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 2019 Semi-Annual Meeting
Iowa State University, Ames, IA
April 3-5, 2019

Student: Brady McBride (Mines)

Faculty: Dr. Kester Clarke (Mines)

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

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 March 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 and Ti alloys.
- Benefit: Low temperature superplasticity could result in reduced cost and cycle time due to reduced deformation temperatures and increased strain rates.

Recent Progress

- Five successful ARB cycles of Al 5083
- Modification of existing ARB process to reduce edge cracking
- Preliminary EBSD, TEM data from Al 1100 and Al 5083 roll bonded material
- Design grips for superplastic tensile testing to mitigate sources of error

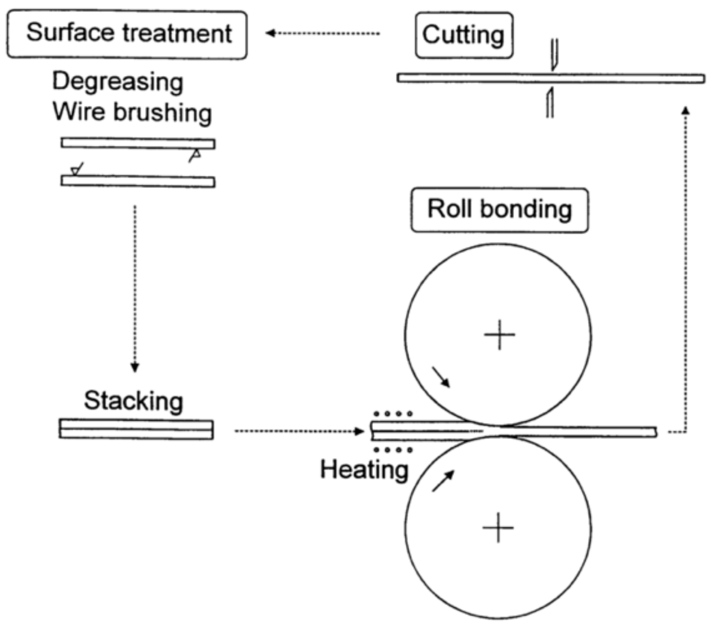
Metrics

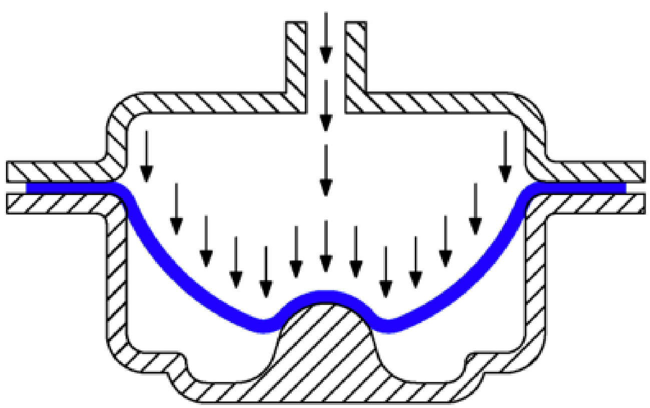
Description	% Complete	Status
1. Literature review	65%	●
2. ARB process development	100%	●
3. Investigate roll bonding process parameters (literature review)	100%	●
4. Mechanical & microstructural characterization	10%	●
5. Process refinement / alloy selection for optimized superplasticity	0%	●

Outline

- Project Overview / Industrial Relevance
- Introduction to Accumulative Roll Bonding (ARB) process
- Development of ARB Process
  - Al 1100 → Al 5083
- Mitigation of edge cracking
- Tensile testing for superplasticity
- Techniques for microstructural analysis
- Future Work

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.

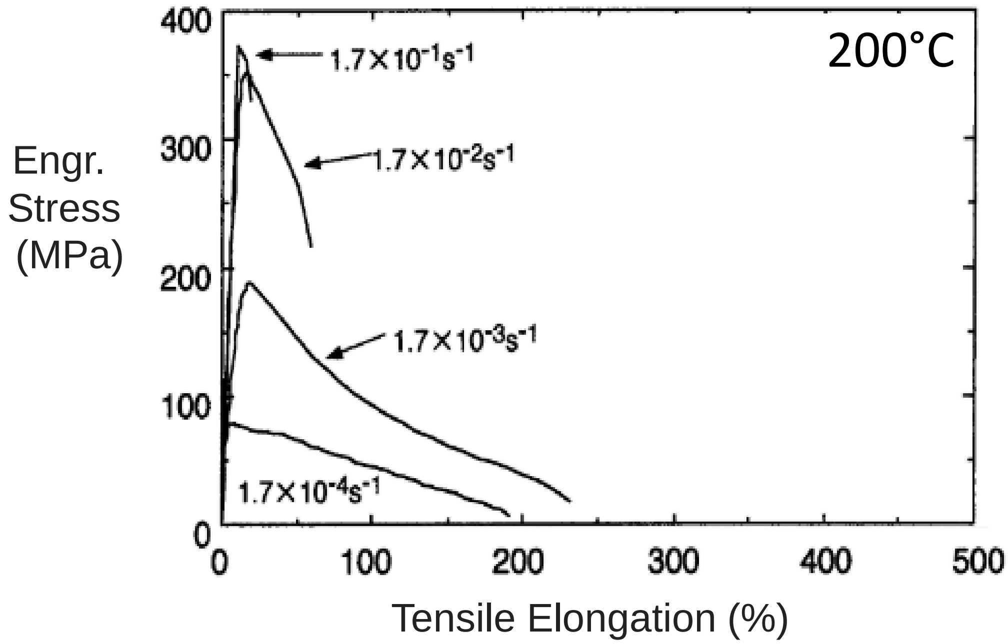
Project Motivation

Conventional superplasticity:

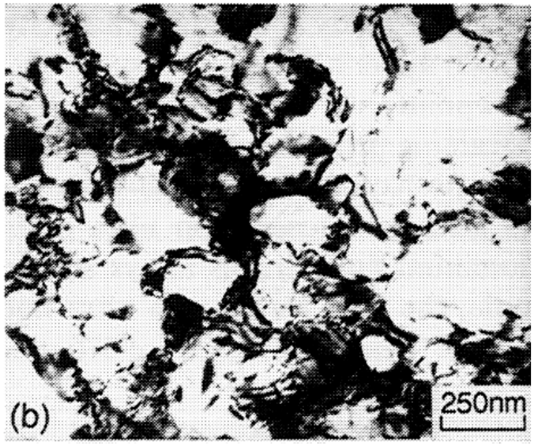
Grain Size: < 10 µm

Temperature: ~ 500 °C (0.9 T_H)

