CANFSA

Center for Advanced Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

Project 31-L: Accumulative Roll Bonding of Al Sheets (AA 5083) Toward Low Temperature Superplasticity

Semi-annual Spring Meeting

April 2022

- Student: Brady McBride (Mines, now ATI Specialty Materials)
- Advisors: Kester Clarke (Mines), Amy Clarke (Mines)
- Industrial Mentors: John Carpenter (LANL), Eric Payton (AFRL)

COLORADO SCHOOL OF MINES   NSF   IOWA STATE UNIVERSITY

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

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- 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.

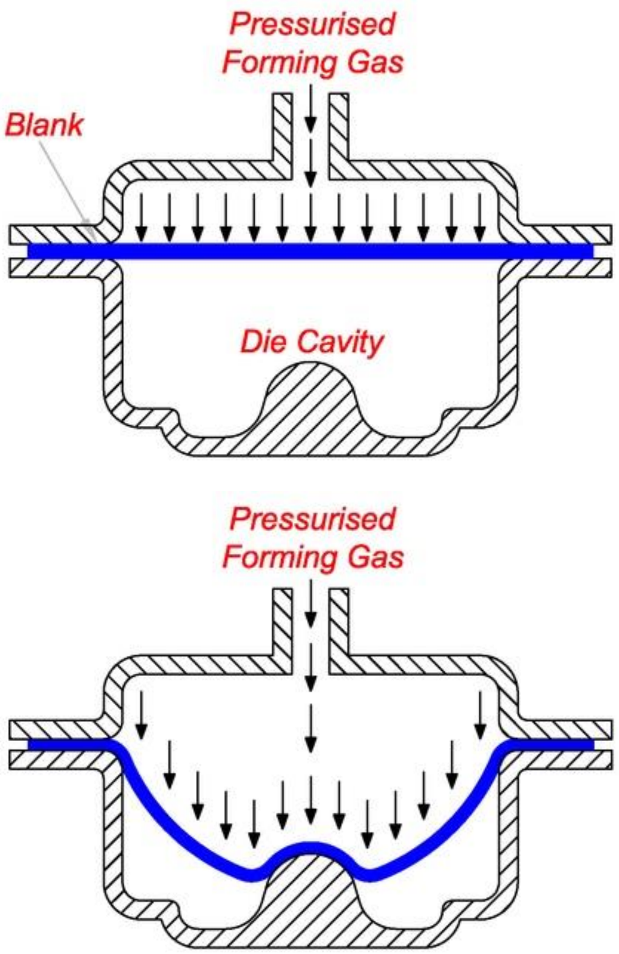
Recent Progress (Defended PhD thesis, December 2021)

- "**Continuous recrystallization during annealing** of AA 5083 produced by accumulative roll bonding (ARB)", *Metall. & Mater. Trans. A*, submitted February 2022.
- "**The limits of low temperature superplasticity** in AA 5083 produced by accumulative roll bonding (ARB)", *Metall. & Mater. Trans. A,* submitted March 2022.
- "**Biaxial low temperature superplasticity** in AA 5083 produced by accumulative roll bonding (ARB)", *J. Mater. Perform. Eng.,* submitted April 2022.

Metrics

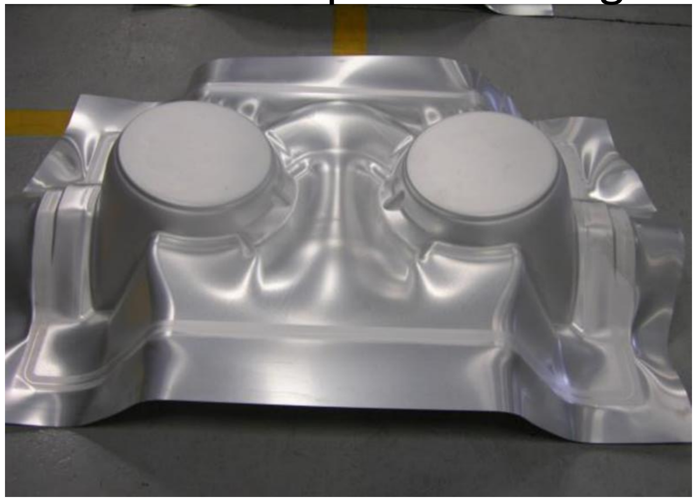
Description	% Complete	Status
1. Develop ARB process with mitigated edge cracking	100%	●
2. Identify optimal conditions for low temperature superplasticity through tensile testing	100%	●
3. Characterize microstructure evolution with ARB processing and tensile deformation	100%	●
4. Formalize limits for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

Industrial Relevance: Superplastic Forming



LightMetalAge

Aircraft lamp can housing



Barnes et *al.*, *Mat. Sci. Forum*, 2003.

2018 Bentley Continental GT

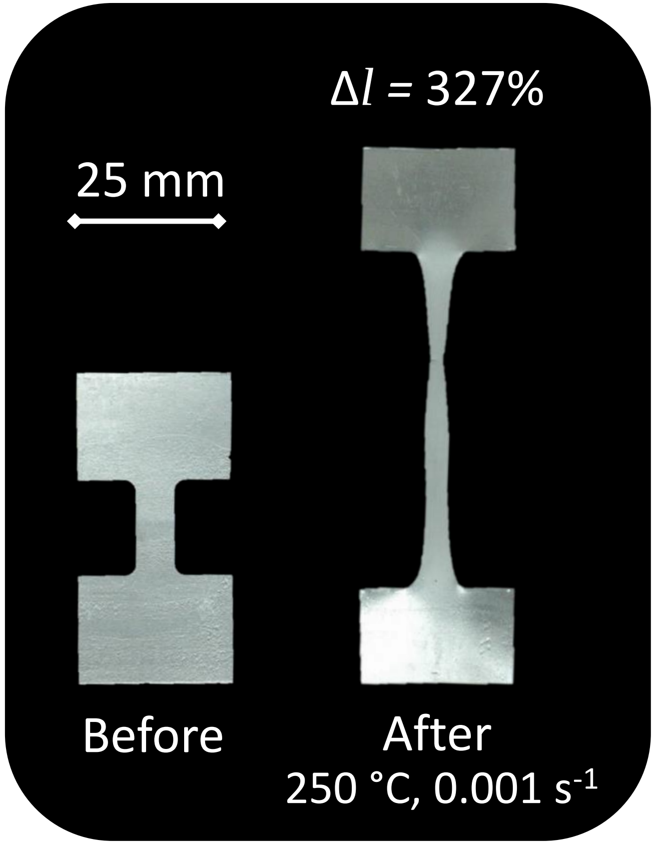
LightMetalAge

Conventionally processed AA 5083:	
Grain size:	10 µm
Temperature:	500°C
Strain rates:	$1 \times 10^{-3}\ s^{-1}$
Thinning ratios:	2.0
Void fraction:	2%

Industrial Relevance:
Reduced Temperature Formability

Uniaxial tension

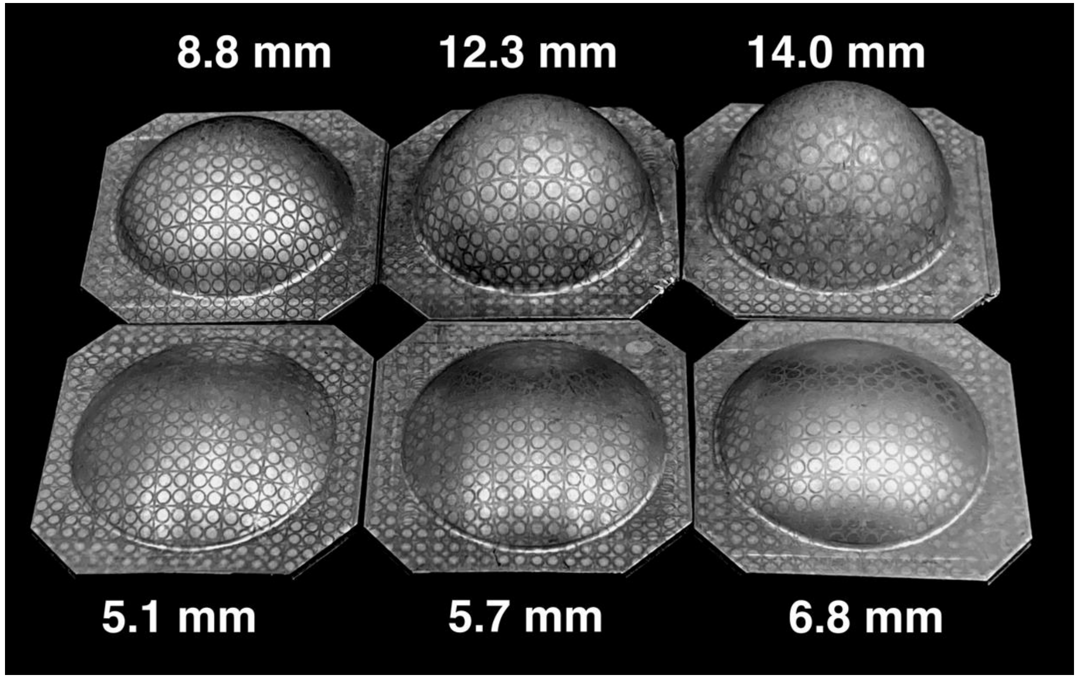
ARBed
(< 1 µm)



Biaxial bulge testing

ARBed
(< 1 µm)

Coarse
grained
(≈ 10 µm)



250°C, 0.001 s^{-1*}

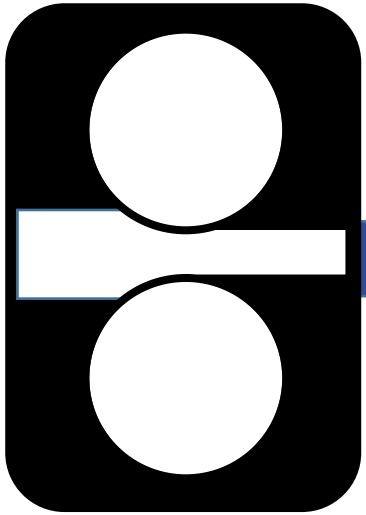
*load-controlled nominal strain rate

Project Overview & Milestones

Microstructural Engineering

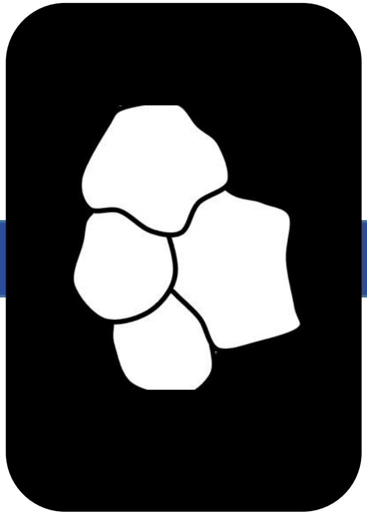
Industrial Relevance

"Mitigation of edge cracking…"



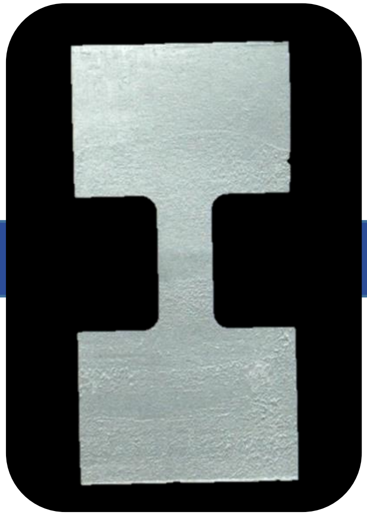
J. Manuf. Proc.

"Continuous recrystallization…"



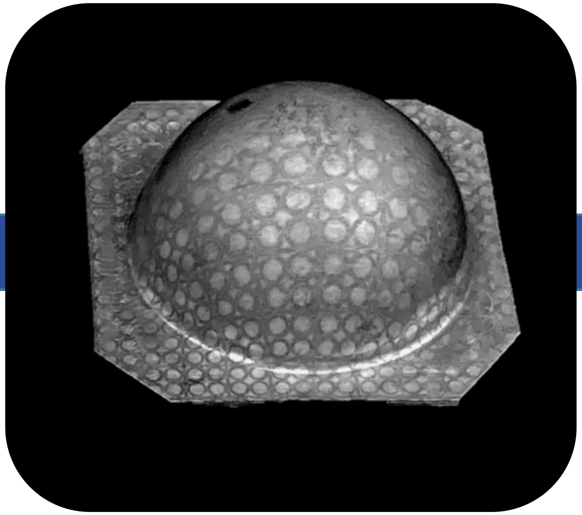
Metall. & Mater. A

"Limits of low temperature superplasticity…"



Metall. & Mater. A

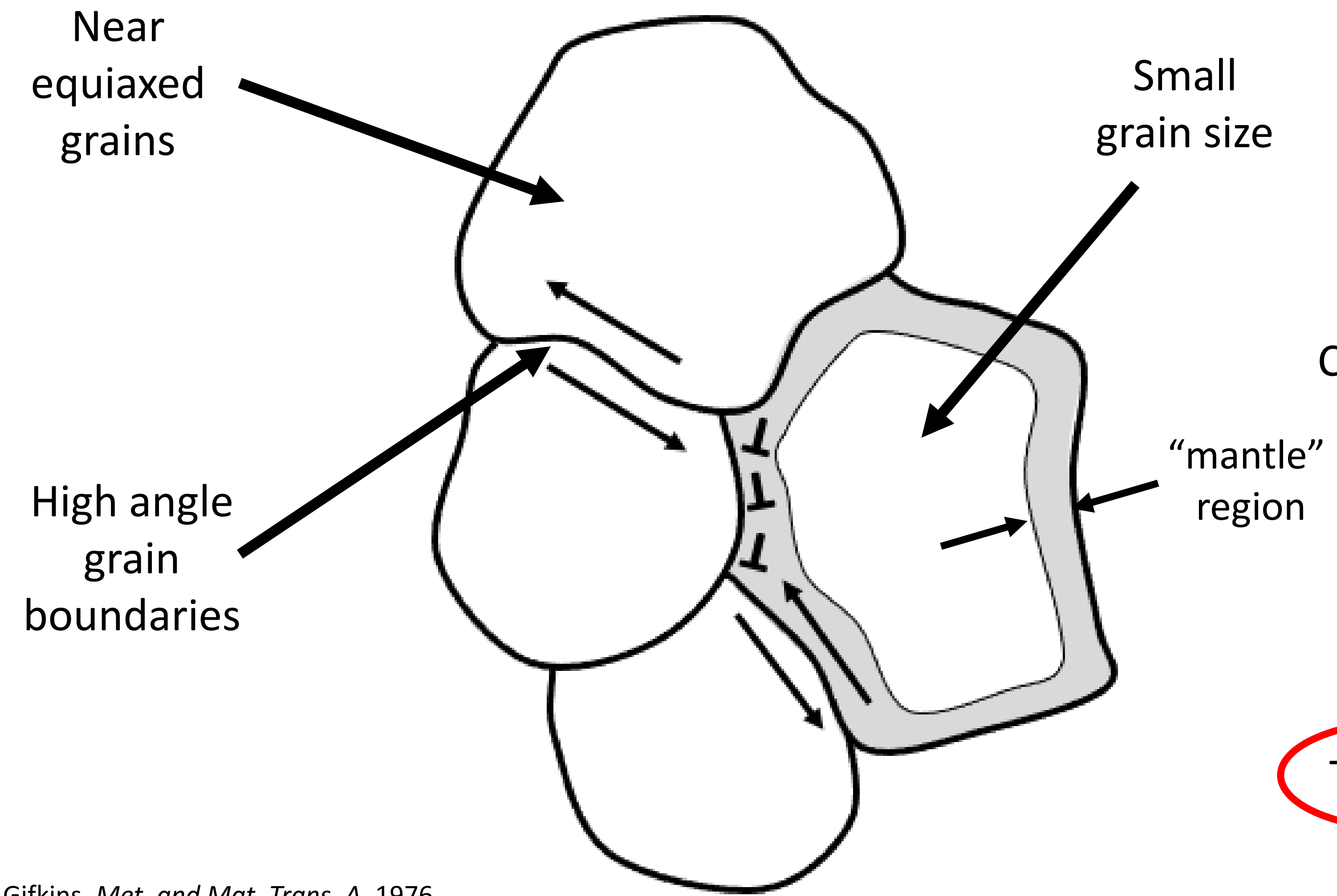
"Biaxial low temperature superplasticity…"



J. Mater. Perform. Eng.

Introduction: Superplasticity

Gifkins grain boundary diffusion accommodation model



Convention superplasticity in AA 5083:

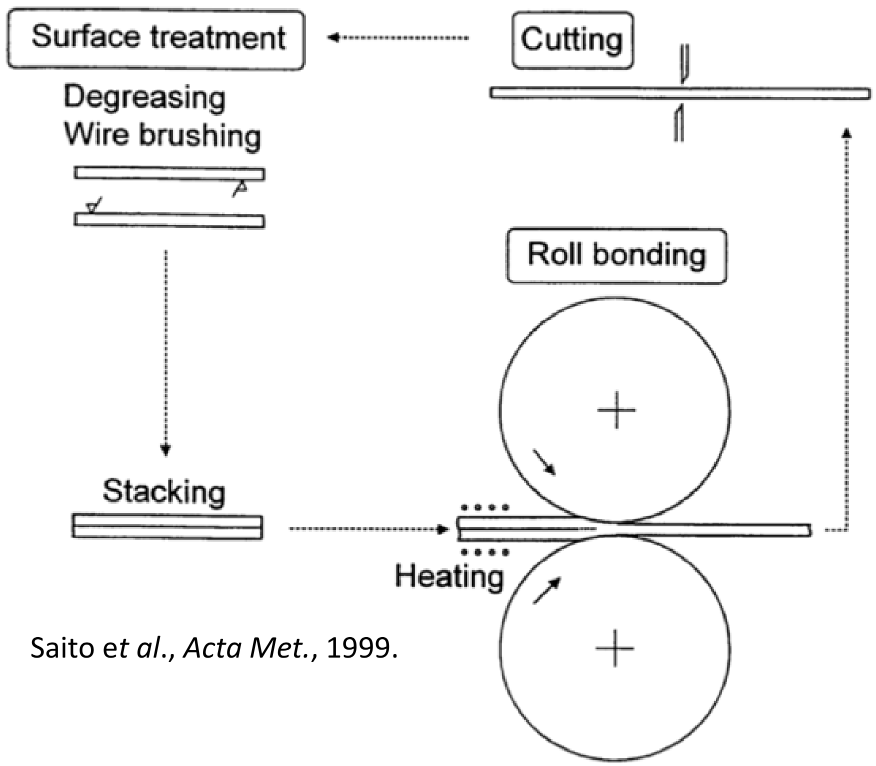
$$\dot{\varepsilon} = A\frac{DGb}{kT}\left(\frac{b}{d}\right)^{p}\left(\frac{\sigma}{G}\right)^{\frac{1}{m}}$$

T > 500°C

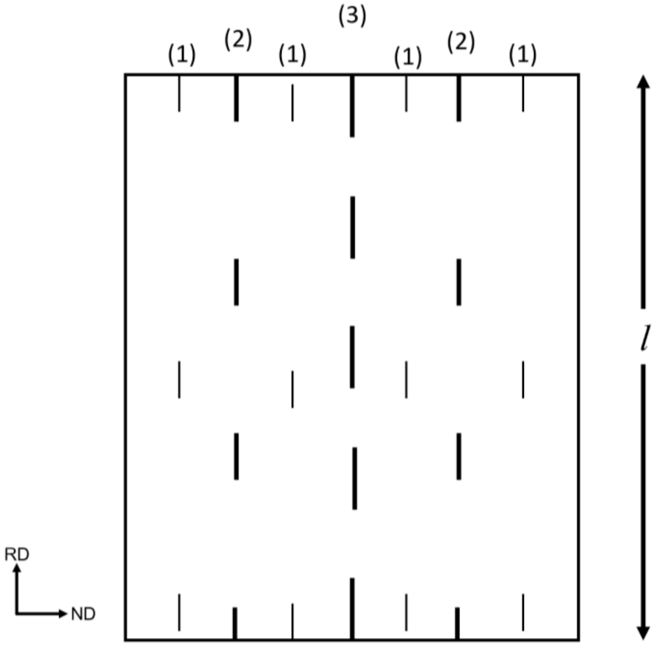
10 µm

Gifkins, *Met. and Mat. Trans. A*, 1976.

