CANFSA

Center for Advanced Non-Ferrous Structural Alloys

An Industry/University Cooperative Research Center

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

Spring Meeting

April 7th – 9th 2020

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

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

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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
- Article on lateral constraint in *Journal of Manufacturing Processes*
- Microstructural characterization of Al 5083 after 5 ARB cycles
- Final grip design & furnace temperature profiles completed for high temperature testing

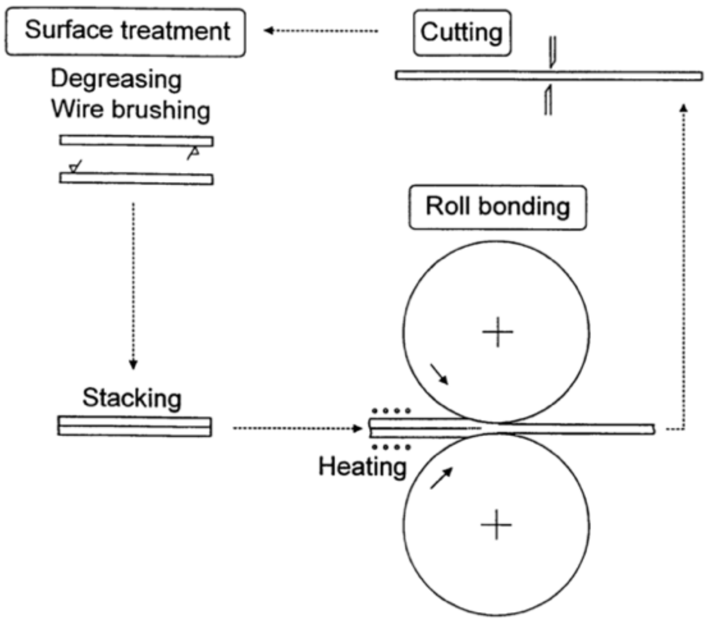
Metrics

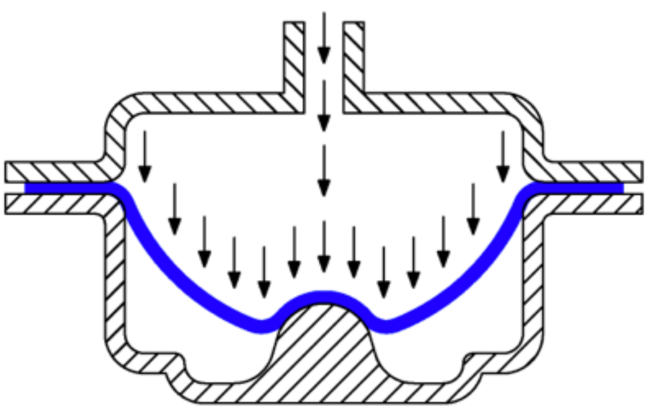
Description	% Complete	Status
1. Literature review	80%	● (green)
2. Characterize 5-cycle microstructure	100%	● (green)
3. Static annealing trials	0%	● (yellow)
4. Round 1: HT Tensile Testing & Characterization	0%	● (green)
5. Round 2: HT Tensile Testing & Characterization	0%	● (green)

Outline

- Introduction to Accumulative Roll Bonding (ARB)
- Characterization of ARBed Microstructure
- Preliminary Tensile Results
  - Tensile elongation
  - Grain-size stability
  - Cavitation
- Project Objectives

Industrial Relevance





Enhanced properties:

- Hall-Petch strengthening
- low temperature superplasticity

Applications:

- superplastic forming
- high strength sheet components

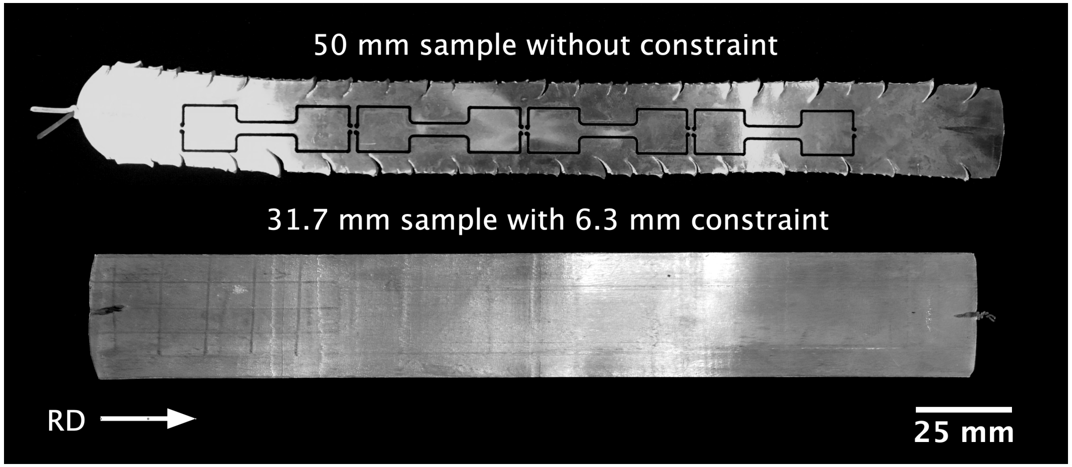
Benefits:

