Project 31-L: Accumulative Roll Bonding of Al 5083 Toward Low Temperature Superplasticity

Summer 2020 Videoconference

June 29 – July 1, July 8 – 10 2020

Student: Brady McBride (Mines)

Faculty: Kester Clarke (Mines)

Industrial Mentors: John Carpenter (LANL), Ravi Verma (Boeing), Eric Payton (AFRL)

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

Project Duration

PhD: September 2017 to May 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 5083.
- Benefit: Low temperature superplasticity could result in reduced cost and cycle time due to reduced deformation temperatures and increased strain rates.

Recent Progress

- Completed PhD proposal
- Produced 100 tensile specimens with 5 cycles of ARB processing
- Conducted low temperature static annealing trials
- Finalized new grip design & furnace temperature profiling

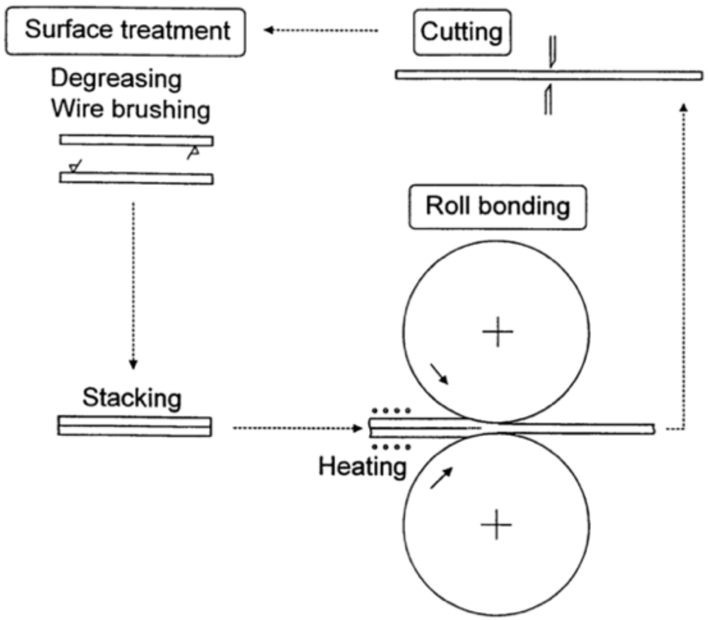
Metrics

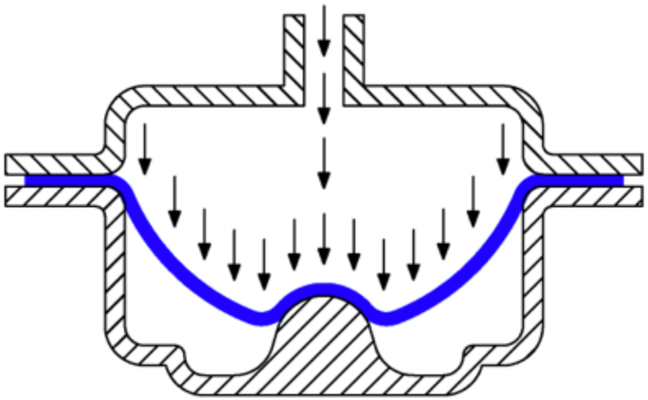
Description	% Complete	Status
1. Literature review	80%	●
2. Production of ARBed samples	100%	●
3. Static annealing trials	75%	●
4. Round 1: HT Tensile Testing & Characterization	0%	●
5. Round 2: HT Tensile Testing & Characterization	0%	●
6. Round 3: HT Tensile Testing & Characterization	0%	●

Outline

- Introduction to ARB and superplasticity
  - Conventional superplasticity
  - Low temperature superplasticity
- Recent work
  - Bulk sample production
  - Microstructural characterization
- Static annealing trials
  - Recovery, recrystallization, grain growth during static annealing
- Plans for immediate tensile testing
- 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.

Conventional superplasticity in Al 5083

Al-4.4Mg-0.45Mn
  Solid solution strengthening (Mg)
  Dispersoid strengthening (Mn)

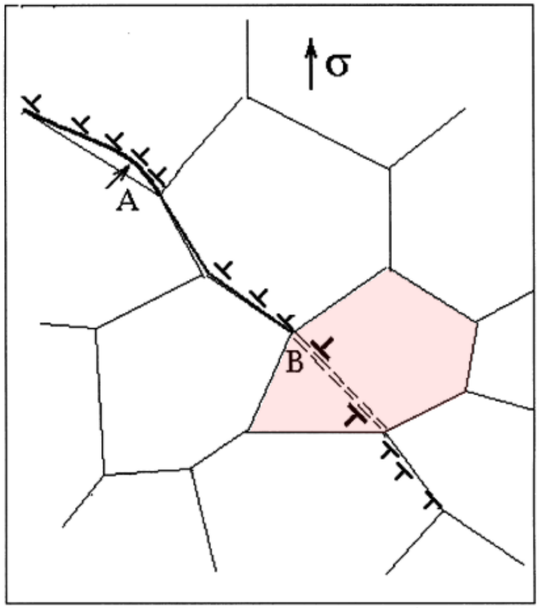
→

Cold work and recrystallization
≈10 µm grains

Superplastic response:

Temperature:	500 °C
Strain rates:	1E^{-2} to 1E^{-4} s^{-1}
Tensile elongation:	200 - 300 %

Grain boundary sliding:
- Small, equiaxed grains
- High angle grain boundaries

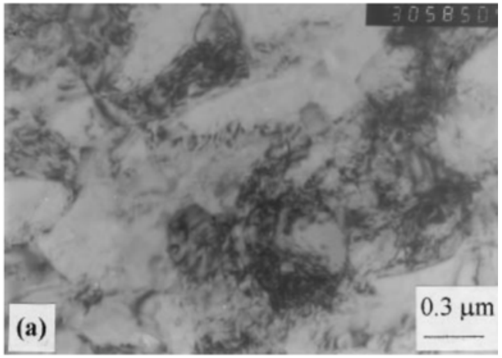


Grain boundary sliding (GBS) inhibited by triple points and precipitates

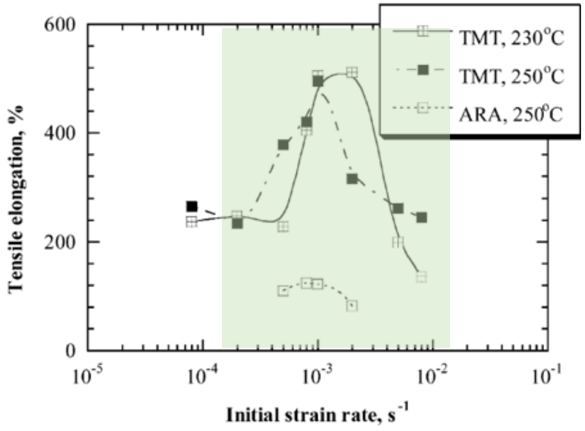
Kaibyshev, *Acta Materialia*, 1998.

