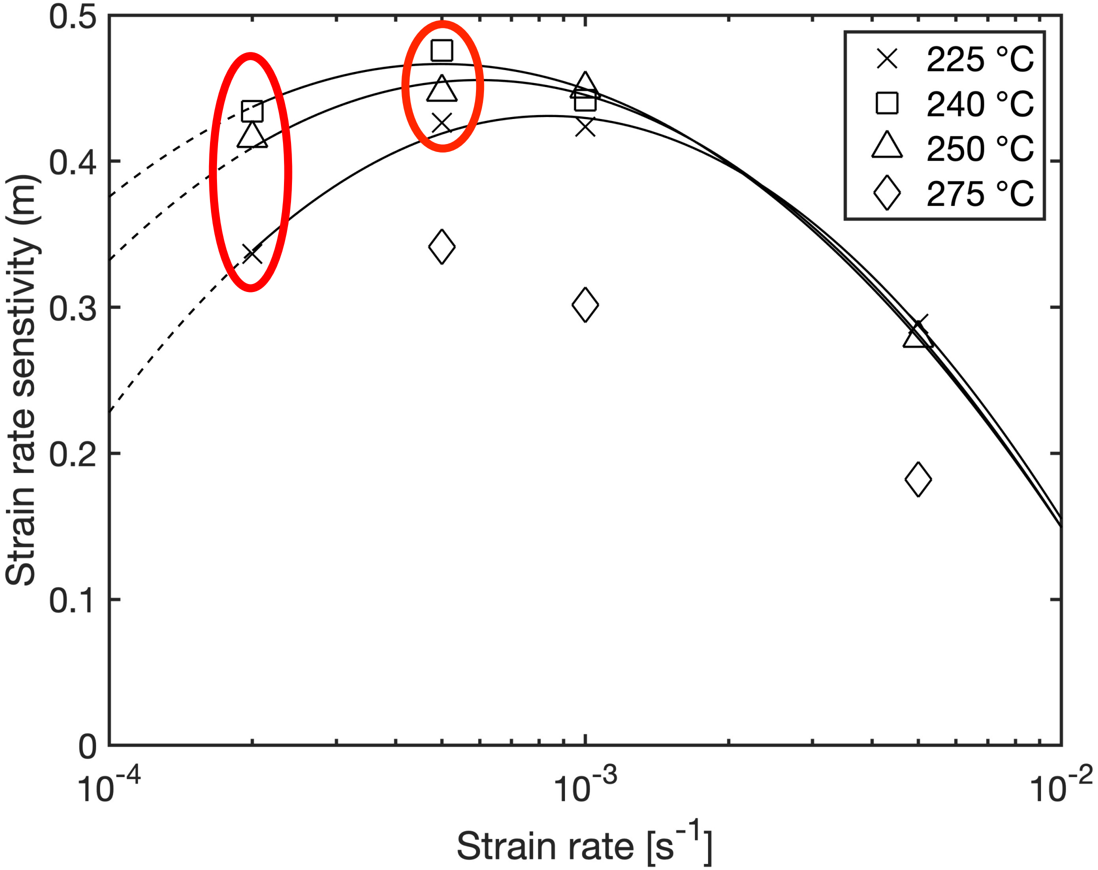




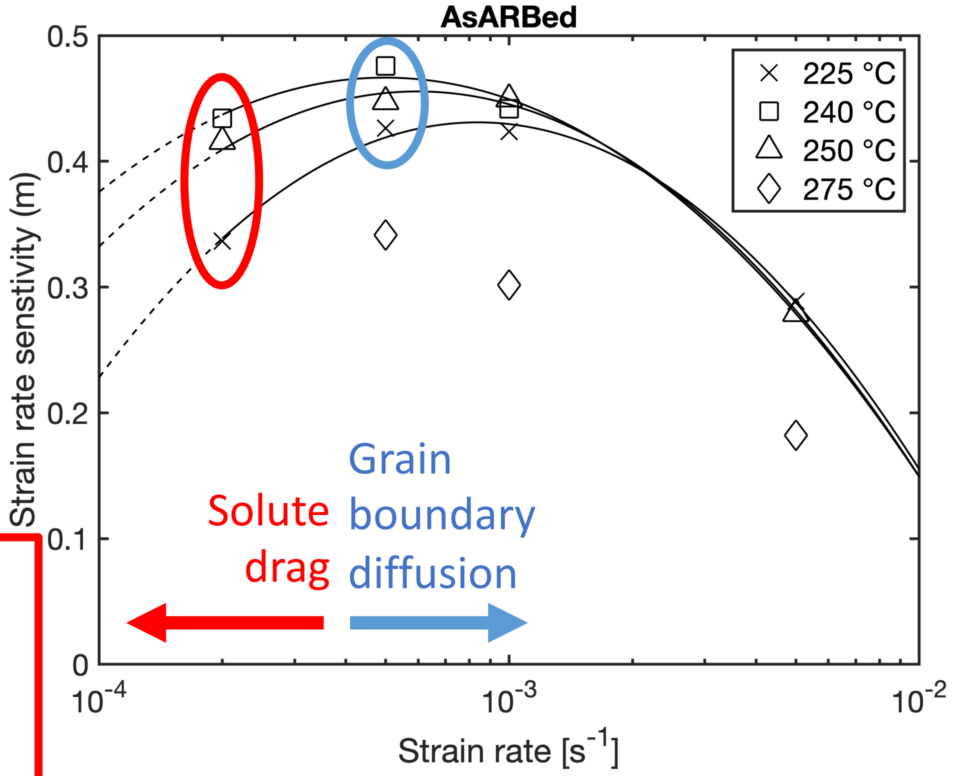
Decreased total tensile elongation

Optimal Parameters for Low Temperature Superplasticity





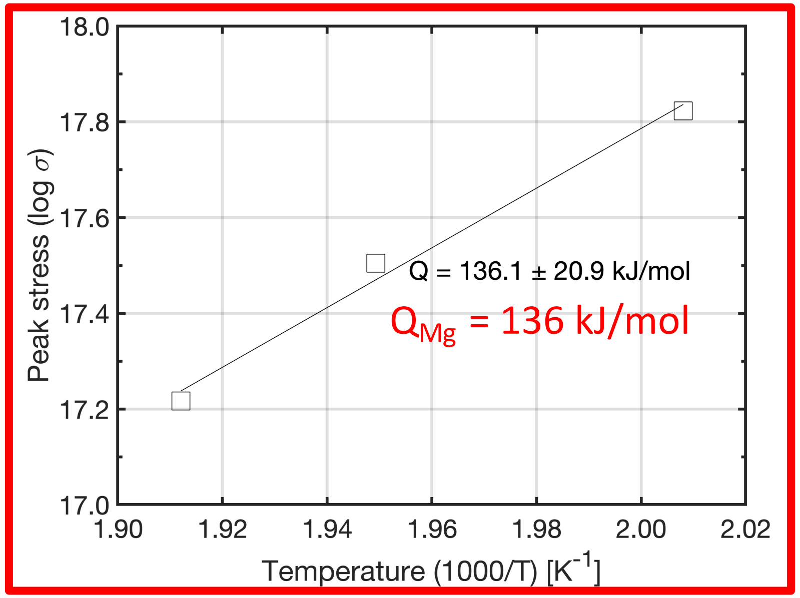
Identifying Strain Rate and Temperature Limits



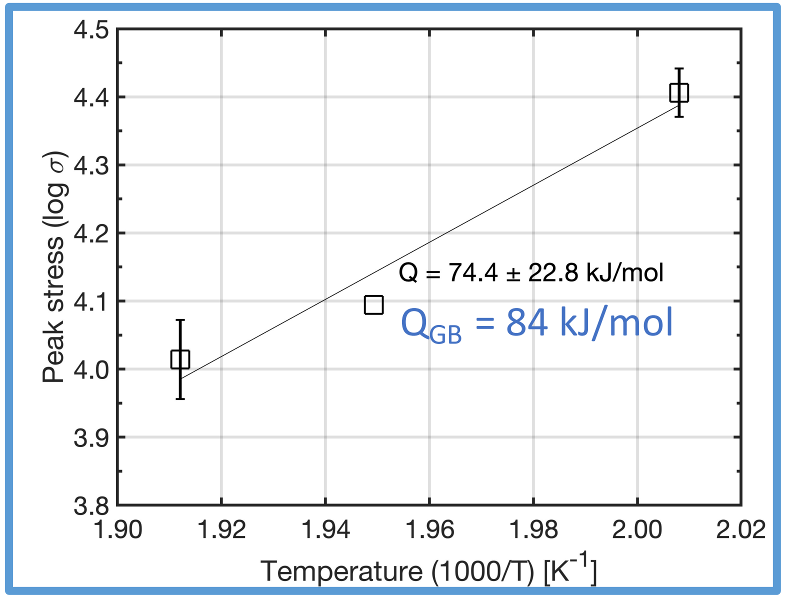
Activation energy for deformation

$$Q = \frac{k}{m}\frac{\delta \ln \sigma}{\delta 1/T}\bigg|_{\varepsilon,\dot{\varepsilon},d}$$