Accumulative Roll Bonding (ARB)



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

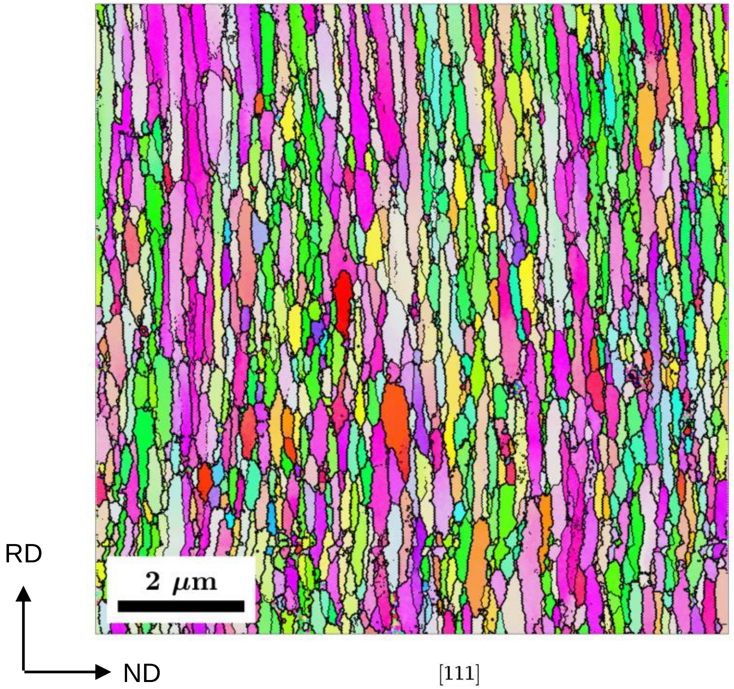


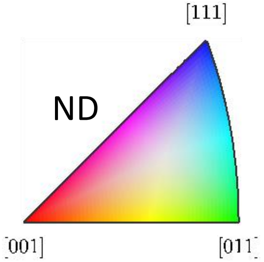
Schematic of bonding interfaces after 3 ARB cycles.

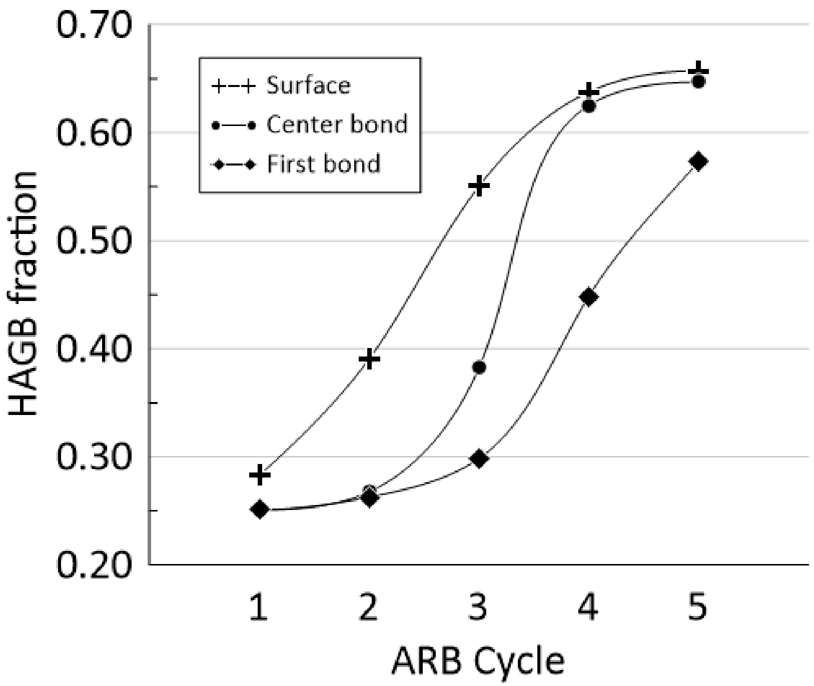
Outcomes of ARB:
- laminate sheet
- interface development
- strain retention

Grain Refinement through ARB

Mid-thickness grain morphology
after 5 ARB cycles



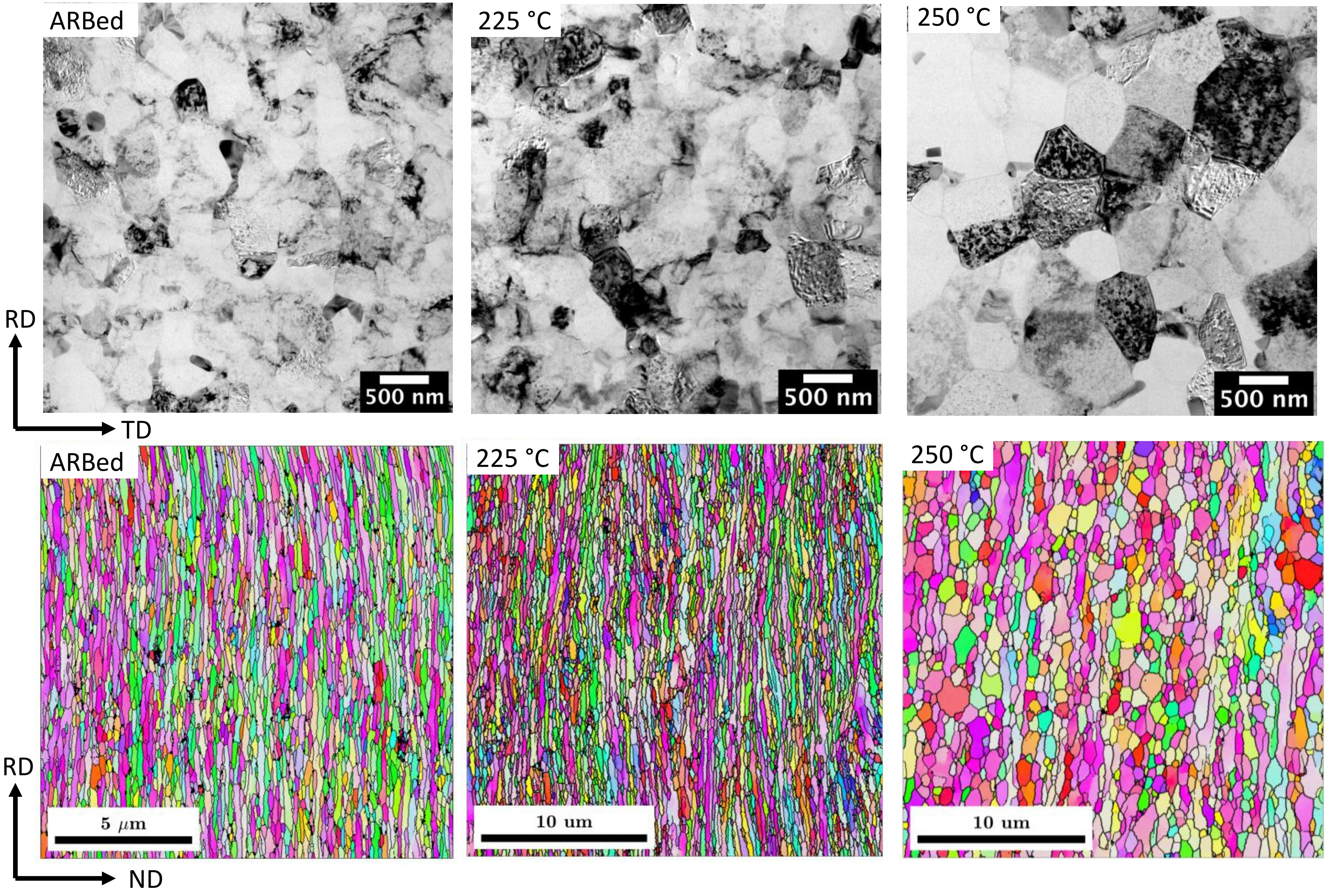




in-situ recrystallization:
- submicron grain size
- large HAGB fraction

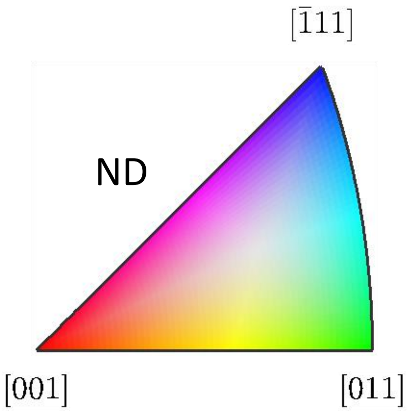
Evidence for _Continuous_ Recrystallization

