SAND2022-2289C

Sandia National Laboratories

Exceptional service in the national interest

Exploring the Stress Corrosion Cracking Susceptibility of Additively Manufactured 316L in Boiling Magnesium Chloride

Speaker: Erin Karasz

SNL: Michael Melia, Jason Taylor, David Autenrieth, Phillip Reu, Kyle Johnson, Philip Noell

2022 TMS

February 28, 2022

Anaheim, CA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

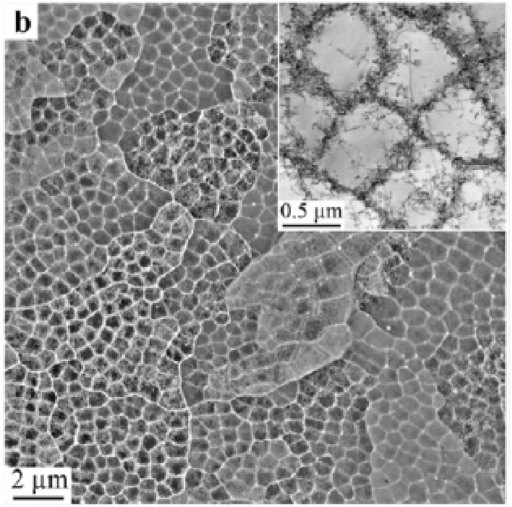
Additively Manufactured Metals

Additively manufactured (AM) metals are different from wrought:

- Microstructure
  - Sub-grain structure
  - Melt pool boundaries
- Processing defects
  - Lack of fusion pores
  - Surface roughness
- Residual stresses

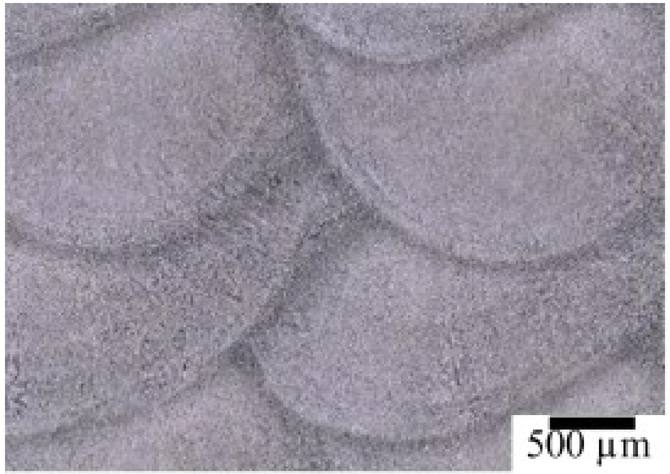
This work focuses on the relationship between residual stress and stress corrosion cracking in AM 316L.