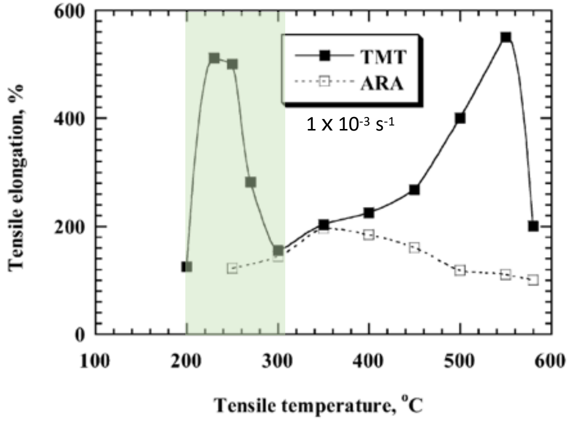
Low temperature superplasticity in Al 5083

Severe warm rolling (ε=4)

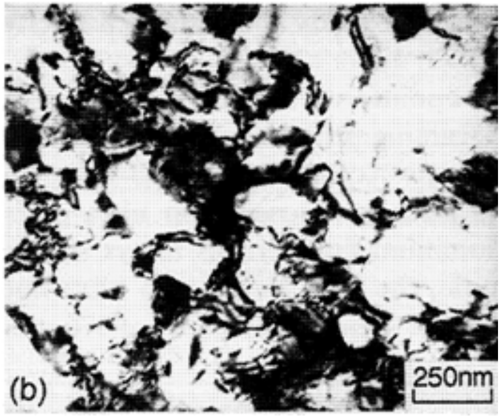


8 mm gauge length

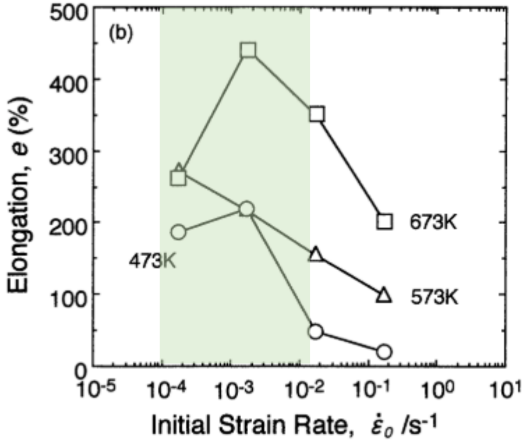




5 ARB Cycles (ε=4)



10 mm gauge length



< 300 °C grain boundary sliding (GBS)
> 300 °C grain growth

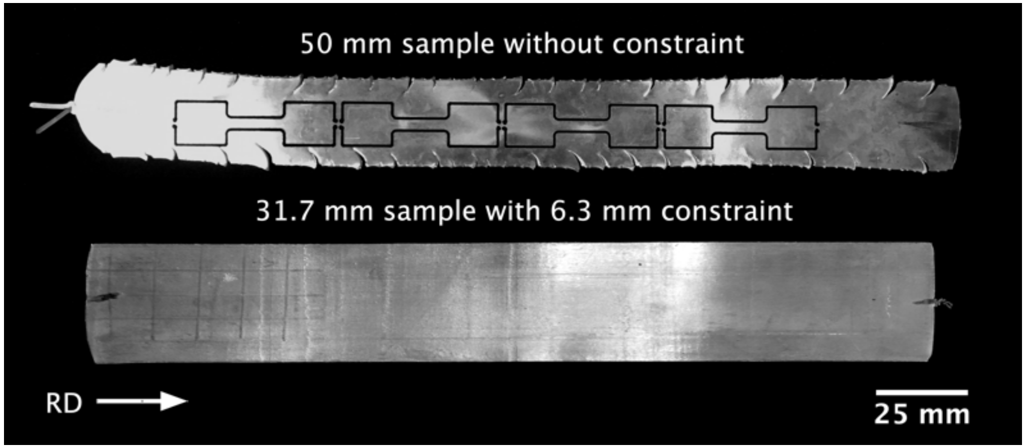
Parameters of interest:

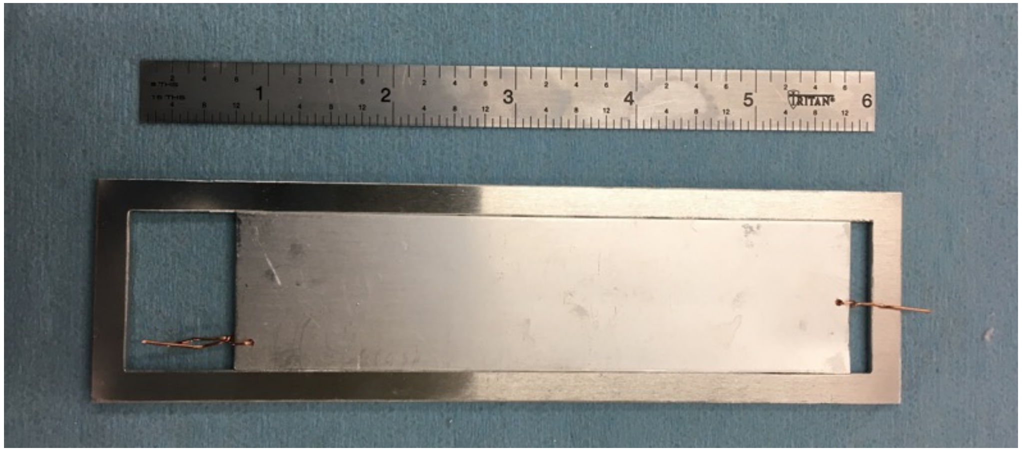
Strain rates:	1E^{-2} to 1E^{-4} s^{-1}
Temperatures:	200 to 300 °C

Hsiao & Huang, *Scripta Materialia*, 1999.
Tsuji et al, *Materials Transactions*, 1999.

Recent Work

Process Development for Bulk Sample Production



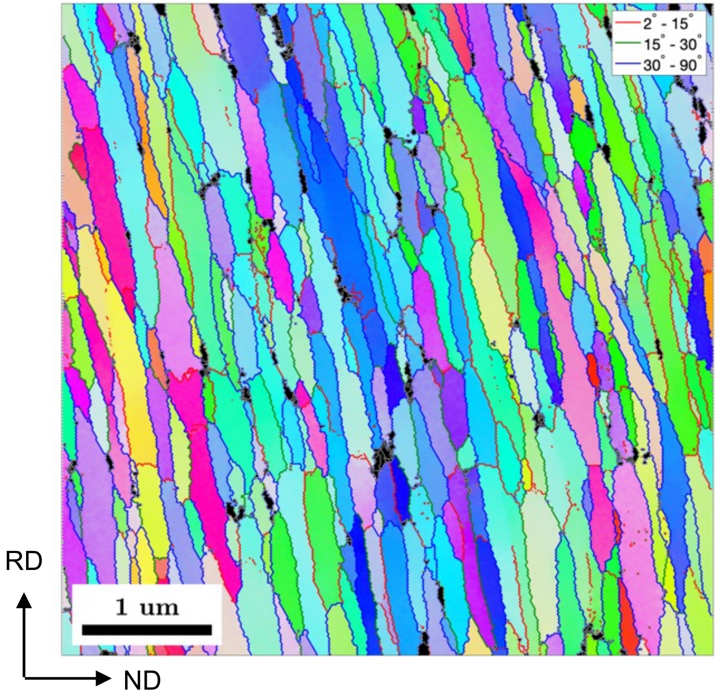


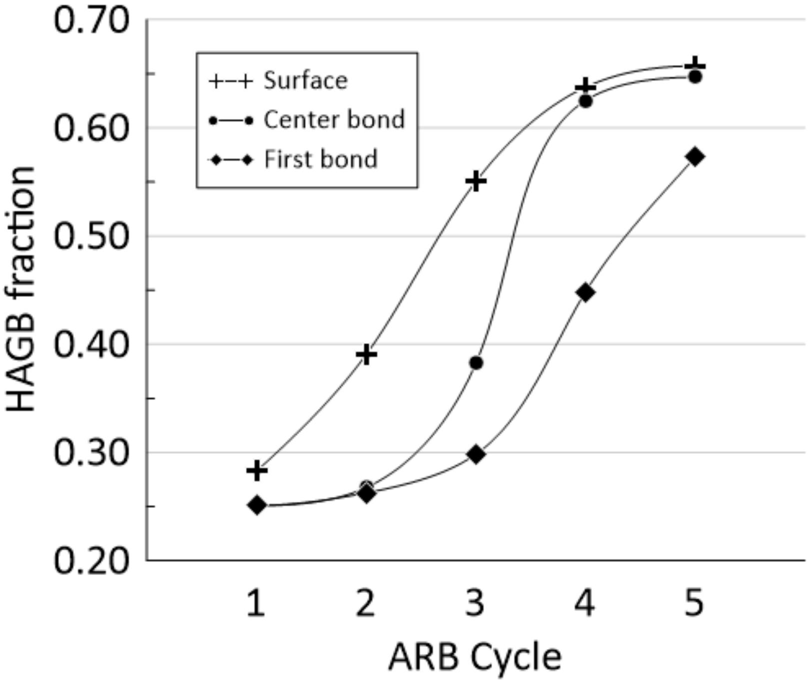
Production of 100 samples with 5 ARB processing cycles