15 minute static anneal treatments

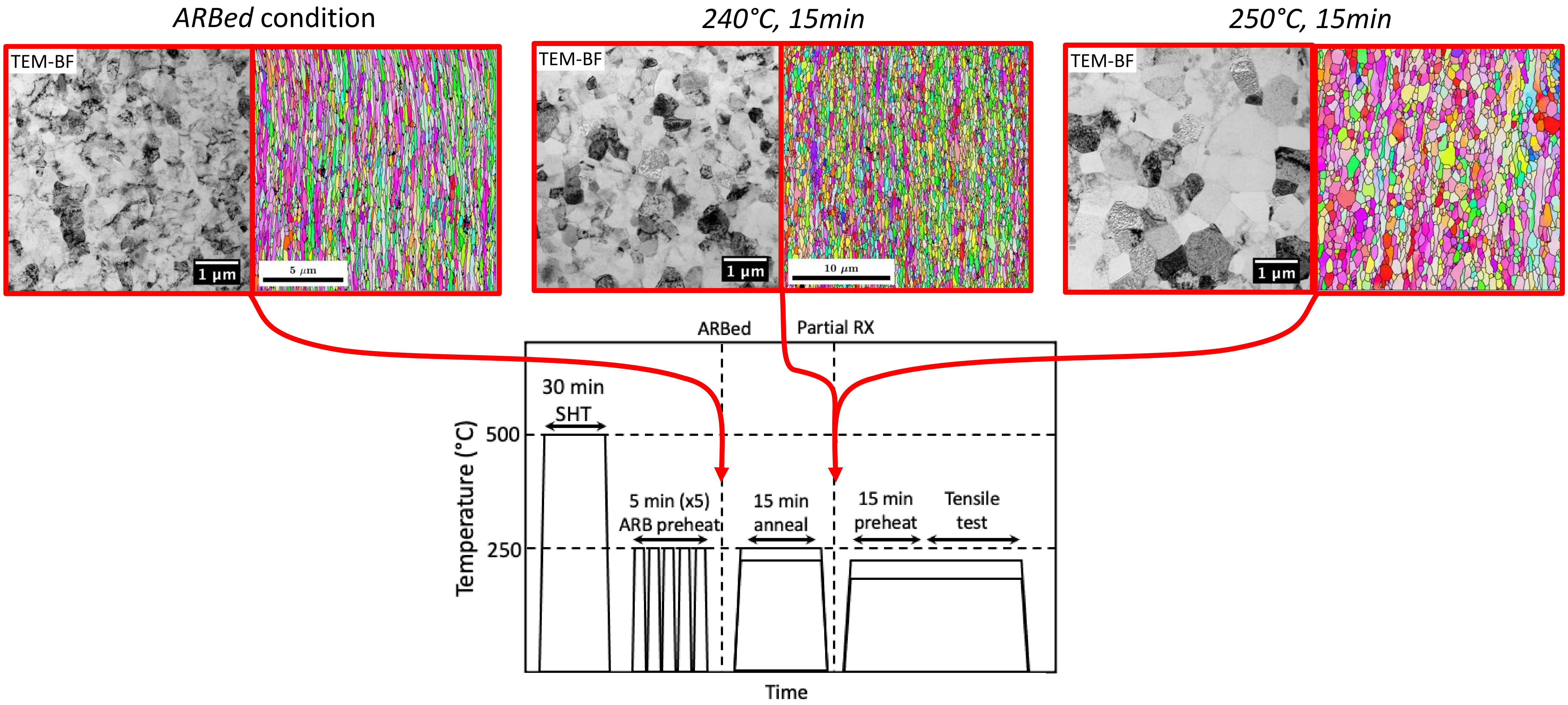


Continuous recrystallization between 225 and 250°C due to large HAGB fraction

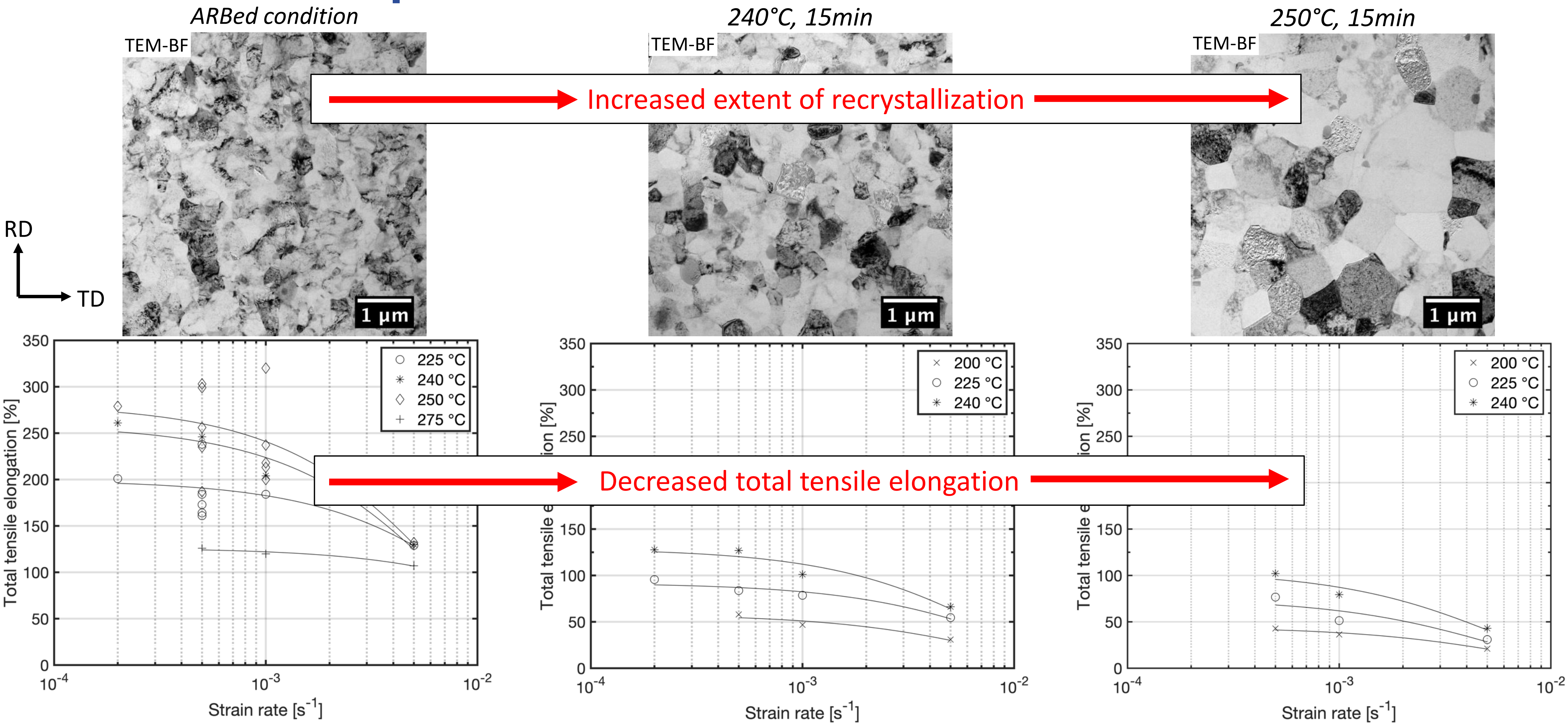
Significant grain growth above 250°C



Effect of Partial Recrystallization on Tensile Response



Effects of Partial Recrystallization on Tensile Response



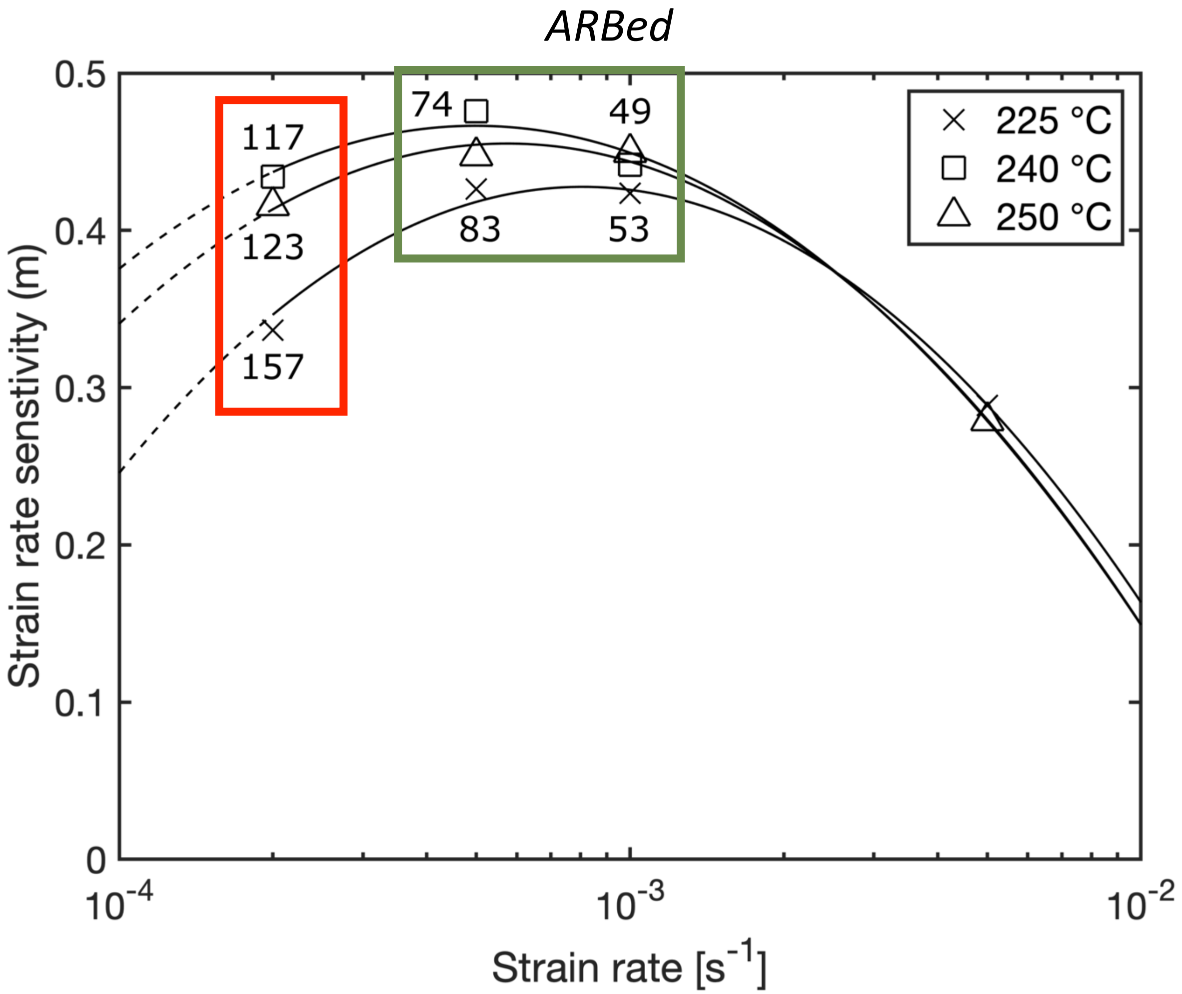
Conclusions: Microstructural Stability

1. ARBed microstructure is submicron with large HAGB fraction.

2. Microstructure is resistant to ***dis***continuous recrystallization due to large HAGB fraction.

3. Total tensile elongation decreases with extent of static annealing.

Identifying Deformation Mechanisms



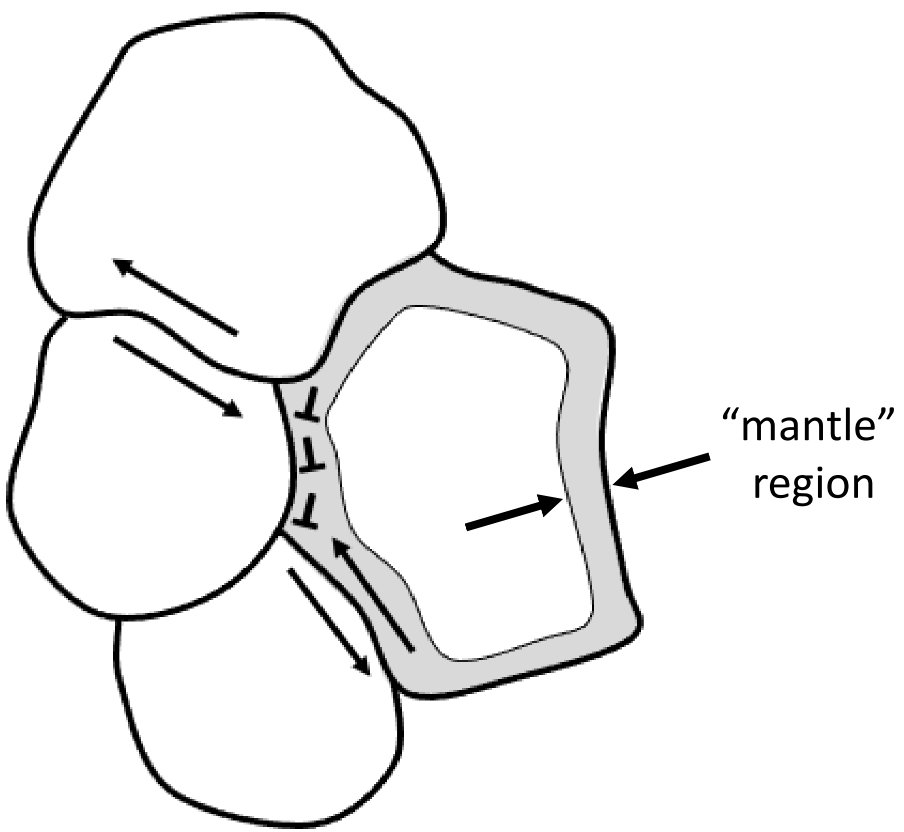
Gifkin's model for grain boundary sliding:

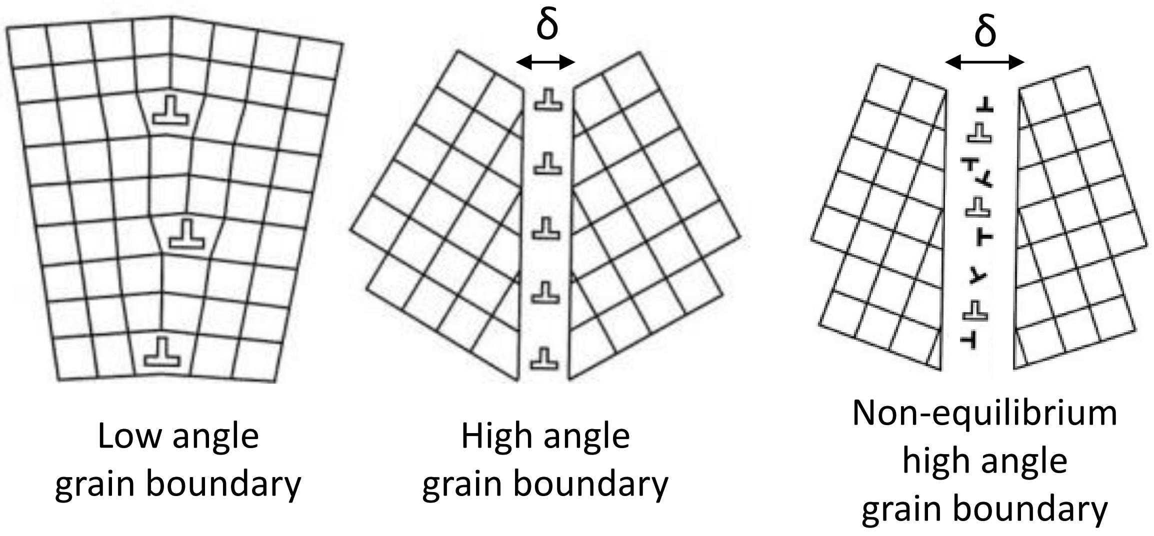
$Q_{GB} \approx 84$ kJ/mol

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

$m_{GB} \approx 0.5$

The Significance of Grain Boundary Character



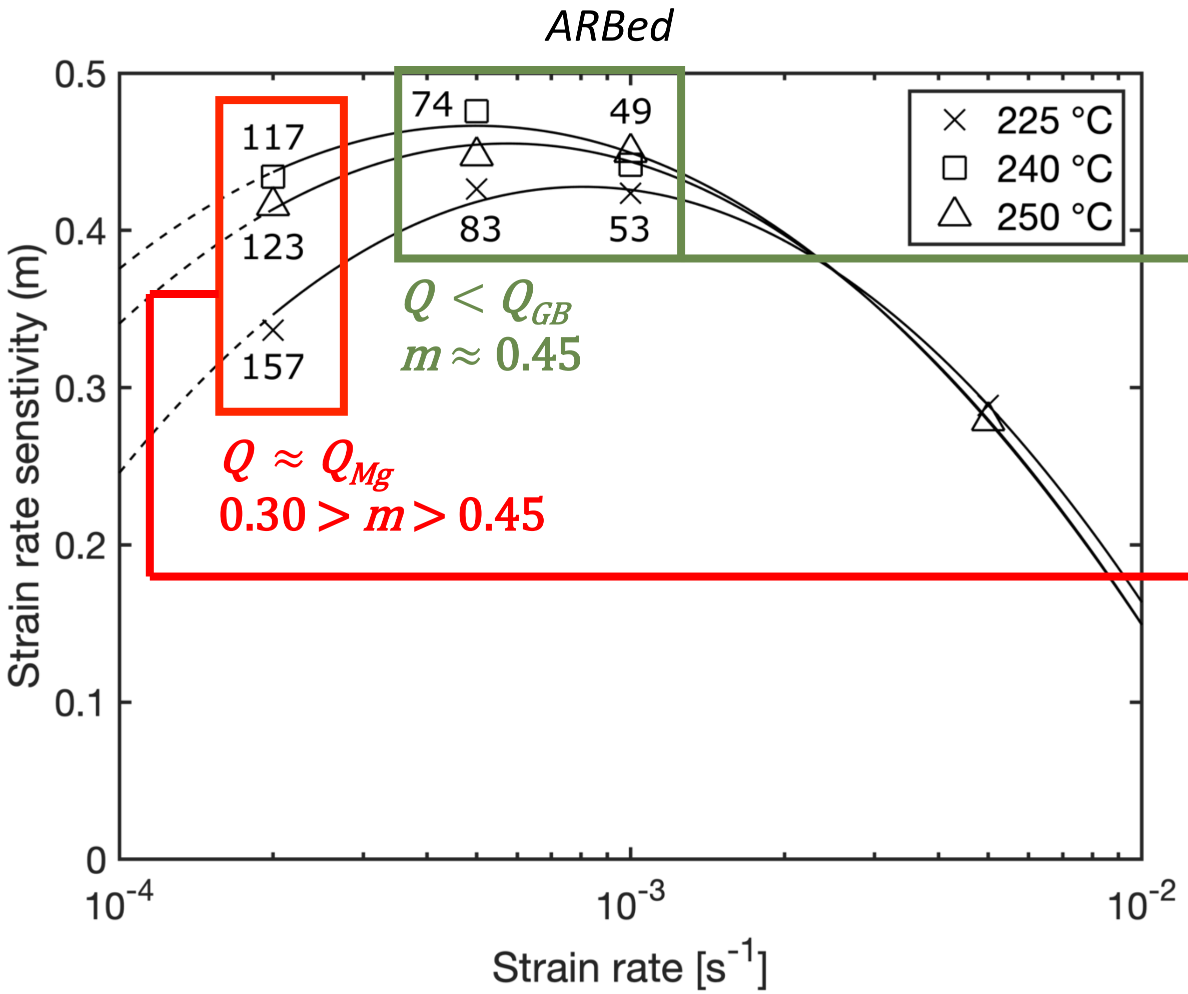


Non-equilibrium grain boundaries have:

- larger widths, δ
- higher diffusivities (lower activation energy)
- possible solute segregation (Mg)

I.A. Ovid'ko *et al.*, 2006.

Identifying Primary Deformation Mechanisms



Non-equilibrium grain boundaries
→ reduce activation energy for GBS

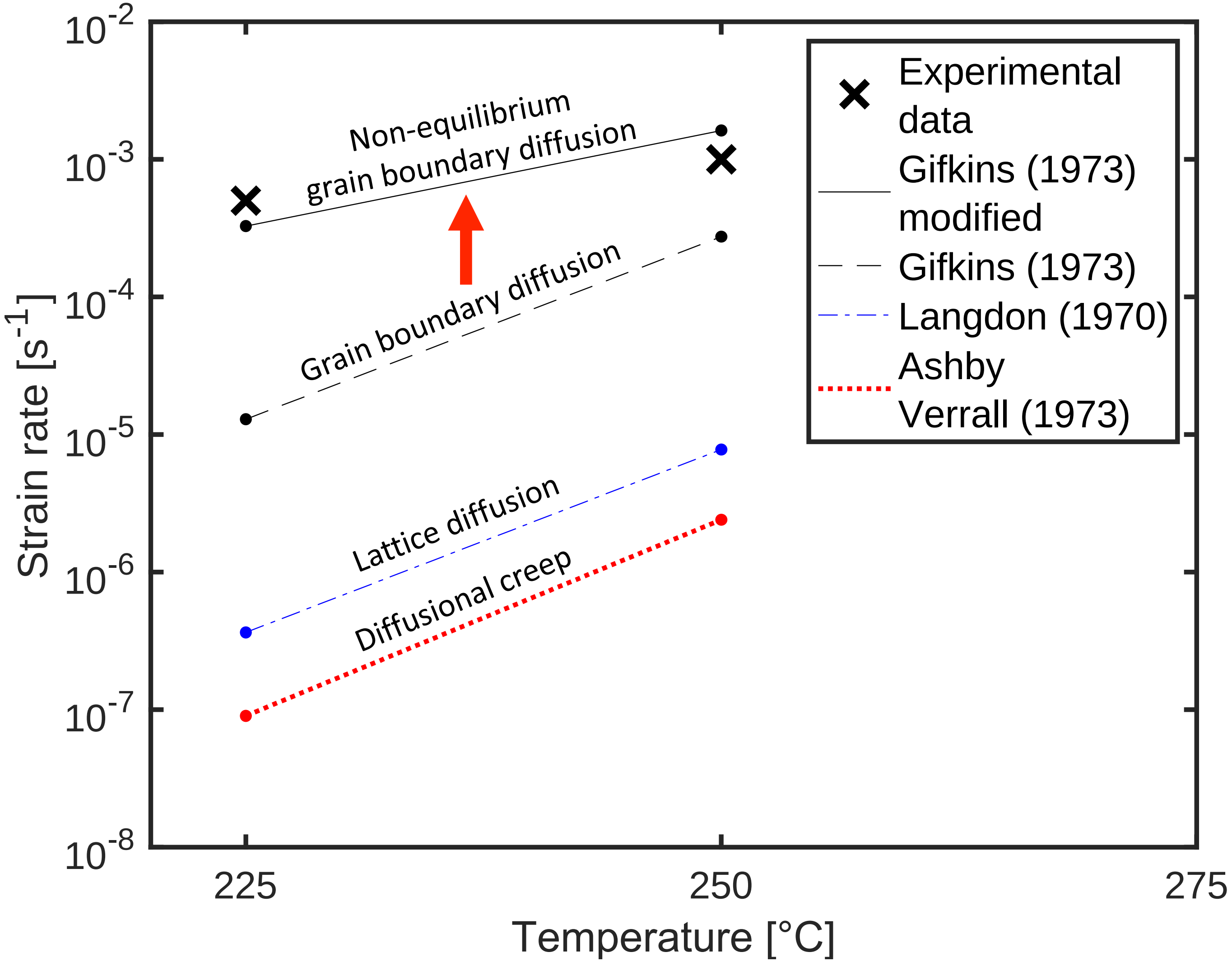
Lower strain rates, lower stresses, lower ⊥ velocity
Enhanced thermal mobility of Mg solute
→ Solute drag

$m_{GB} \approx 0.5$

$Q_{GB} \approx 84$ kJ/mol

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

Comparison to Grain Boundary Sliding Models



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

Grain boundary sliding models predict significantly lower strain rates

Modifications to Gifkins core-mantle model:

1. Grain boundary width ≈ 4δ
2. Activation energy ≈ 0.5 Q_{GB}

results in $10^2 - 10^3$ increase in diffusivity [m^2/s]

Conclusions: Uniaxial Tensile Performance

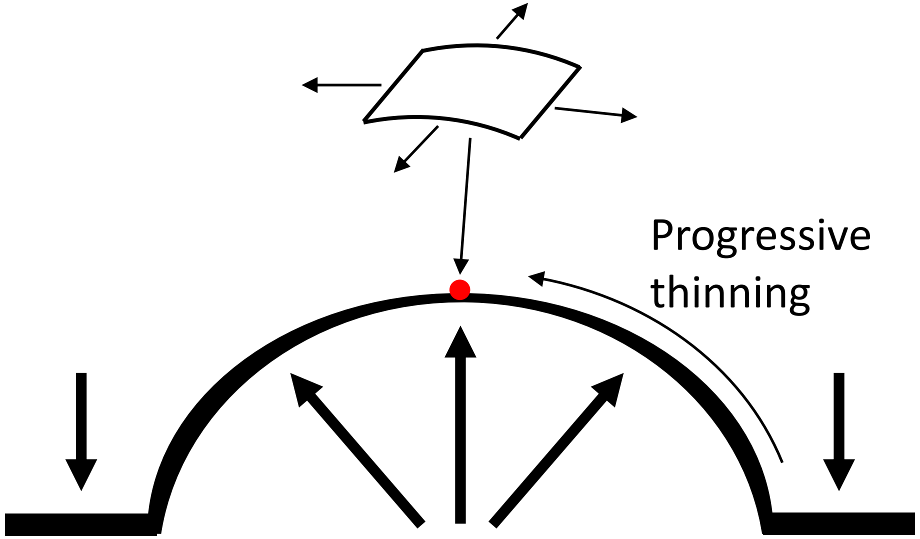
1. Grain boundary sliding occurs with *lower* activation energies than conventionally reported (84 *kJ/mol*).