Sub-Grain Structure



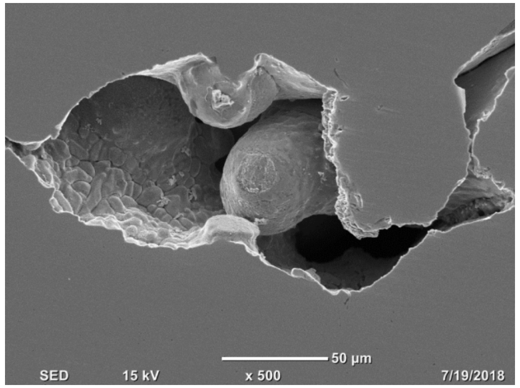
Voisin, 2021

Melt Pool Boundaries



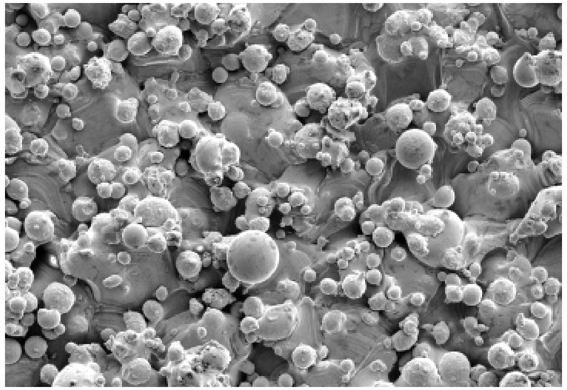
Melia, 2019

Porosity



Melia, 2019

Surface Roughness

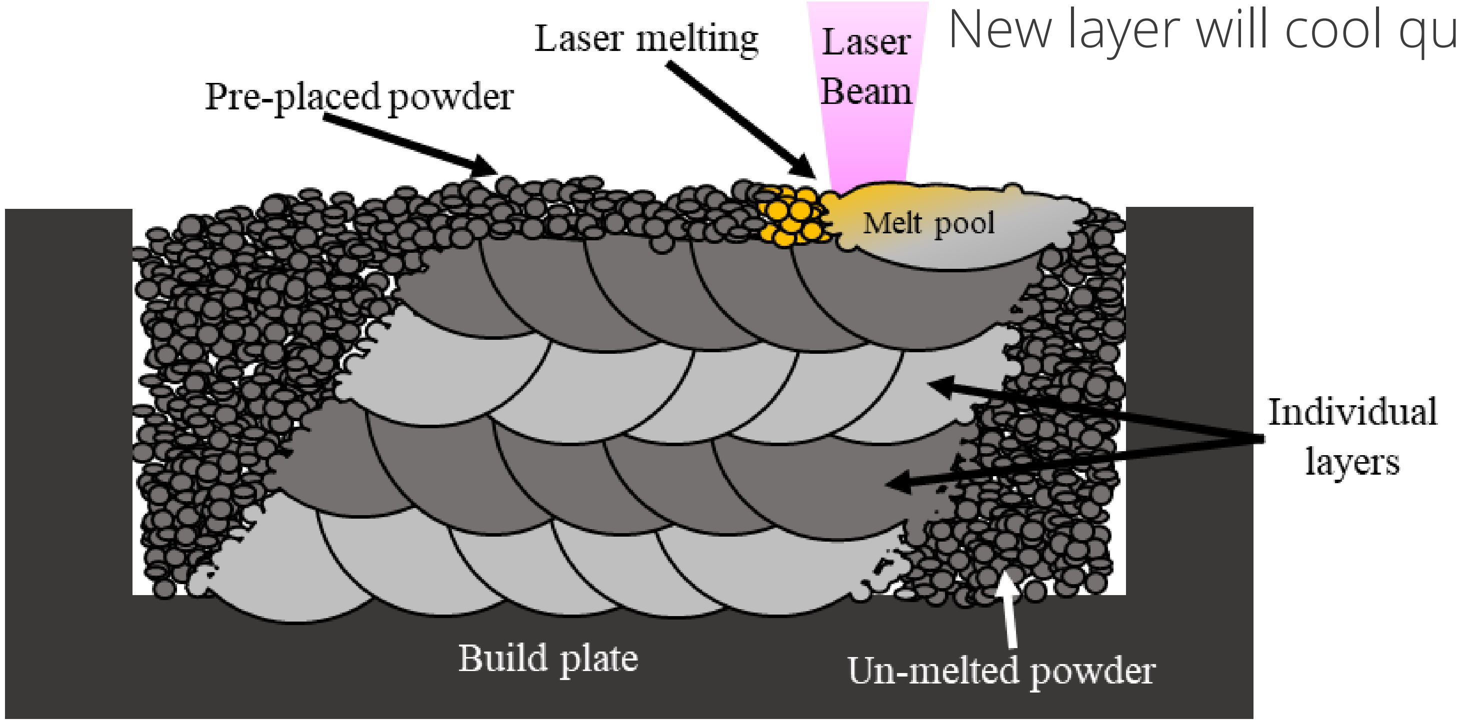


Melia, 2020

Laser Powder Bed Fusion & Residual Stress

Residual stress is a by-product inherent to the AM process and can contribute to stress corrosion cracking.

Heat from melting a new layer will heat layer underneath
Expansion of lower layer is restricted (part beneath has cooled)
New layer will cool quickly, contract faster than layers beneath



Melia, 2020

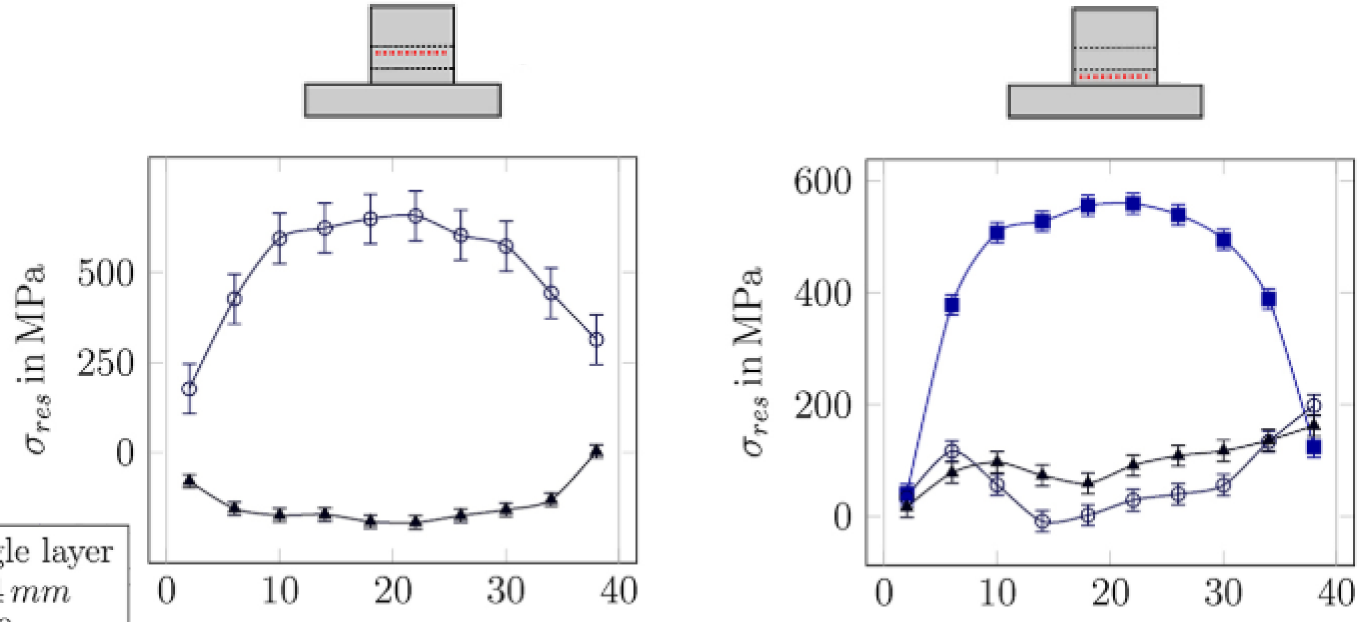
Laser Powder Bed Fusion & Residual Stress

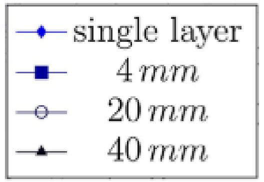
From Strantza et al.

- Each layer of can have fluctuations in residual stress
- Residual stress varies on scale of part

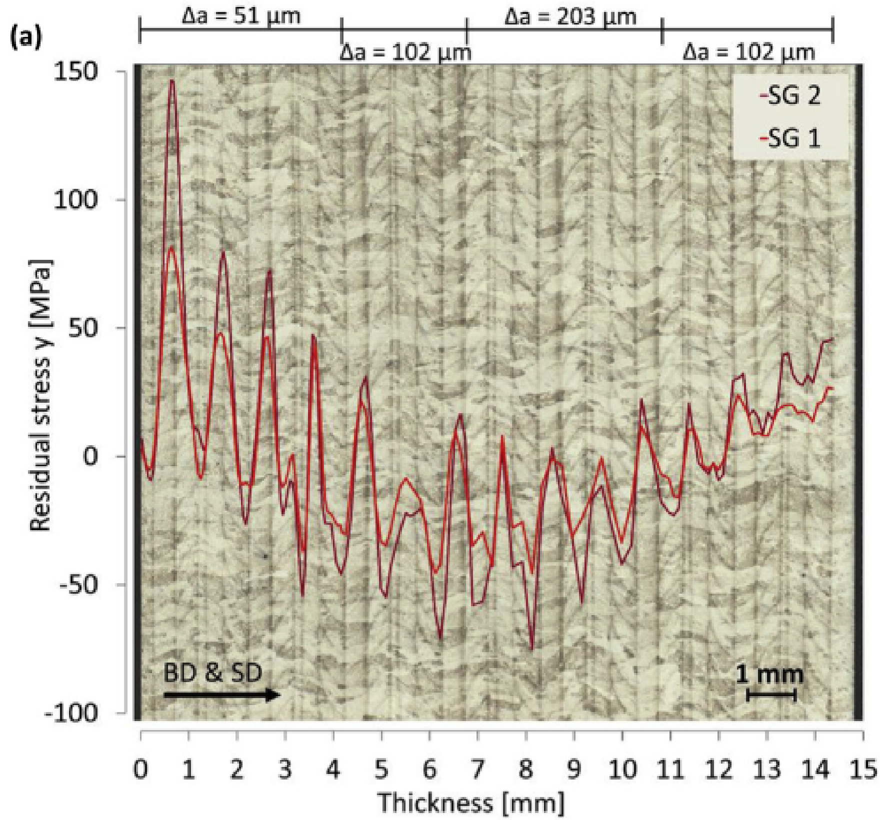
From Bayerlein et al.