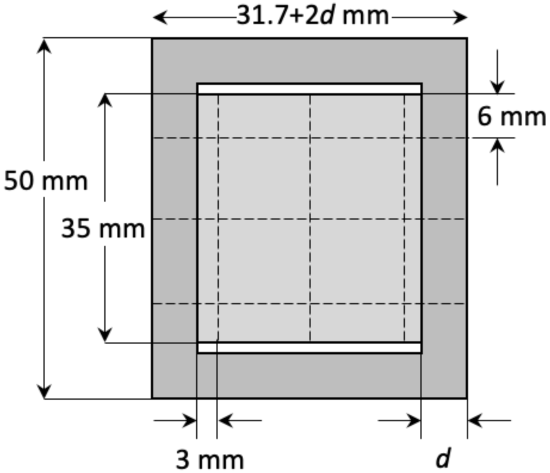
- reduced cycle time
- reduced die wear
- reduced processing cost

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

Developed Processing Procedure

Al 5083 - 5 ARB Cycles





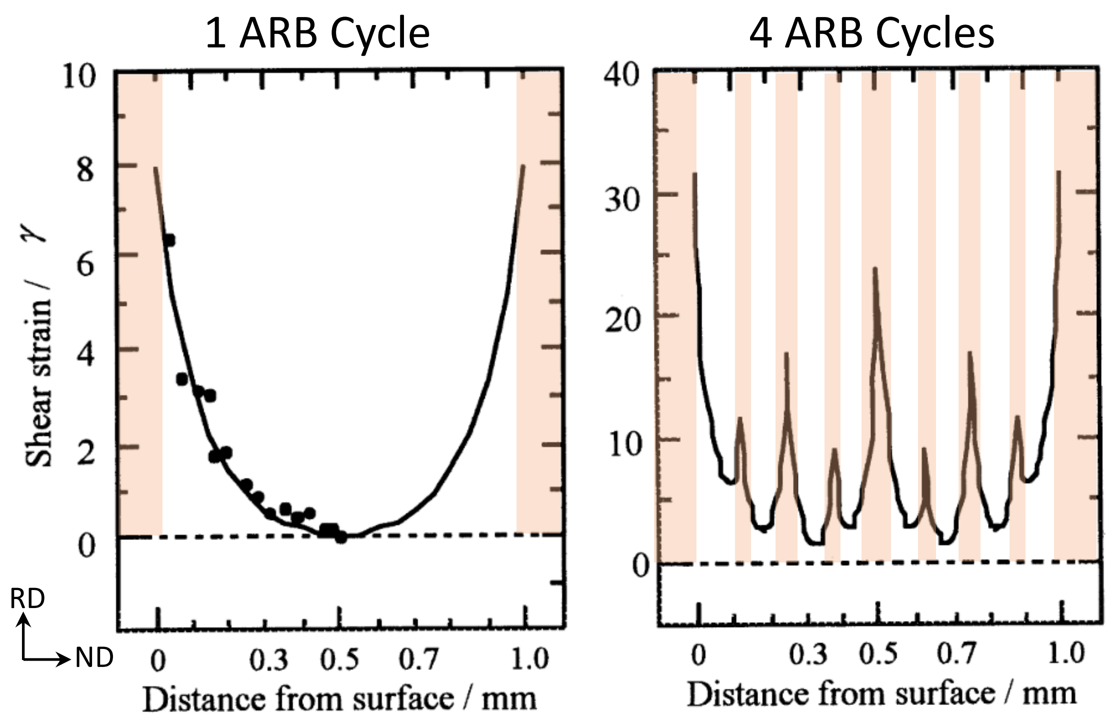
Repeatable mitigation of edge cracking for up to 5 cycles of ARB using constraining frames

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

Characterization of ARBed Microstructure

Grain refinement encouraged by:

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



Microstructural Considerations

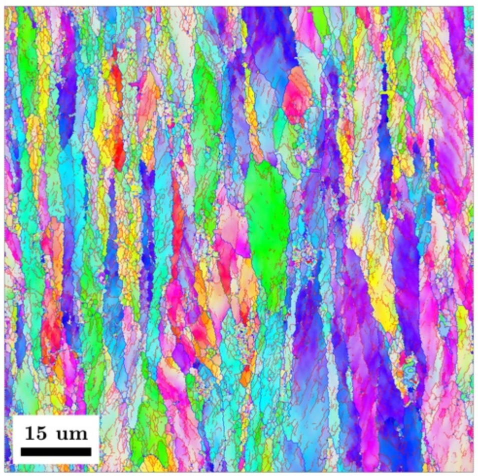
1. What is the extent of grain refinement?
2. Is grain refinement homogenous through thickness?

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

Characterization of ARBed Microstructure

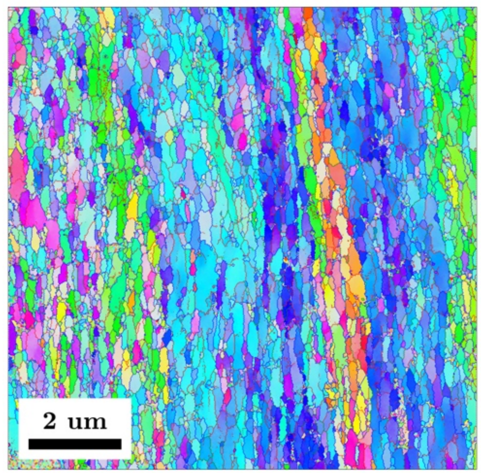
1. What is the extent of grain refinement?