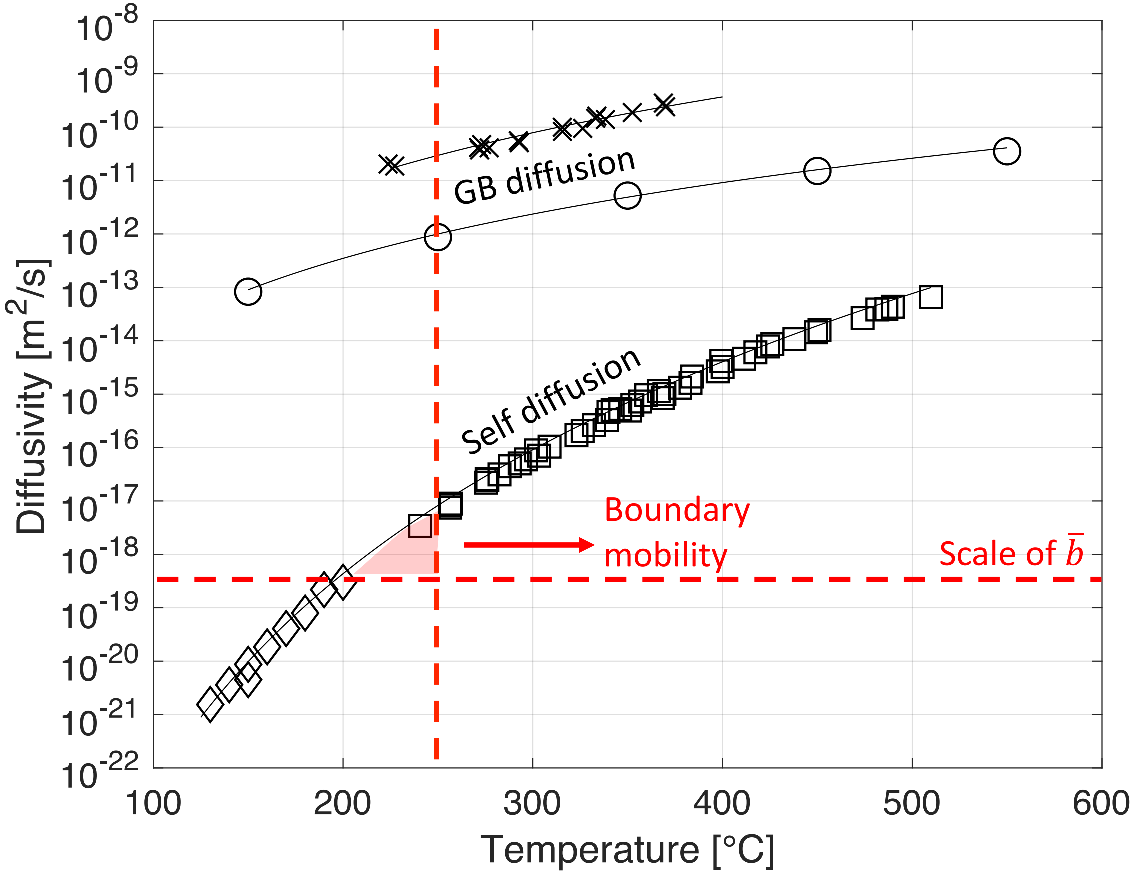
< 0.0005 s^{-1}
Solute drag limited



> 0.0005 s^{-1}
Grain boundary diffusion limited



Kinetics of Deformation Mechanisms



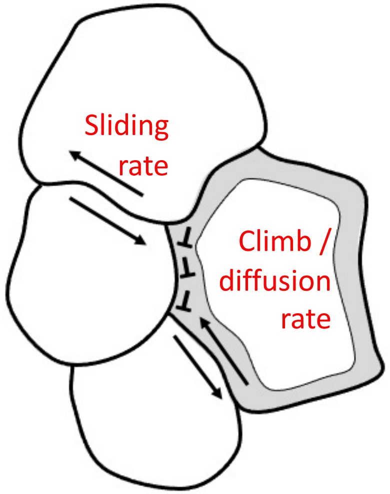
T ≥ 250 °C

Grain growth hinders grain boundary sliding

225 ≥ T ≥ 250 °C

Gifkin's predicted strain rate:

$$\dot{\varepsilon} = A \frac{D_{Gb}}{kT} \left(\frac{b}{d}\right)^{\frac{1}{m}} \left(\frac{\sigma^2}{G}\right)$$



T ≤ 225 °C

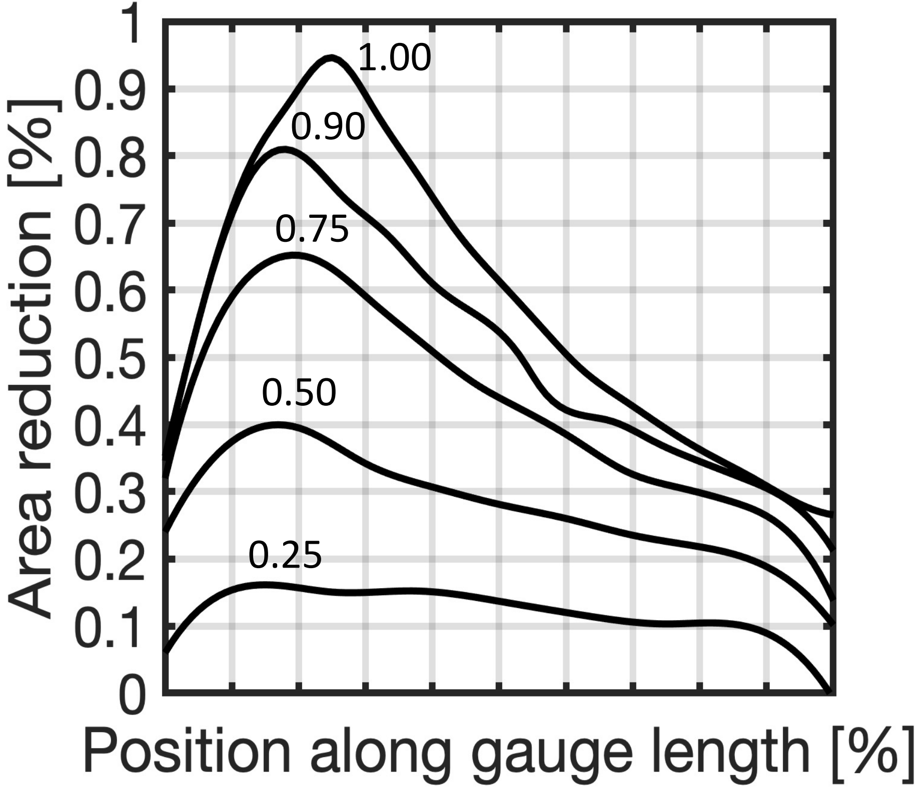
Lower temperatures require lower strain rates;
Lower strain rates result in lower stresses;