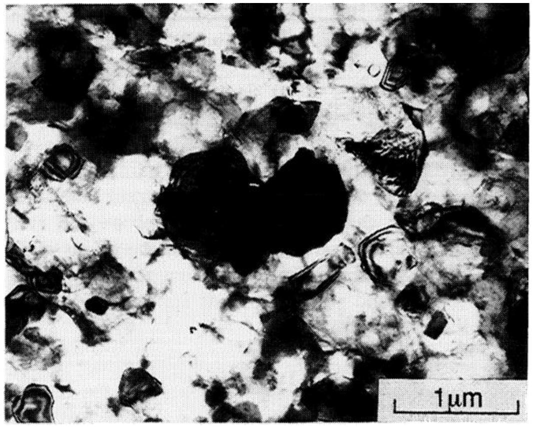
Elongation: ~ 300%



6 ARB Cycles – 250 nm



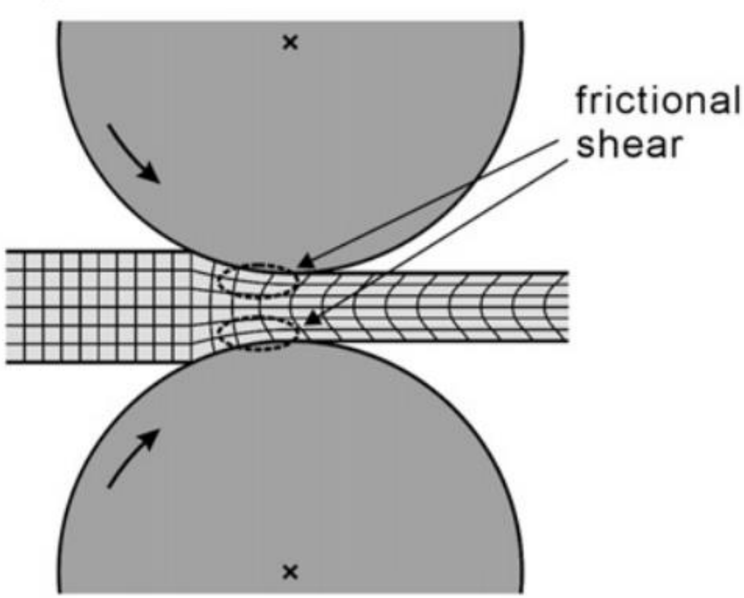
200 °C, 220% elongation – 580 nm

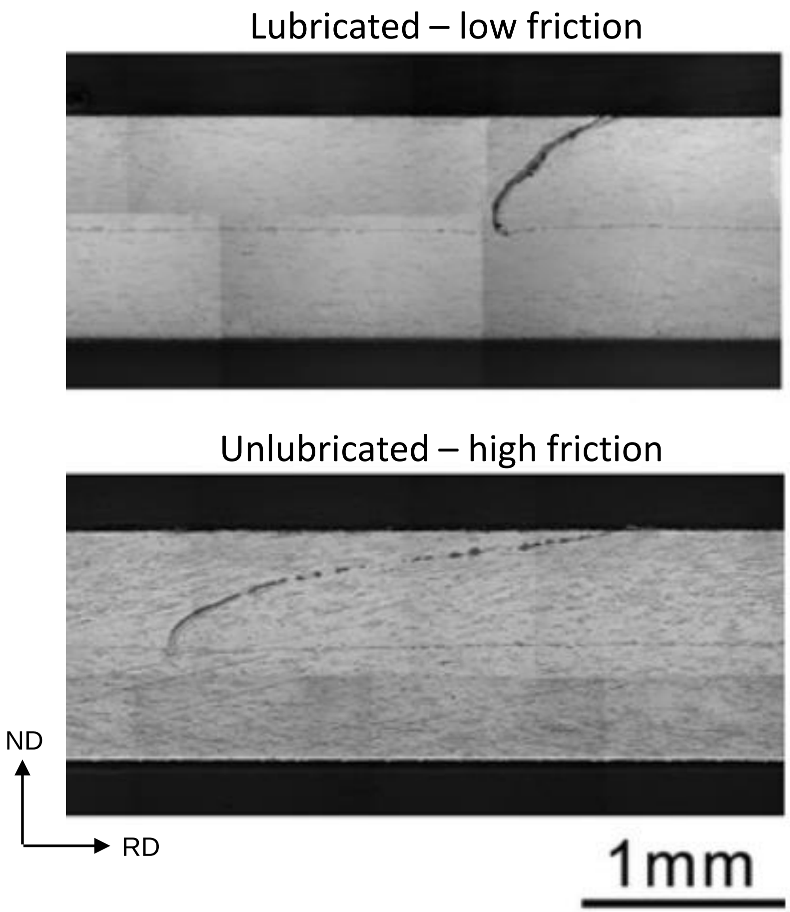


Tsuji et al., *Materials Transactions*, 1999.

Role of Redundant Shear

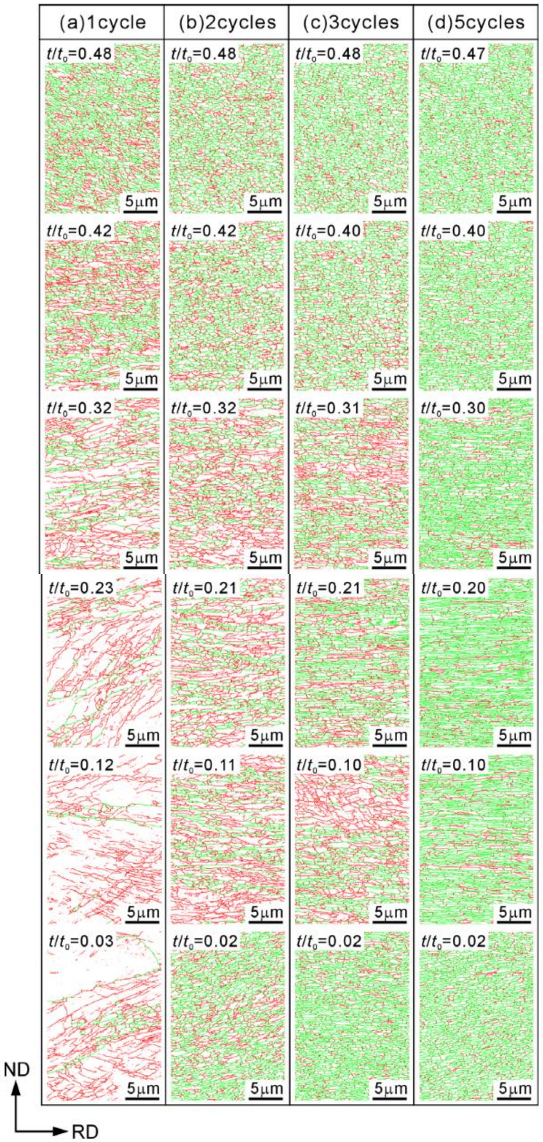
Q: How is ARB different from conventional rolling?





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

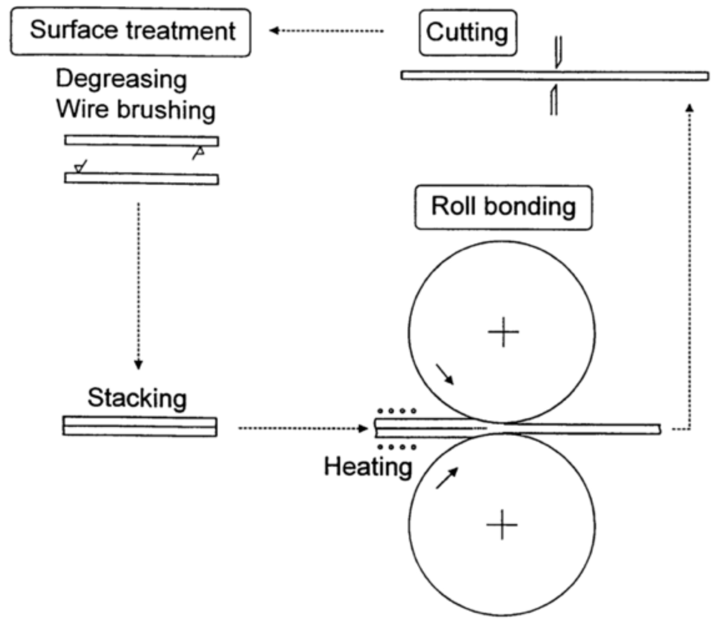
Role of Redundant Shear



θ≥15°

2°≤θ<15°

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

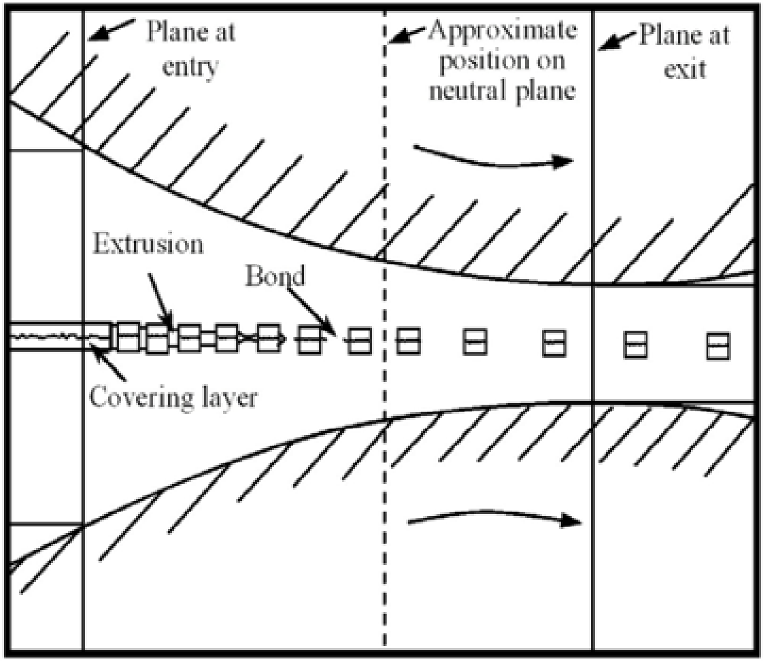


Homogenous microstructure through thickness after 5 ARB cycles in <u>1mm thick samples</u>

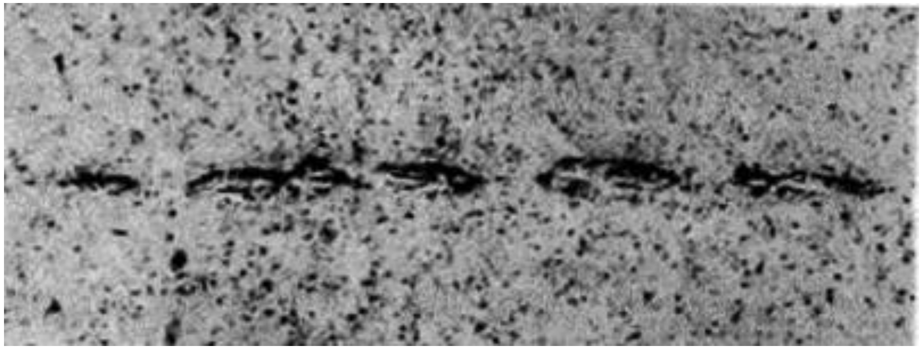
Surface Preparation

Acetone Degrease → Wire Brush → Roll 50% Reduction

(Preheat)