1 ARB Cycle



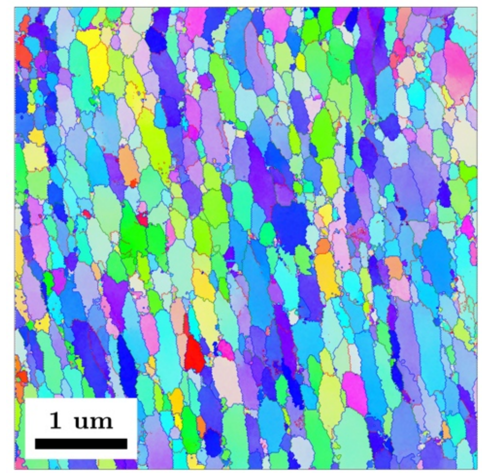
Heavily substructured grains

3 ARB Cycle

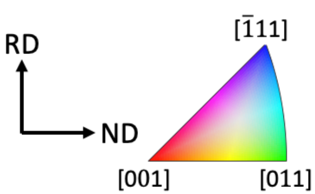


Near-equiaxed (sub)grains in bands

5 ARB Cycle



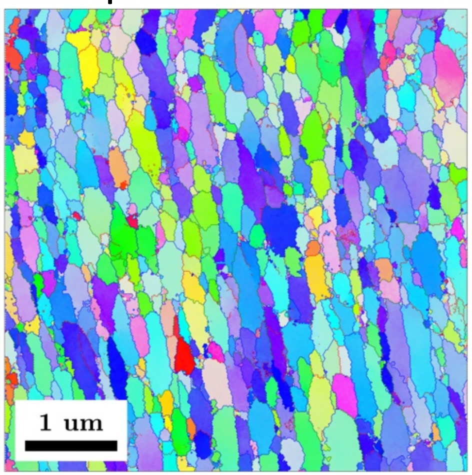
Near-equiaxed grains



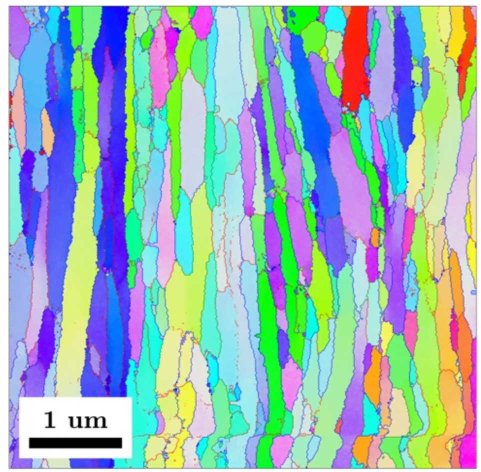
Characterization of ARBed Microstructure