Transition from D_{GB} to D_{Mg} for rate controlling mechanism

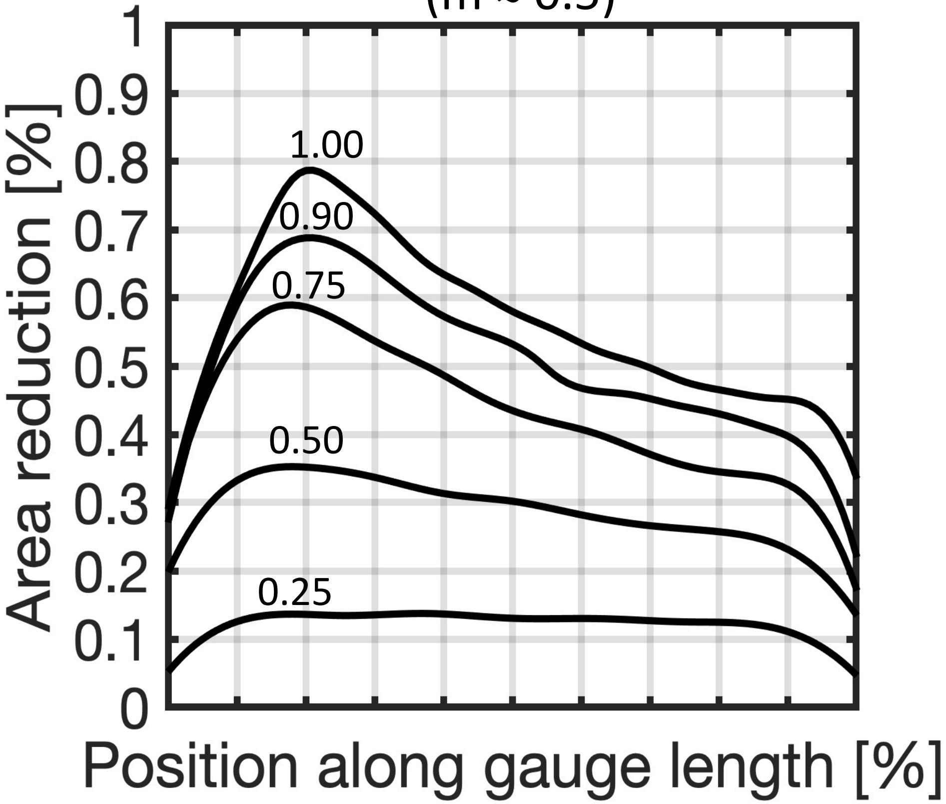
Characterization of Optimal Conditions

Strain Uniformity During Deformation

225 °C 0.0005 s^{-1}
(m ≈ 0.45)

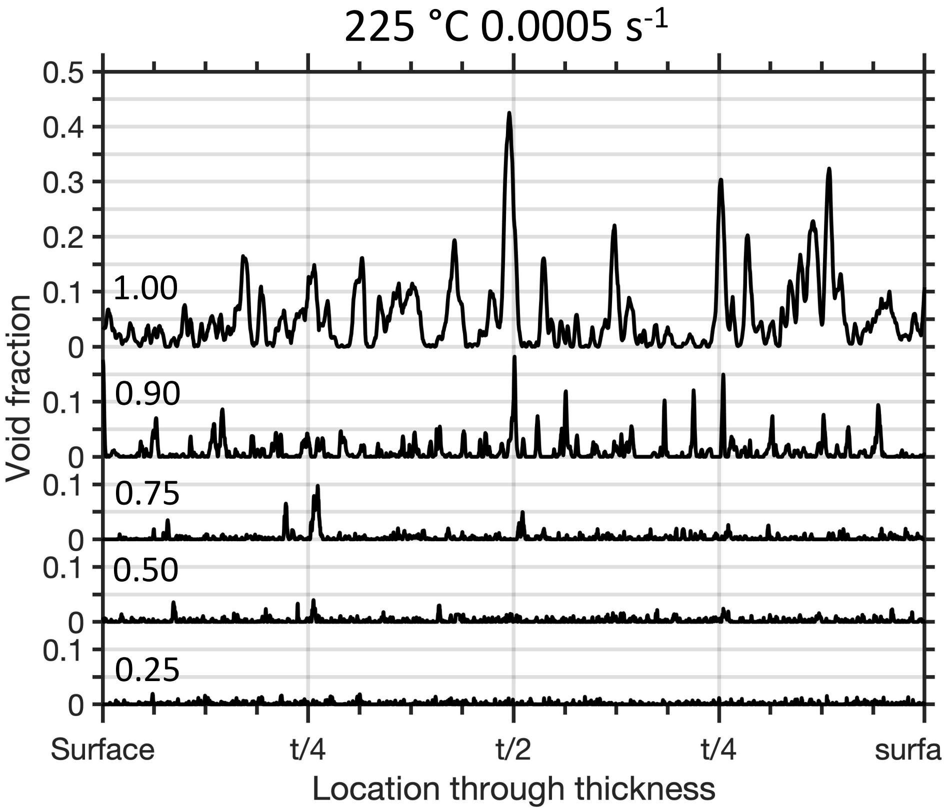


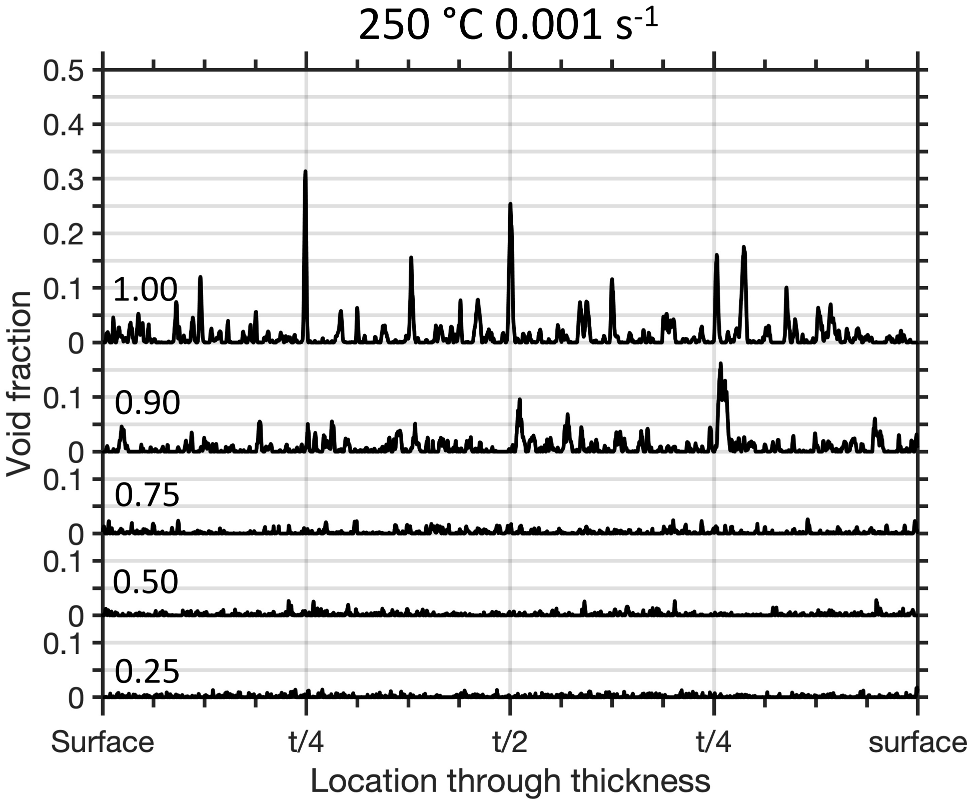
250 °C 0.001 s^{-1}
(m ≈ 0.5)



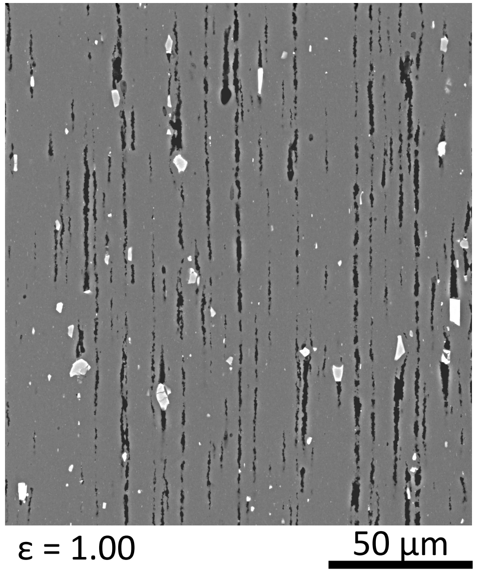
Significant strain localization after ε = 0.75 (*e* = 1.10)