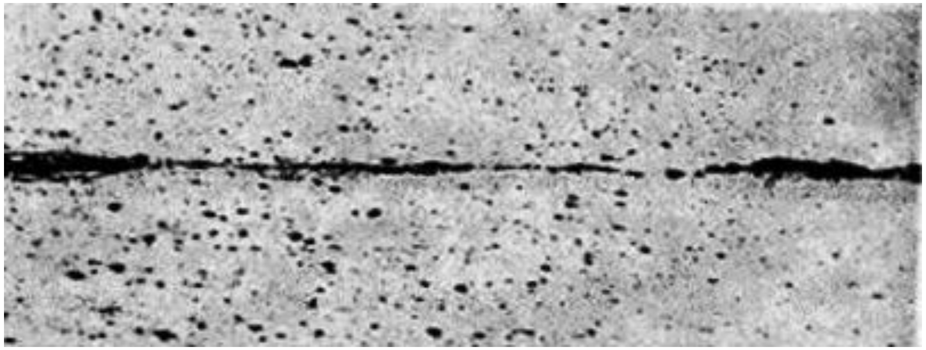


Room Temperature



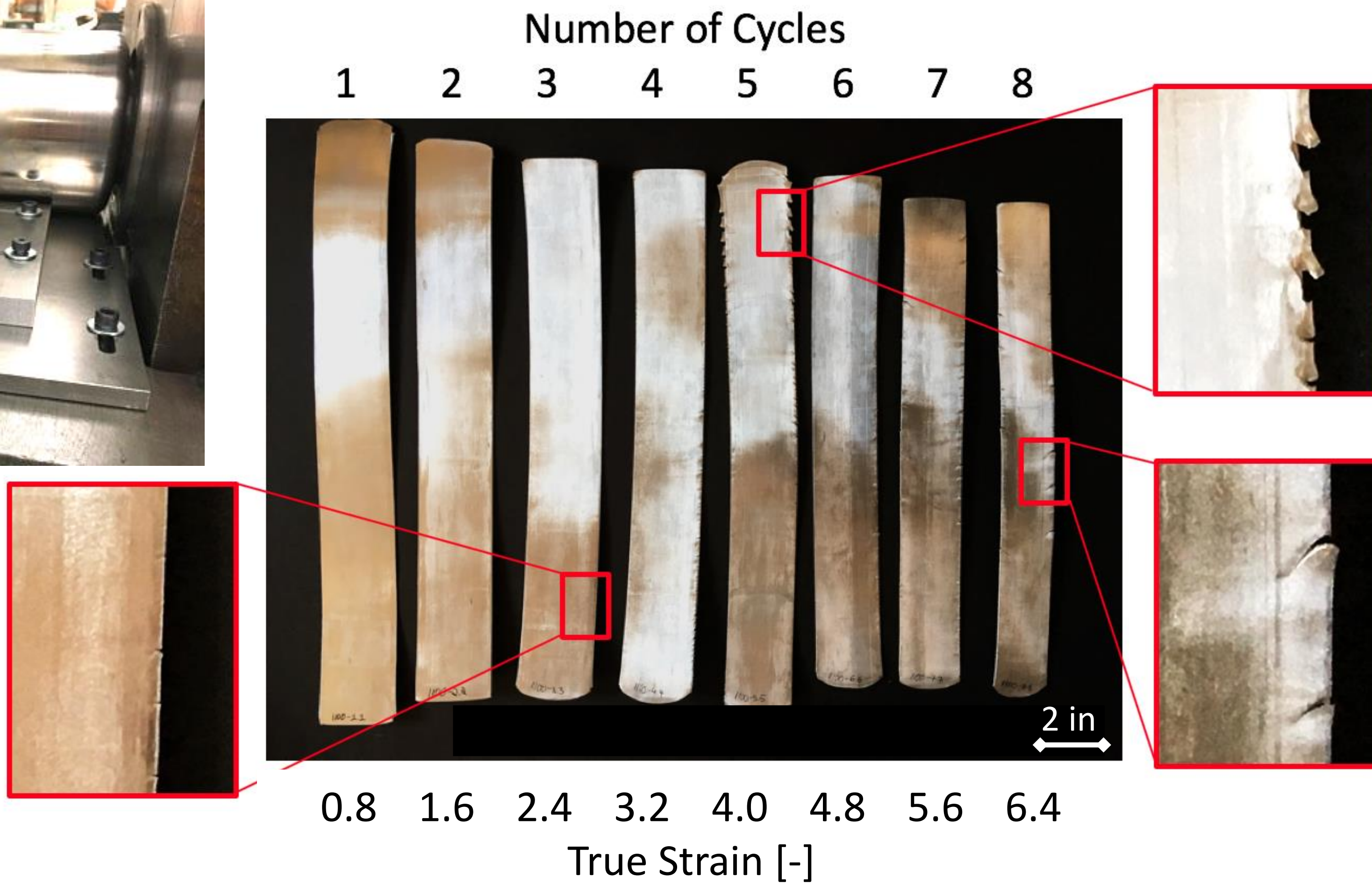
100 µm

> 300 °C



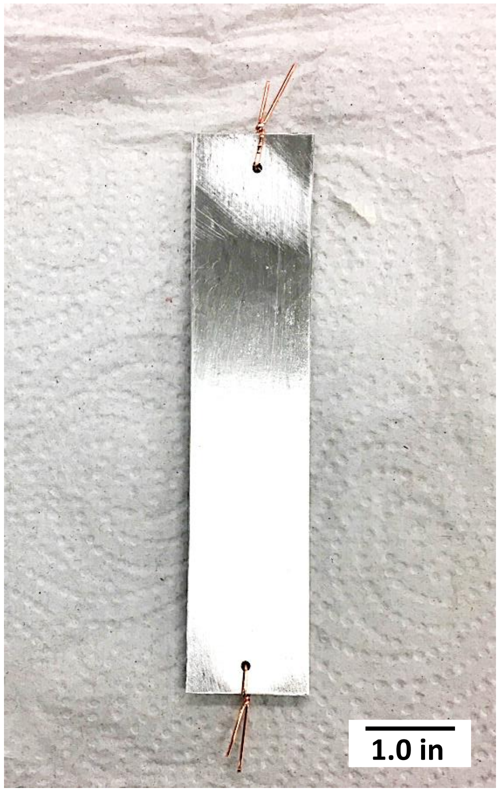
M.G. Nicholas, *British Welding Journal*, 1961.

Al 1100 ARBed Samples



Edge Crack Mitigation

Material Overhang
Al 2024 – 2 ARB cycles

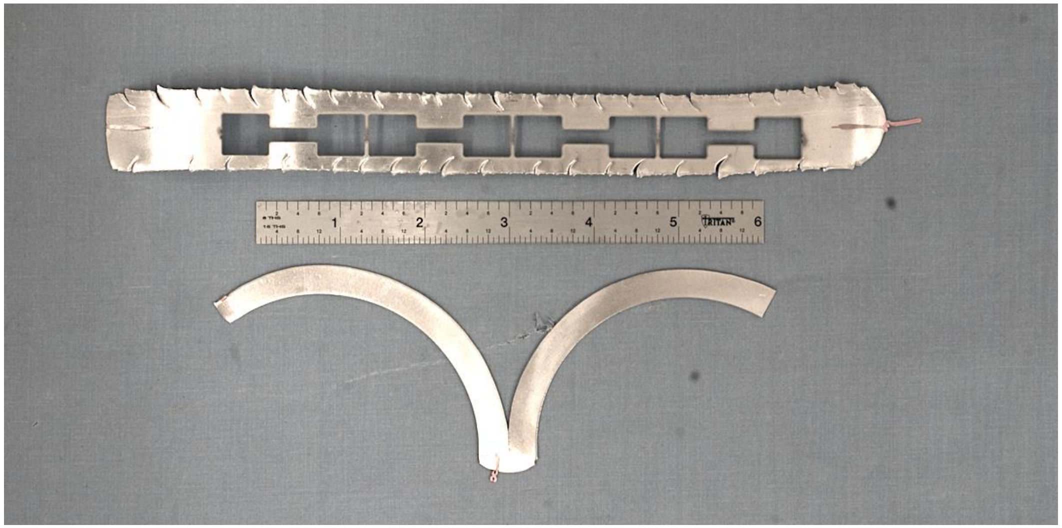


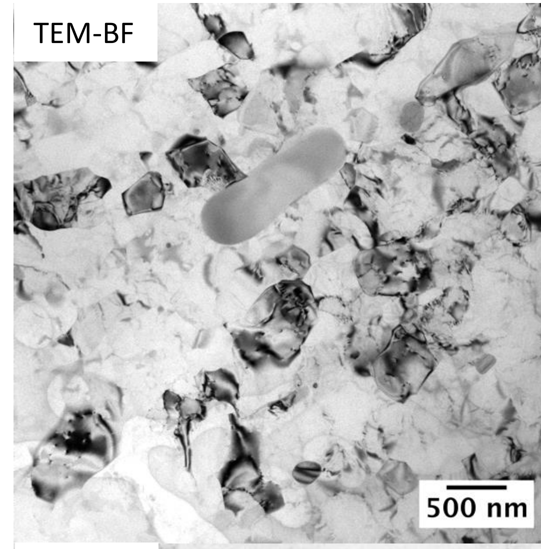
Wire Binding

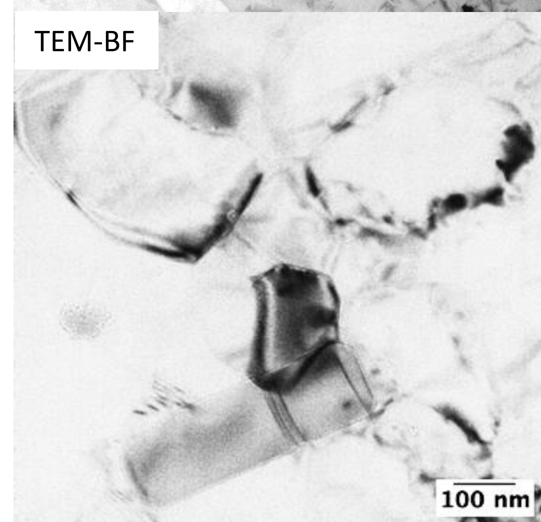
Lateral Spreading
Al 5083 – 4 ARB Cycles

Drill Holes → Scotch Brite → Acetone Degrease → Wire Brush → Wire Bind → 250°C 5 min → Roll 50% Reduction