2. Non-equilibrium HAGBs likely responsible for *increasing* grain boundary diffusion rates.

3. Partial static recrystallization leads equilibrium grain boundary structure.

4. Solute partitioning (Mg) to grain boundaries may contribute to enhanced solute drag at low temperatures and strain rates.

Biaxial Bulge Testing



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

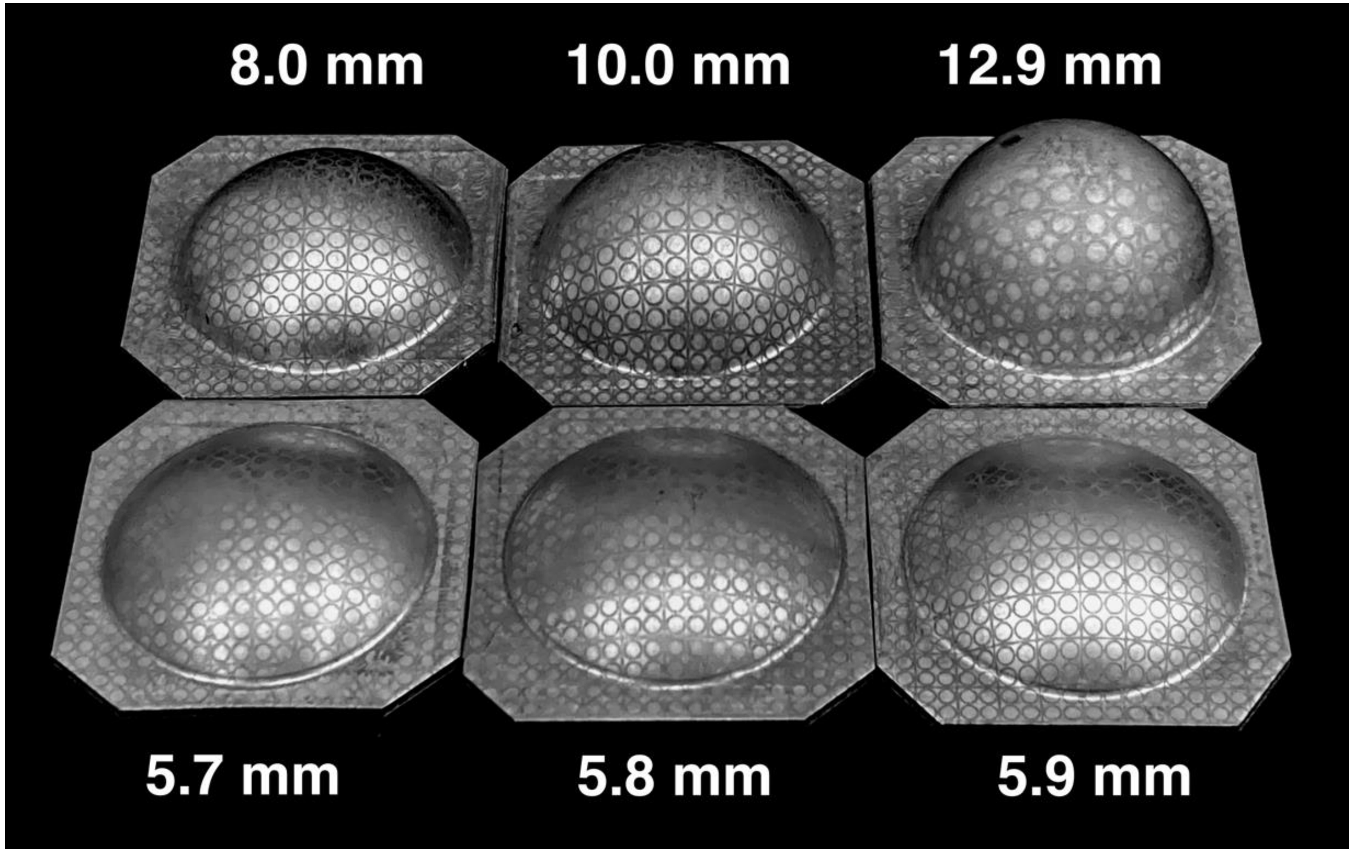
Pressure to deform at constant strain rate

Biaxial Bulge Testing Results

225 °C, 0.0005 s^{-1}*

ARBed (< 1 µm)

Coarse grained (≈ 10 µm)



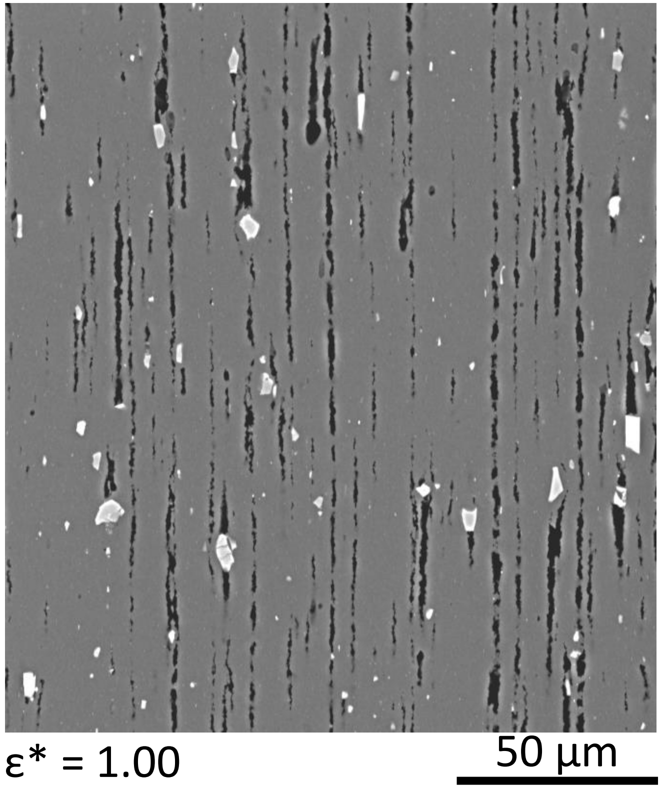
ARBed material demonstates biaxial superplasticity with:

1) lower temperatures
2) lower forming pressures

*strain rates listed are anticipated values, not necessarily observed values

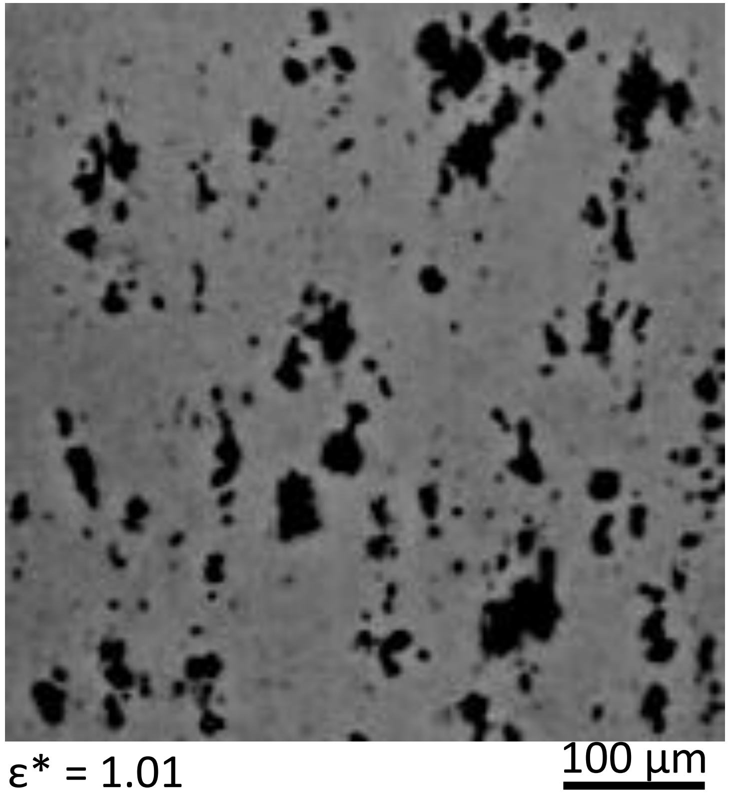
Comparison of Damage Accumulation

ARBed
(< 1 µm)
225°C, 0.0005 s^{-1}



ε* = 1.00

Coarse
grained
(≈ 10 µm)
500°C, 0.001 s^{-1}



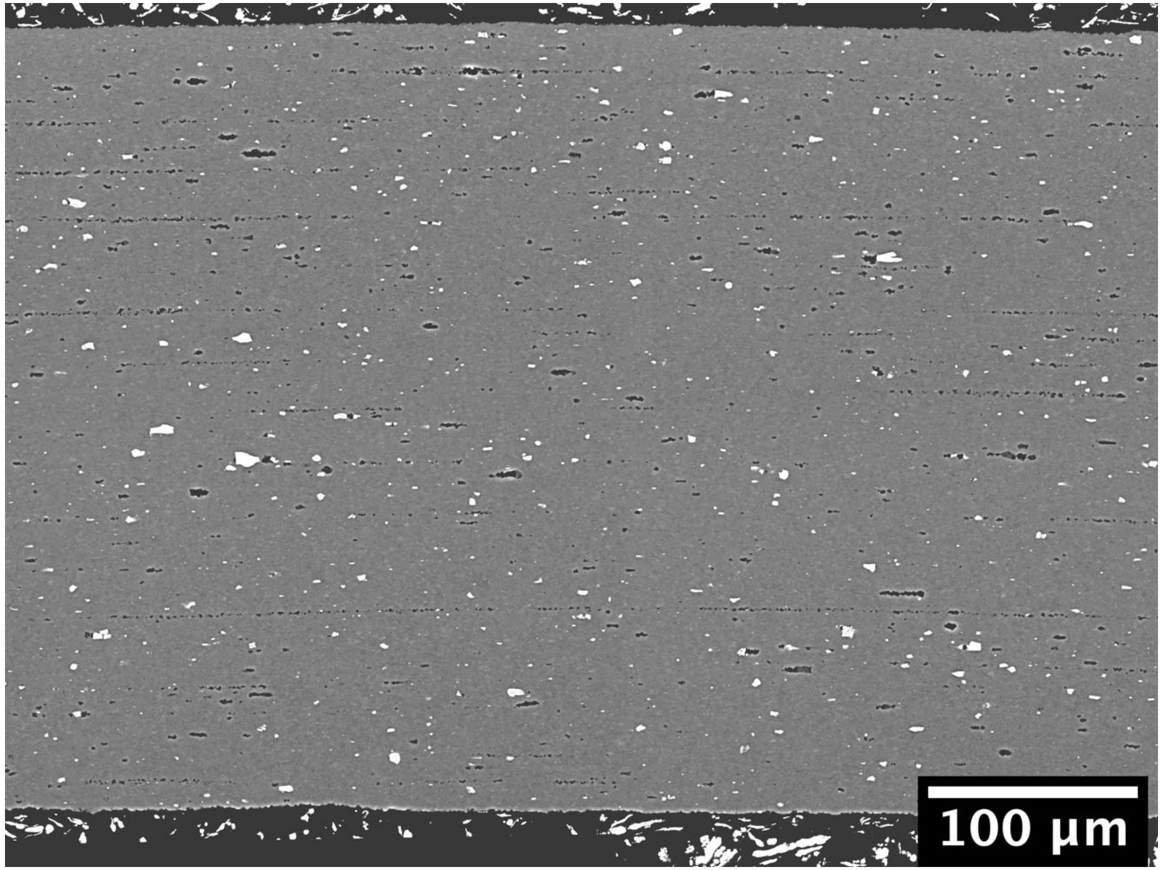
ε* = 1.01

Mean void size ≈ mean grain size

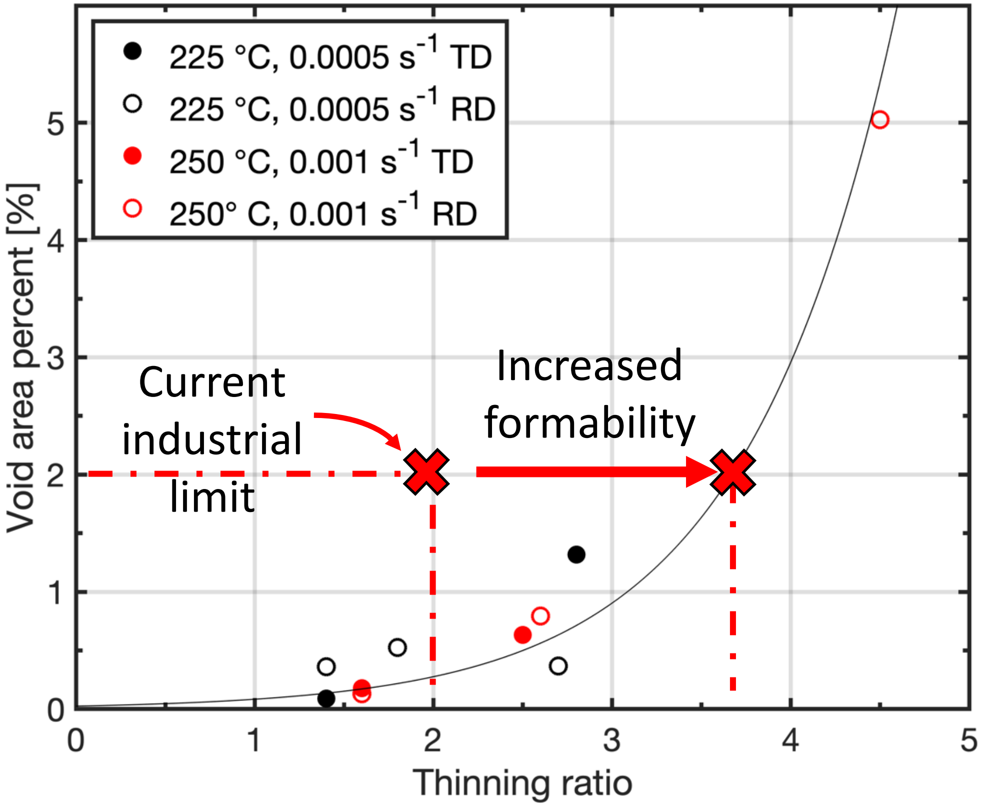
*tensile strain of bulk sample

Formability of ARBed material

250°C, 0.001 s^{-1}, t_o/t_f = 1.6

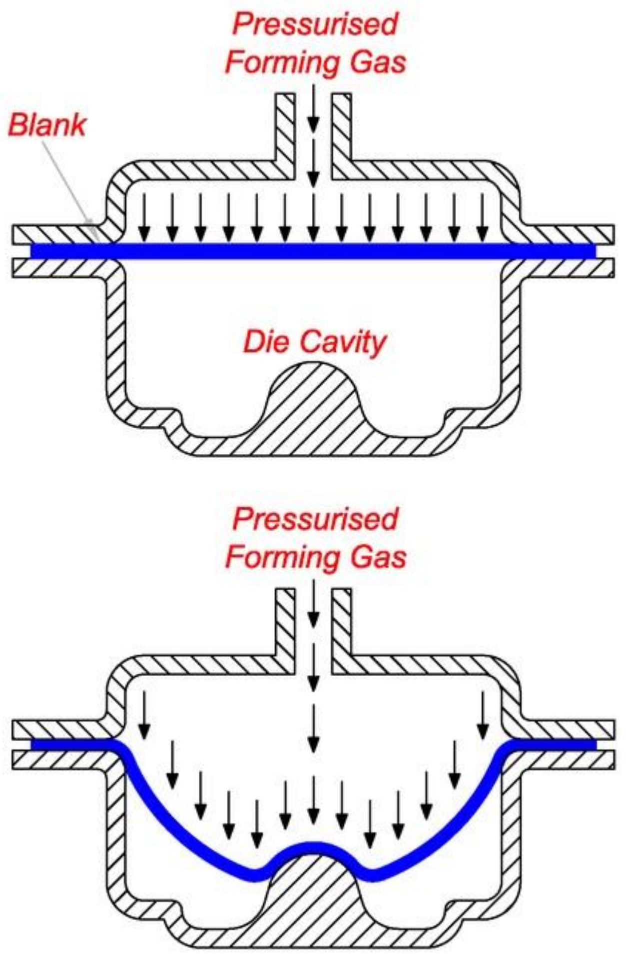


Cross-section along RD at apex of biaxial bulge sample



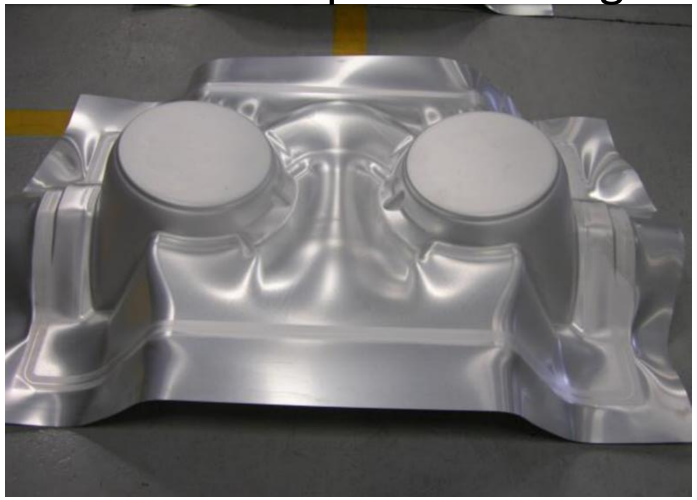
Higher thinning ratios can be achieved with lower void fractions due to smaller void sizes.