2. Is grain refinement homogenous through thickness?

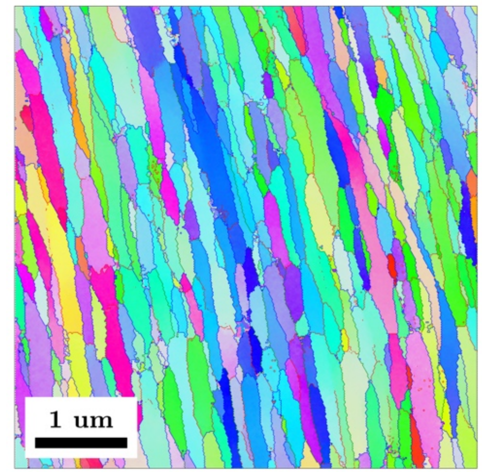
10 μm from surface

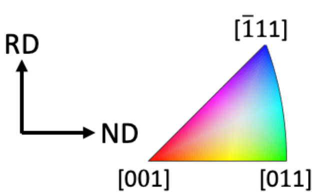


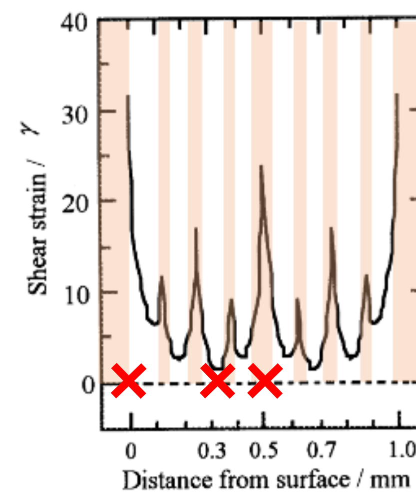
First bond



Centerline bond

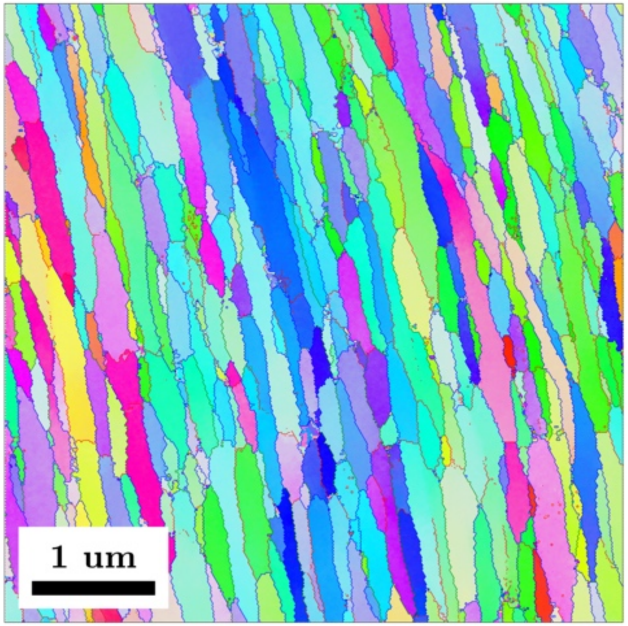


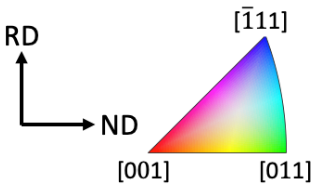


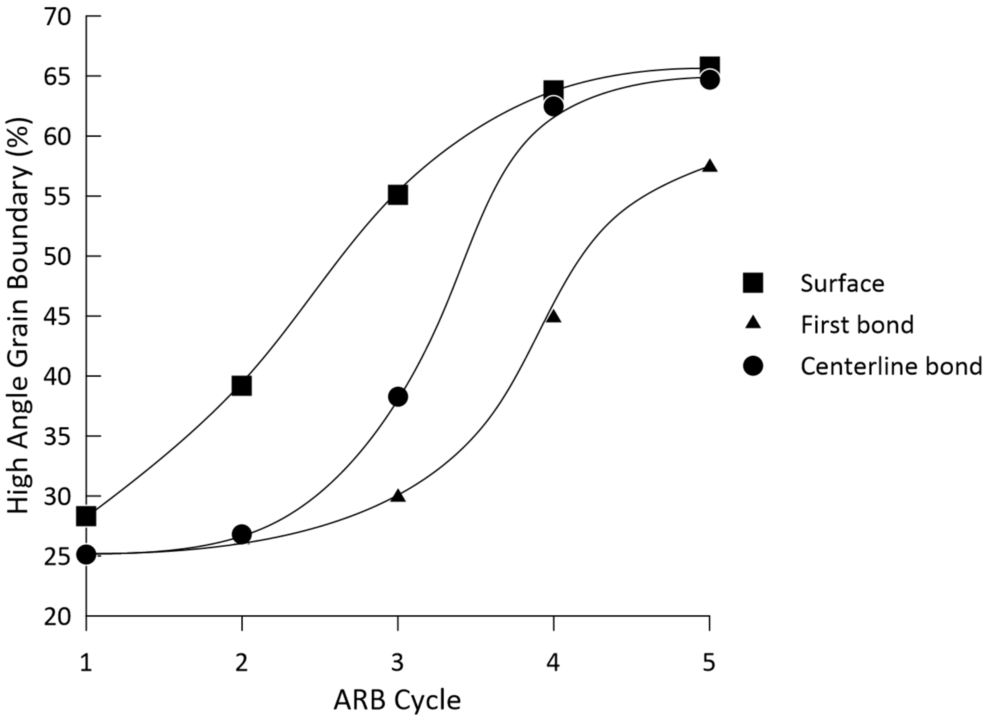


Characterization of ARBed Microstructure

Average grain size
≈250 nm x 1 µm x 1 um grain size



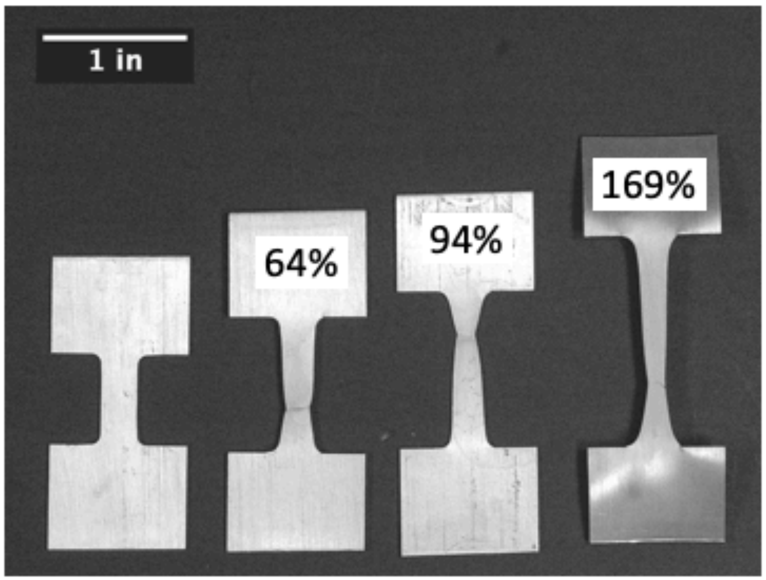




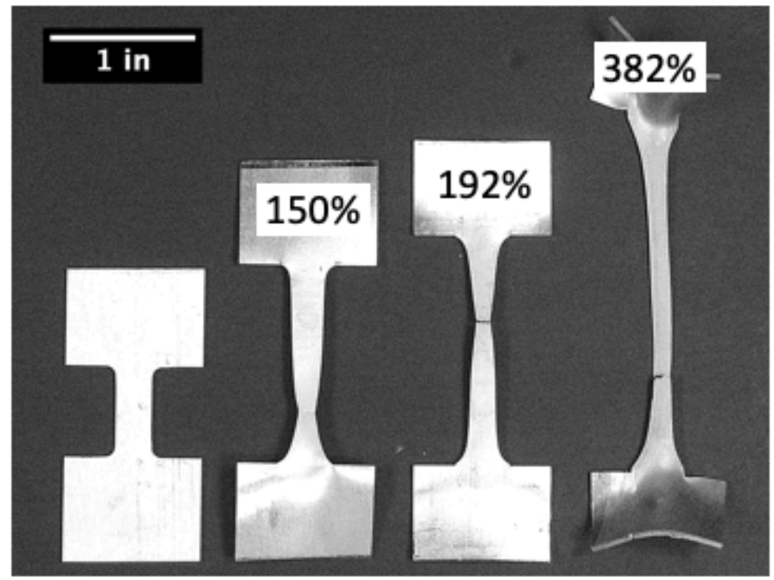
High angle grain boundaries (HAGB) <u>approach saturation</u> after 5 cycles