B. McBride, K. Clarke, A. Clarke, *Journal of Manufacturing Processes (2020)*

Characterization of ARBed Microstructure

Midthickness grain morphology after 5 ARB cycles



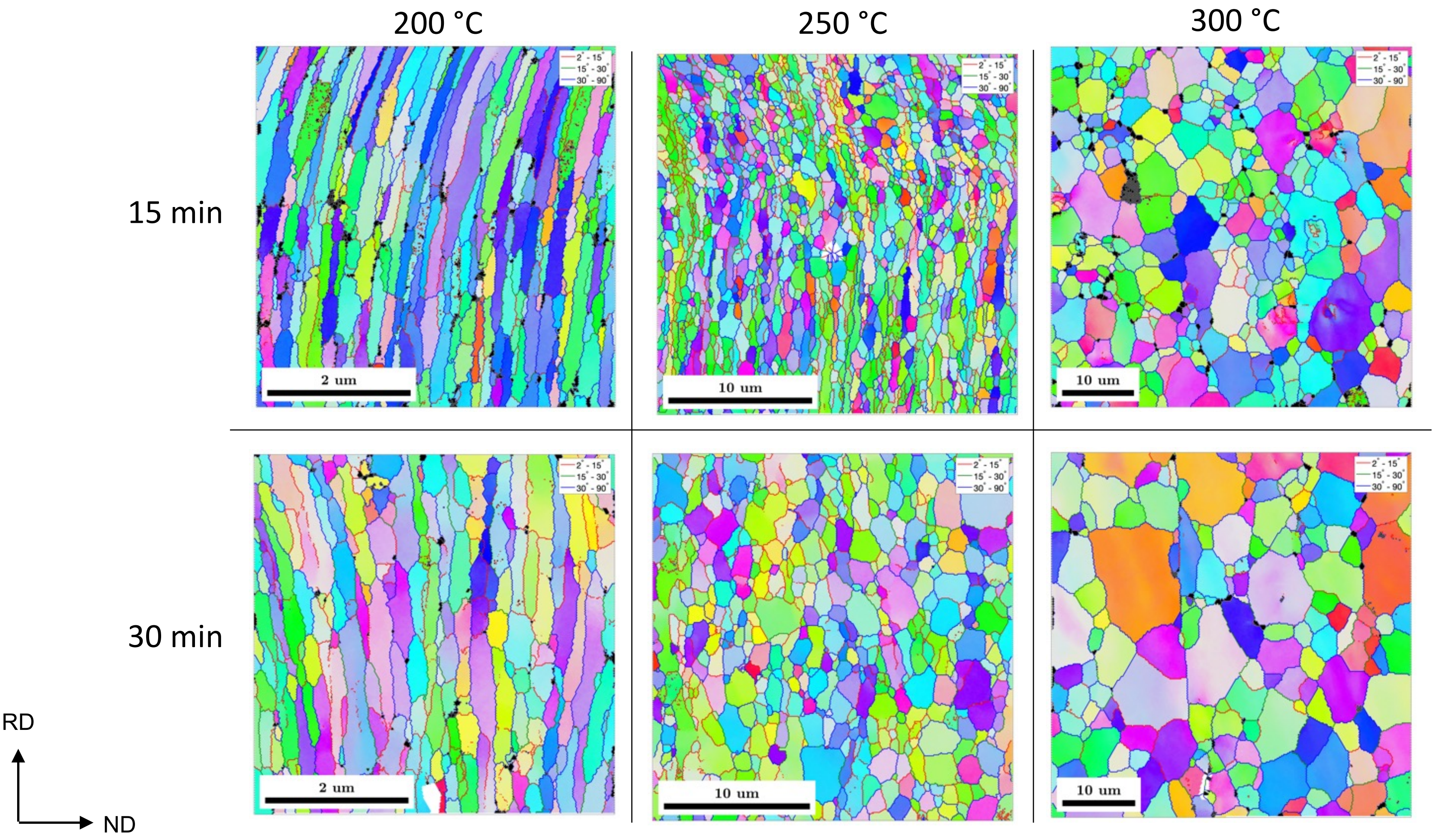


Average grain size: 243 nm x 66 nm
Average aspect ratio: 3.7
High angle grain boundary: ≈60 %

Microstructural Stability after ARB Processing

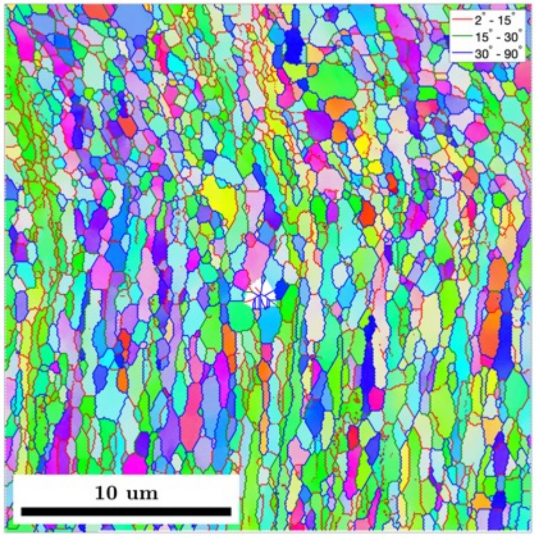
Static Annealing Trials

EBSD scans conducted near midthickness
after annealing 5 ARBed microstructure

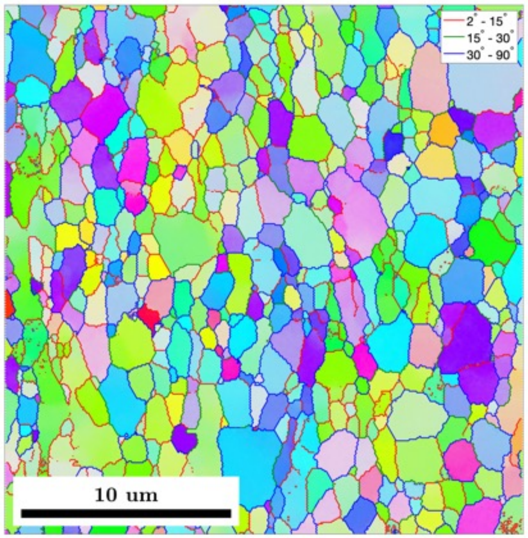


Static Annealing Trials

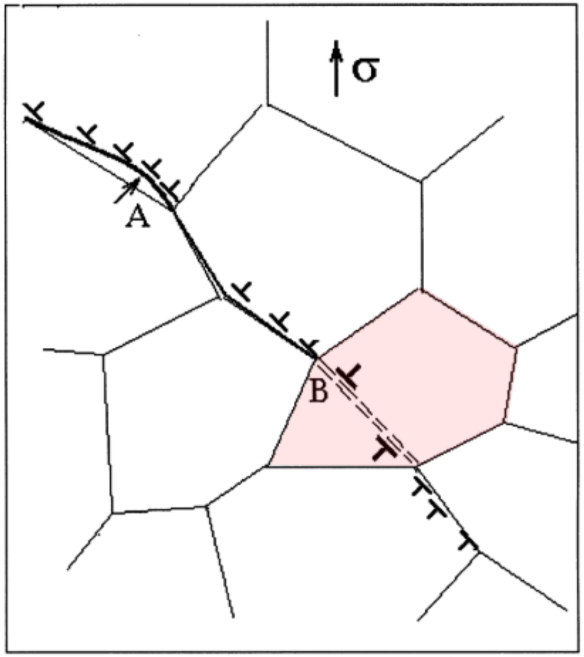
250 °C, 15 min



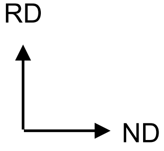
250 °C, 30 min



Can static annealing enhance grain boundary sliding?



Grain boundary sliding (GBS) inhibited by triple points and precipitates



Kaibyshev, *Acta Materialia*, 1998.