- Cutting samples at different heights results in different residual stresses





σxx measured across, horizontal; (cut 18 mm, 2 mm)
Bayerlein, 2018



Strantza, 2019

Varying Residual Stress

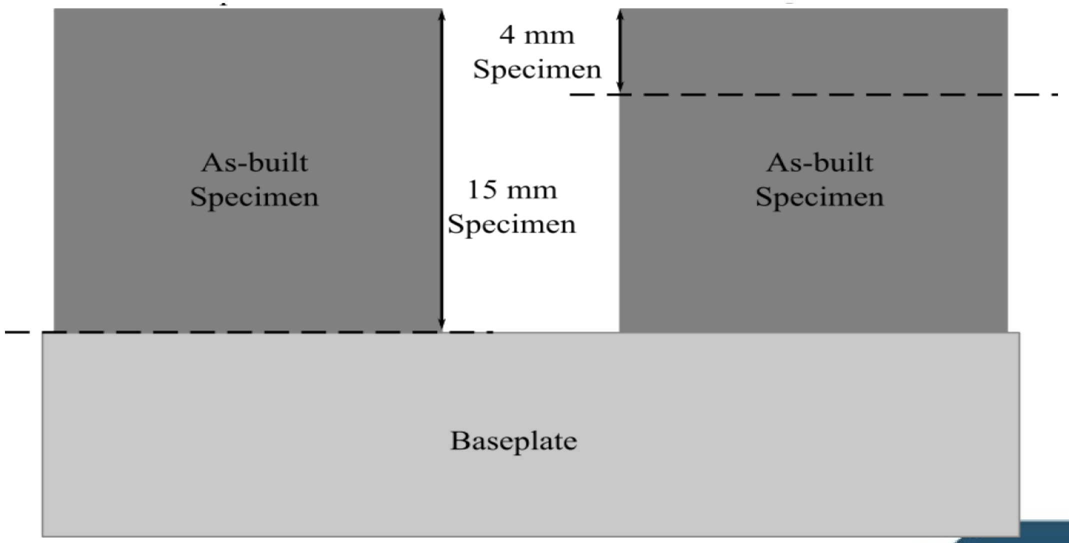
Utilize multiple methods to vary residual stress:

- Cut samples at different heights from build plate → preserve microstructure
  - 4, 6, 8, 10, 15 mm
- Heat treatment → change microstructure/mechanical properties
  - 600, 800, 1200 °C; 1 hour