5 Cycles of Al 5083

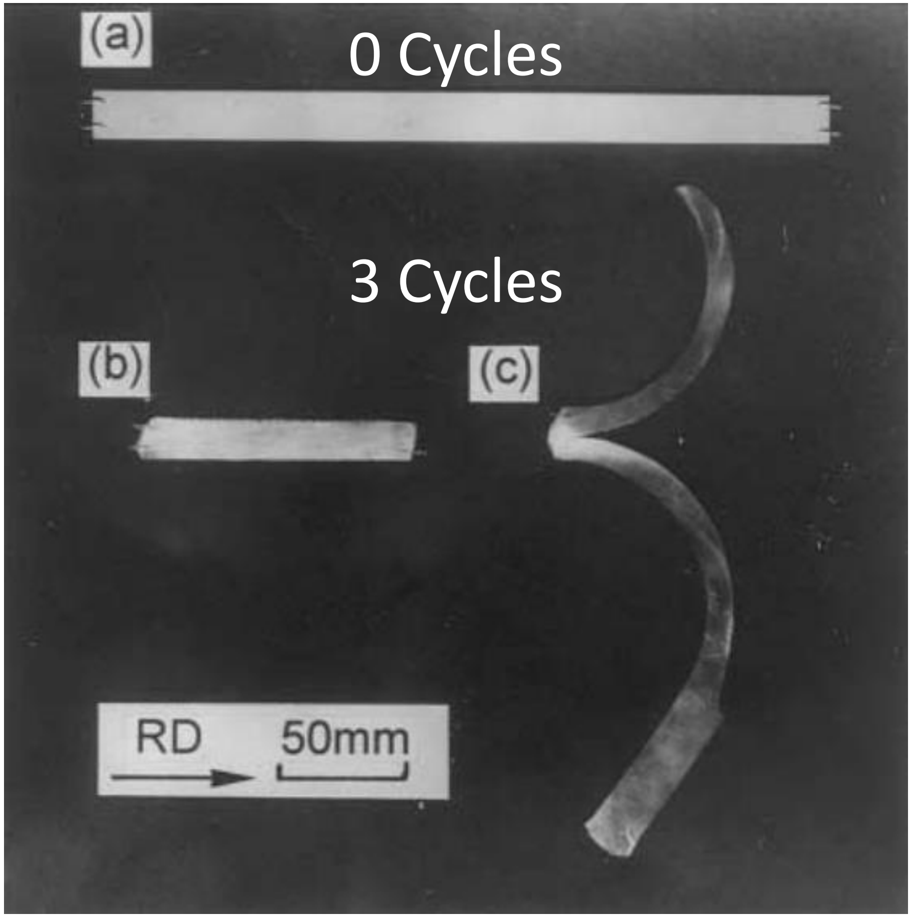


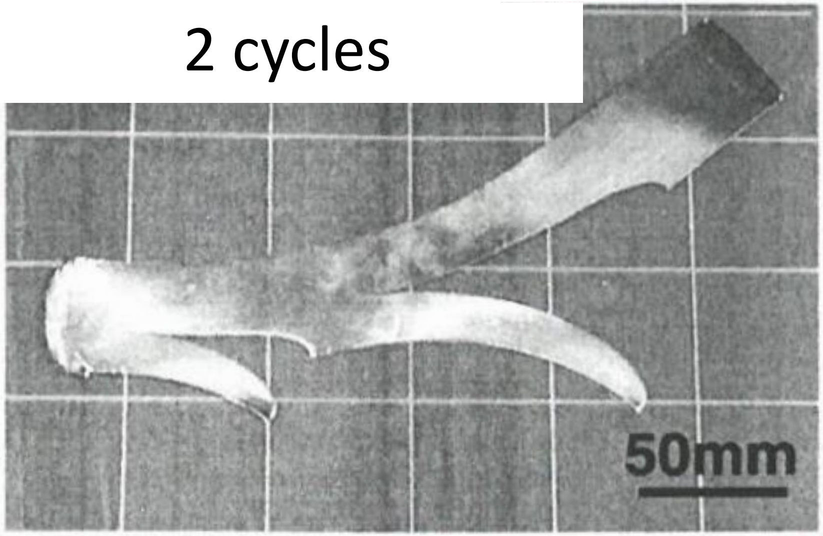




ARB Cycles:	5
Individual layers:	32
True Strain:	~4.0
Effective reduction:	~96.9%
Grain size:	~500 nm

Edge Cracking in Literature





Al 5083 rolled at 200 °C

Saito et al., *Acta Materialia*, 1999.

N. Tsuji, *Severe Plastic Deformation*, 2006.

Edge Crack Mitigation

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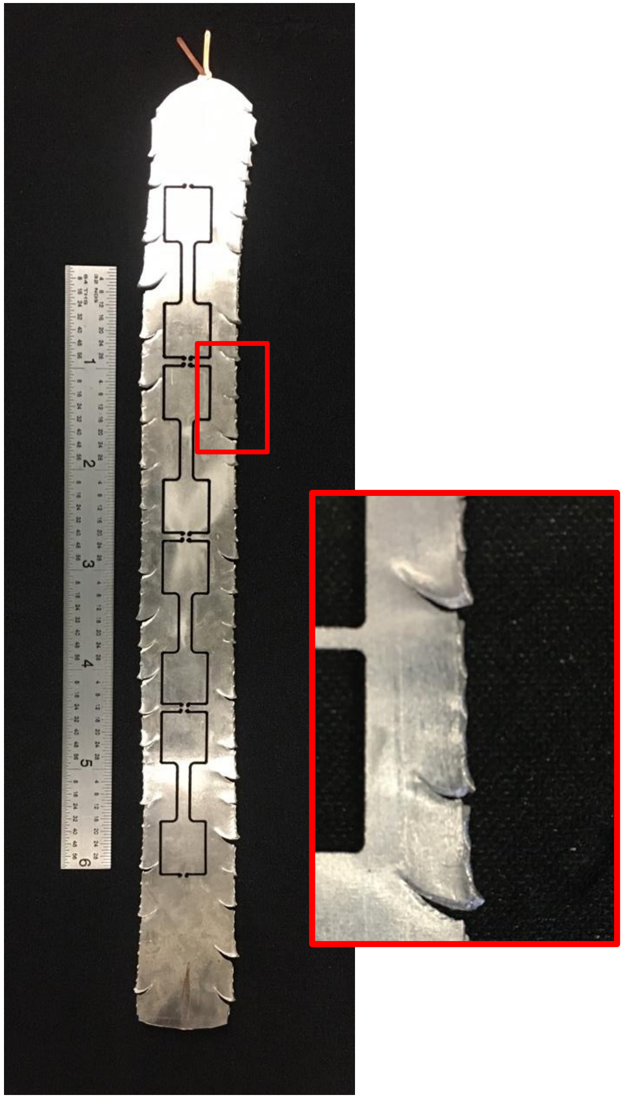
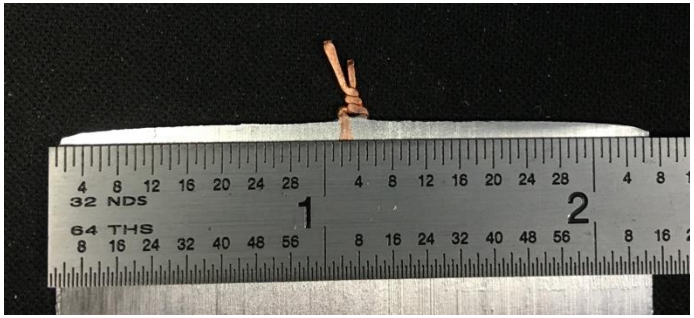
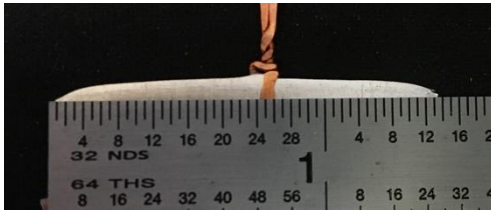
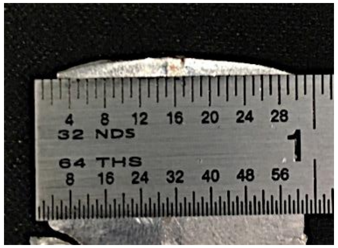




2 ARB Cycles



4 ARB Cycles

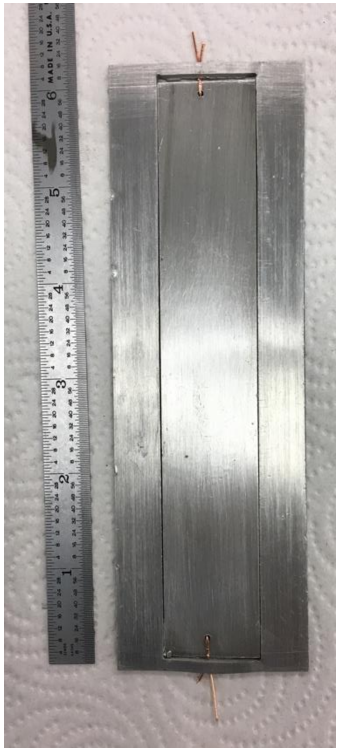


5 ARB Cycles

Edges elongate less than centerline due to lateral spreading, leading to edge cracking