Industrial Relevance: Superplastic Forming



LightMetalAge

Aircraft lamp can housing



Barnes et *al.*, *Mat. Sci. Forum*, 2003.

2018 Bentley Continental GT

LightMetalAge

ARB processed 5083:

Grain size:	~~10 µm~~ 1 µm
Temperature:	~~500°C~~ 225°C
Strain rates:	1×10^{-3} s^{-1}
Thinning ratios:	~~2.0~~ 3.5
Void fraction:	2%

Thank You!

Brady McBride
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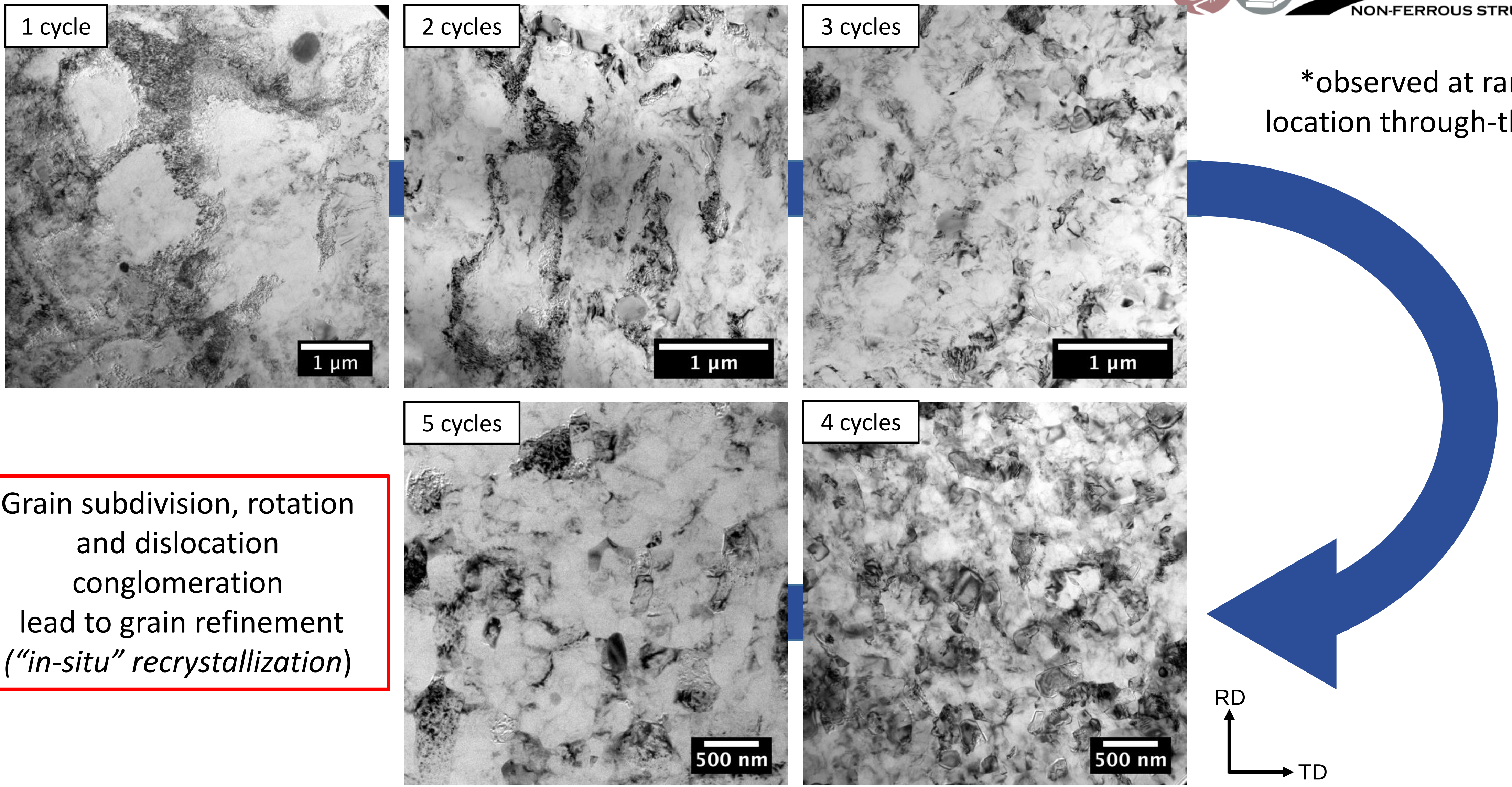
Colorado School of Mines (former)
ATI Specialty Materials (current)

Supplemental Slides

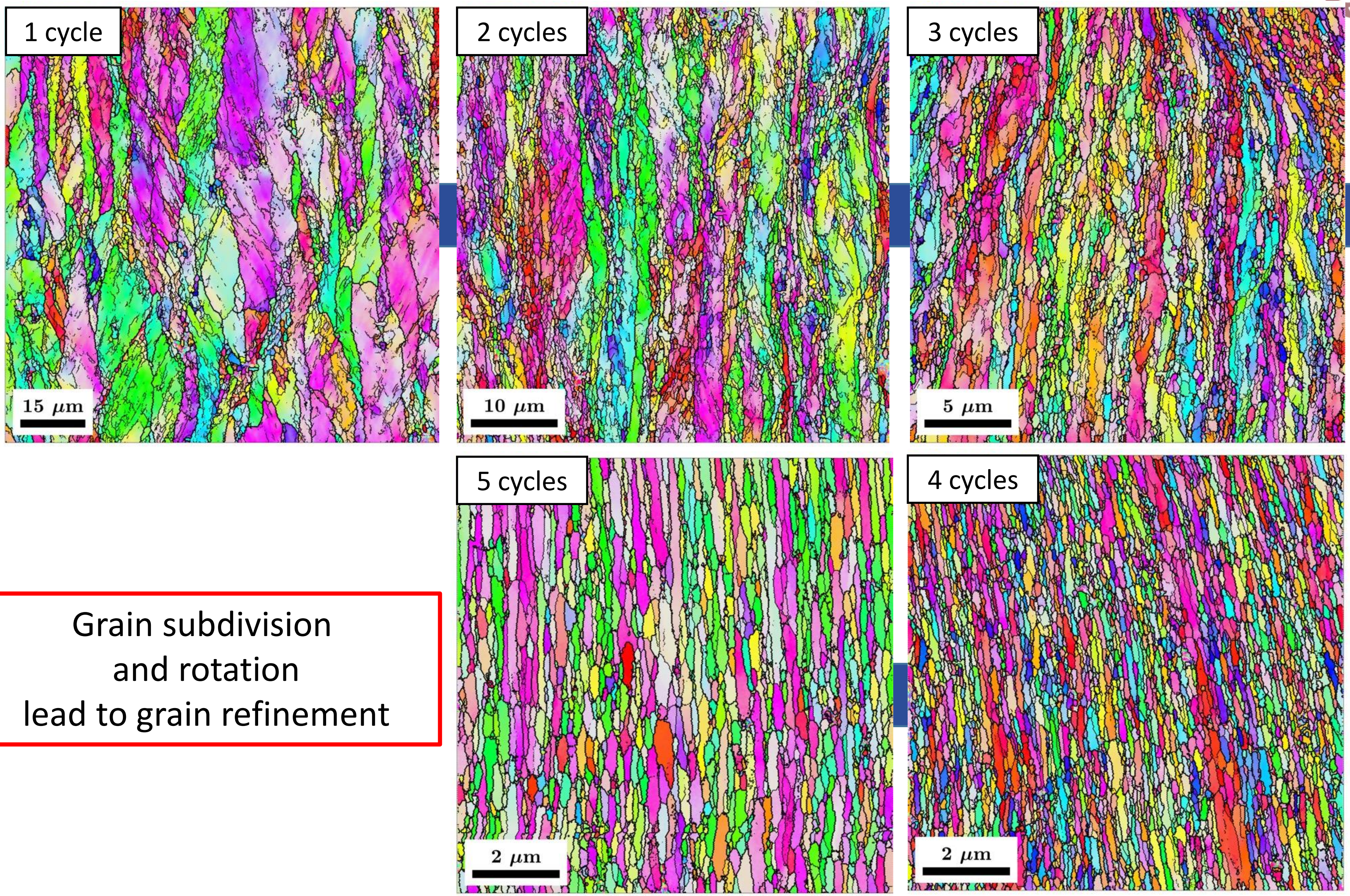
Grain Refinement (Brightfield TEM)



*observed at random location through-thickness

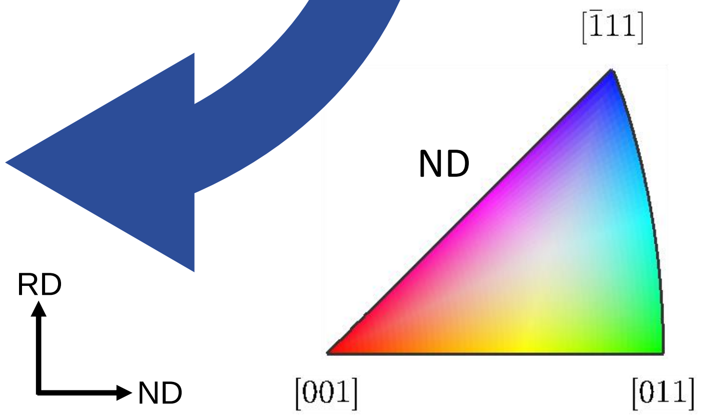
Grain subdivision, rotation and dislocation conglomeration lead to grain refinement (*"in-situ" recrystallization*)

Grain Refinement (Inverse pole figure maps)

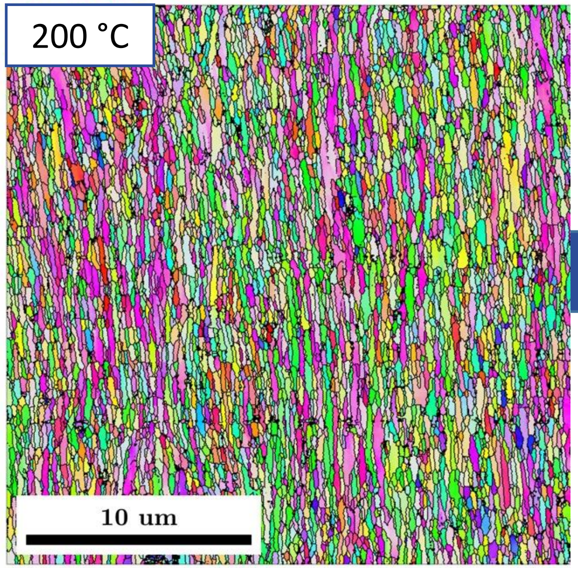


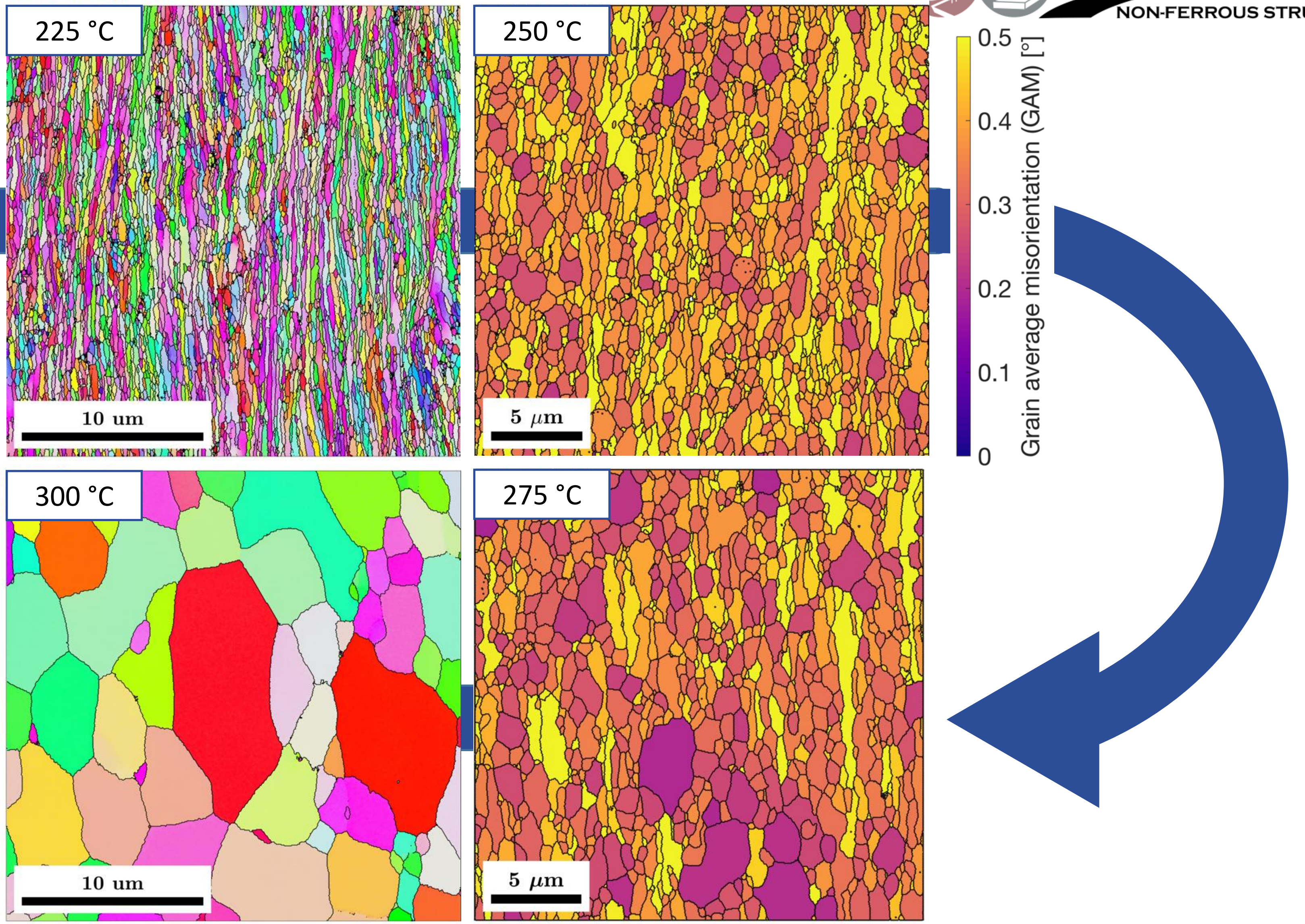
*observed in the vicinity of the centerline bond

Grain subdivision
and rotation
lead to grain refinement

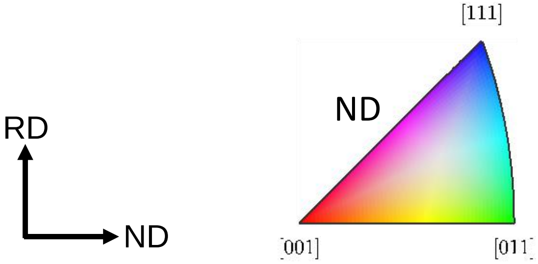


15 minute Static Annealing Trials (EBSD)

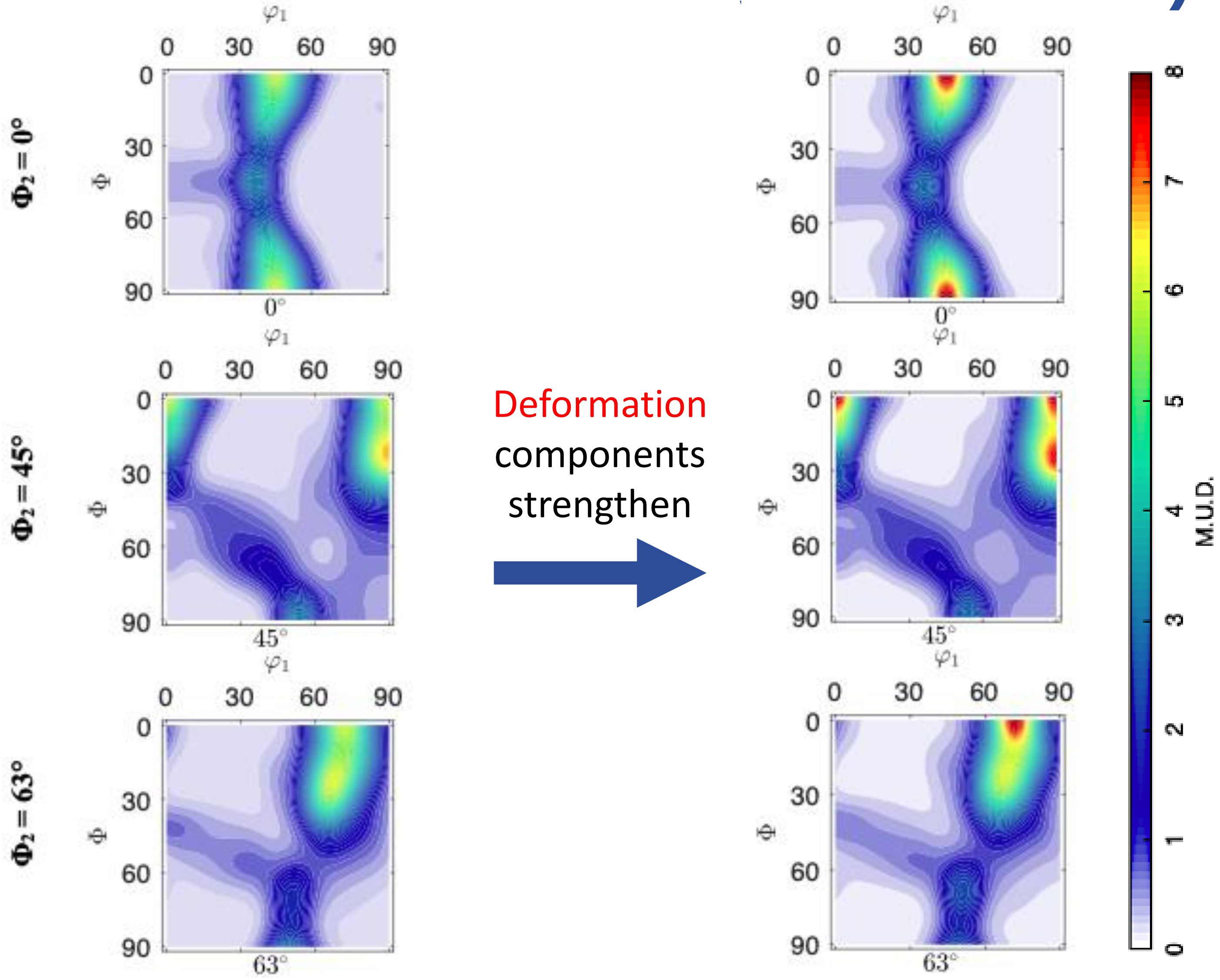




Gradual reduction in strain energy (GAM) throughout microstructure



15 minute Static Annealing Trials (XRD)