Damage Accumulation

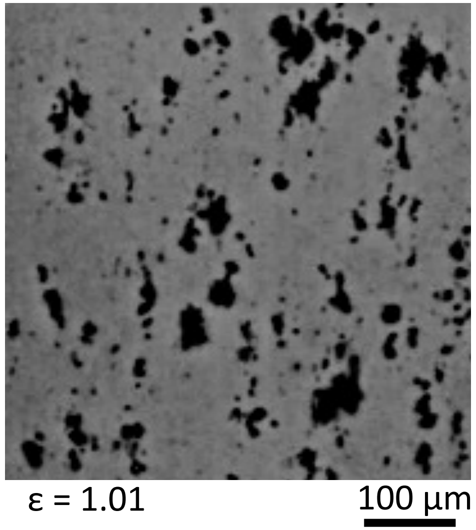

225 °C 0.0005 s^{-1}


250 °C 0.001 s^{-1}

225 °C 0.0005 s^{-1}



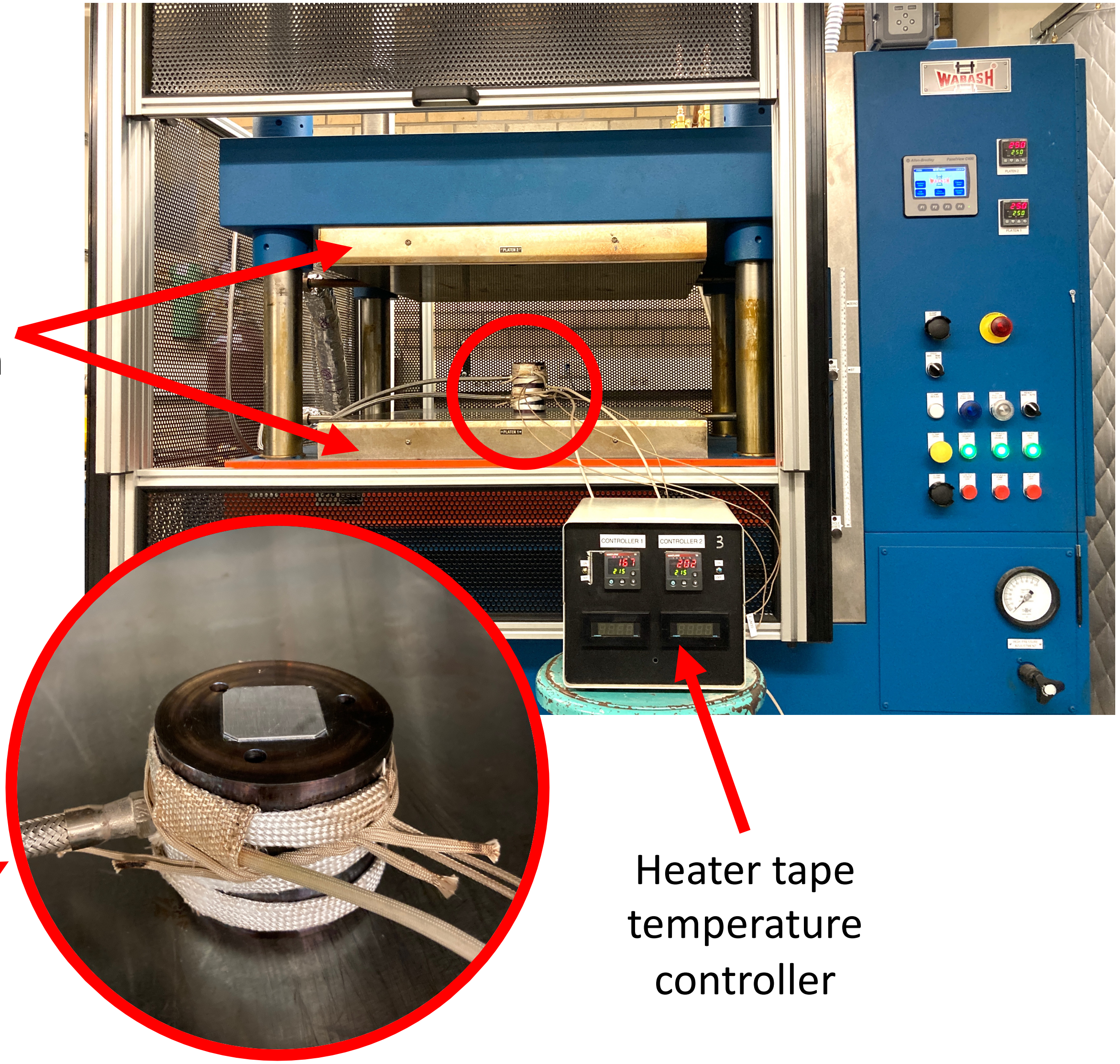
500 °C 0.001 s^{-1}



Significant strain-induced void growth (voids > 1 µm) for $\varepsilon > 0.75$ ($e > 1.1$)

Bulge Formability Testing

Biaxial Bulge Testing

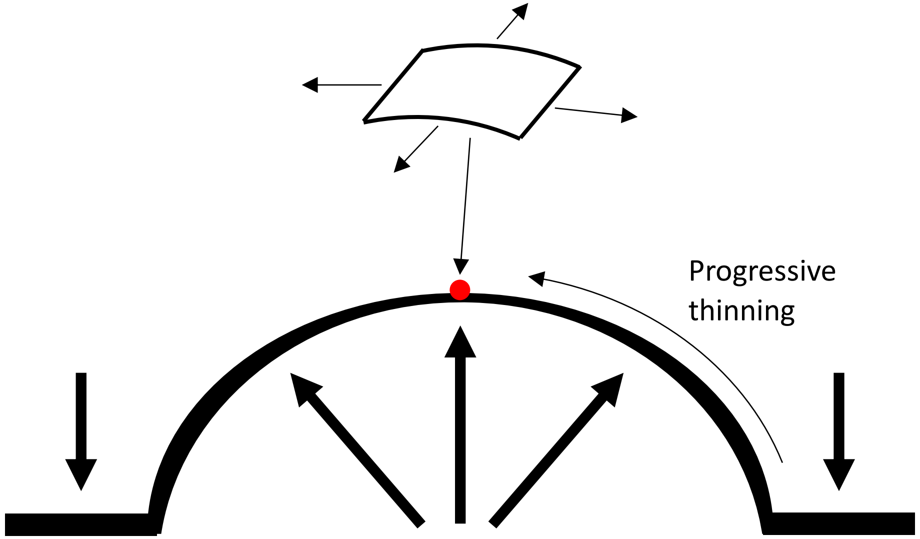


Platens provide clampdown force

Pressurized argon

Heater tape temperature controller

Biaxial strain state



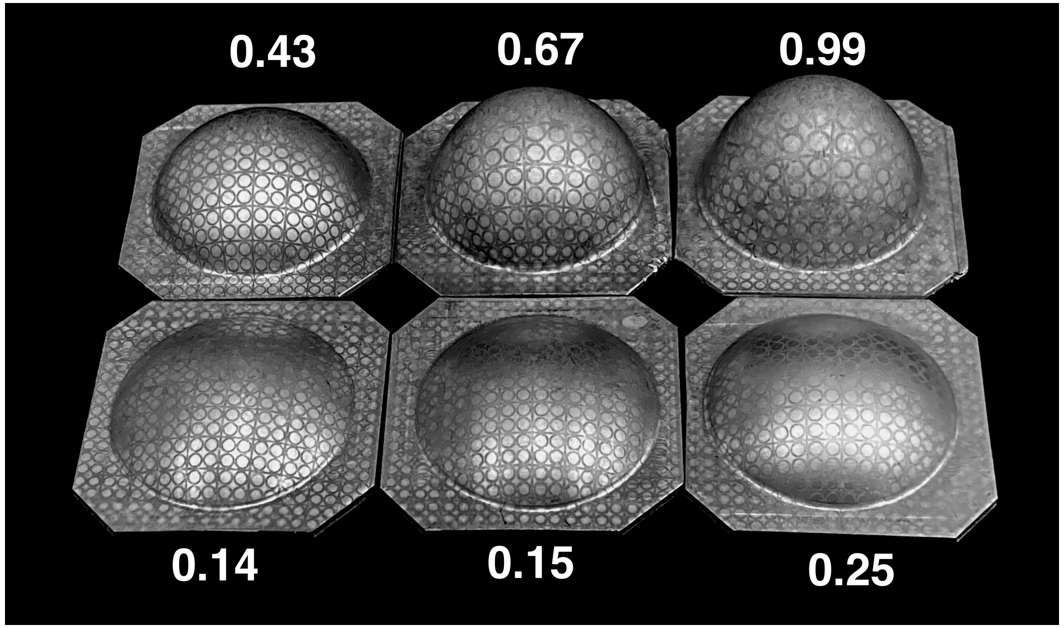
$$P = \frac{4 s_o \sigma}{r} \cdot e^{-\dot{\varepsilon}t}\sqrt{e^{-\dot{\varepsilon}t}\left(1 - e^{-\dot{\varepsilon}t}\right)}$$