Imposing Lateral Constraint

0.080” Al 1100 window



Constrained

4 ARB Cycles
~0.035” spread

Unconstrained

2 ARB Cycles
~0.060” spread

Imposing Lateral Constraint

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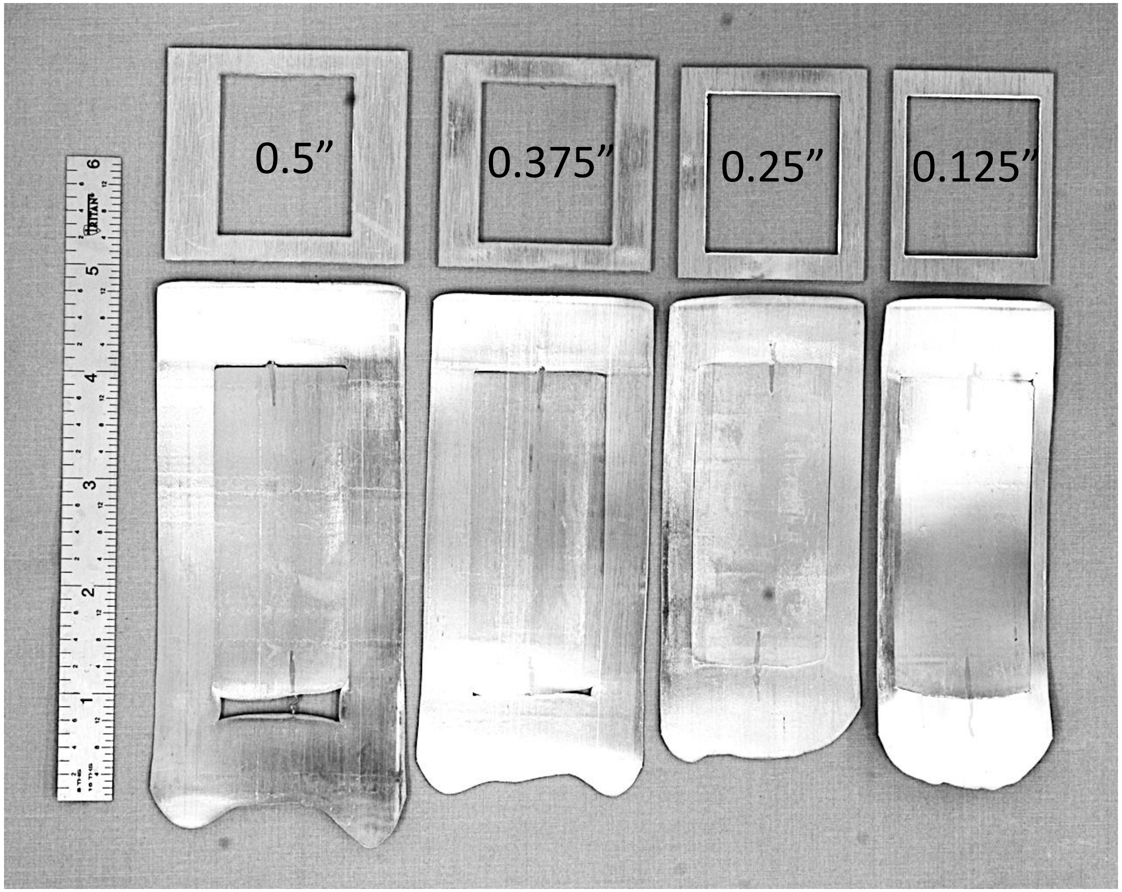
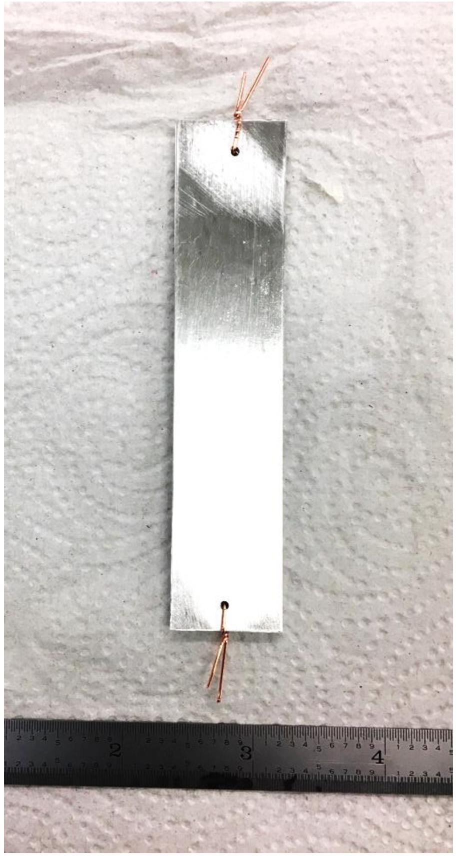


0.030” 0.027” 0.039” 0.030”

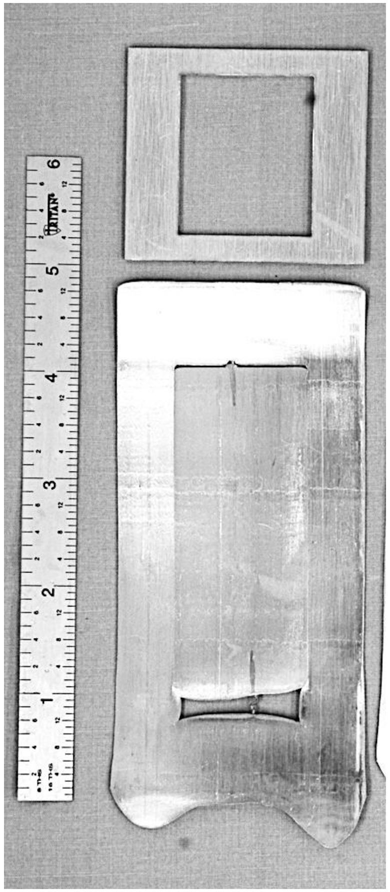
Lateral constraint keeps spreading below 0.040”

3 Constraints Needed

Edge Guides
Align Material to Mill



Wire Binding
Prevent relative movement



Lateral Constraint
Prevent lateral spreading

Superplastic Tensile Design

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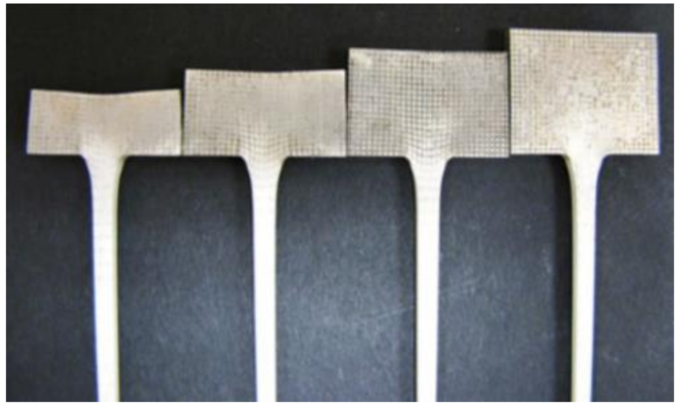
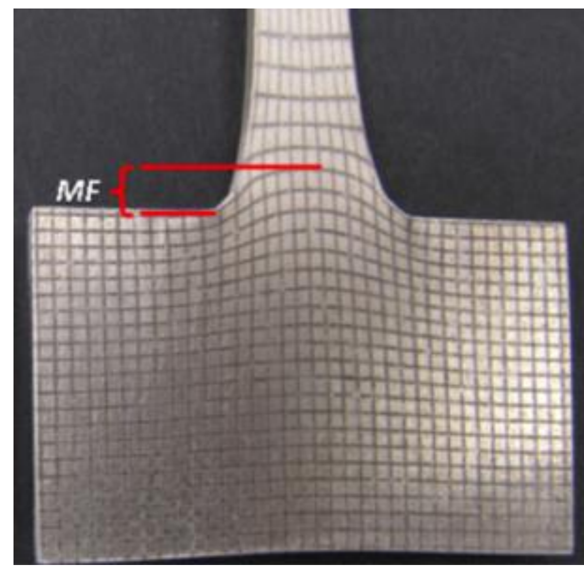
Temperatures:	200 – 500 °C
Strain Rates:	$10^{-2} – 10^{-4}$ s^{-1}
Anticipated loads:	10 – 100 lbs
Control modes:	Constant crosshead Constant strain rate

Superplastic Tensile Design

Variation in
gauge aspect ratio



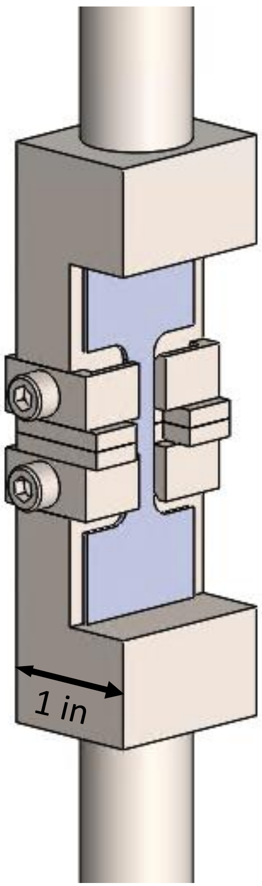
Variation in
grip aspect ratio



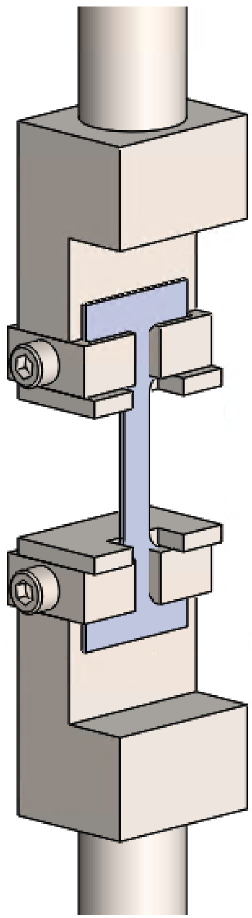
Material flow leads to:
- elevated flow stress
- elevated strain
- inaccurate strain rates

Abu-Farha et al., *Experimental Mechanics,* 2011.