Preliminary Tensile Results

Conventional Processing
≈15 µm grain size



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



RD
ND

As Machined 196 °C 290 °C 377 °C

As Machined 196 °C 290 °C 377 °C

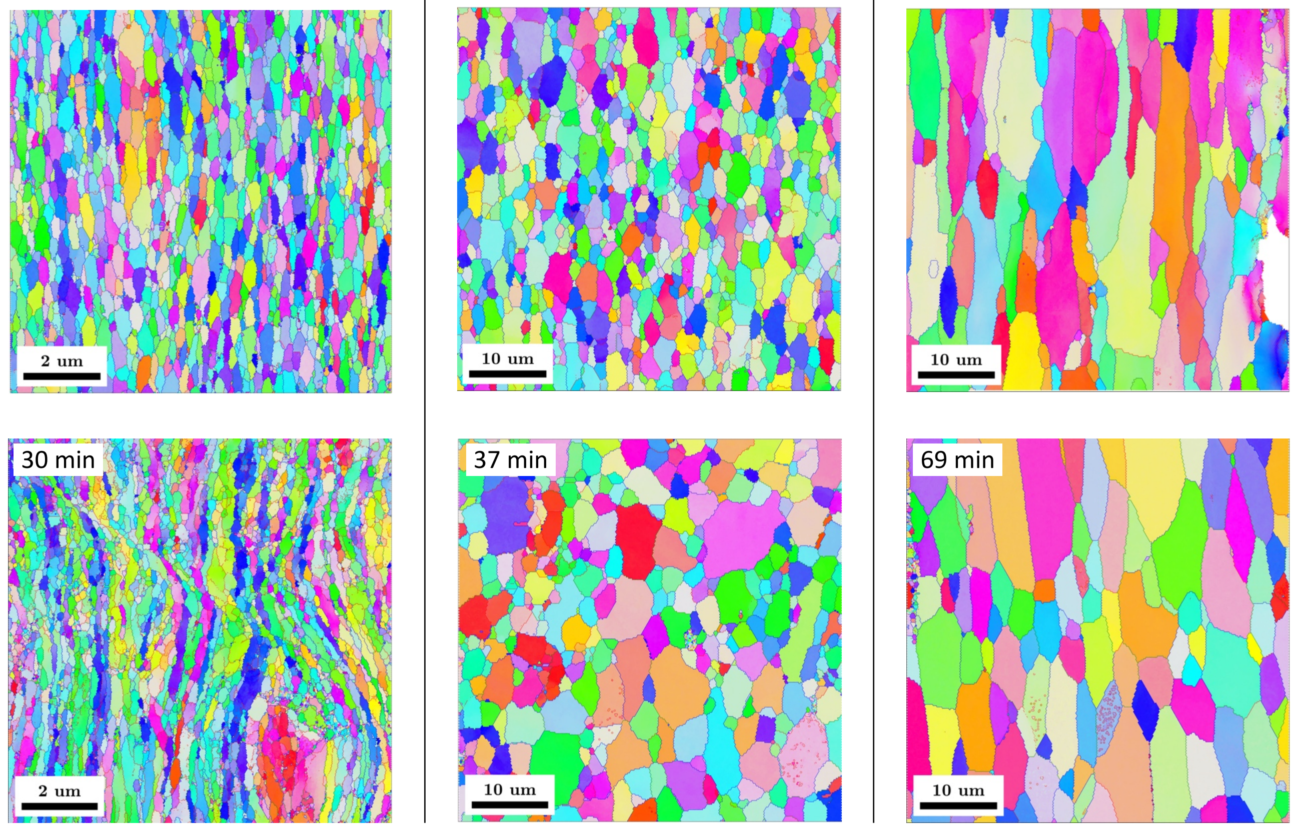
All tested at $\varepsilon_0 = 1 \times 10^{-3}\ s^{-1}$

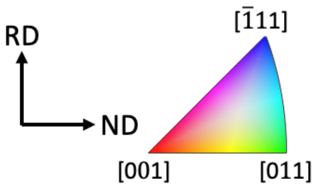
Microstructural Evolution

196 °C | 290 °C | 377 °C

Gauge Section

Grip Section (static anneal)