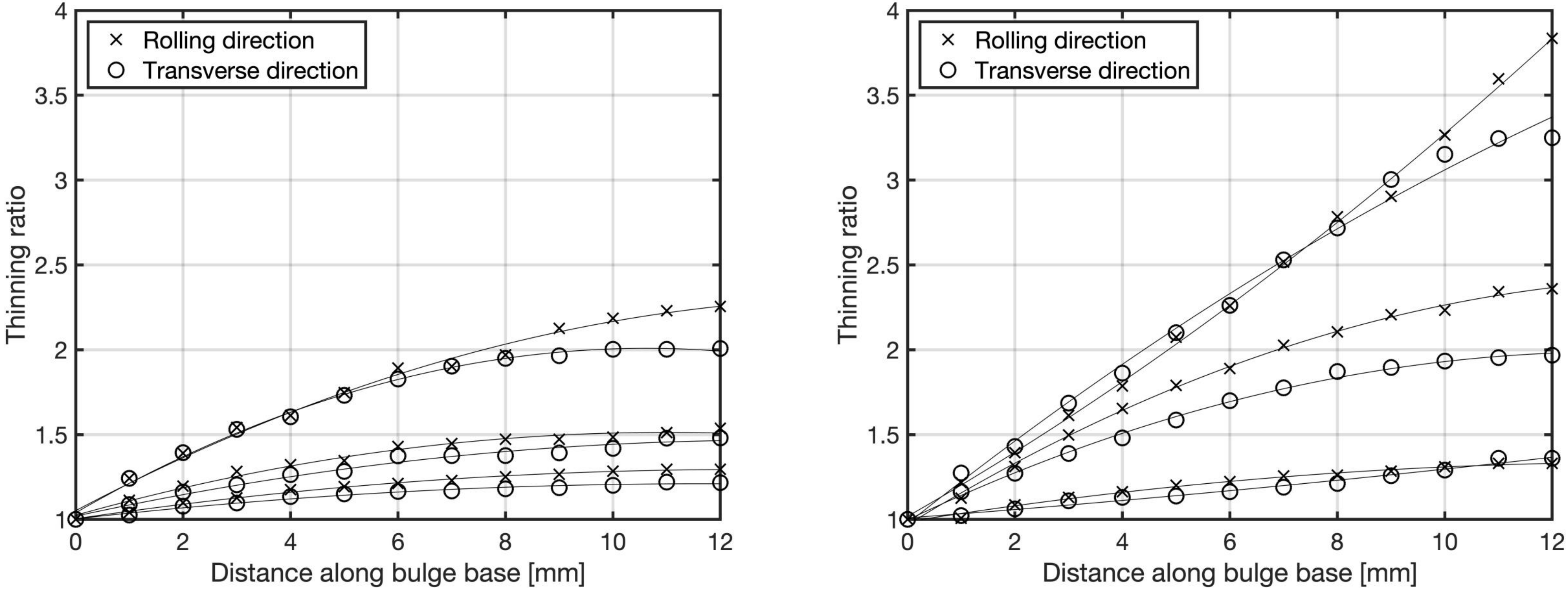


(a) *ARBed*

(b) 250 °C, 15 min

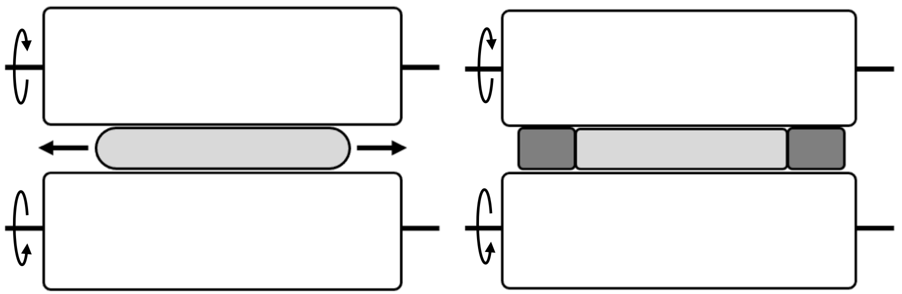
Annealing reduces
intragranular orientation gradients
leading to
texture strengthening

Thinning Ratios



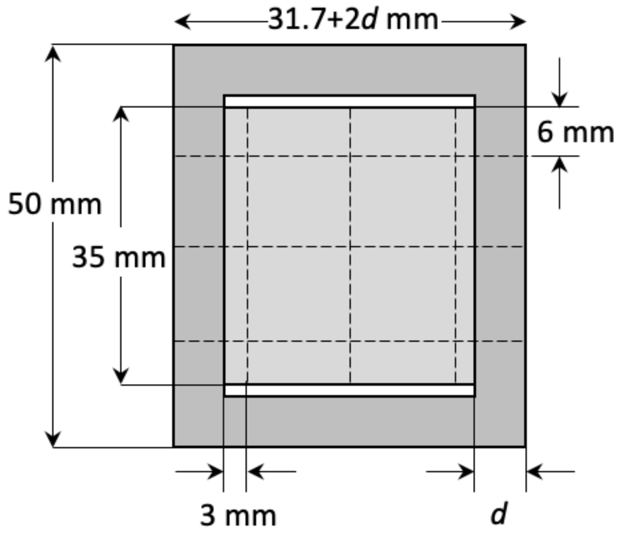
Center Proprietary – Terms of CANFSA Membership Agreement Apply

Mitigation of Edge Cracking

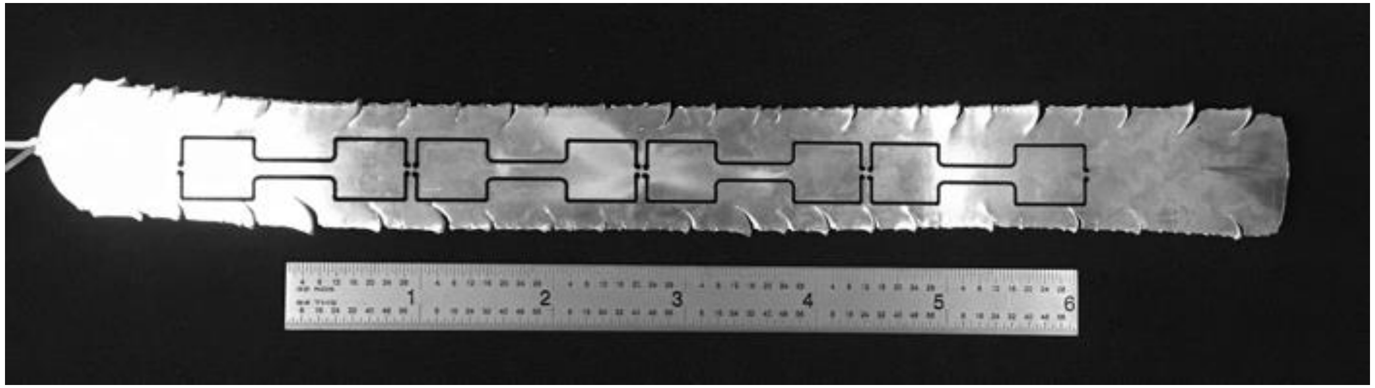


Lateral spreading
leads to
edge cracking

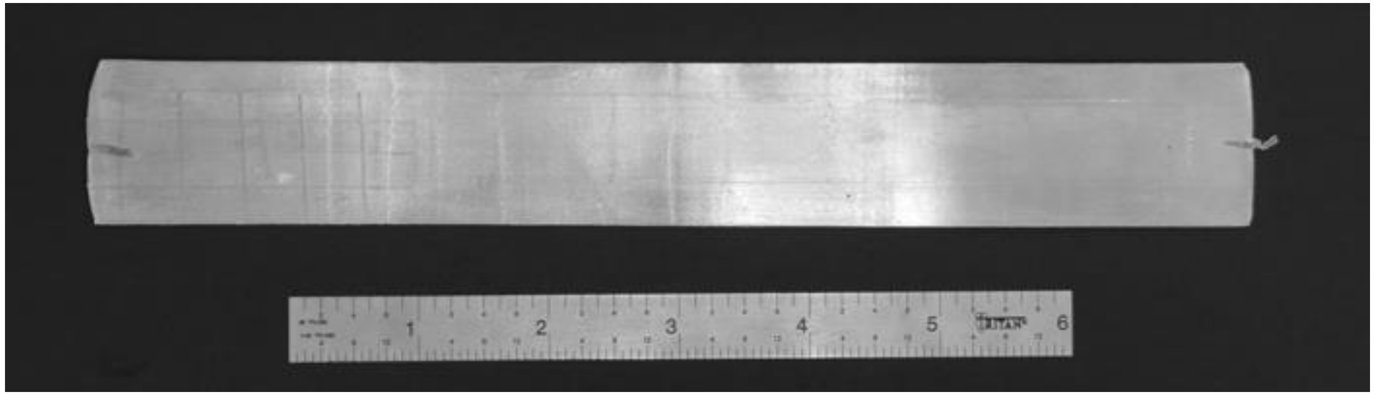
Lateral constraint
reduces
lateral spreading



5083 5 ARB – No Constraint

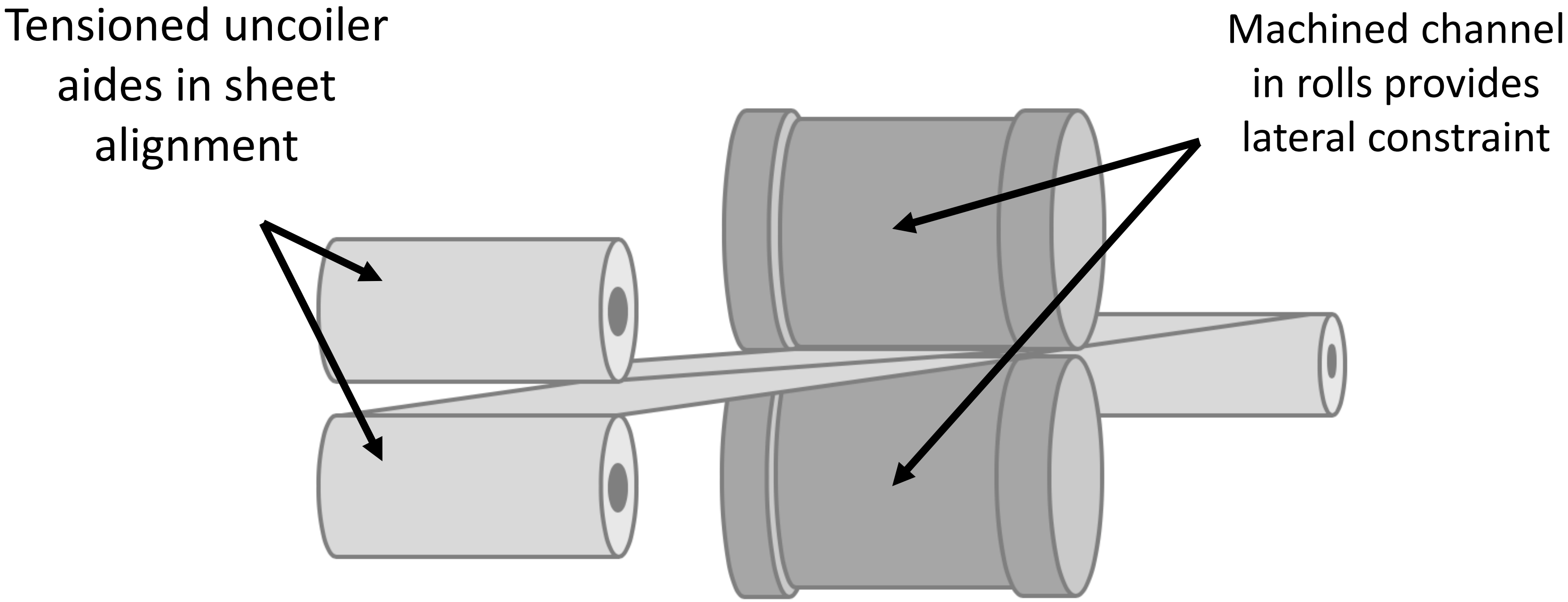


5083 5 ARB – 6 mm Constraint



McBride *et al.*, *J. Manu. Proc.*, 2010.

Scaling for Industry



100-ton Fenn Rolling Mill

133 mm (5.25”) cold rolls
100,000 lb capacity
37 RPM single speed

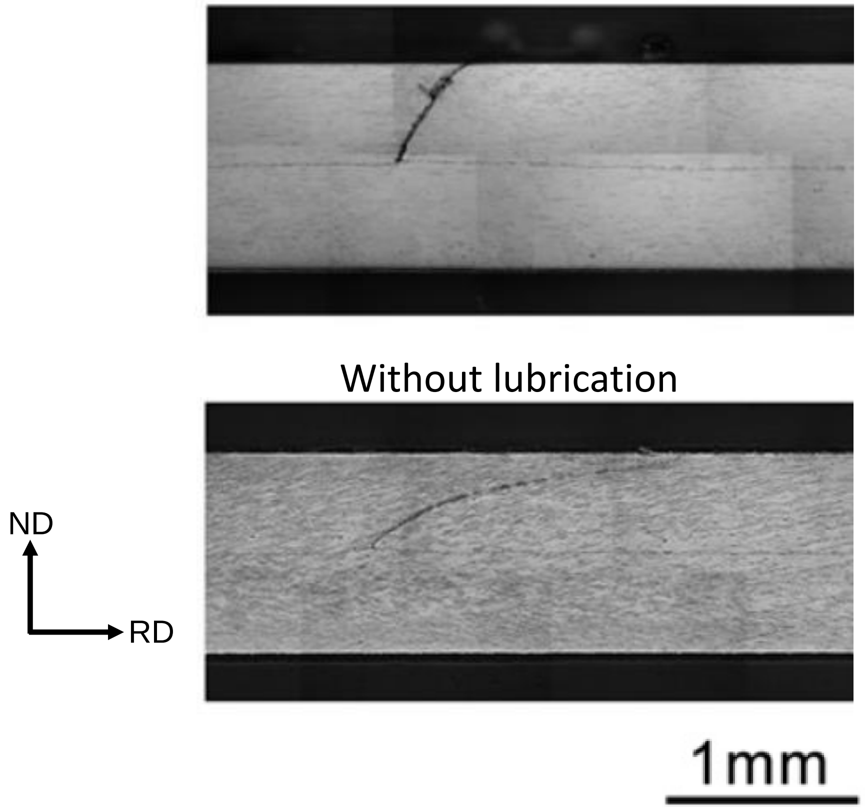
Configurable for:
4-high cold rolling
Hot rolling (200 °C)
Rod rolling (25 mm to 10 mm)

How is ARB Processing Different from Conventional Rolling?