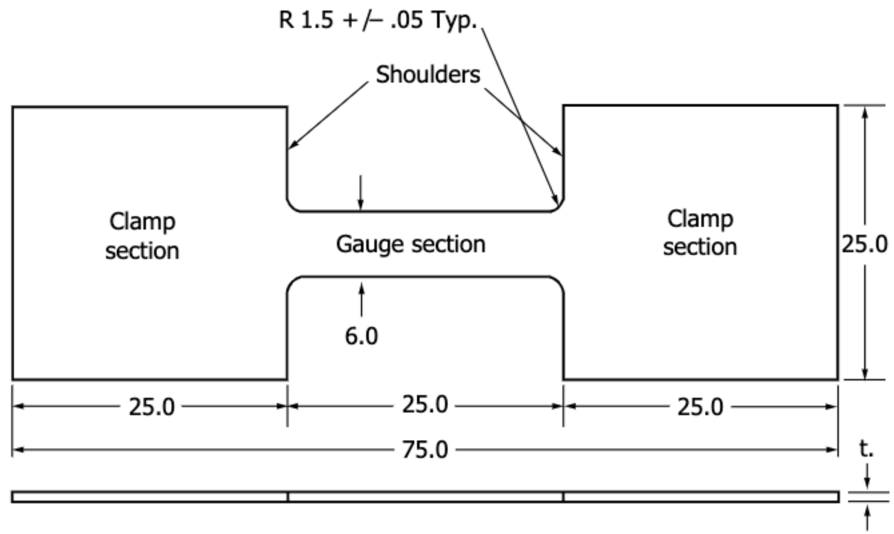
Superplastic Tensile Design



Drop-in placement



During testing



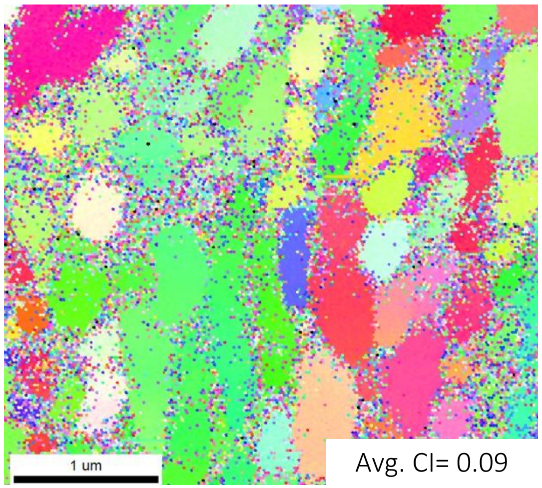
From ASTM E2448, dimensions in mm

Features:

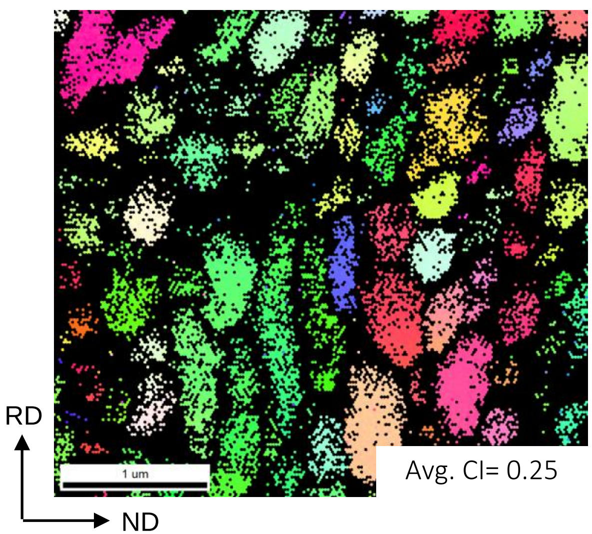
- drop-in specimen placement
- all load distributed through shoulder

Microstructural Characterization: Electron Backscatter Diffraction (EBSD)

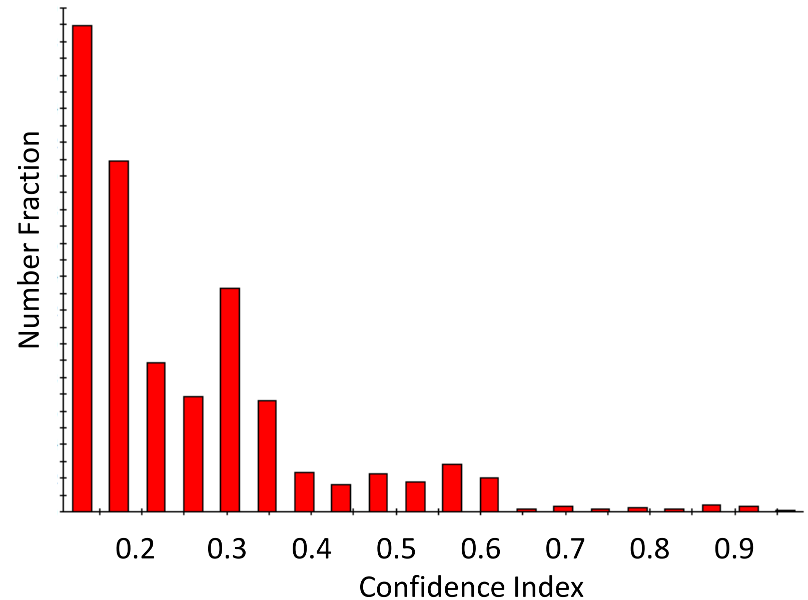
Al 1100 6 ARB



Avg. CI= 0.09

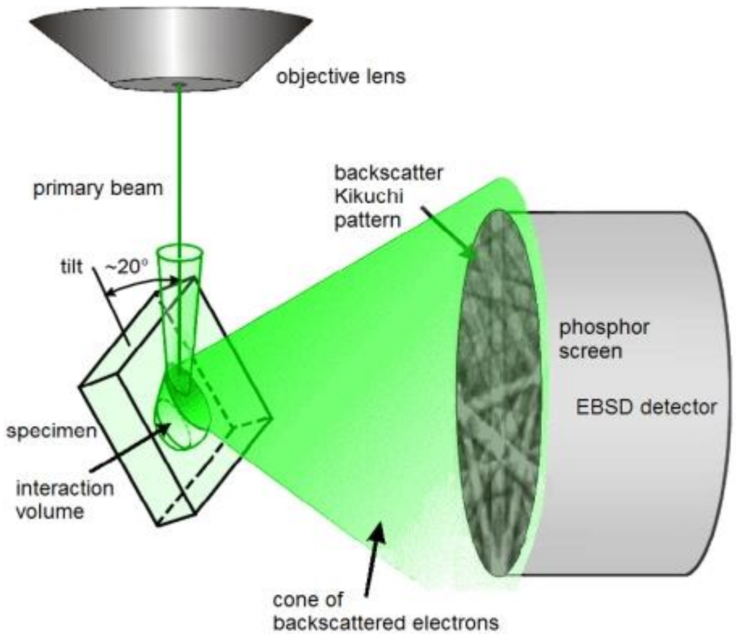


Avg. CI= 0.25

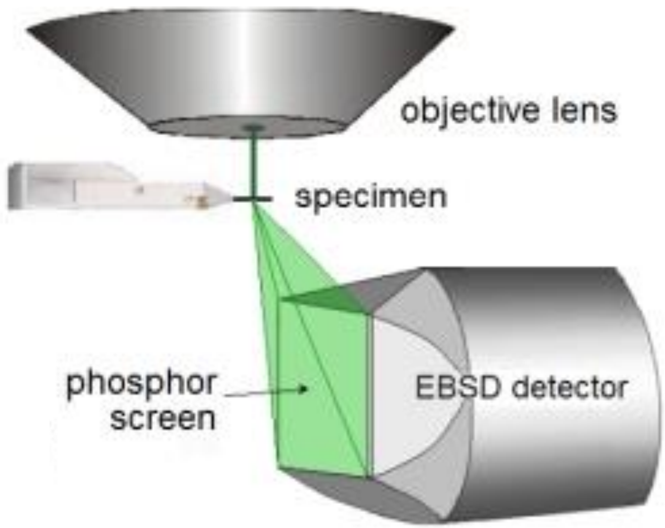


EBSD to quantify grain size and study subgrain development

Microstructural Characterization: Transmission Kikuchi Diffraction (TKD)