Static Annealing Trials – Next Steps

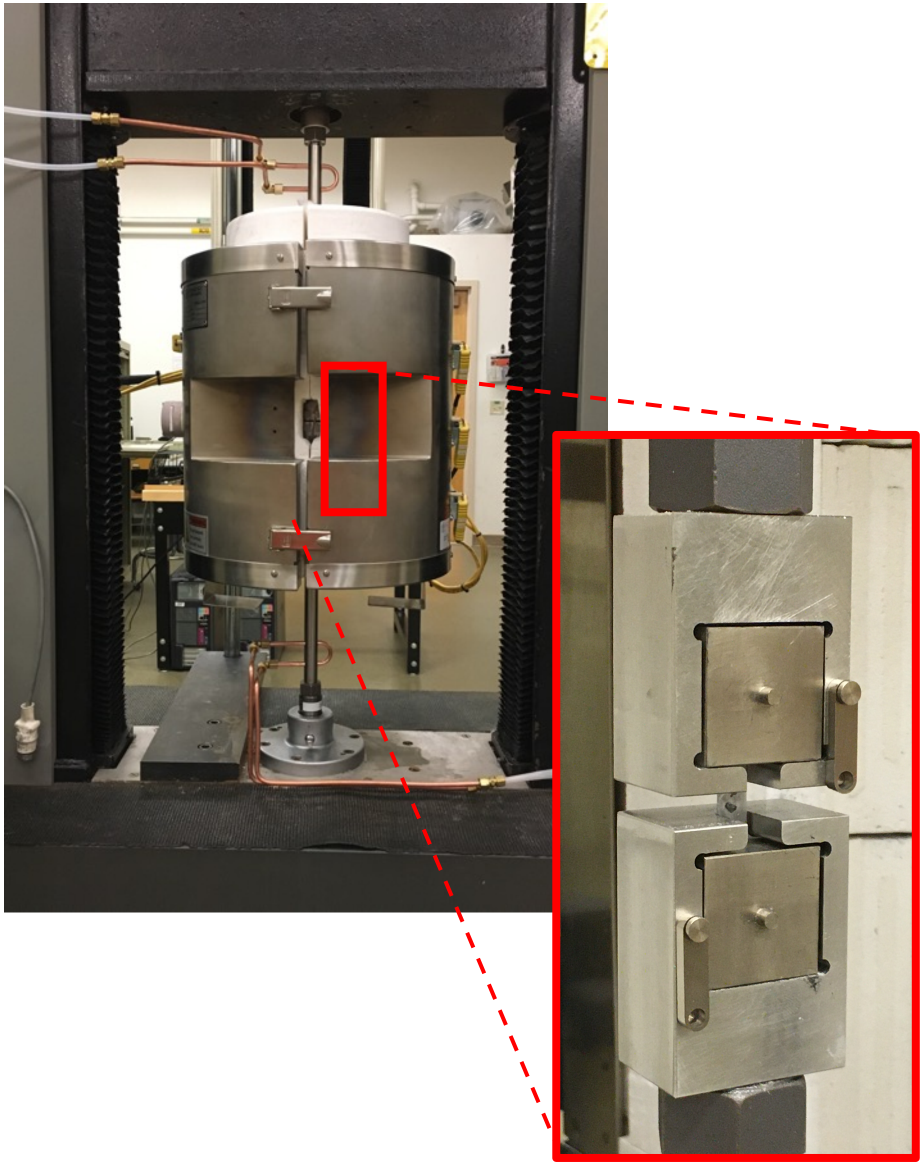
Tentative research question:

- To what extent can Al 5083 microstructures produced by accumulative roll bonding (ARB) be engineered to be conducive for superplasticity?

1. Quantify grain size, grain growth, texture after static annealing
2. Investigate recrystallization with differential thermal analysis

Testing for Superplasticity

Testing for Superplasticity



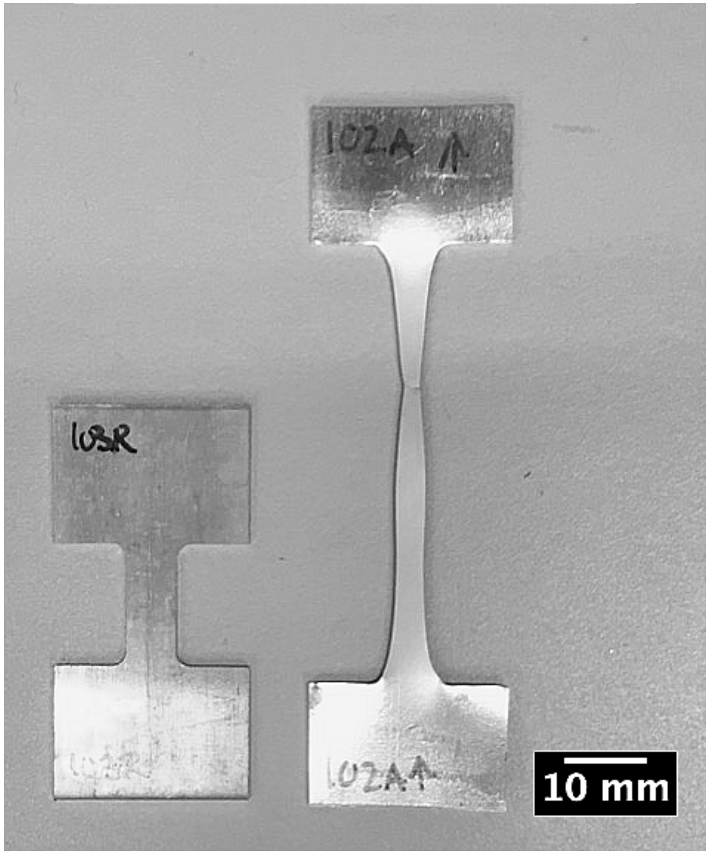
Testing scenarios:

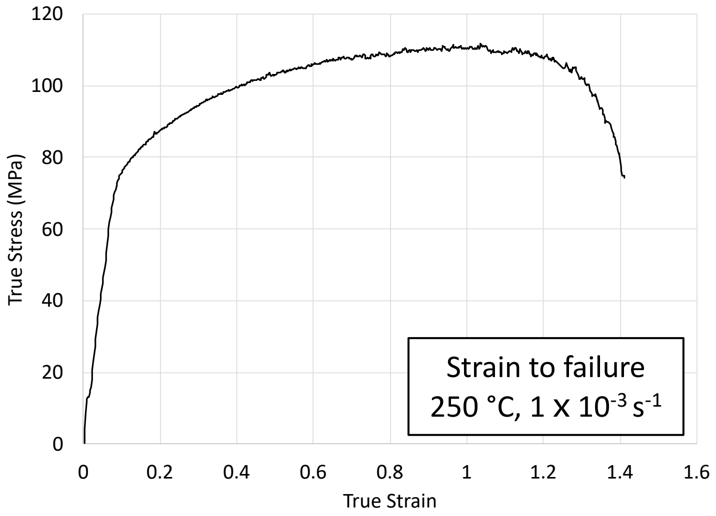
1. Strain-to-failure
2. Strain rate jump tests
3. Interrupted strain