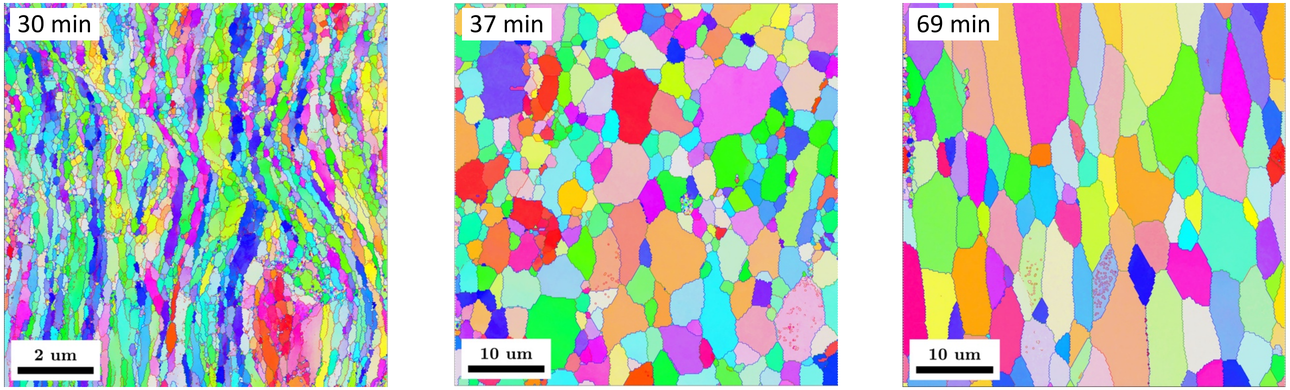


Does static annealing lead to a microstructure more conducive for superplasticity?

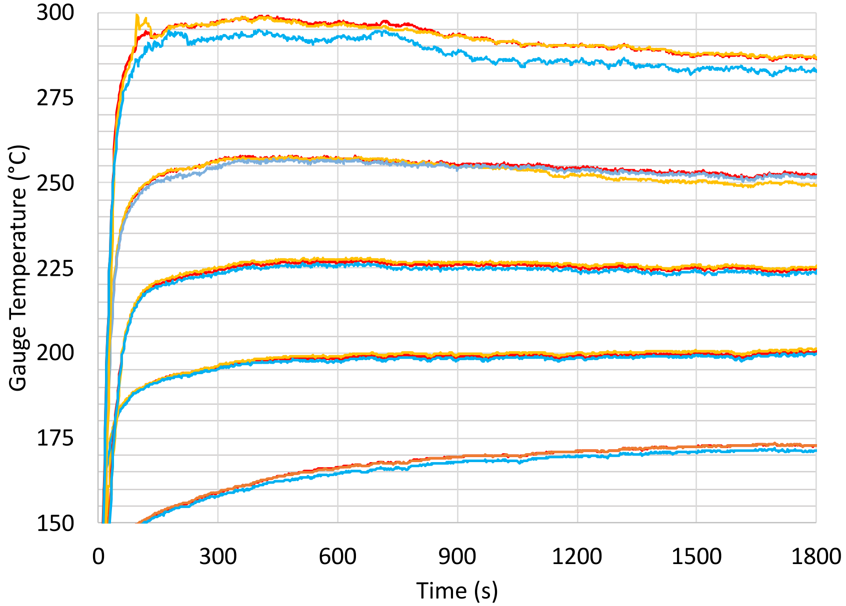
Static Annealing Trials

Grip Section
(static anneal)

196 °C | 290 °C | 377 °C



Sample Heating Profiles

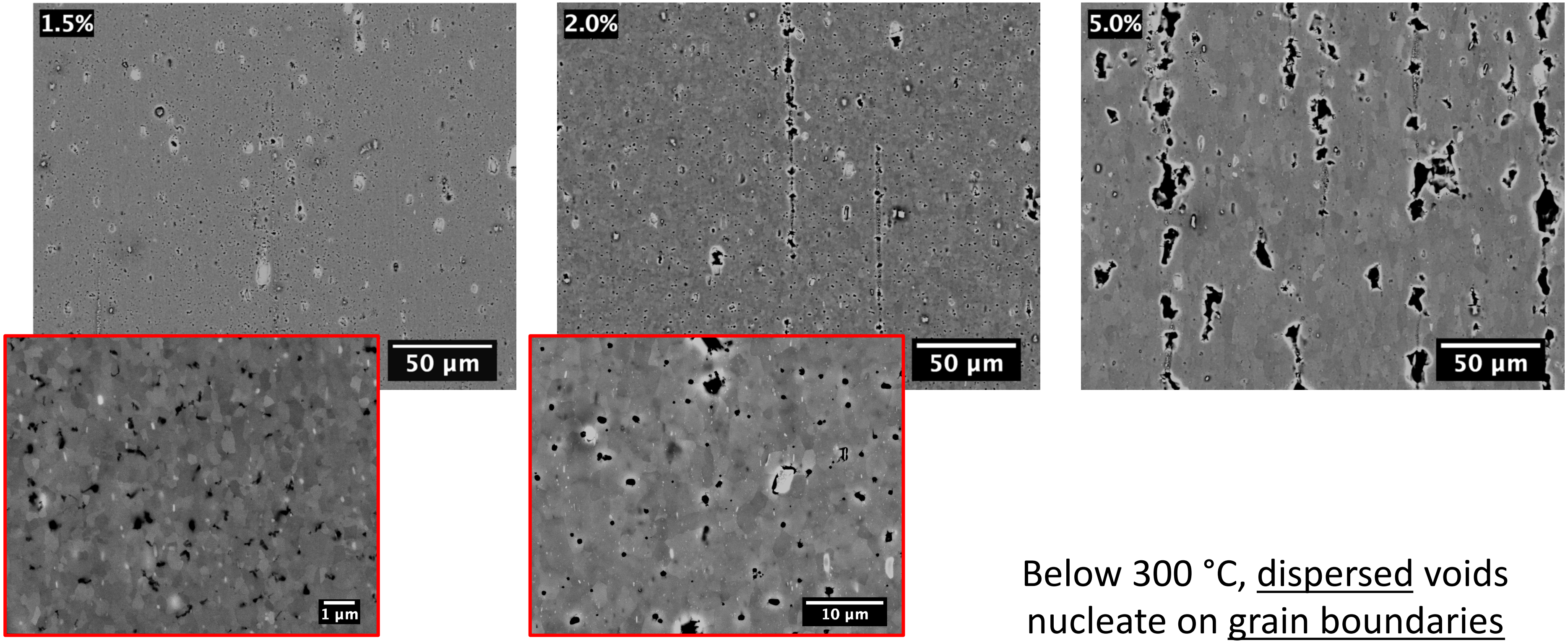


1. Static Annealing Parameters
   - 200, 250, 300 °C
   - 15, 30 minutes

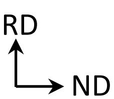
2. Potentially use DSC to complement results