EBSD



TKD

TKD: Less through-thickness interaction, ideal for submicron grains

EBSD.info

Next Steps

1. Utilize knowledge of edge cracking to produce bulk material

→ Aluminum alloys 5083, 5182, 5754

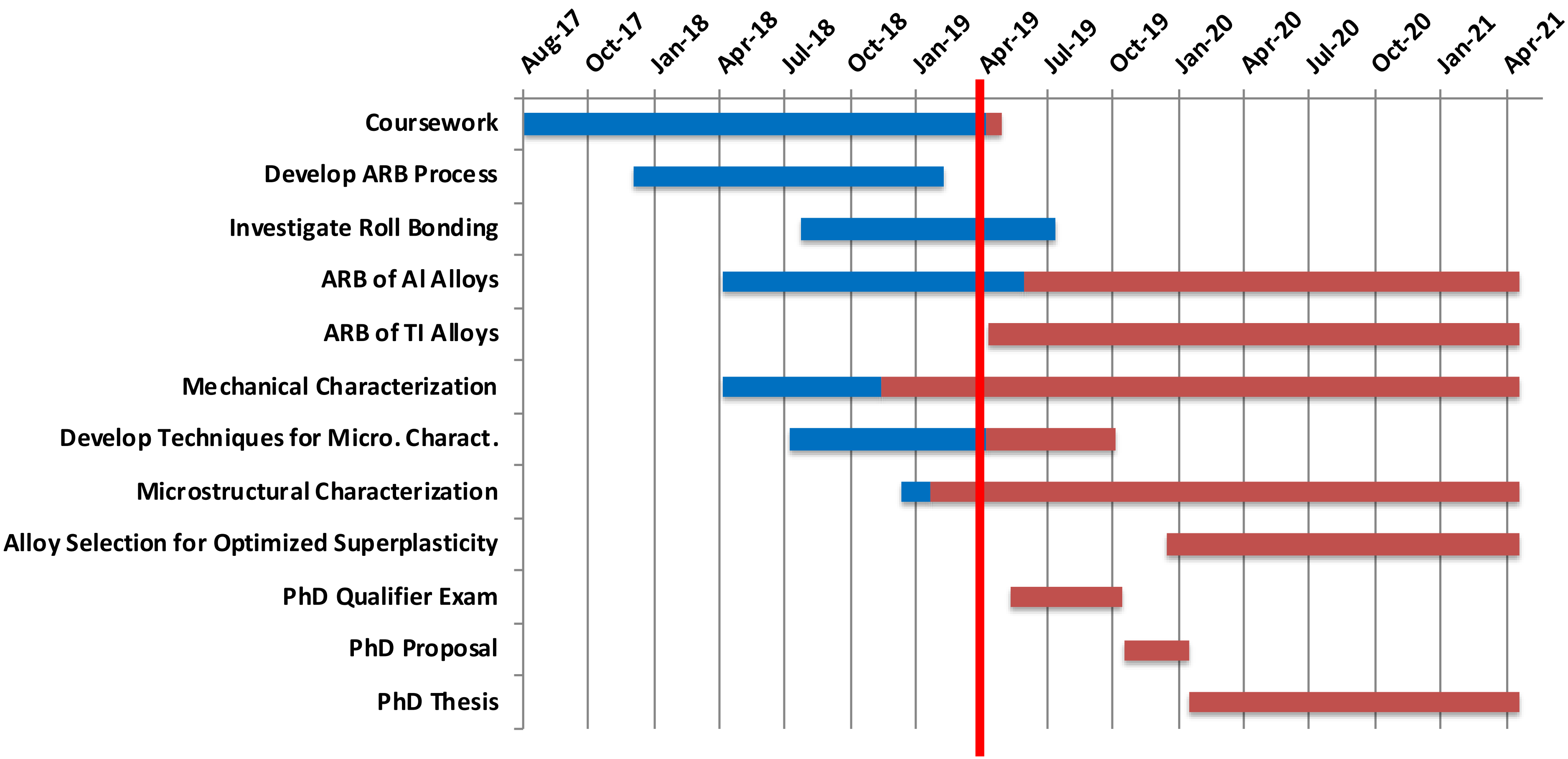
2. Finalize and test superplasticity tensile setup

3. Continue to develop techniques for microstructural analysis

→ focused ion beam (FIB) and transmission Kikuchi diffraction (TKD)

4. Transition to titanium alloys (CP Ti)

Progress


Aug-17
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Jan-18
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Jul-18
Oct-18
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Jul-19
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Jan-20
Apr-20
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Oct-20
Jan-21
Apr-21
Coursework
Develop ARB Process
Investigate Roll Bonding
ARB of Al Alloys
ARB of TI Alloys
Mechanical Characterization
Develop Techniques for Micro. Charact.
Microstructural Characterization
Alloy Selection for Optimized Superplasticity
PhD Qualifier Exam
PhD Proposal
PhD Thesis

Thank you!

Brady McBride
bmcbride@mines.edu

References

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[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] N. Kamikawa, T. Sakai, and N. Tsuji, "Effect of redundant shear strain on microstructure and texture evolution during accumulative roll-bonding in ultralow carbon IF steel," *Acta Materialia*, vol. 55, pp. 5873-5888, 2007.

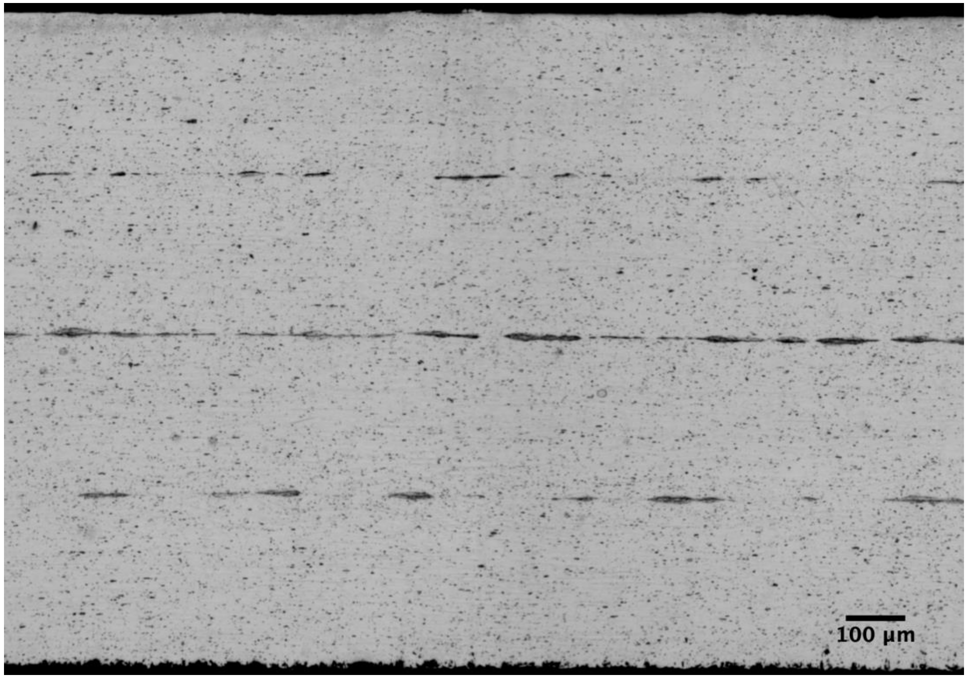
[5] M.G. Nicholas, D.R. Milner, Pressure Welding at Elevated Temperatures, British Welding Journal. 8 (1961) 375–383.

[6] N. Tsuji, "Production of Bulk Nanostructured Metals by Accumulative Roll Bonding (ARB) Process," in *Severe Plastic Deformation: Toward Bulk Production of Nanostructured Materials*, B. Altan, Nova Science, 2006, pp. 545-565.

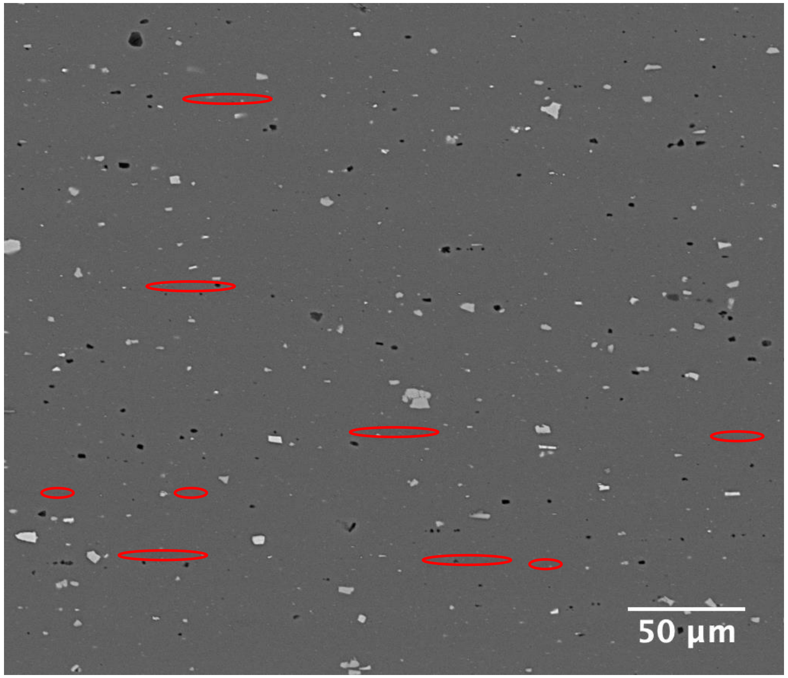
[7] F. Abu-Farha, M. Nazzal, and R. Curtis, "Optimum specimen geometry for accurate tensile testing of superplastic metallic materials," *Experimental Mechanics*, vol. 51, pp. 903-917, 2010.