316L Stainless Steel Laser Powder Bed Fusion
15 x 15 x 15 mm blocks

Large residual stress on top surface after cut

Small residual stress on top surface after cut

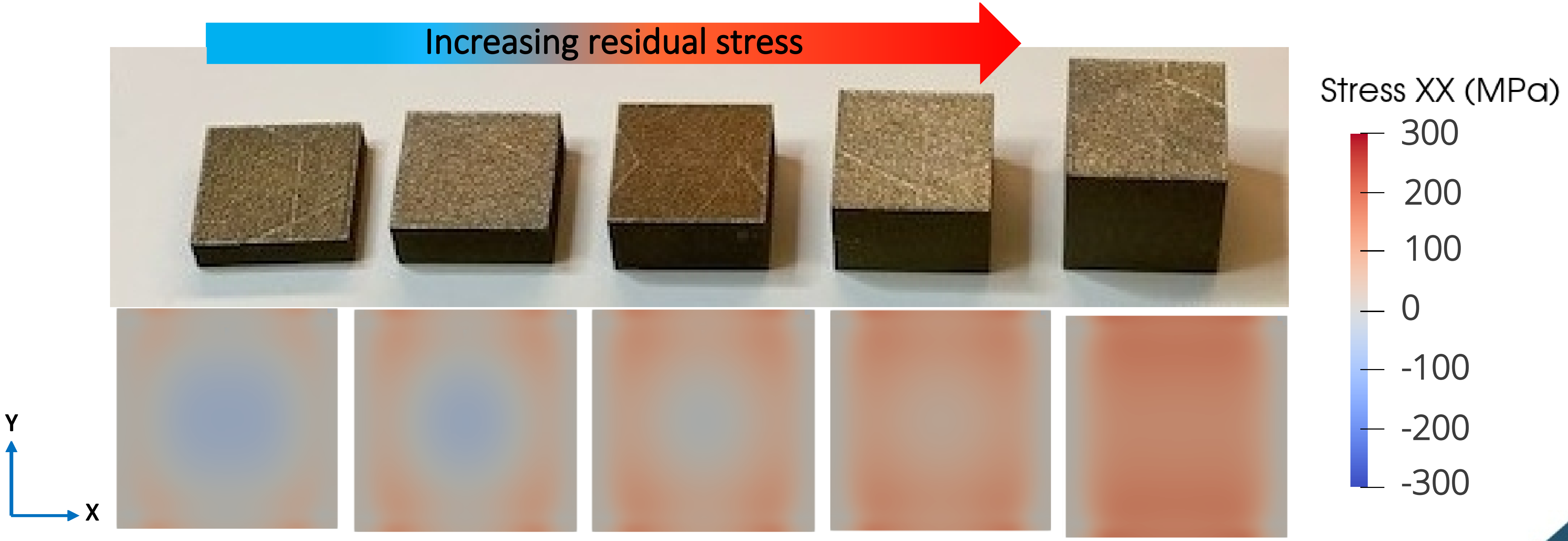


Finite Element Analysis

Simulation using Sierra Mechanics Module

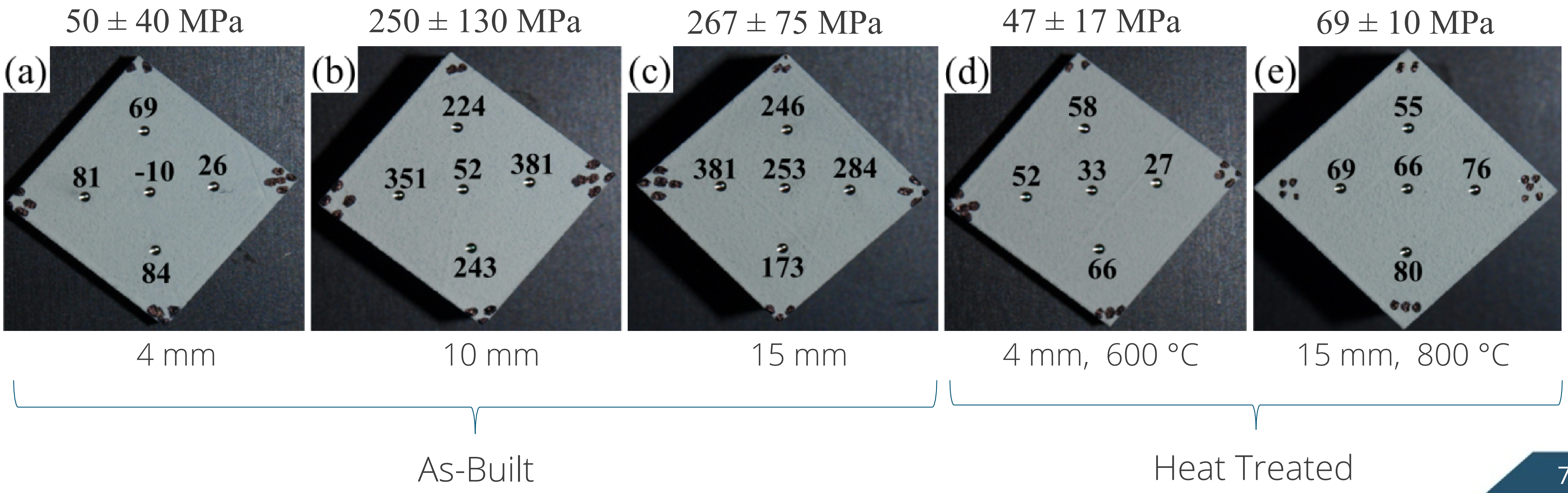
Shorter Samples (4, 6, 8 mm)
- Tensile stresses around the perimeter
- Compressive stresses near center of the surface

Taller samples (10, 15 mm)
- More even stress distribution
- Tensile stresses



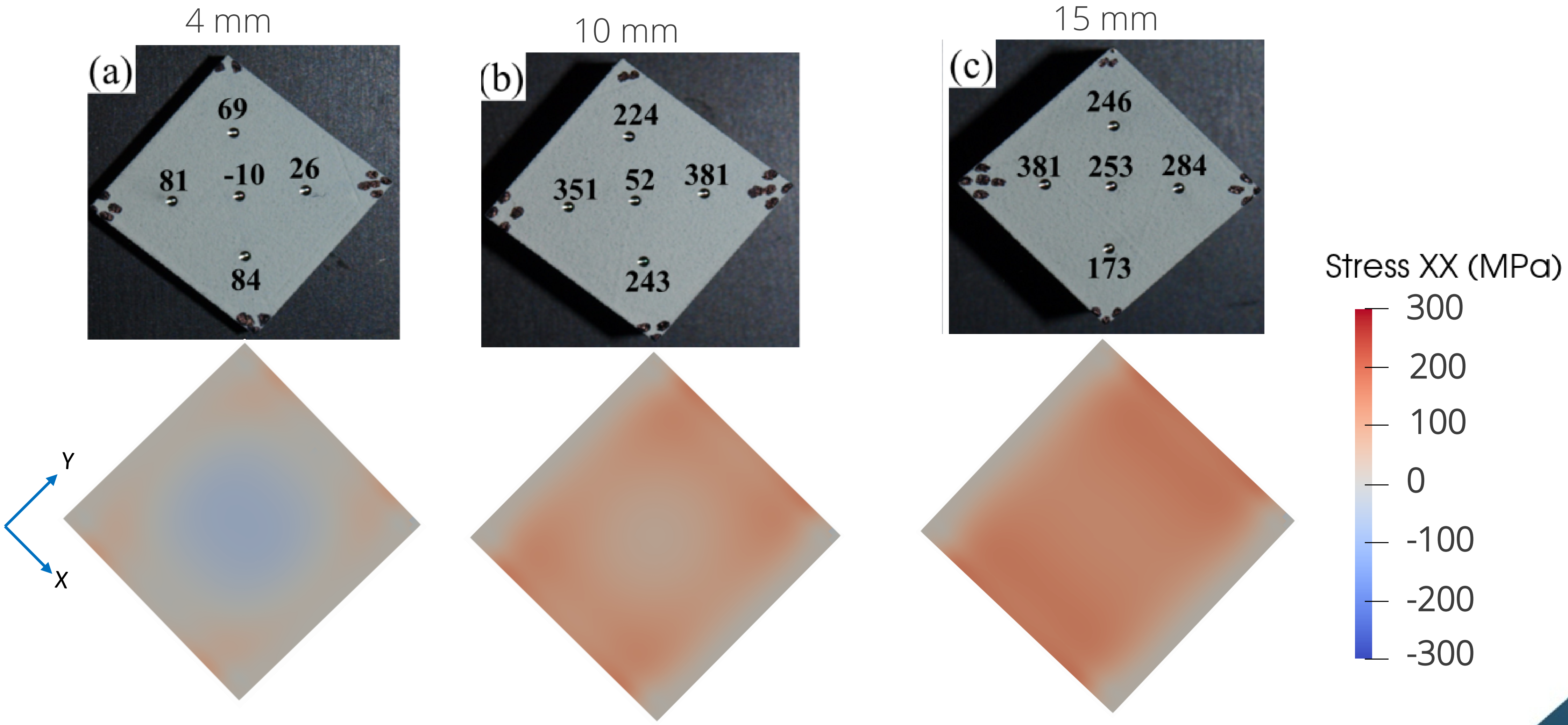
Hole Drilling

- Stresstech Electronic Speckle Pattern Interferometry system
- 0.8 mm diameter drill
- 0.025 mm increments to depth of 0.6 mm, 5 spots per sample
- Imaged with digital camera
- PrismS software analyzed relaxation



Simulation vs Experimental

The values from simulation align well with those from the hole-drilling in as-built samples.