1. Redundant shear

With lubrication

Without lubrication

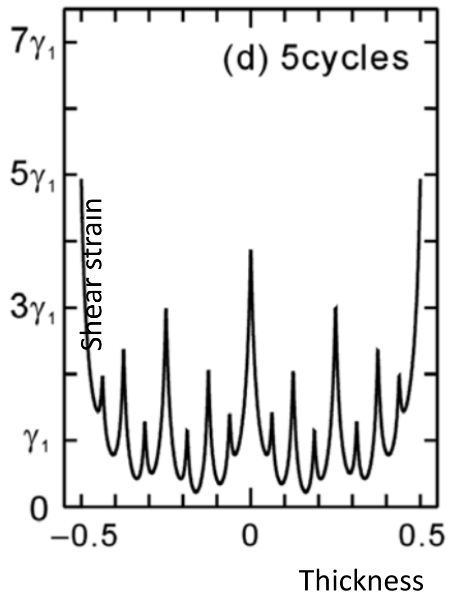


2. Consistent, through-thickness deformation

To obtain ε = 4.0, 96.9 % reduction:

5 ARB cycles	Convention rolling
(2x) 1 mm sheets	32.5 mm plate
↓	↓
(1x) 1 mm sheet	1 mm sheet

3. Introduction of shear through-thickness



Recrystallized Microstructure after ARB Processing

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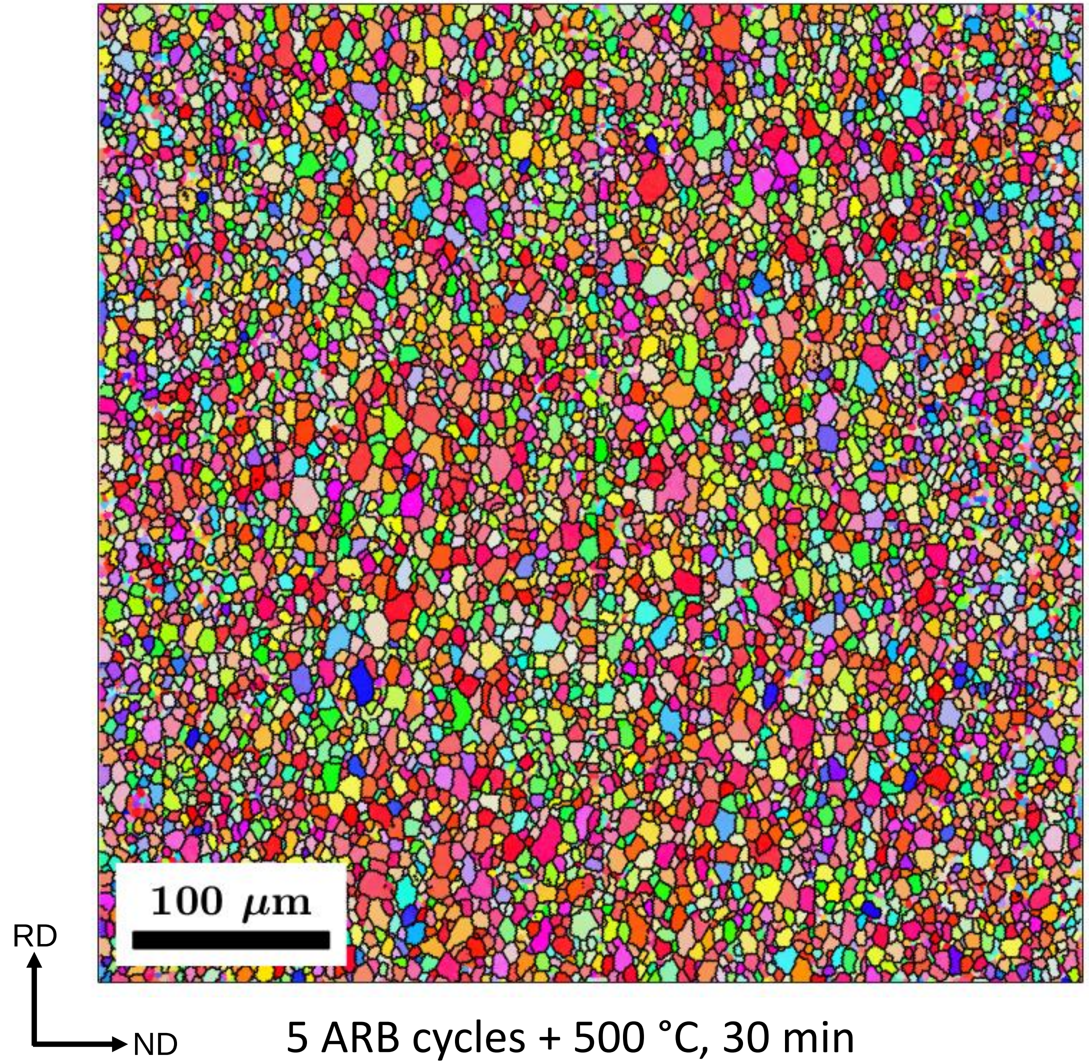
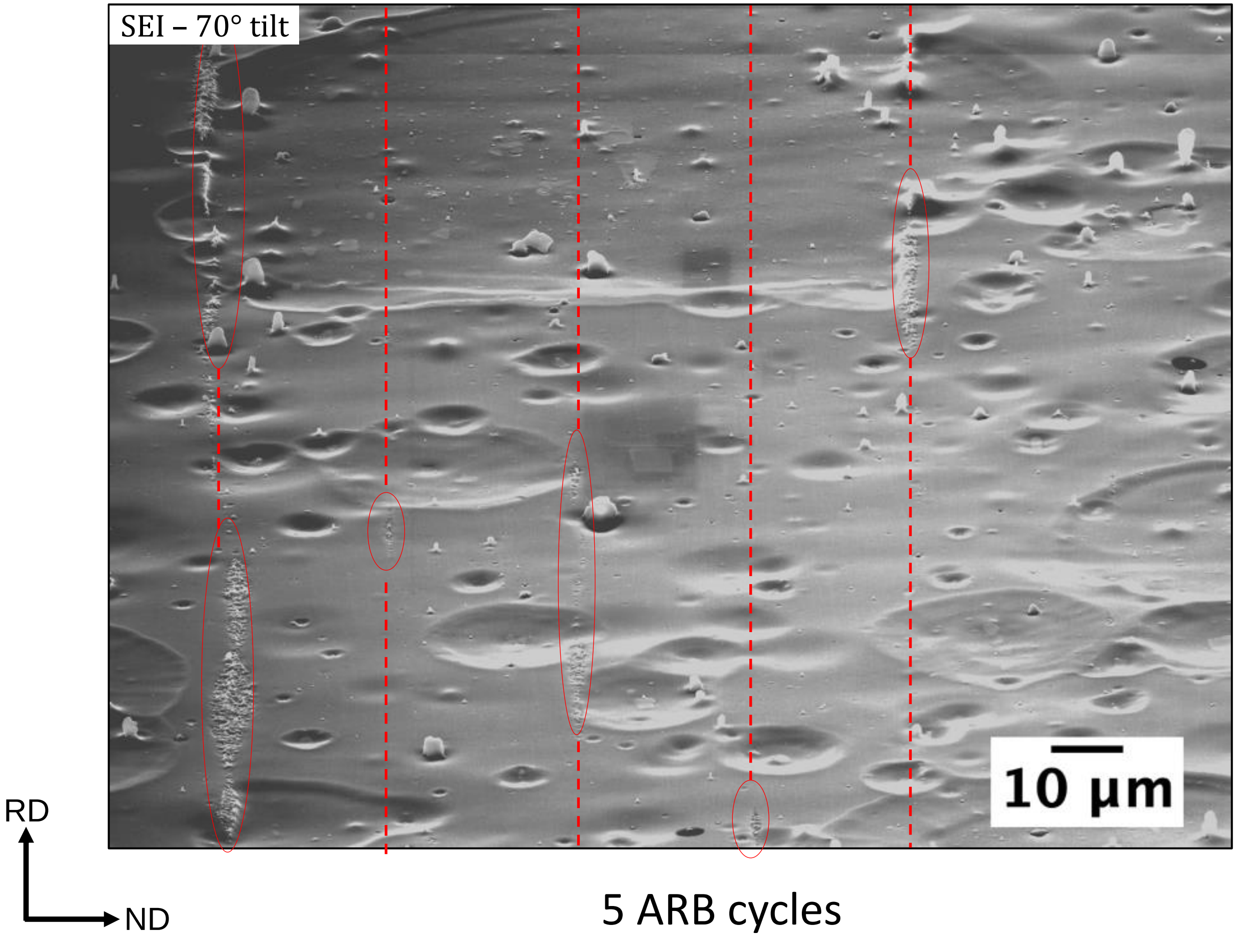


5 ARB cycles + 500 °C, 30 min

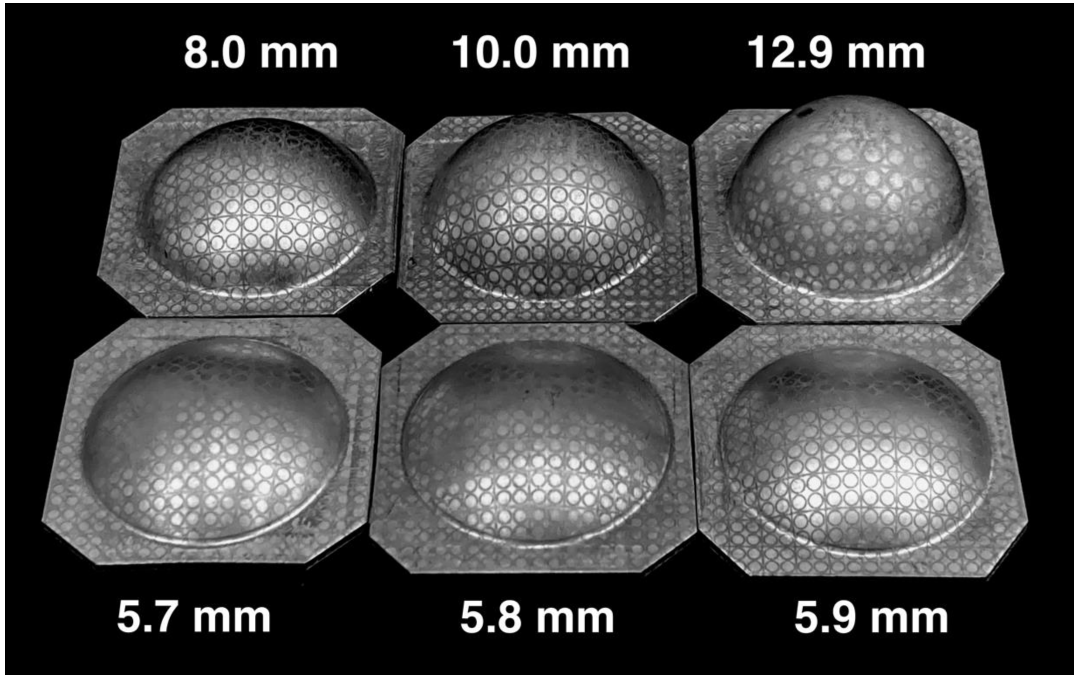
Recrystallization does not seem to occur across bonding interfaces



5 ARB cycles

Biaxial Bulge Testing: Results

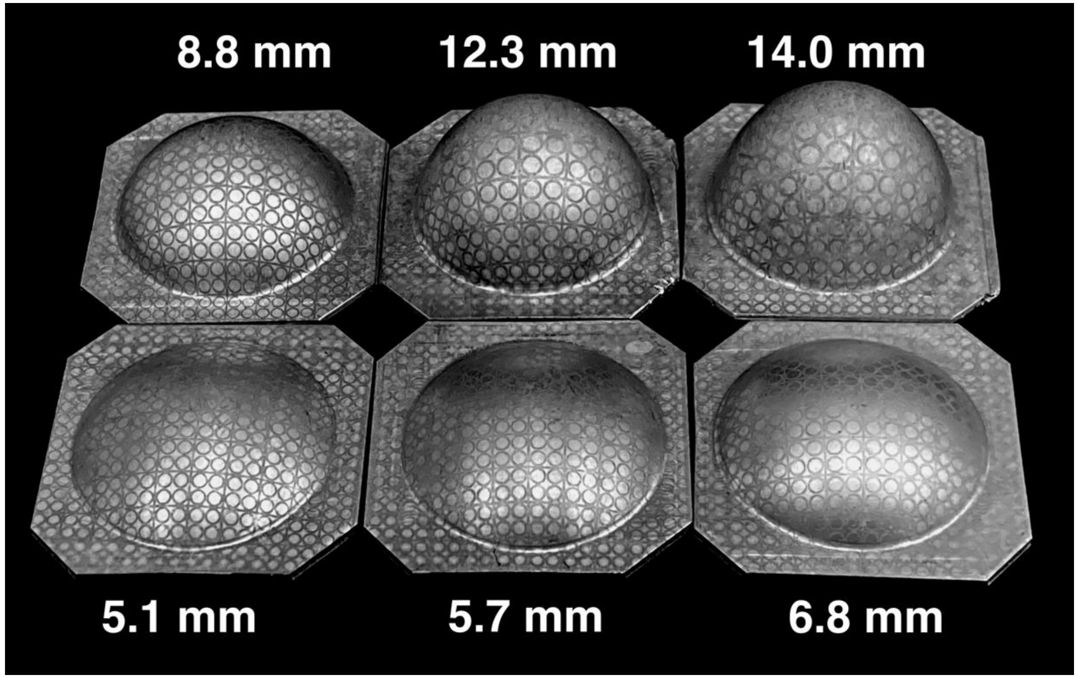
225 °C, 0.0005 s^{-1}*



ARBed (< 1 µm)

Coarse grained (≈ 10 µm)

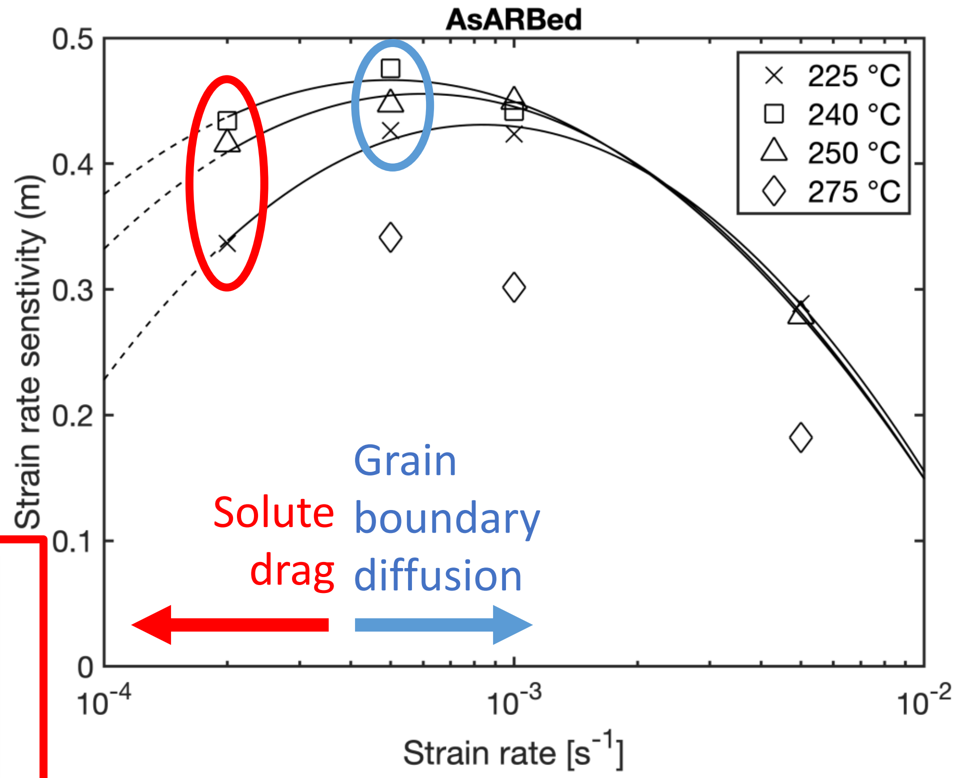
250 °C, 0.001 s^{-1}*



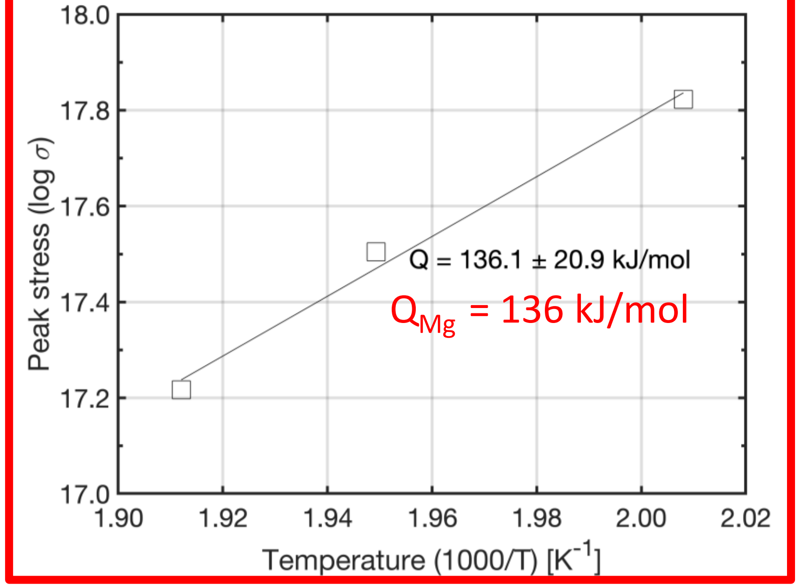
ARBed material exhibits biaxial superplasticity
with lower temperatures and lower forming pressures

*strain rates listed are anticipated values, not necessarily observed values

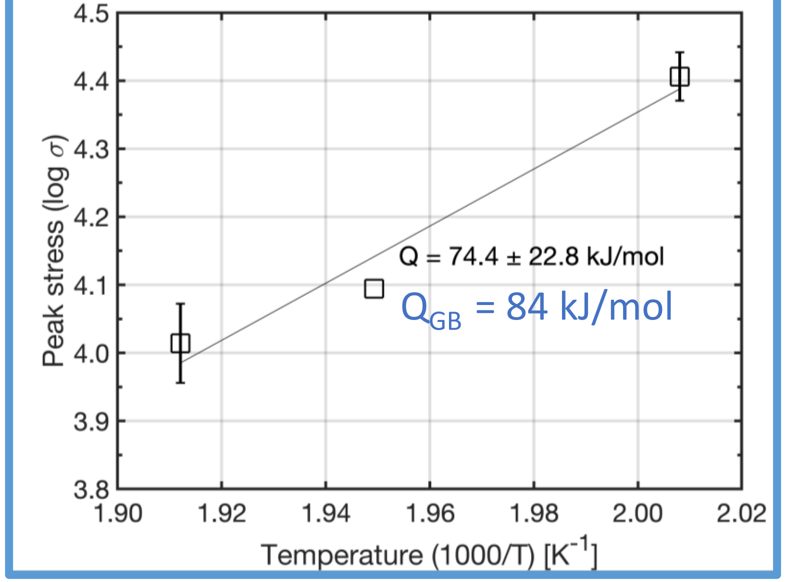
Identifying Strain Rate and Temperature Limits