Bonding Interfaces

Etching exaggerates bonded interfaces



Al 1100
2 ARB Cycles
OIM, Keller's Reagent



Al 5083
5 ARB Cycles
BEI, As-Polished

Fenn Rolling Mill

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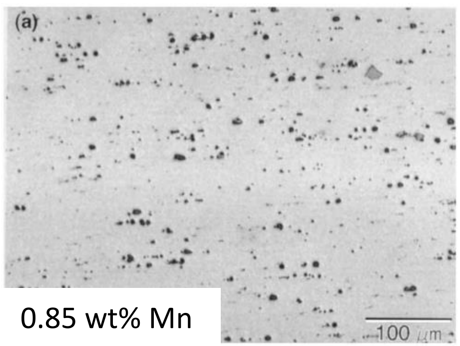
5.25” cold/hot rolls
100,000 lb capacity
37 RPM
50 SFPM

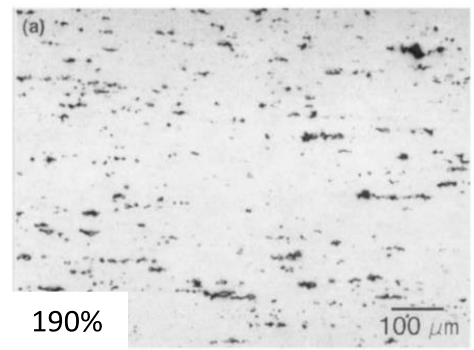
5XXX Aluminum

Alloy	Mg	Mn	Cr	Uses
5083	4.4	0.7	0.15	Marine, auto, aircraft applications
5182	4.5	0.35	<0.1	Automotive body panels, brackets
5754	3.5	<0.1	0.25	Storage tanks, pressure vessels, welded structures



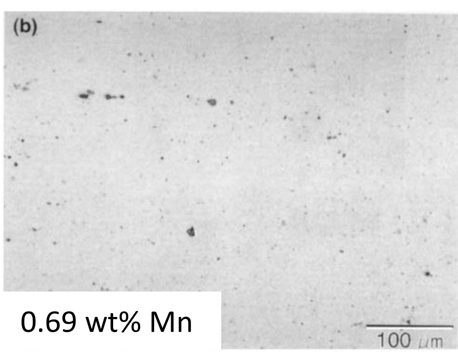
0.85 wt% Mn

500°C, 10^{-3} s^{-1} →

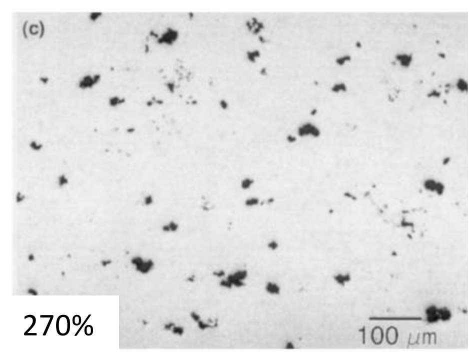


190%

2nd phase particles → Cavity nucleation → Less superplastic ductility



0.69 wt% Mn



270%

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

Microstructural Characterization: Anodizing for LOM

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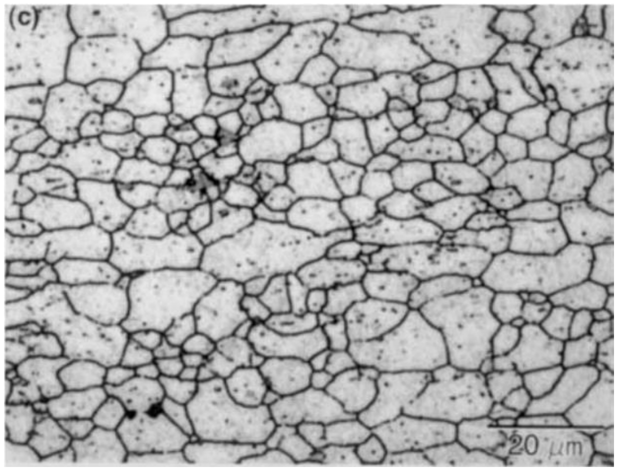
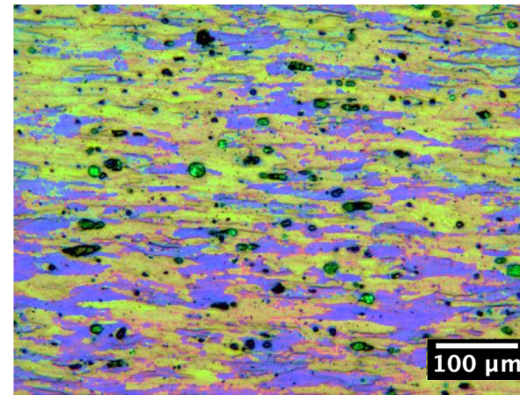
Precipitation Grain Contrast
16 hr at 120 C

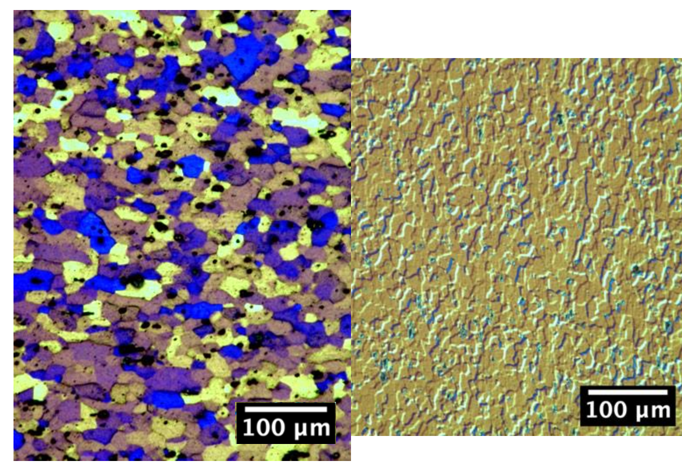


Cleveland et al., *Materials Science and Engineering A*, 2003.

Anodizing with Barker's Reagent



Al 5083, 68% reduction



Recrystallized Al 5083

Anodizing for quick analysis of
grain and deformation structures
without
thermally affecting microstructure

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

Student: *Brady McBride*

Faculty: *Kester Clarke*

Industrial Partners: *Boeing (Ravi Verma), LANL (John Carpenter)*

Project Duration: *August 2017 – May 2021*

Achievement

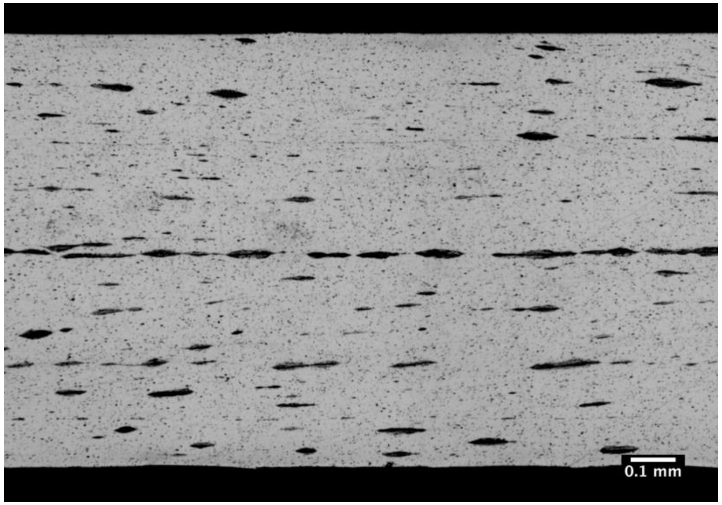
- Development of a process capable of producing ultra-fine grained microstructures in Al and Ti alloys that exhibit superplasticity at lower temperatures than conventional processing methods.

Significance and Impact

- Low temperature superplasticity would enhance superplastic forming operations by reducing cycle time as well as reducing costs related to heating and die wear.

Research Details

- Improved superplastic formability by means of reduced temperature and increased forming strain rates will reduce operating costs and prolong die life.



Cross-section of roll bonded Al 1100 showing interfaces between 128 individual layers of material.

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

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Student: *Brady McBride*

Faculty: *Kester Clarke*

Industrial Partners: *Boeing (Ravi Verma), LANL (John Carpenter)*

Project Duration: *August 2017 – May 2021*

Program Goal

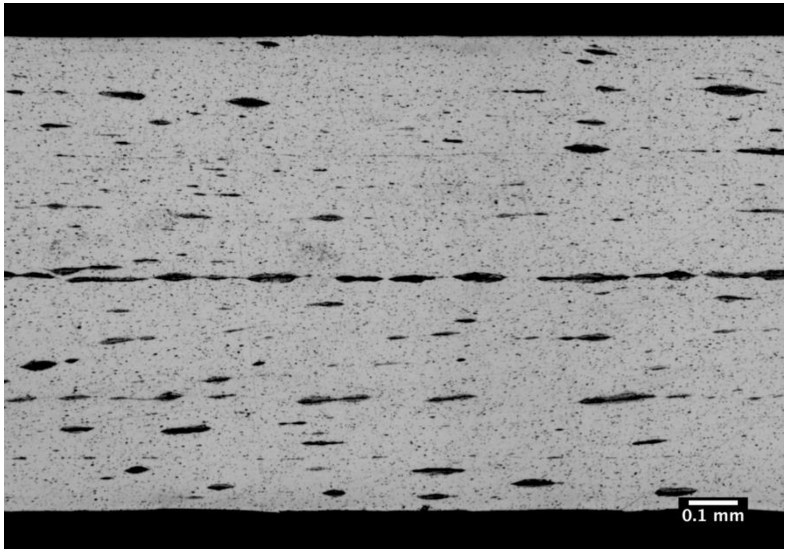
- Investigate enhanced superplasticity of ultra fine grained materials produced by accumulative roll bonding

Approach

- Develop a process for accumulative roll bonding and determine microstructural mechanisms related to superplasticity

Benefits

- Improved superplastic formability by means of reduced temperature and increased forming strain rates will reduce operating costs and prolong die life



Cross-section of roll bonded Al 1100 showing interfaces between 128 individual layers of material.