Boiling $MgCl_2$ Experiments

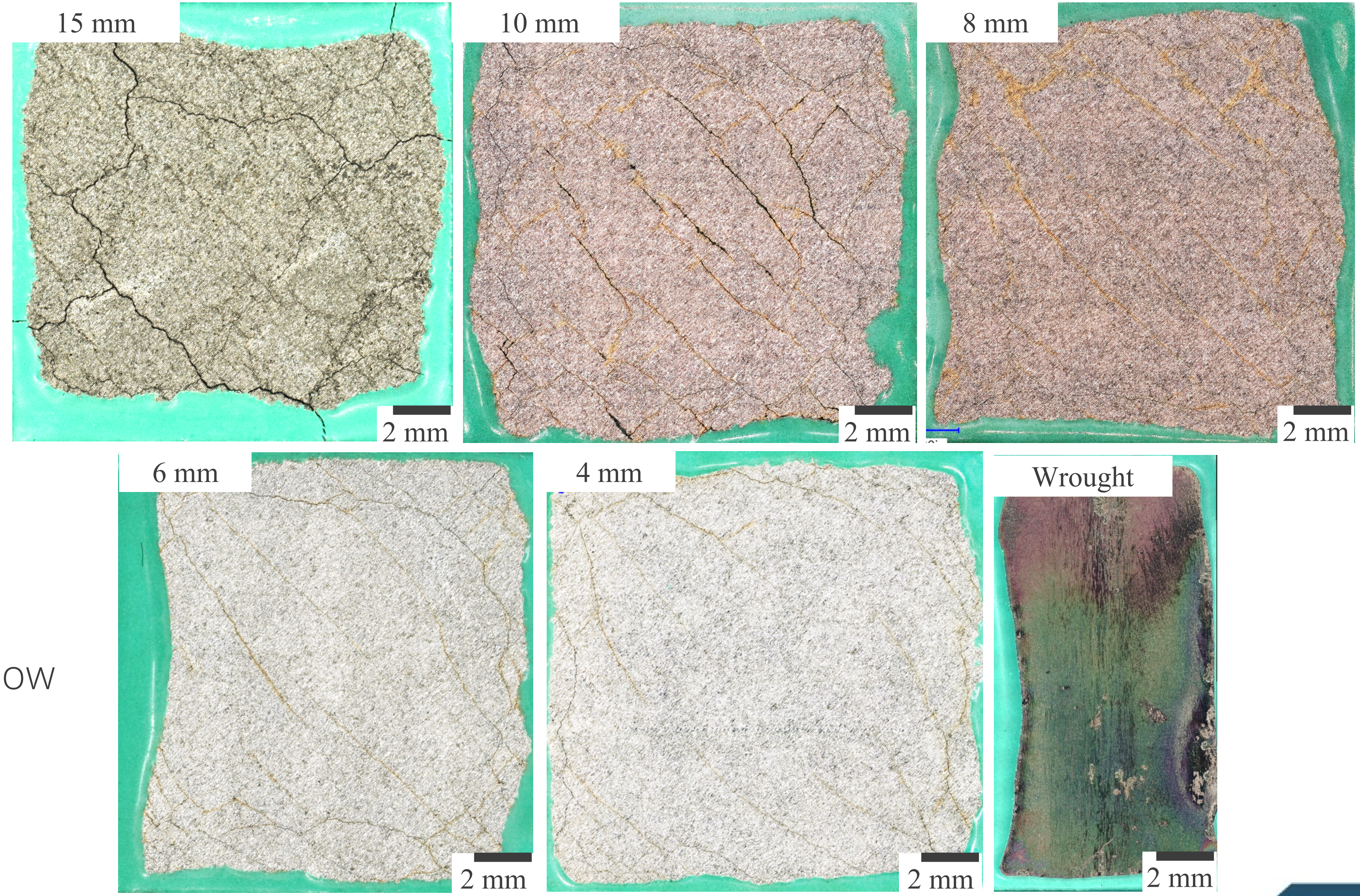
Sides (except for top surface), coated in epoxy
3M Scotchkote liquid epoxy 323

ASTM G36-94
Full immersion in saturated, boiling $MgCl_2$
155 °C

- Samples were checked after 24 hrs
- If no cracks were visible, resubmerged and checked every 72 hours, up to 350 hours of exposure