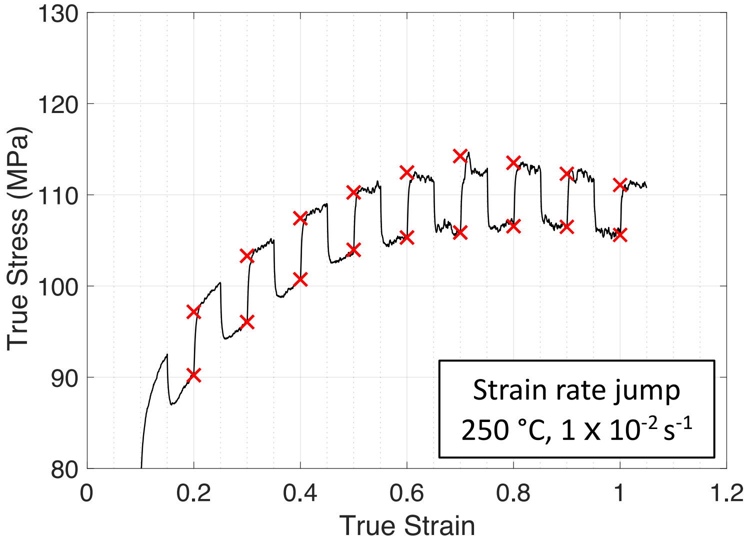
All using constant strain rate

Testing for Superplasticity

Strain to failure
321 % elongation
250 °C, 1 x 10^{-3} s^{-1}







Evaluating Superplasticity

Strain rate jump test

$$m = \frac{\delta \log \sigma}{\delta \log \dot{\epsilon}}$$

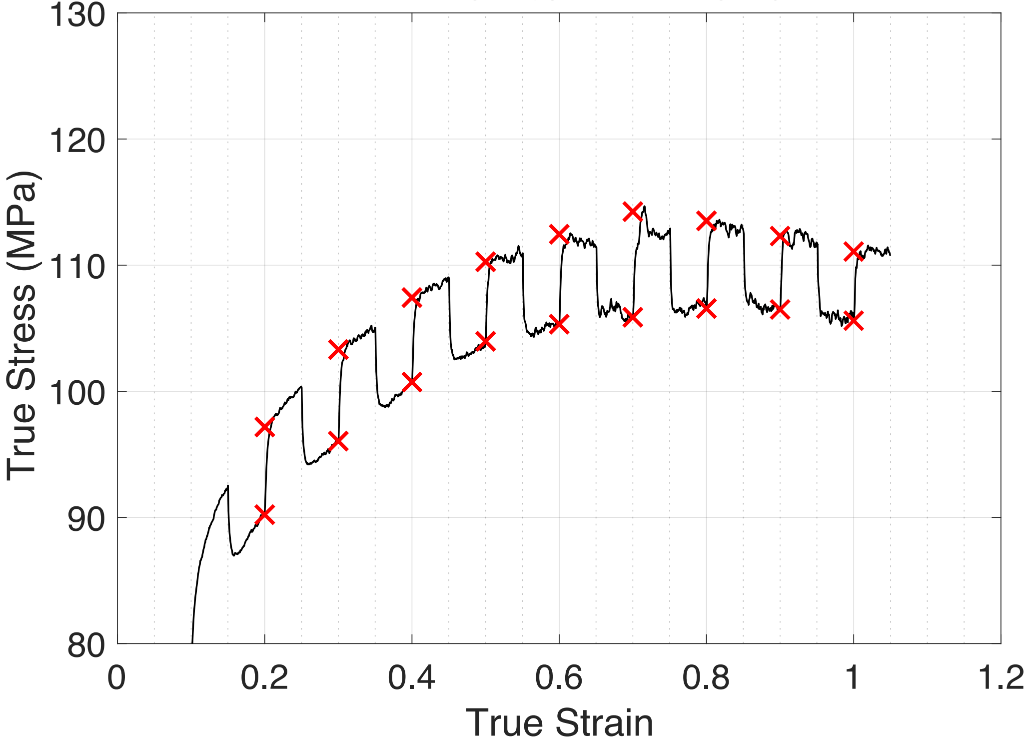
Evaluate *m* at every 0.05 strain increment

↓

Determine evolution of *m* with strain

250 °C

1×10^{-2} to 1.2×10^{-2} s^{-1}



Cleveland et al., *Materials Science and Engineering A*, 2003.

Evaluating Superplasticity

$$\dot{\epsilon} = A\frac{D_0 G b}{kT}\left[\frac{b}{d}\right]^p\left[\frac{\sigma}{G}\right]^{1/m}\exp\left(\frac{-Q}{kT}\right)$$

Quantify the propensity for grain boundary sliding:

1. Activation Energy of Deformation
   Relationship between σ and T^{-1}
   Compare to $Q_{\text{GB diff}}$, $Q_{\text{solute drag}}$, $Q_{\text{bulk diff}}$, etc.

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

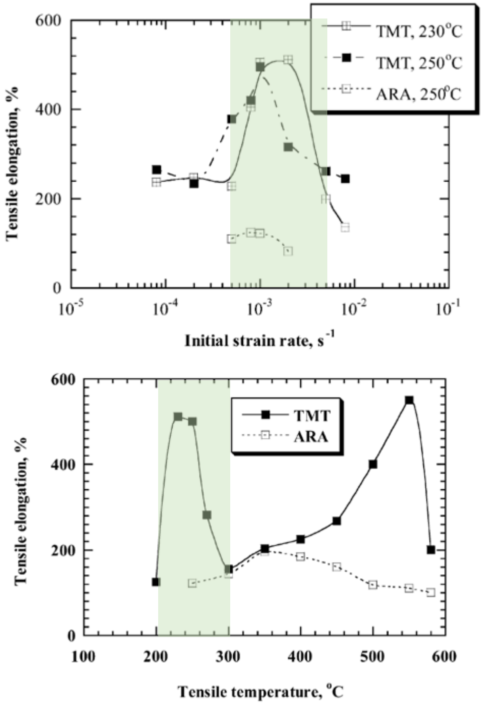
2. Interaction Volume
   Relationship between Q_a and *m*

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

Evaluating Superplasticity – Next Steps

Tentative research question:

- What combination of uniaxial tensile testing parameters (T,$\dot{\varepsilon}$) produces optimal elongations in ARBed Al 5083?



1. Strain-to-failure, strain rate jump tests for:
   Temperatures: 200 – 300 °C
   Strain rates: 1E^{-2} to 1E^{-4} s^{-1}
2. Evaluate activation energy, activation volume
3. Microstructural analysis

Rationale for Proposed Work

Improve forming efficiency

Minimize void formation

Retain ultra-fine grain size

Enhance tensile elongation

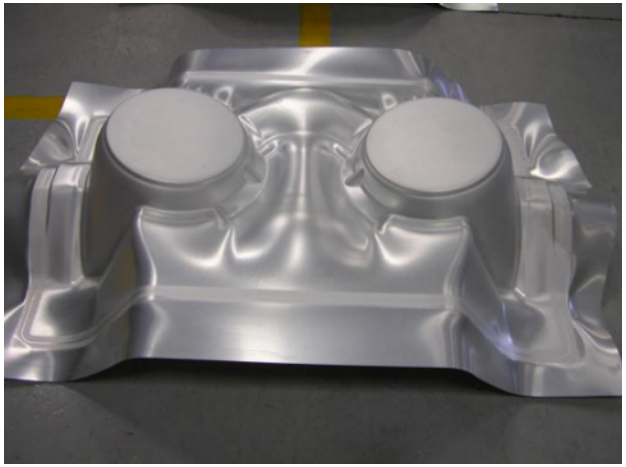
Conventional processing baseline:

Temperature: 500 °C

Strain rates: $1E^{-2}$ to $1E^{-4}$ s^{-1}

Void percentage: < 2 %

Tensile elongation: 200 - 300 %

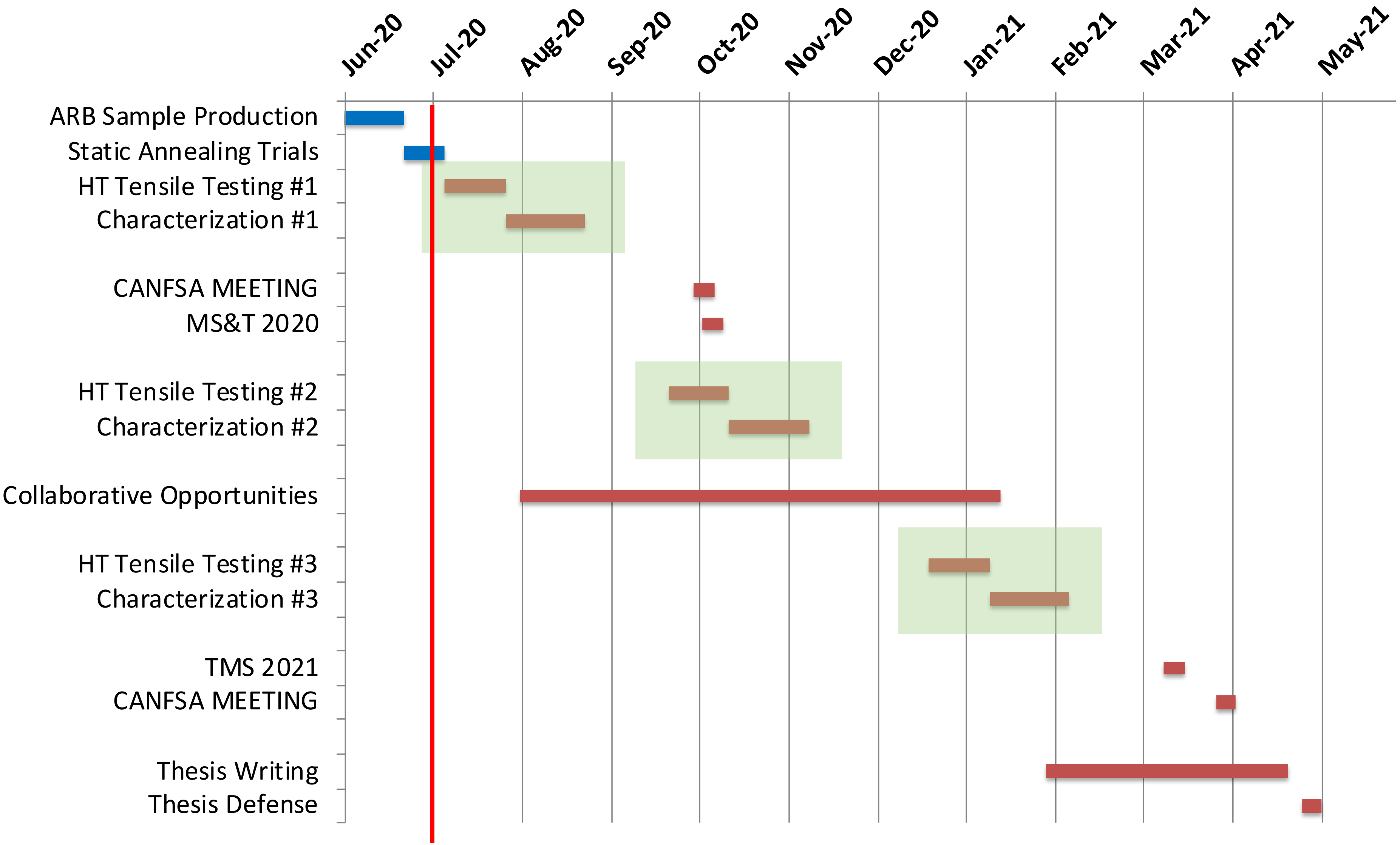


SPF5083 lamp cans for airplanes

Barnes, *Journal of Materials Engr. & Performance*, 2007.

Barnes et al., *Materials Science Forum*, 2013.

Anticipated Timeline



Challenges & Opportunities

- Next steps
  - Thermal analysis on ARBed microstructural stability
  - First round of tensile testing (total elongation, *m* values)

- Feasibility of using activation energy, activation volume to quantify grain boundary sliding (GBS)
  - Additional literature review needed for further understanding

- Access to high capacity rolling mill (e.g. LANL)
  - Small scale formability, anisotropy

Thank you!
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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.

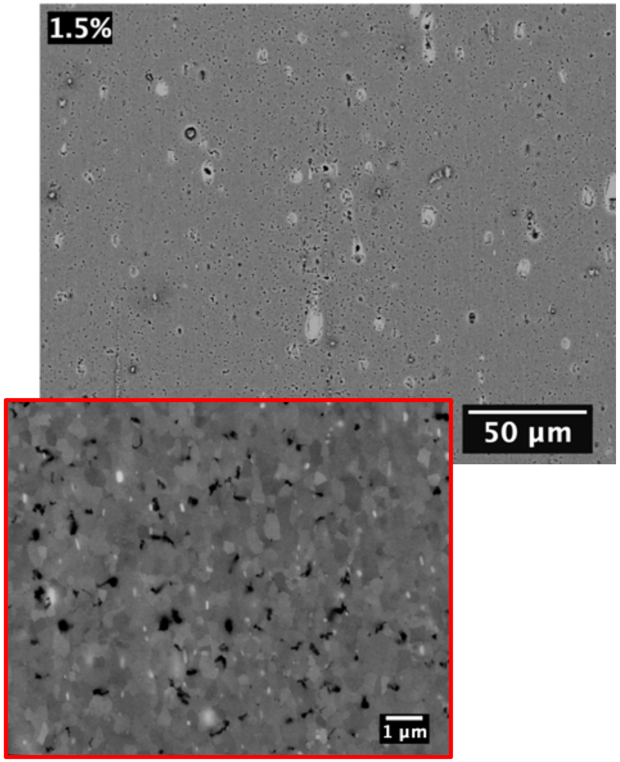
[6] B. N. L. McBride, K. D. Clarke, and A. J. Clarke, “Mitigation of edge cracking during accumulative roll bonding (ARB) of aluminum strips,” *Journal of Manufacturing Processes*, vol. 55, pp. 236–239, 2020

[7] A. J. Barnes, “Superplastic Forming 40 Years and Still Growing,” *Journal of Materials Engineering and Performance*, vol. 16, no. 4, pp. 440–454, 2007.

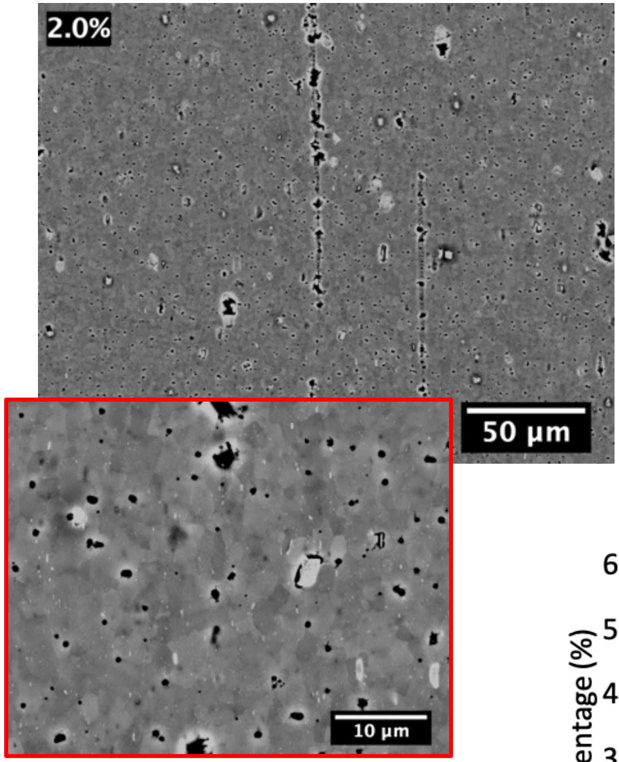
[8] A. J. Barnes, H. Raman, A. Lower, and D. Edwards, “Recent Application of Superformed 5083 Aluminum Alloy in the Aerospace Industry,” *Materials Science Forum*, vol. 735, pp. 361–371, 2013.