Pressure to deform at constant strain rate

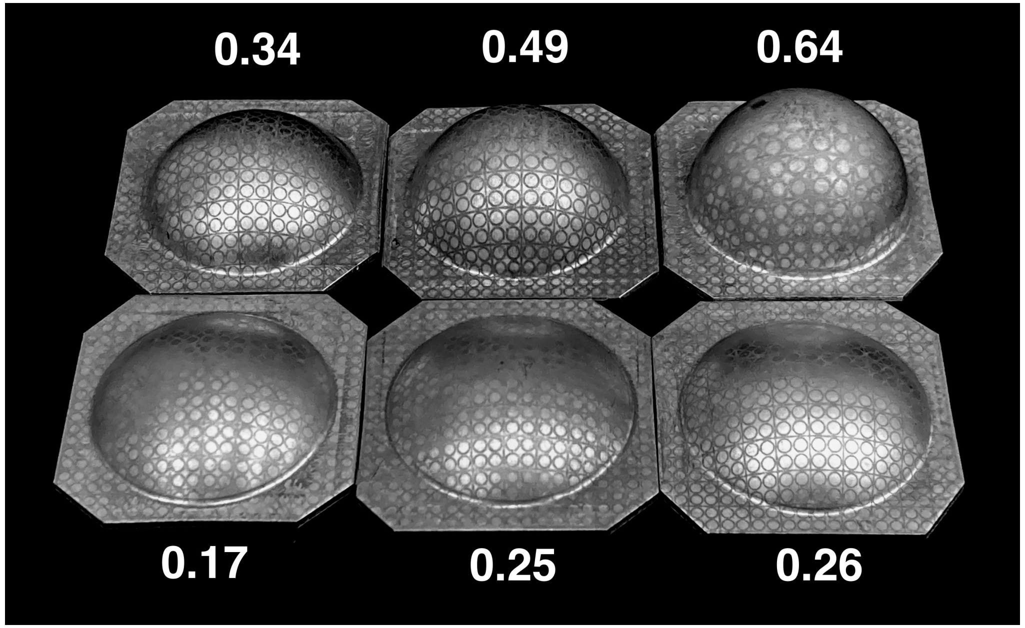
Proof-of-Concept for Low Temperature Formability

5 ARB cycles
1 µm

Coarse grained
10 µm



225 °C 0.0005 s^{-1}

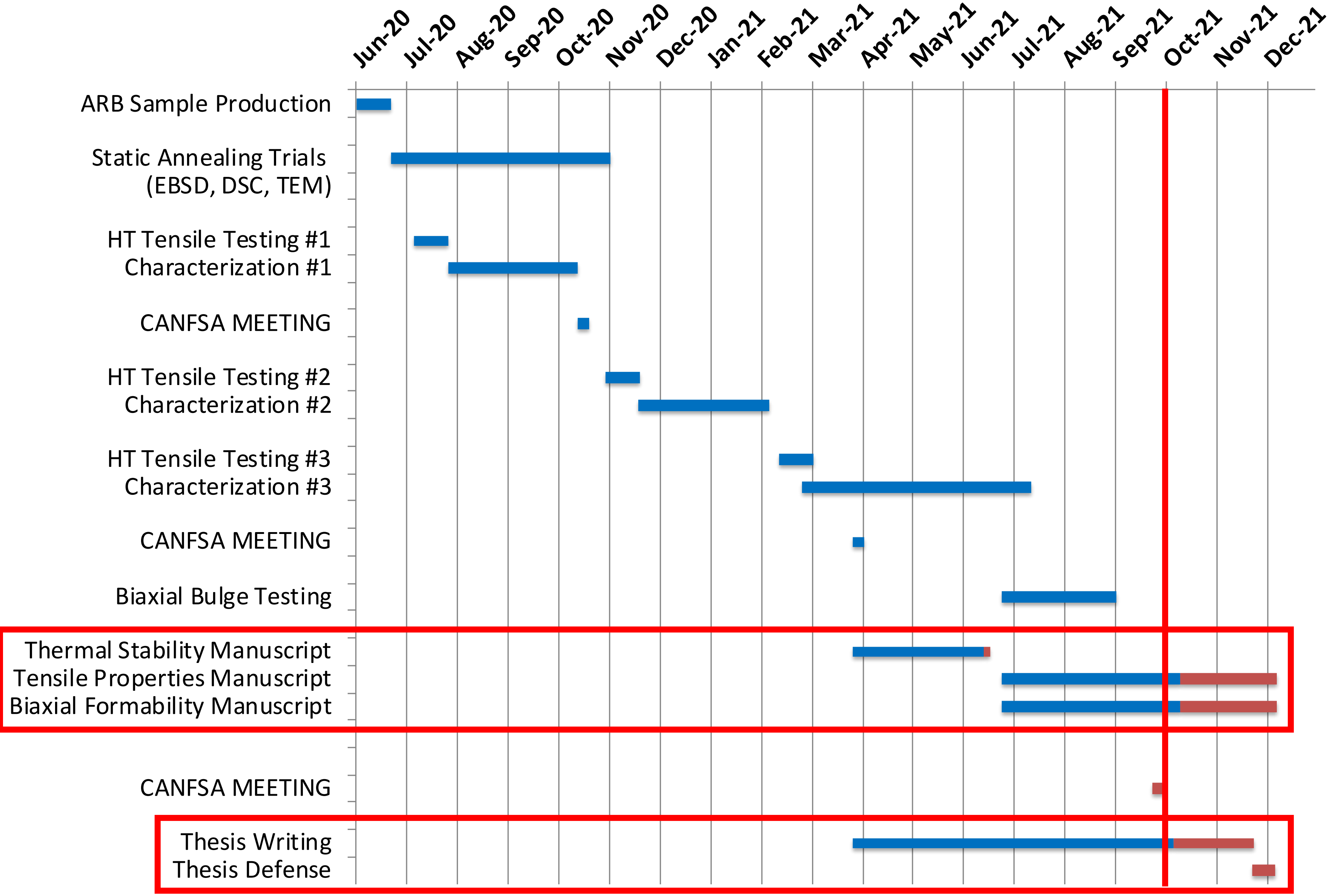


250 °C 0.001 s^{-1}

ARB processing can achieve high biaxial strains with lower temperatures and lower forming pressures

Gantt Chart

CANFSA
CENTER FOR ADVANCED
NON-FERROUS STRUCTURAL ALLOYS



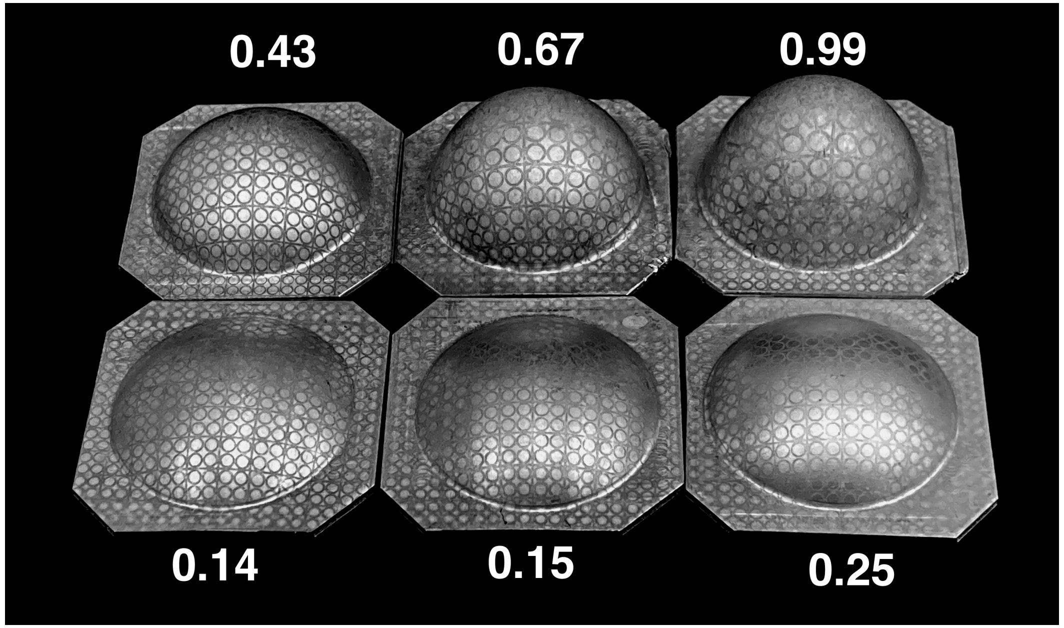
Challenges & Opportunities

Biaxial bulge testing

- provides novel insight in biaxial formability
- collaboration with exchange student M. Ciemiorek working on cross accumulative roll bonding (CARB)