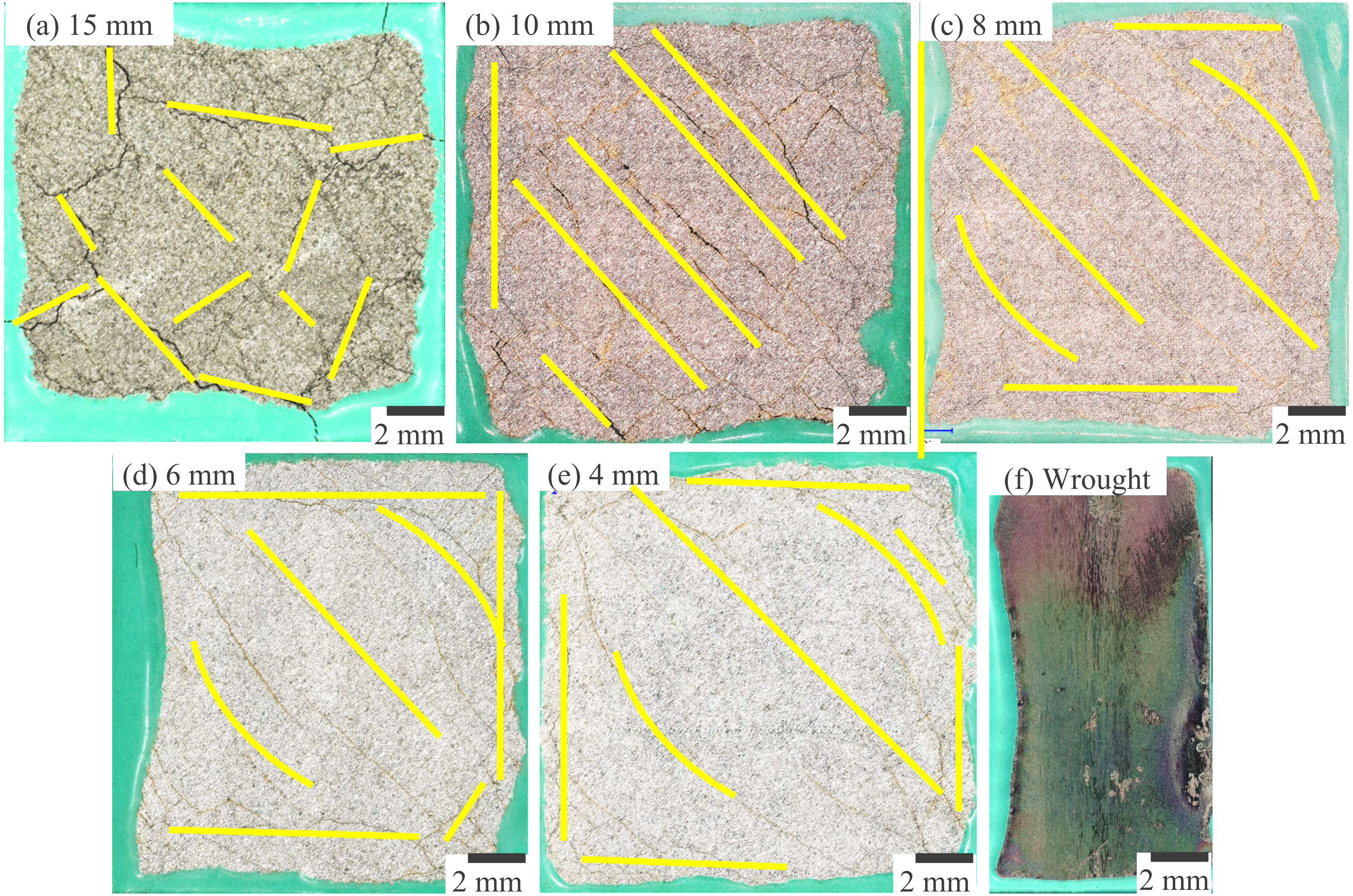
As-Built Samples

- All as-built showed cracking within 24 hours
- Shorter samples show oriented cracking
- Tallest sample more distributed cracking
- 15 & 10 mm tall samples show more pronounced cracks



As-Built Samples

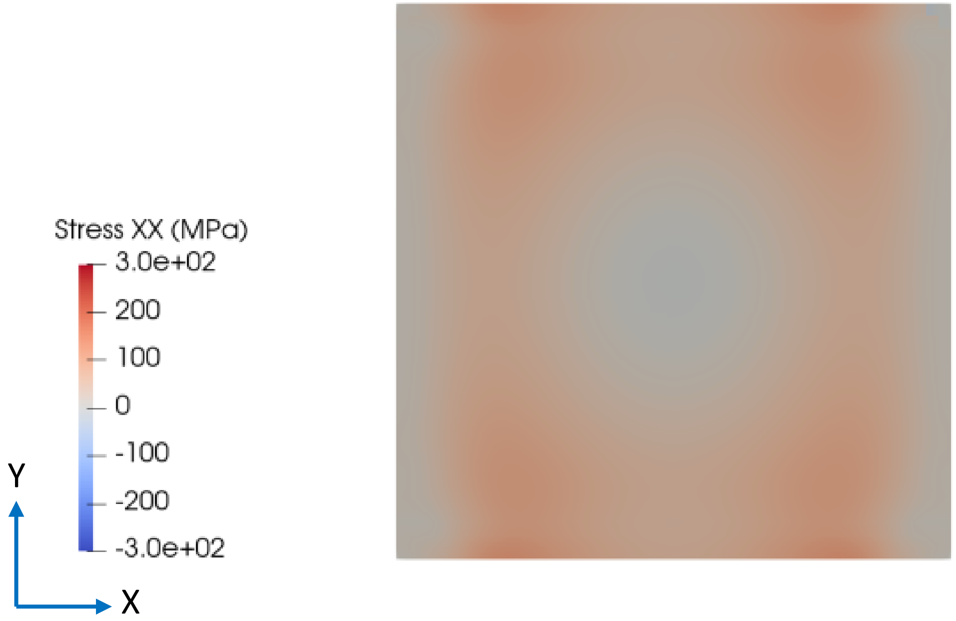
- All as-built showed cracking within 24 hours
- Shorter samples show oriented cracking
- Tallest sample more distributed cracking
- 15 & 10 mm tall samples show more pronounced cracks

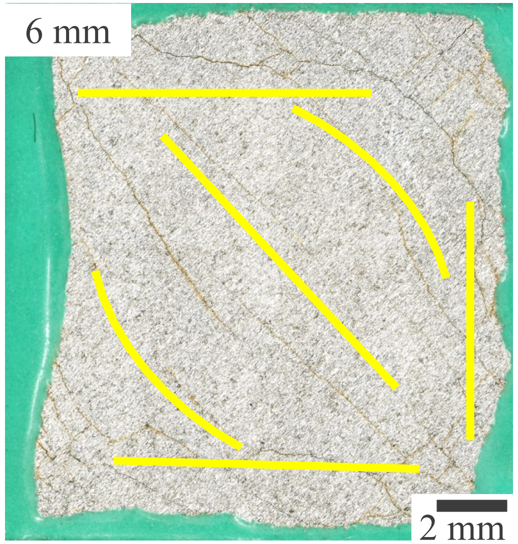


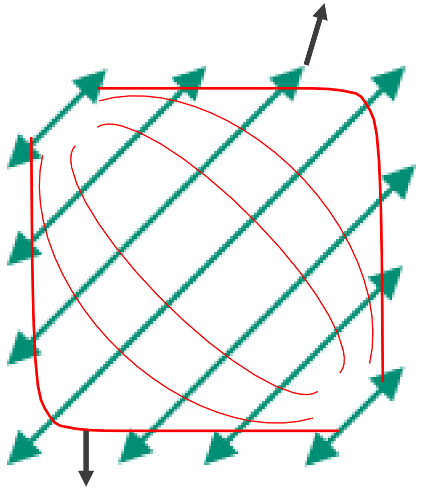
As-Built Sample Crack Location

Cracks in shorter samples run perpendicular to the melt tracks near the center of the sample

Cracks around circumference of the surface, align well with high stress areas identified in simulation