Void Formation

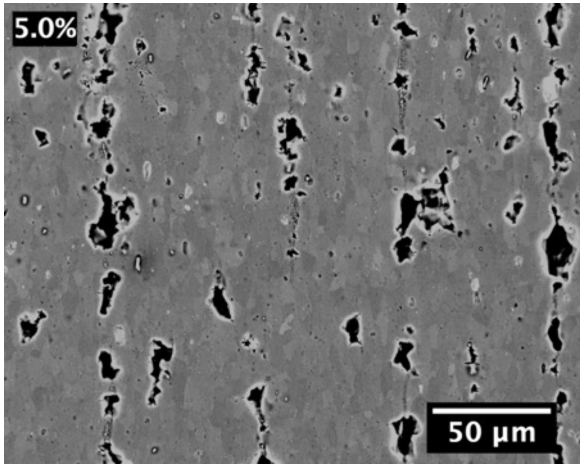
196 °C



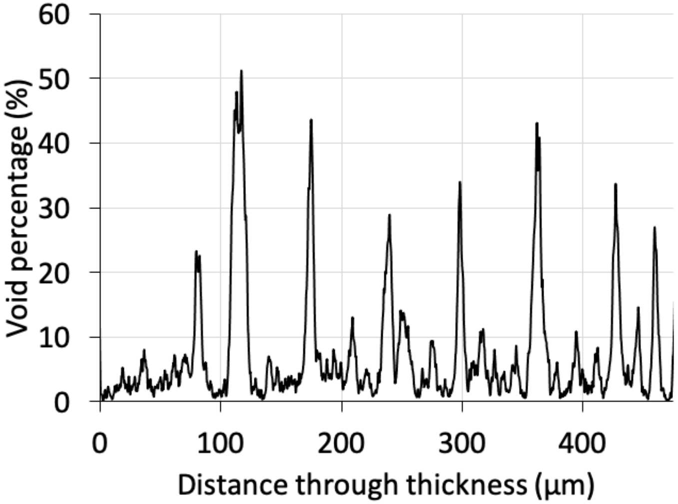
290 °C



377 °C



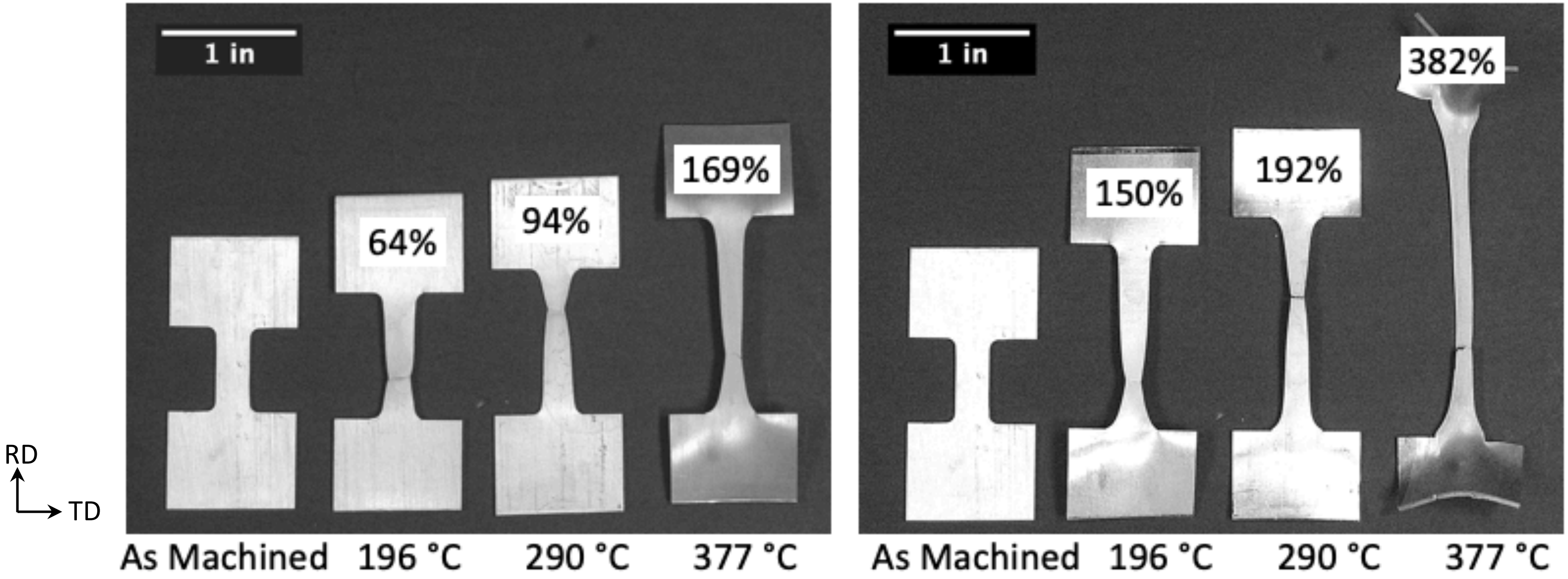
377 °C void intensity profile



Can quantify void size, shape and distribution after tensile testing.

Additional Slides

Preliminary Tensile Tests



Conventional Processing
≈15 µm grain size

5 ARB Cycles
≈250 nm x 1 µm x 1 um grain size

All tested at $\varepsilon_0 = 1 \times 10^{-3}\ s^{-1}$

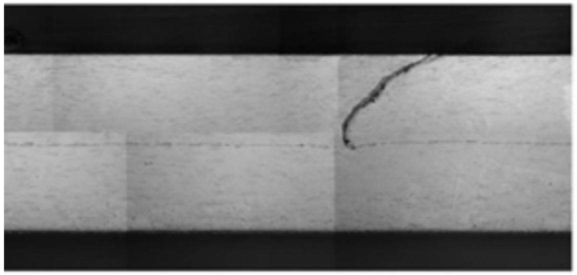
Proof-of-concept for low temperature “superplasticity”

Accumulative Roll Bonding

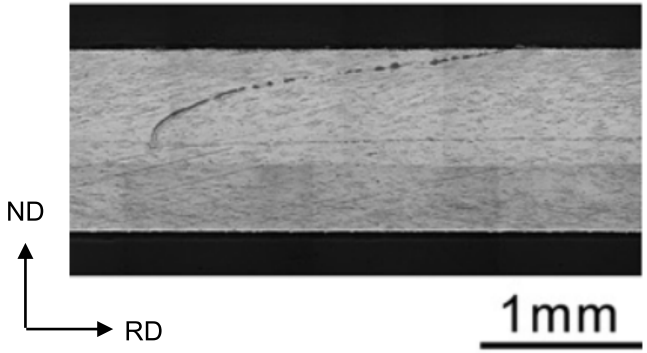
How is ARB different from severe rolling?

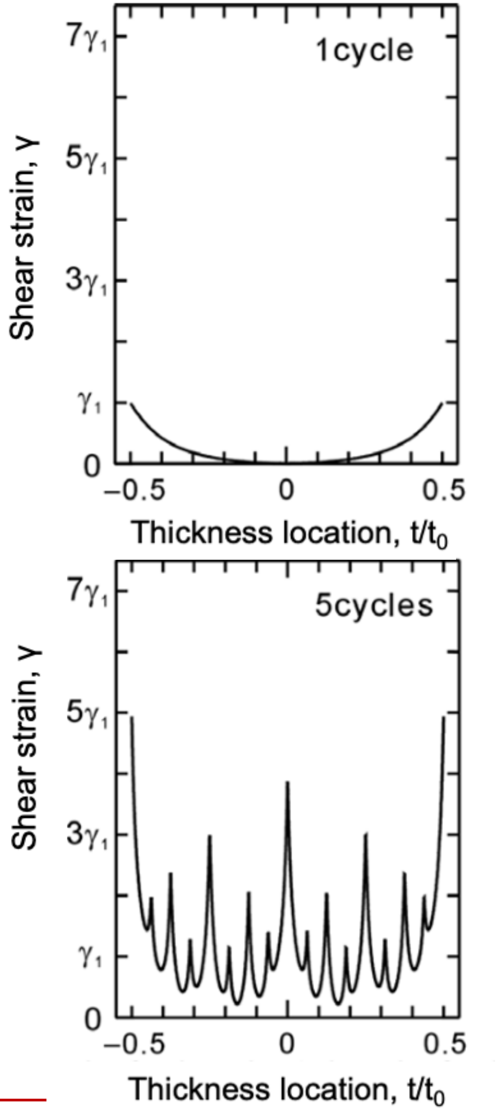
1. High redundant shear
2. Sheared region distribution through thickness

Lubricated – low friction



Unlubricated – high friction





Kamikawa et al., *Acta Materialia*, 2007.