Biaxial bulge analysis

- complex analytical models with many variables



Thank you!
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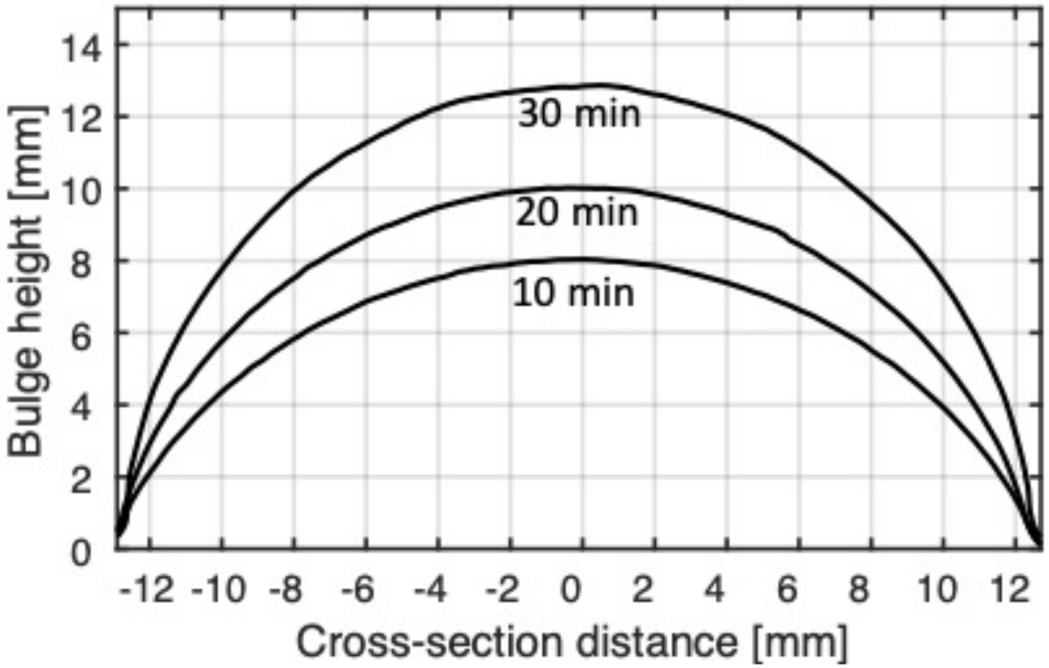
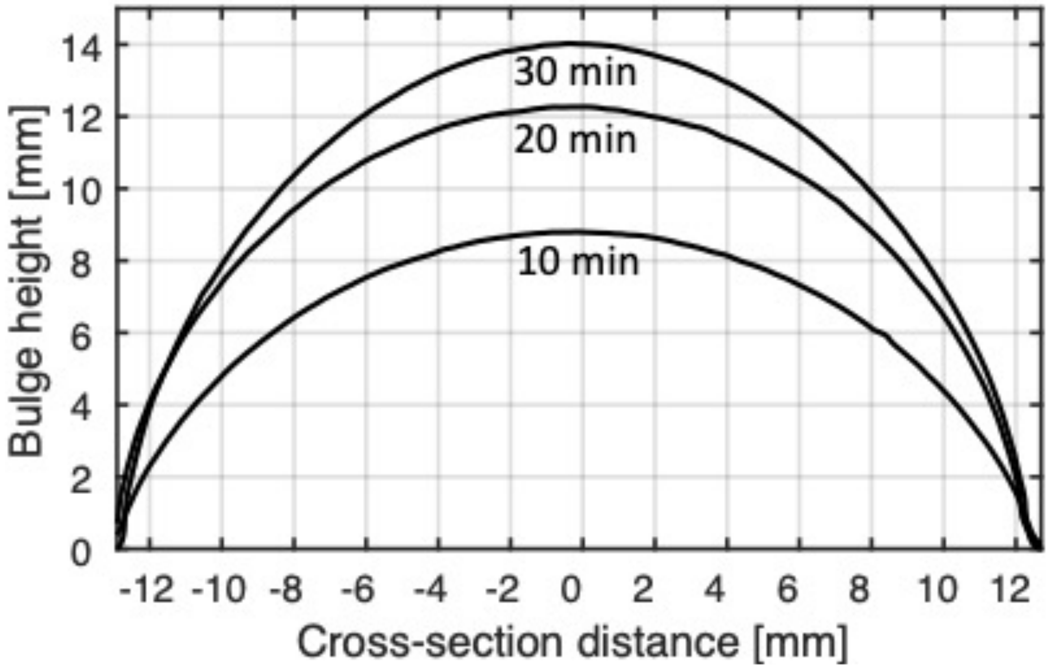
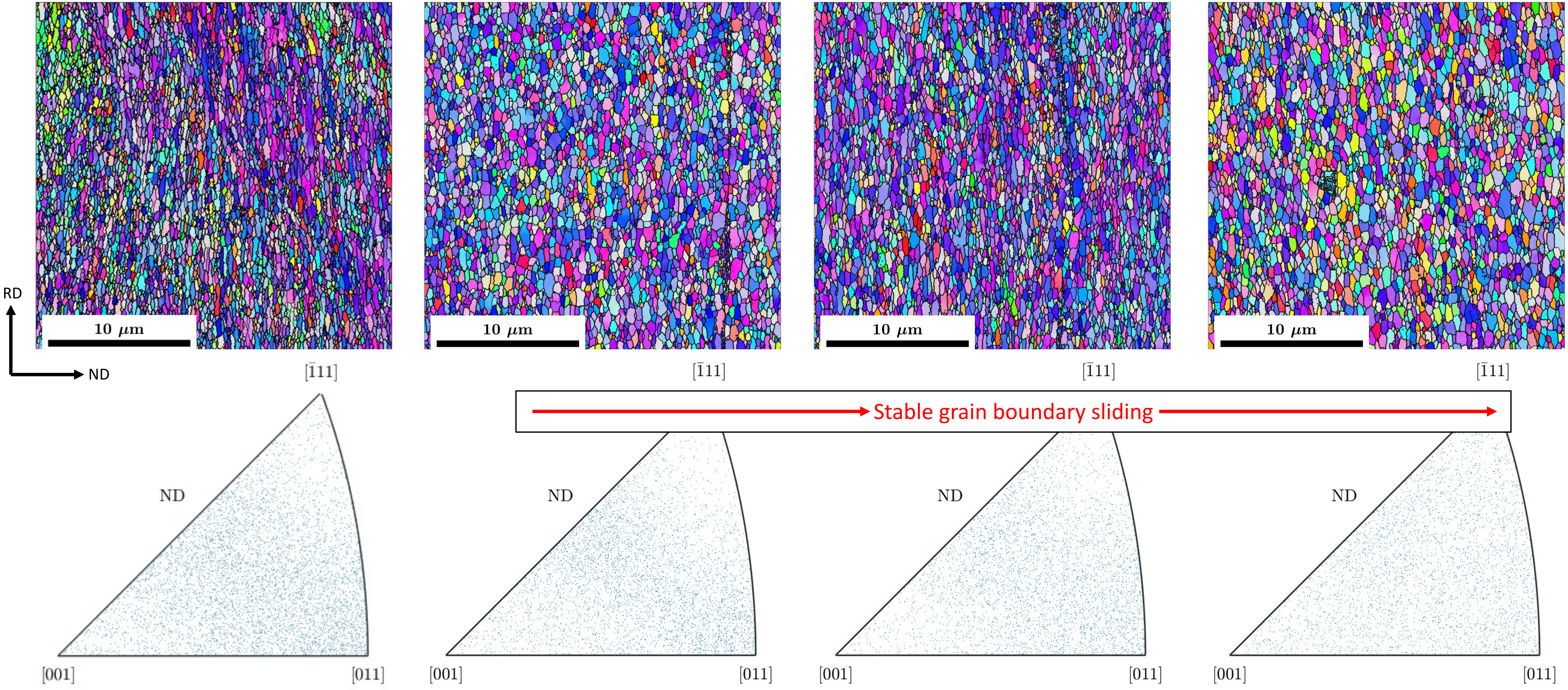
Analysis of Bulge Test Specimens