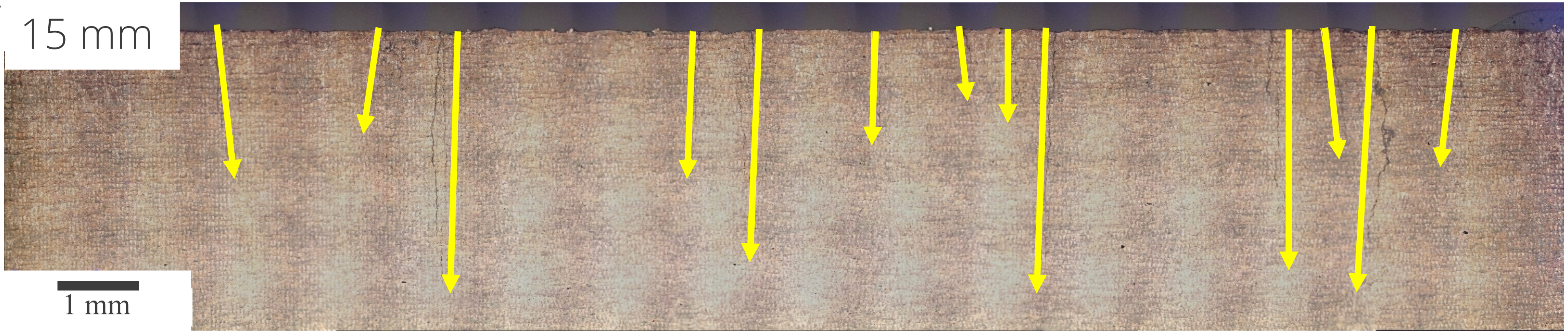


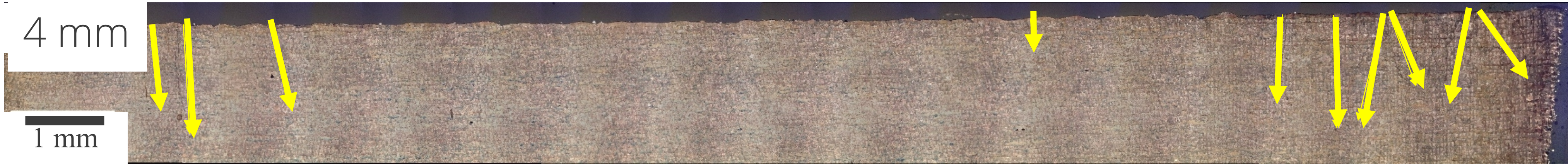




As-Built Sample Crack Depth

Cross-sectioned on the diagonal
Imaged with Keyence





Shorter Samples

- Deeper cracks near sample edge (higher stress regions)
- Cracks in the center probably too small to optically image

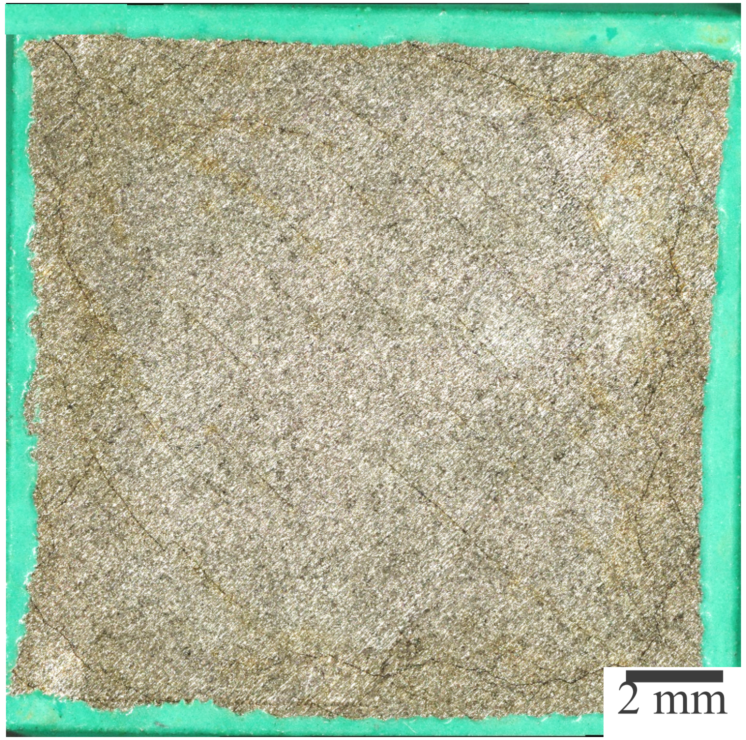
Taller Samples

- Deepest cracks distributed across the cross-section

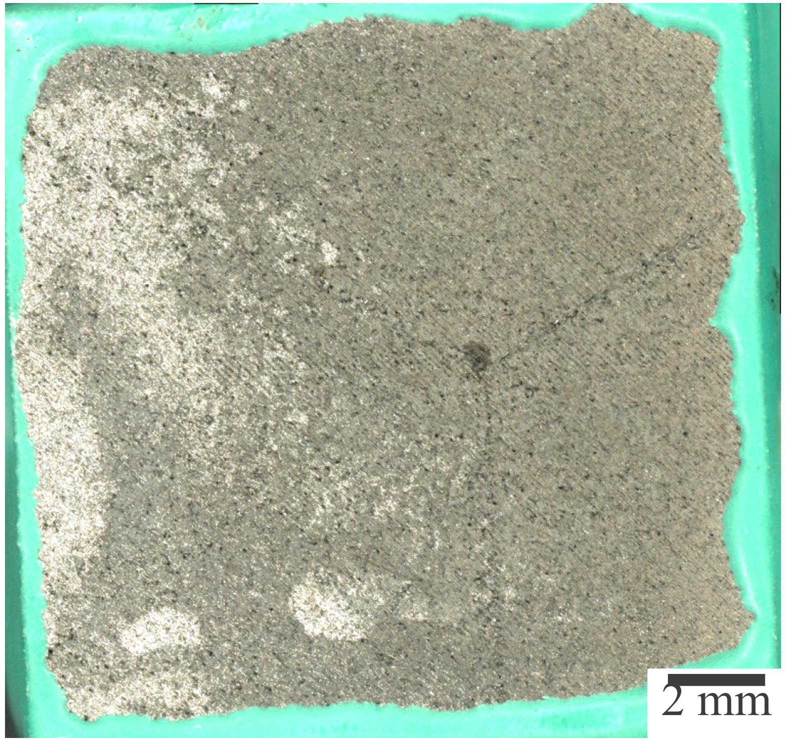
Heat Treated Samples

- No visible cracks for heat treatments of 800 °C or higher
- 800 °C has relieved all the residual stresses