< 0.0005 s^{-1}
Solute drag limited



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

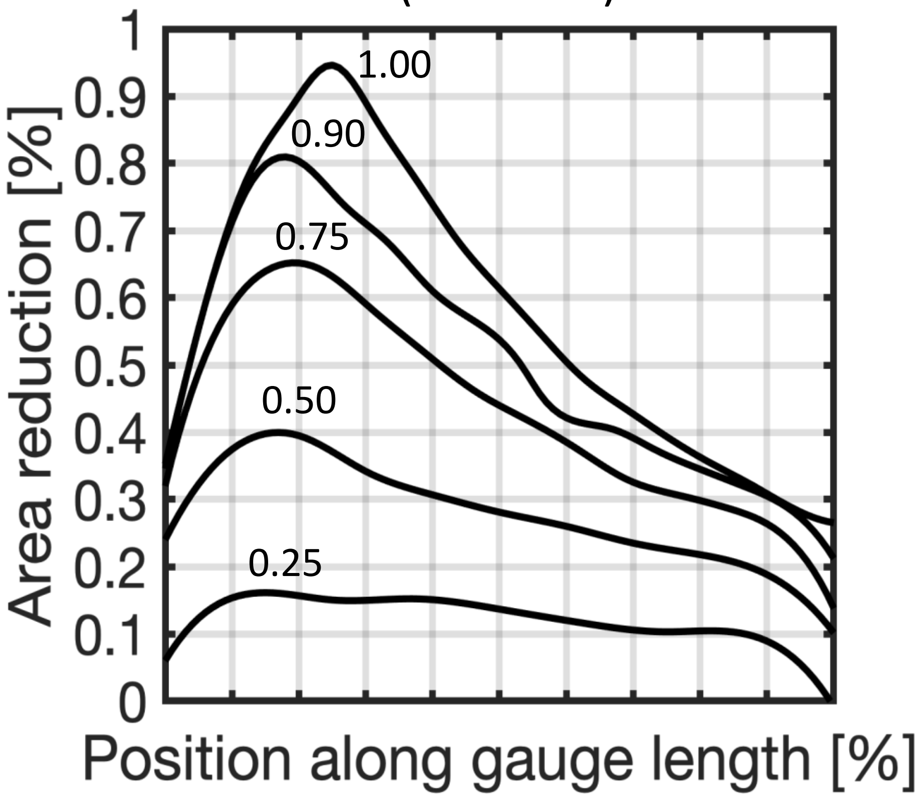


Activation energy for deformation

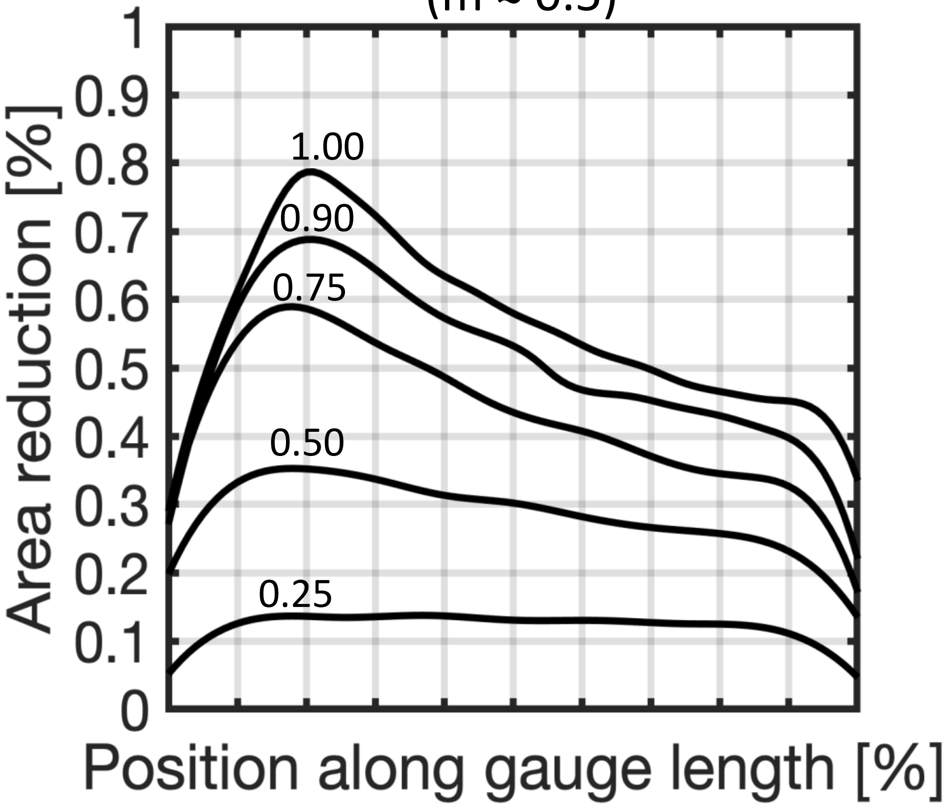
$$Q = \frac{k}{m}\frac{\delta \ln \sigma}{\delta 1/T}\bigg|_{\varepsilon,\dot{\varepsilon},d}$$

Strain Uniformity During Deformation

225 °C 0.0005 s^{-1}
($m \approx 0.45$)

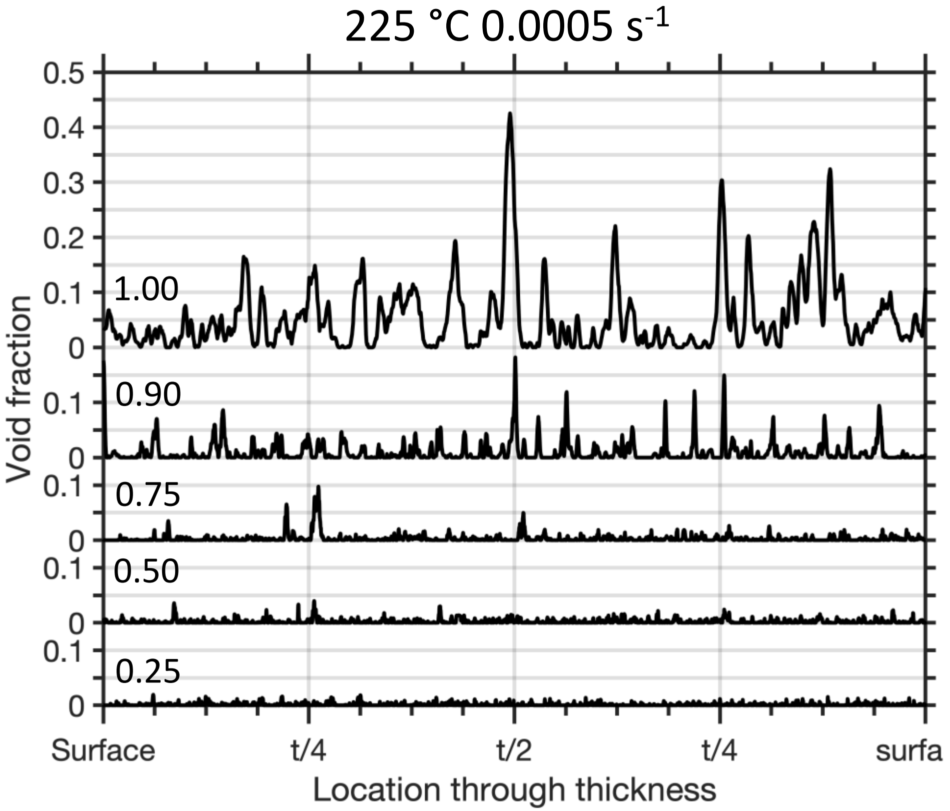


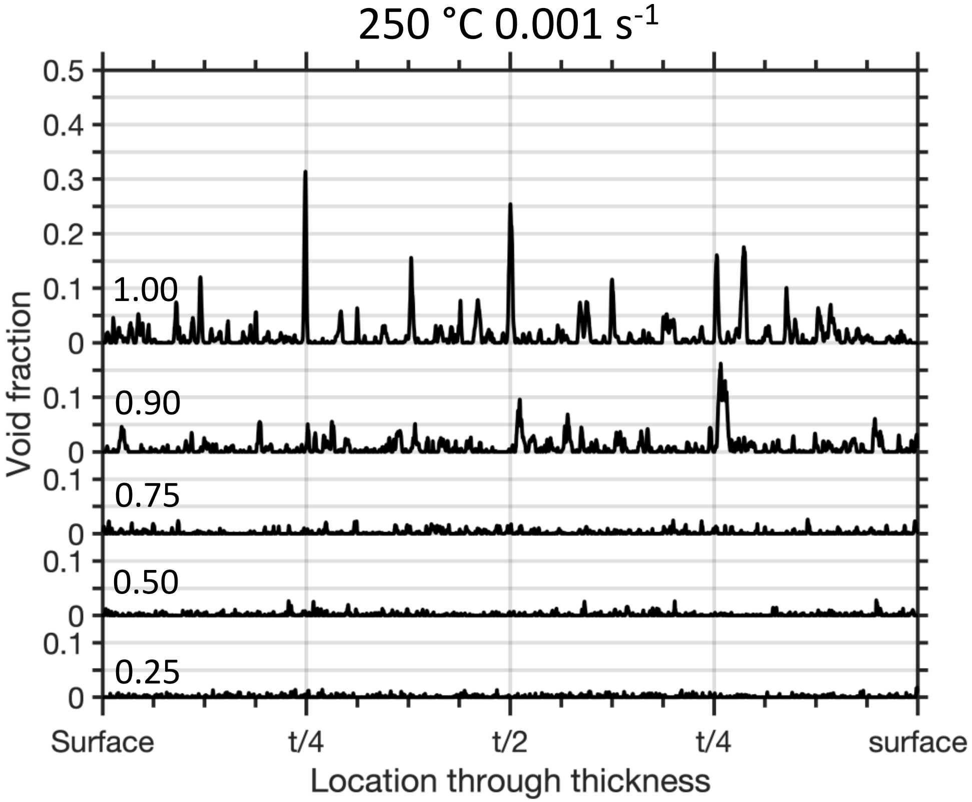
250 °C 0.001 s^{-1}
($m \approx 0.5$)



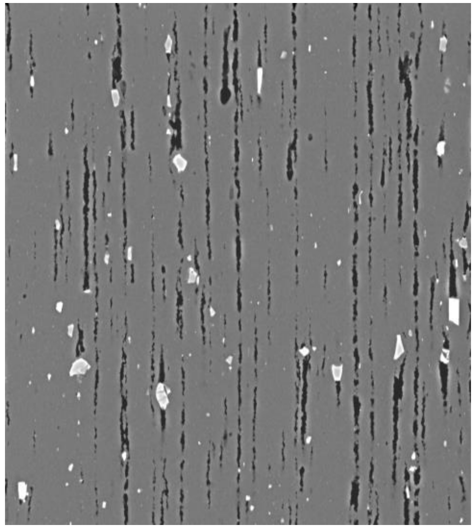
Significant strain localization after $\varepsilon = 0.75$ ($e = 1.10$)

Damage Accumulation



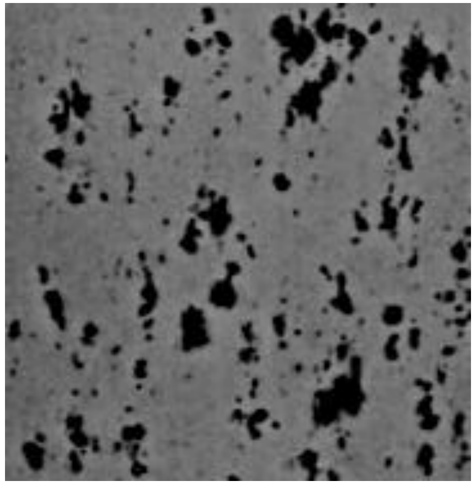


225 °C 0.0005 s-1



ε = 1.00 50 µm

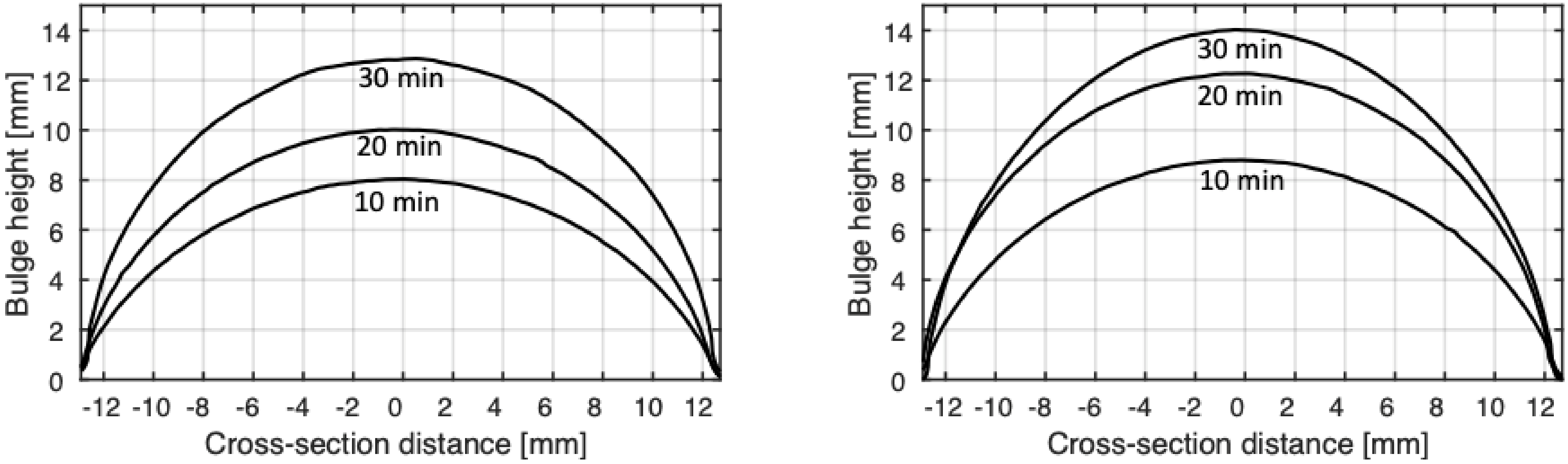
500 °C 0.001 s-1



ε = 1.01 100 µm

Significant strain-induced void growth (voids > 1 µm) for ε > 0.75 (*e* > 1.1)

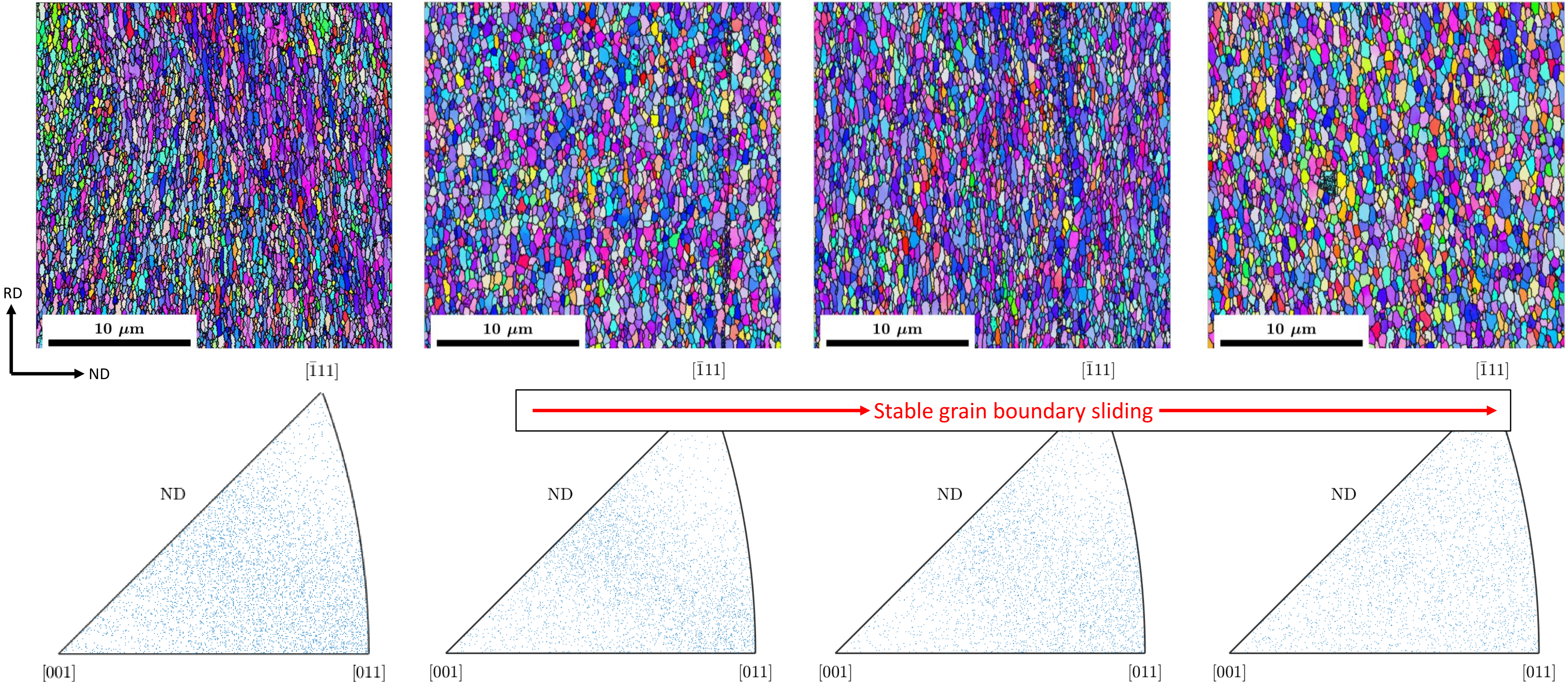
Analysis of Bulge Test Specimens



Height and thickness profiles → Analytical models for superplastic forming

Incremental strain at 225 °C, 0.0005 s^{-1}

ε = 0.1, 200s | ε = 0.25, 500s | ε = 0.5, 1000s | ε = 0.75, 1500s



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