Height and thickness profiles → Analytical models for superplastic forming

225 °C, 0.0005 s^{-1}



ε = 0.1, 200s

ε = 0.25, 500s

ε = 0.5, 1000s

ε = 0.75, 1500s

Stable grain boundary sliding

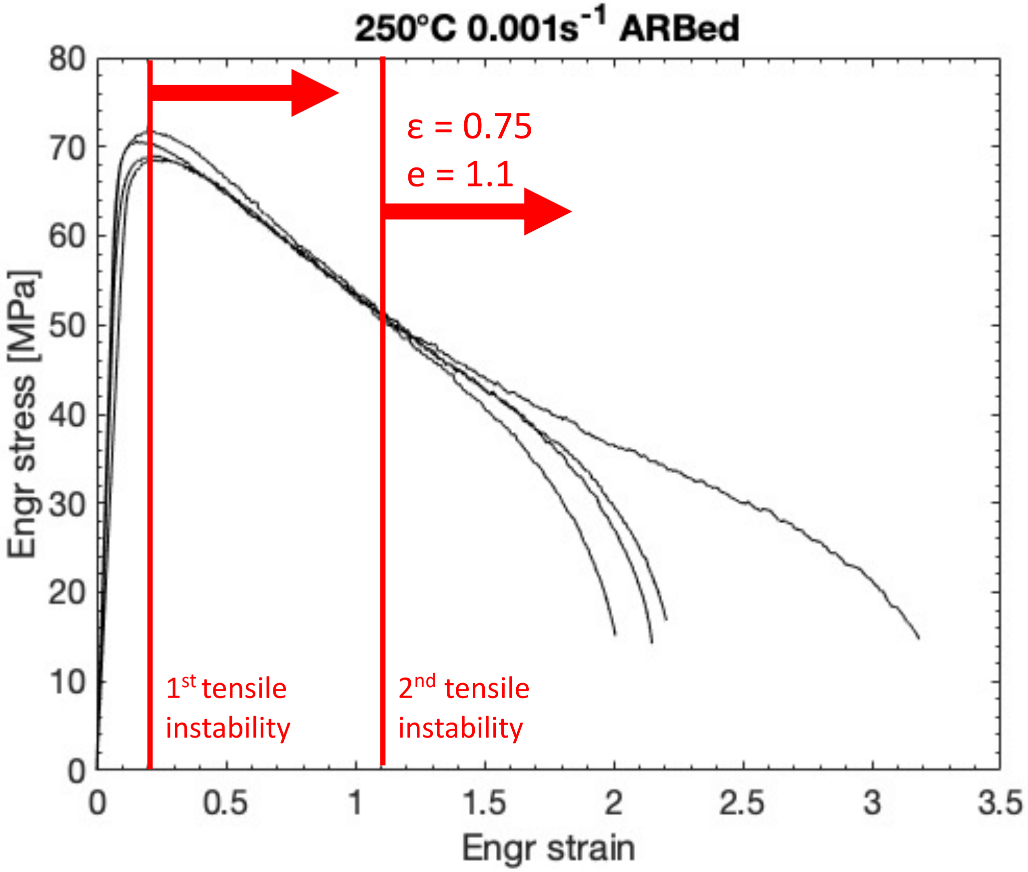
Supplemental slides

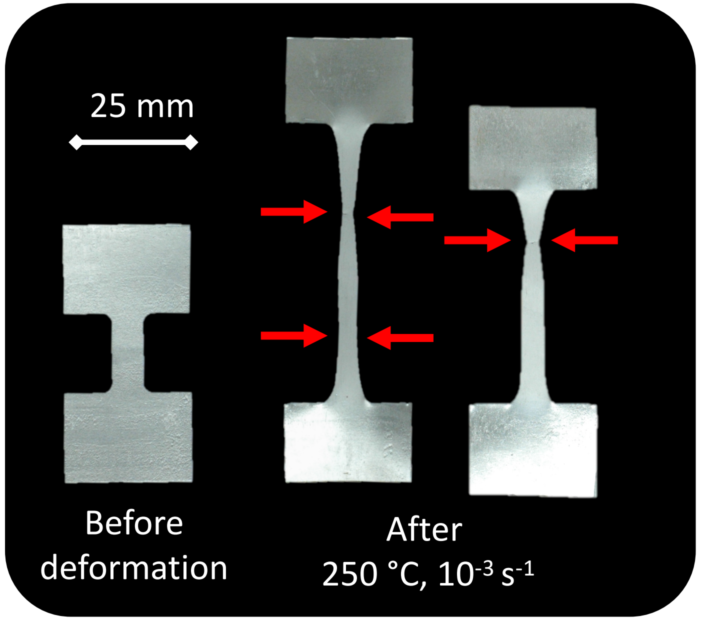
Remaining Questions

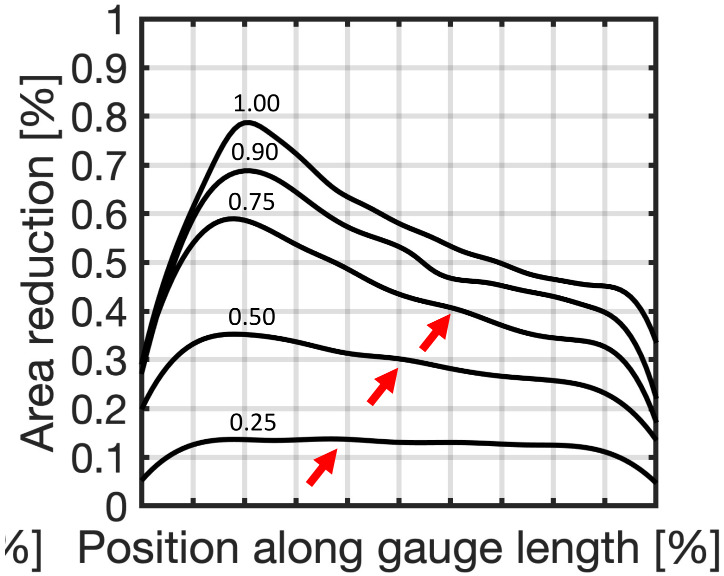
- What causes the transition from D_{GB} to D_{Mg} controlled grain boundary sliding?
  - Why are lower strain rates less conducive for D_{GB}?
    - Lower strain rates have lower STRESSES, the driving force for dislocation glide is LOWERED
      - Maybe look at dislocation velocity compared to strain rate?
      - Maybe look at effect of temperature and stress on dislocation velocity?
      - What does the effect of a threshold stress do/mean?
    - Dislocation climb still remains thermally activated
  - Higher activation energy for D_{Mg}, more sensitive to temperature