Cavitation during Deformation

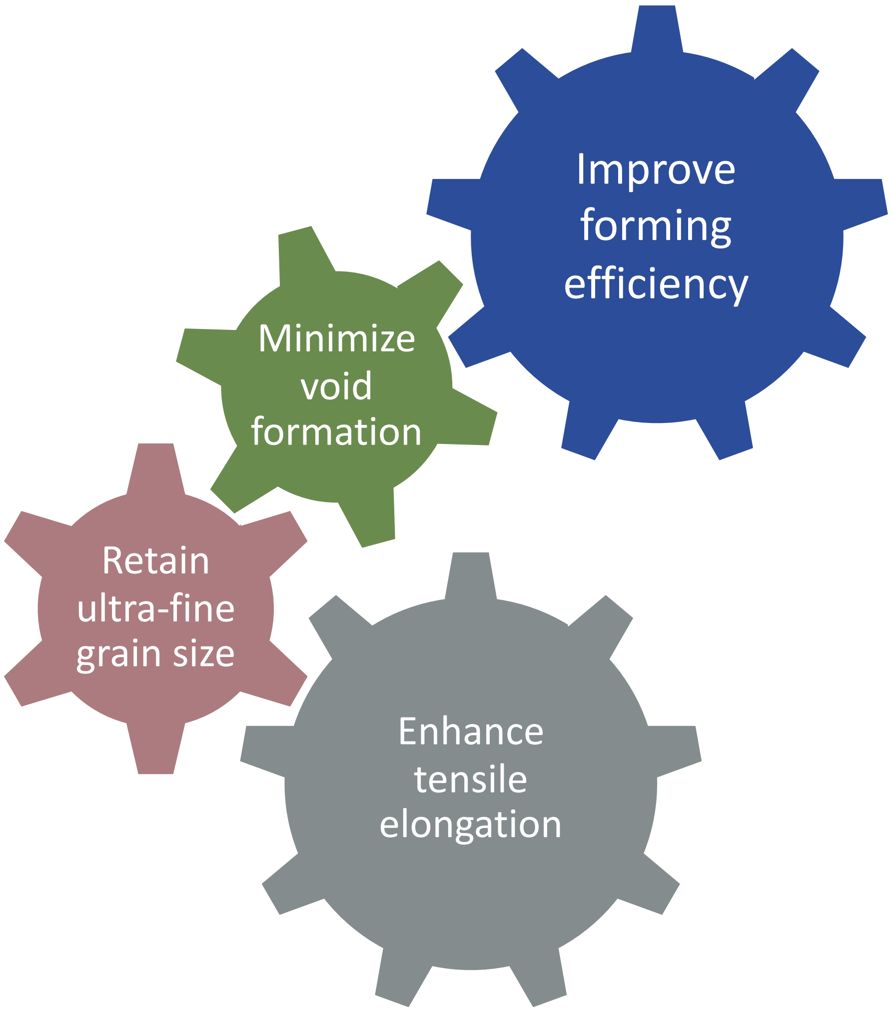
196 °C | 290 °C | 377 °C



Below 300 °C, <u>dispersed</u> voids nucleate on <u>grain boundaries</u>



Optimizing Superplasticity



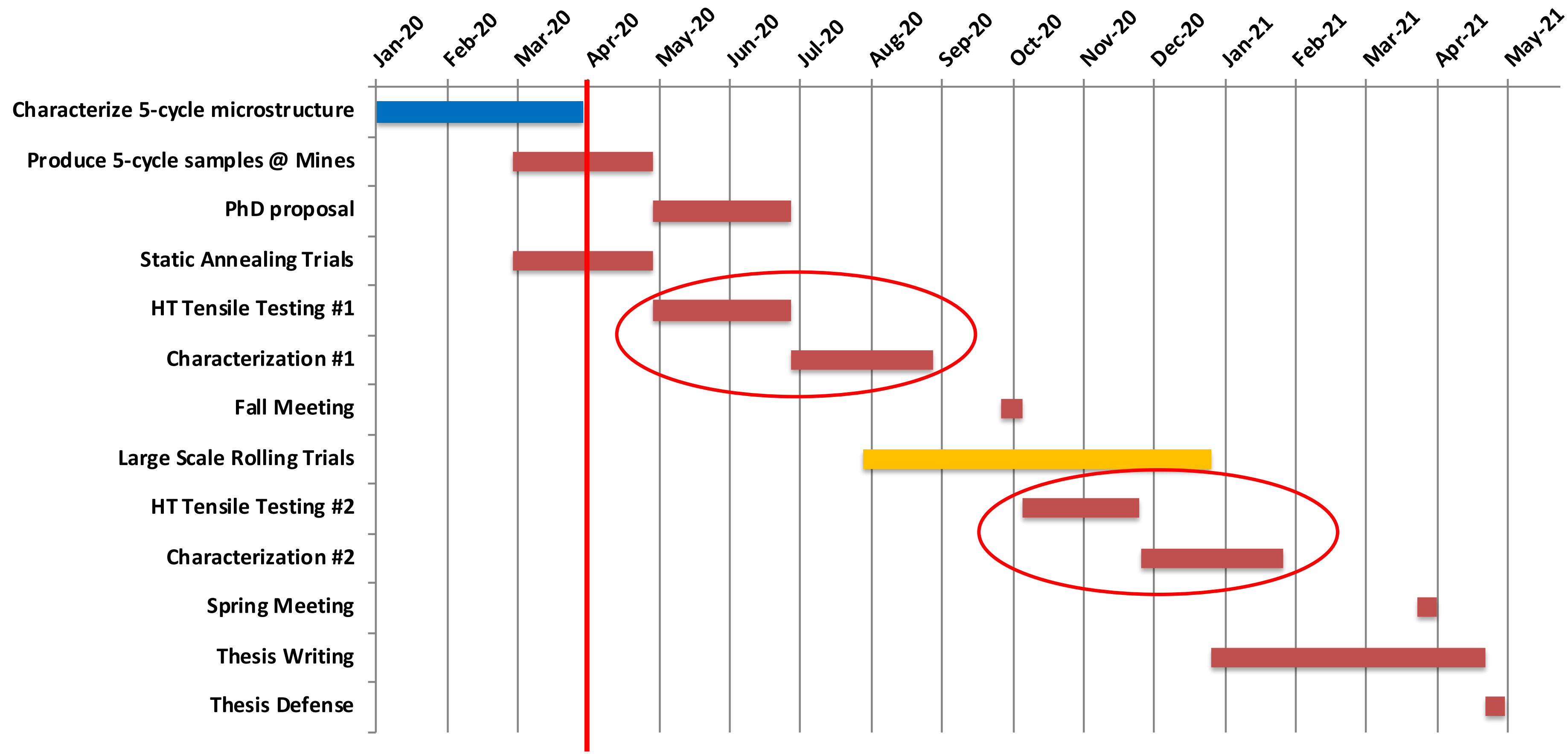
Variables to investigate:

- temperature
- strain rate
- static annealing processes

Conventional processing baseline:

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

Progress


Jan-20
Feb-20
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May-20
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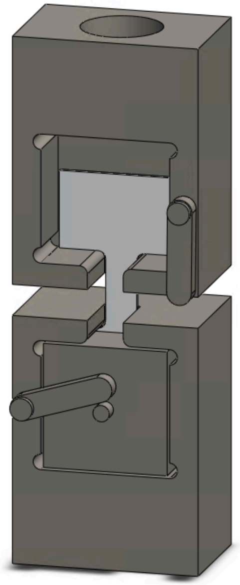
Oct-20
Nov-20
Dec-20
Jan-21
Feb-21
Mar-21
Apr-21
May-21
Characterize 5-cycle microstructure
Produce 5-cycle samples @ Mines
PhD proposal
Static Annealing Trials
HT Tensile Testing #1
Characterization #1
Fall Meeting
Large Scale Rolling Trials
HT Tensile Testing #2
Characterization #2
Spring Meeting
Thesis Writing
Thesis Defense

Challenges & Opportunities

- Increased HT tensile testing capabilities Mines
  - Inconel fixtures for other HT testing (ASTM E2448)
- Access to high-capacity rolling mill (>50 tons)
  - Bulk production of samples for testing
  - Larger samples → formability, anisotropy testing



Thank you!
Brady McBride
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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] B. McBride, K. Clarke, A. Clarke, “Mitigation of edge cracking during accumulative roll bonding of aluminum strips”, *Journal of Manufacturing Processes* (Accepted) (2020)