Static Annealing Trials

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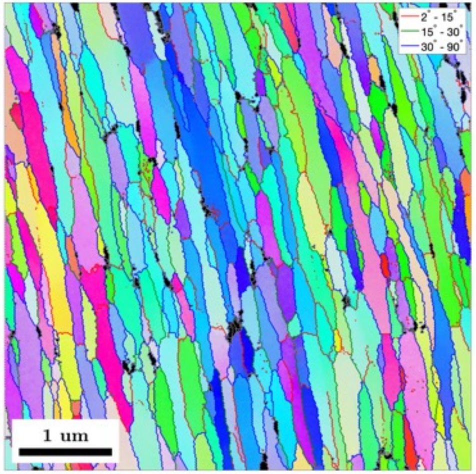
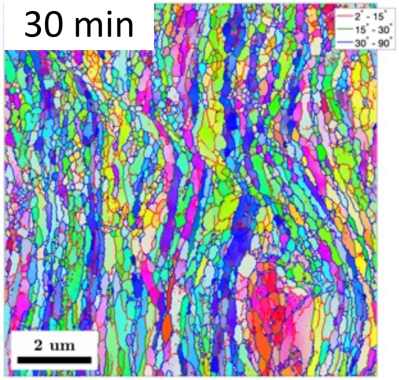
Condition for GBS: Small, equiaxed grains.

5 ARB Cycles



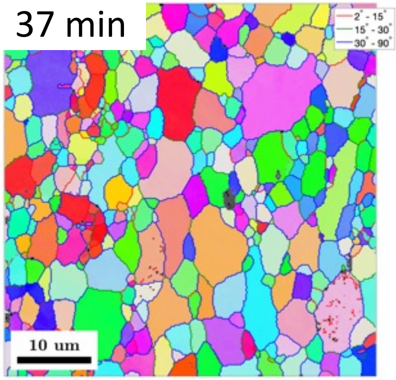
196 °C

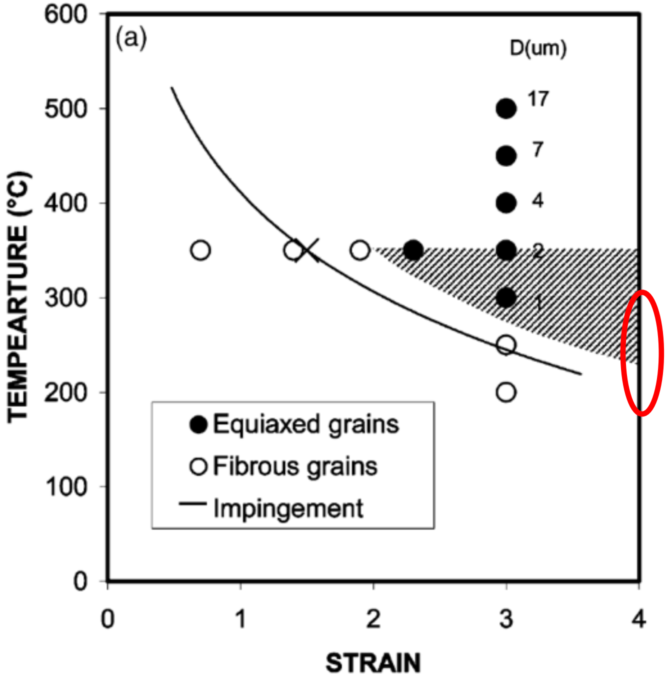
30 min



290 °C

37 min

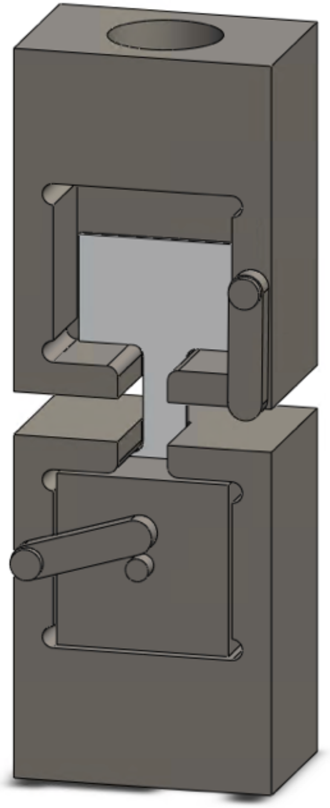


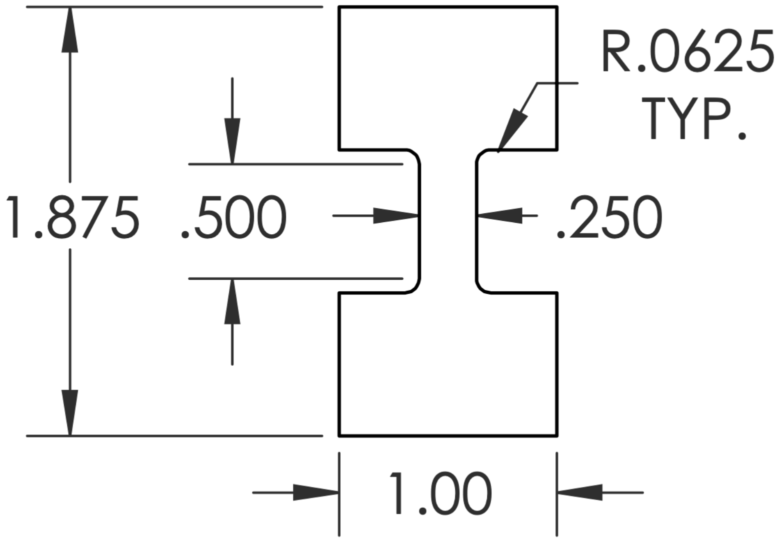


Can <u>static annealing</u> between
200 - 300 °C transform
elongated grains into equiaxed grains?

Gholinia et al, *Acta Materialia*, 2002.

Tensile Geometry





Characterization of ARBed Microstructure

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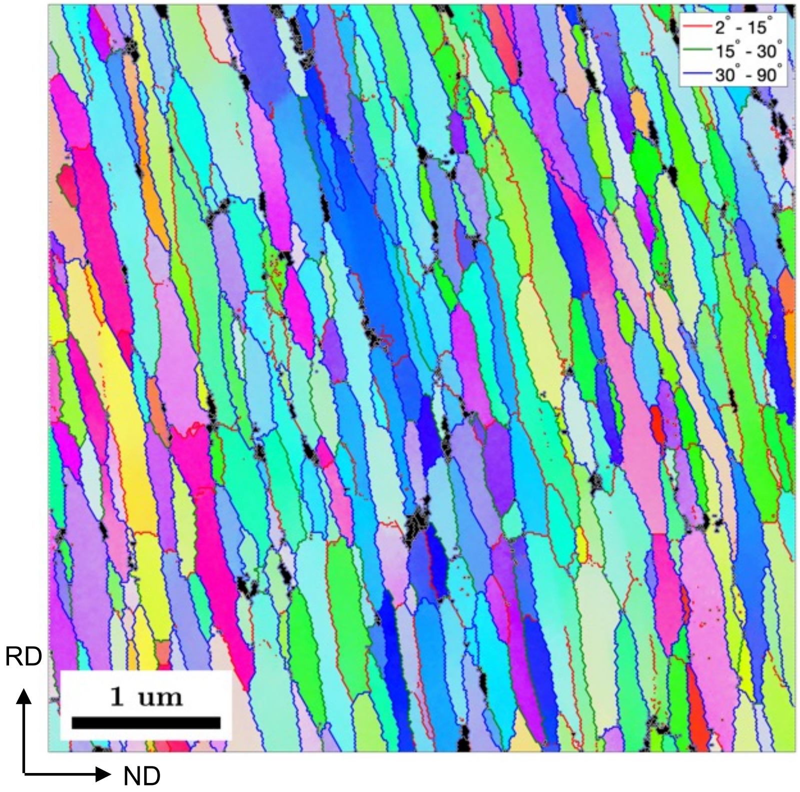

5 ARB cycles produce submicron highly elongated grains