- Read paper on equilibrium grain boundary

Variability in total tensile elongations

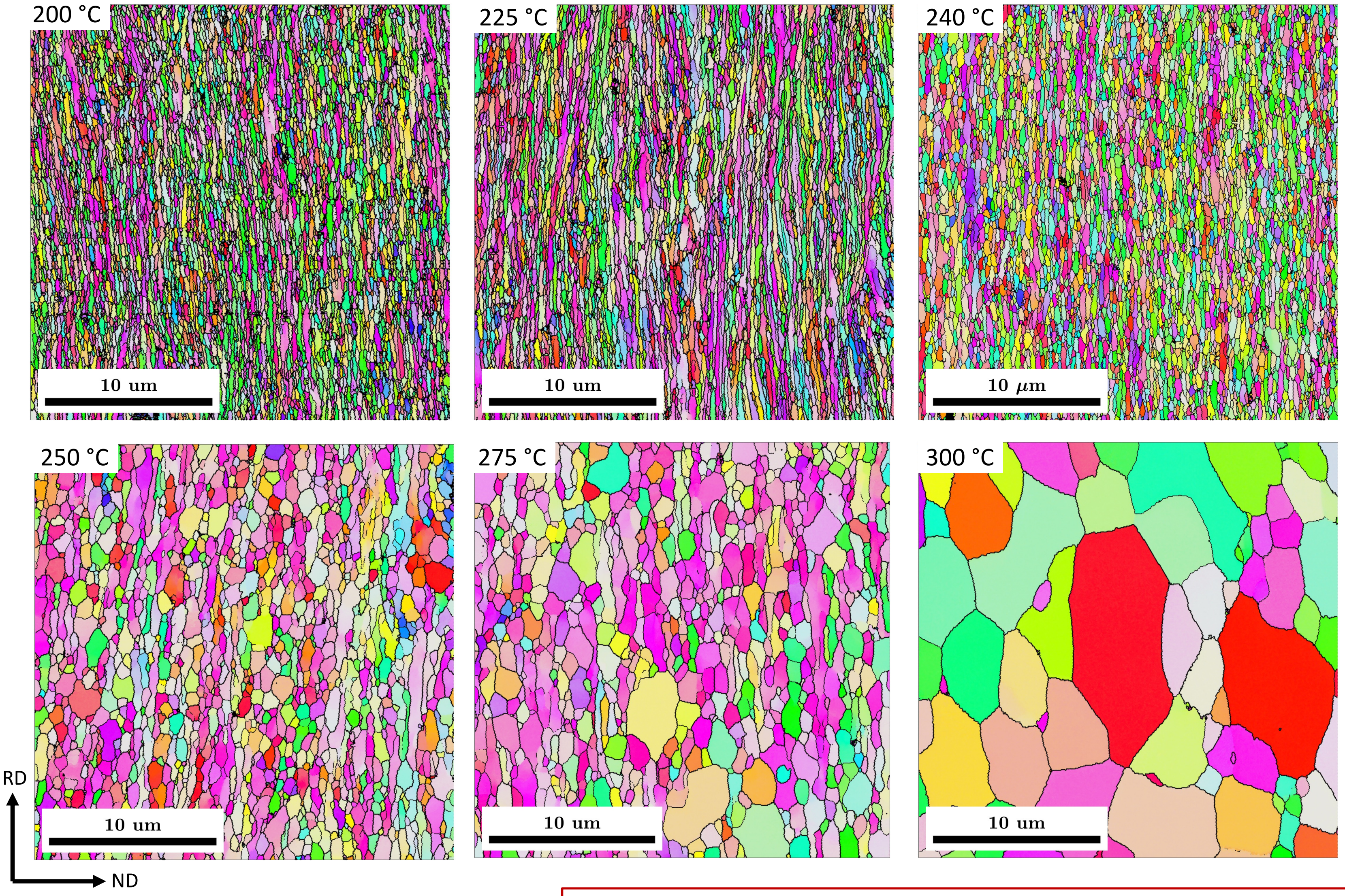


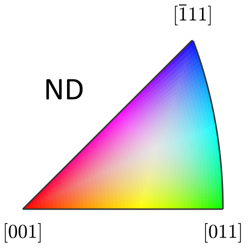




Multiple necks leads to higher tensile elongations

Grain Growth

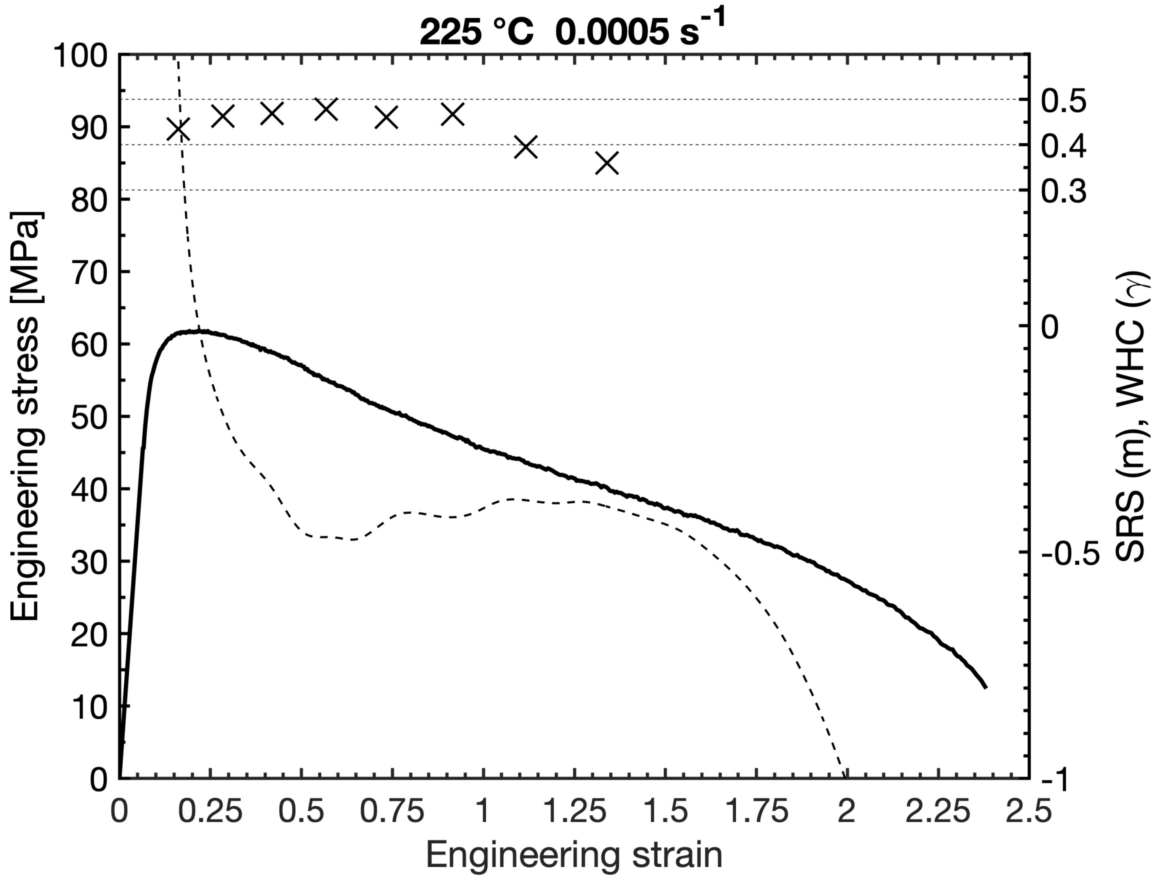


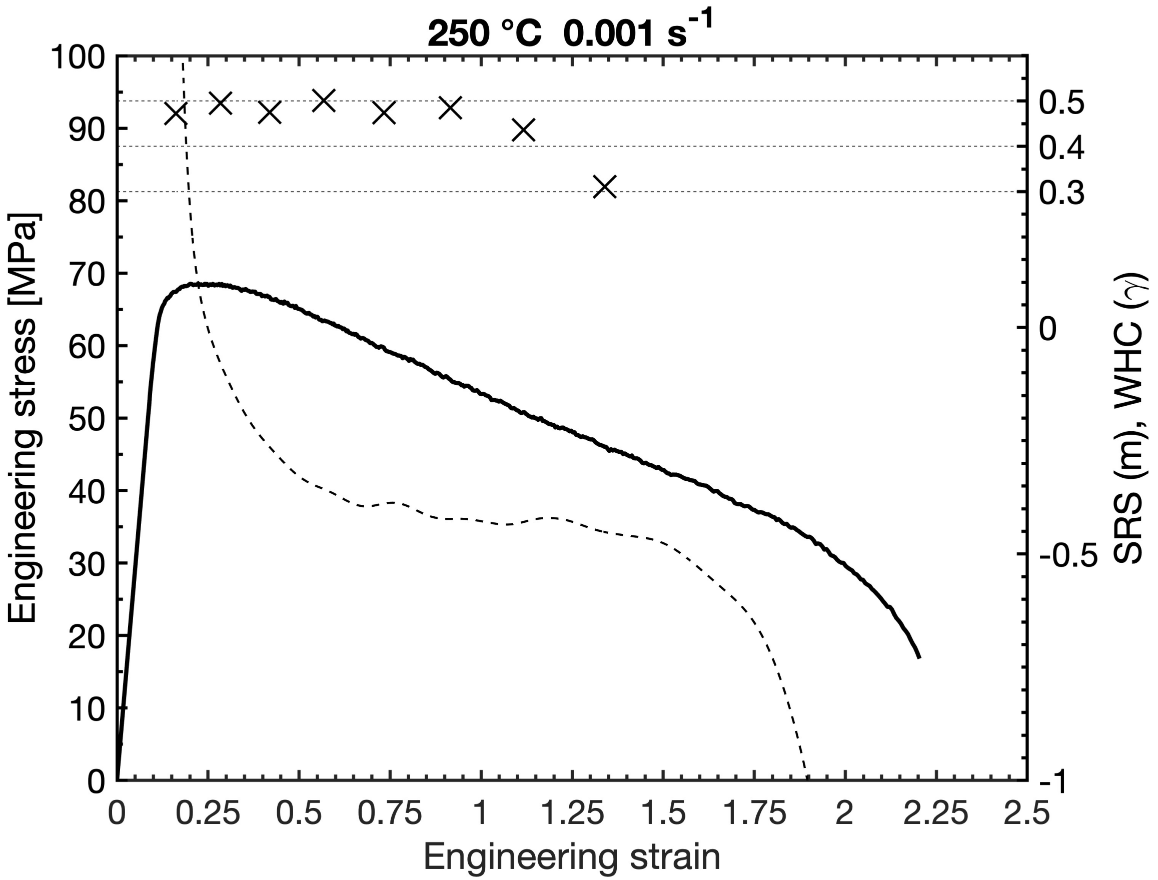


For tensile testing:

15 minute preheat used to equilibrate samples

Flow Curves for Low Temperature Superplasticity





References

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

[3] N. Tsuji, K. Shiotsuki, and Y. Saito, “Superplasticity of ultra-fine grained Al-Mg Alloy by ARB,” *Materials Transactions*, vol. 40, no. 8, pp. 765–771, 1999.

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

[5] Hsiao, I. C., and J. C. Huang. "Deformation mechanisms during low-and high-temperature superplasticity in 5083 Al-Mg alloy." *Metallurgical and Materials Transactions A*, vol. 33, no .5, pp. 1373-1384, 2002.