[4] N. Kamikawa, T. Sakai, N. Tsuji, “Effect of redundant shear strain on microstructure and texture evolution during accumulative roll-bonding in ultralow carbon IF steel”, Acta Materialia vol. 5, pp. 5873-5888, 2007.

[5] I. Hsiao, J. Huang, “Deformation mechanisms during low- and high-temperature superplasticity in 5083 Al-Mg alloy”, *Metallurgical and Materials Transactions A*, vol. 33, pp. 5873-5888, 2007.

[6] J. Pilling, N Ridley, “*Superplasticity in Crystalline Solids*”, CRC Press London, 1989.

Tensile Testing Procedures

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

p, grain size exponent

- examining effect of d on σ, $\dot{\varepsilon}$
- 0 for power law/solute drag creep
- 2 for lattice diffusion
- 3 for grain boundary diffusion

m, strain rate sensitivity

- examining effect of $\dot{\varepsilon}$ on σ
- 0.2 – 0.4 for dislocation creep
- > 0.5 for grain boundary sliding

Q, activation energy for diffusion process

- examining effect of σ on T
- lattice diffusion
- solute / pipe diffusion
- grain boundary diffusion

Proposed Testing Procedure

Strain-rate-jump test:

- constant T, $\Delta\dot{\varepsilon}$

Elongation-to-failure* test:

- constant T, $\dot{\varepsilon}$

*and interrupted

Hsiao & Huang, *Metallurgical and Materials Transactions A*, 2002.
Pilling & Ridley, *Superplasticity in Crystalline Solids*, 1989.