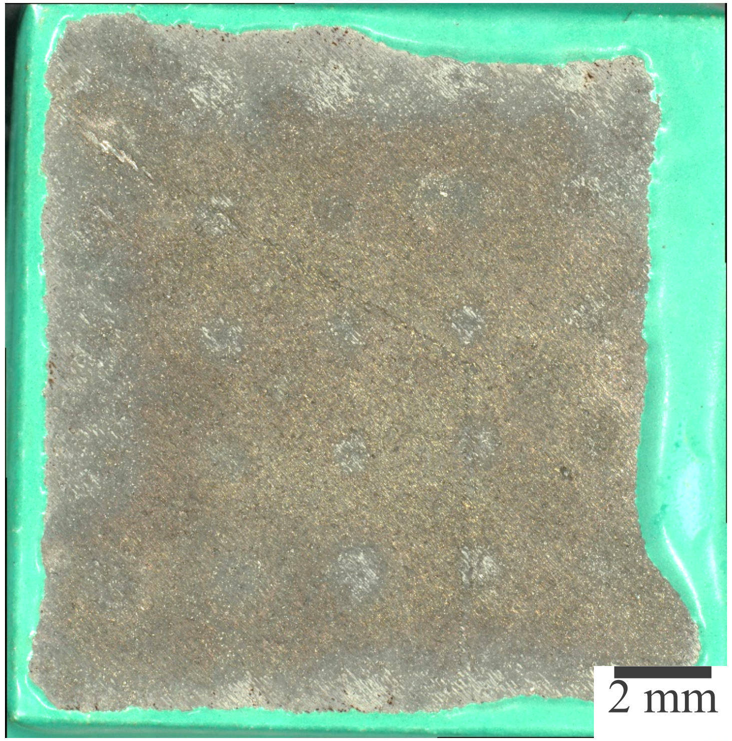
600 °C
σ_{xx} = +100 MPa



800 °C
σ_{xx} = 0 MPa



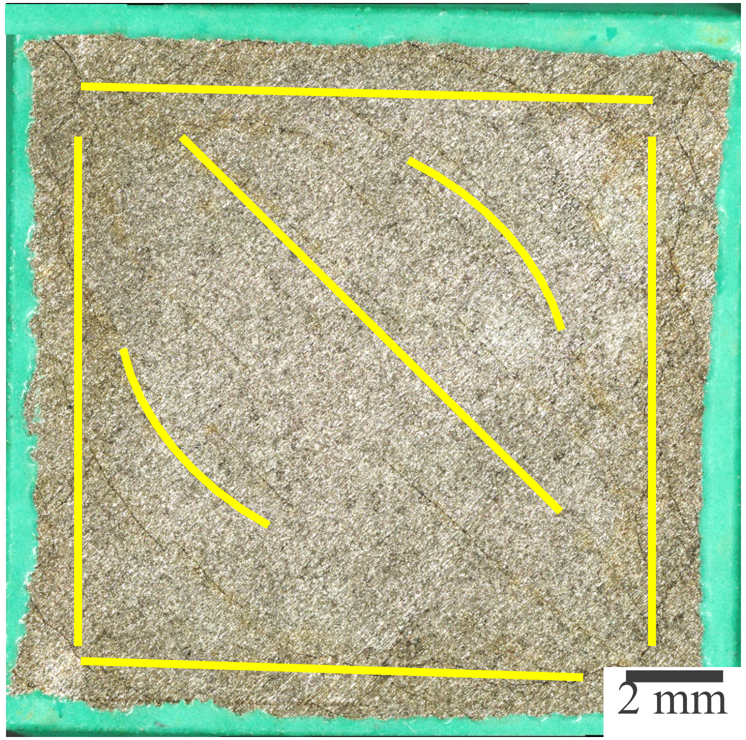
1200 °C
σ_{xx} = 0 MPa



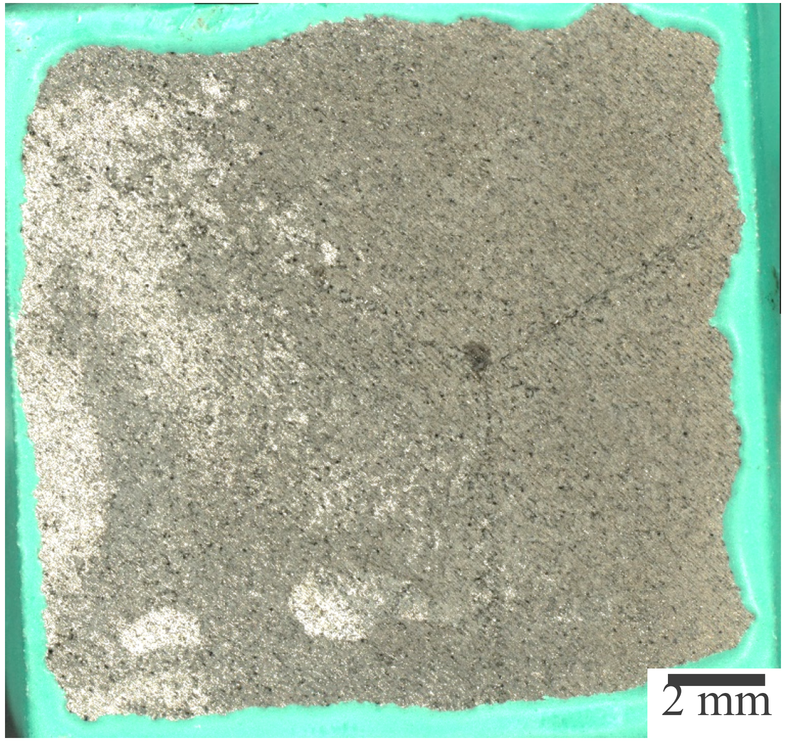
Heat Treated Samples

- No visible cracks for heat treatments of 800 °C or higher
- 800 °C 15 mm has more residual stress than 4 mm 600 °C but no visible cracks

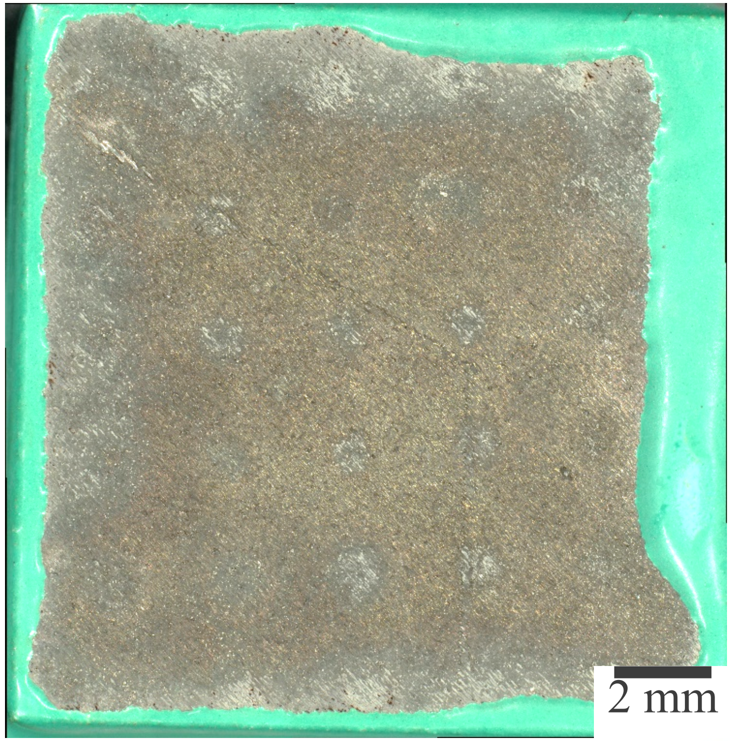
4 mm, 600 °C
σ_{xx} = +50 MPa



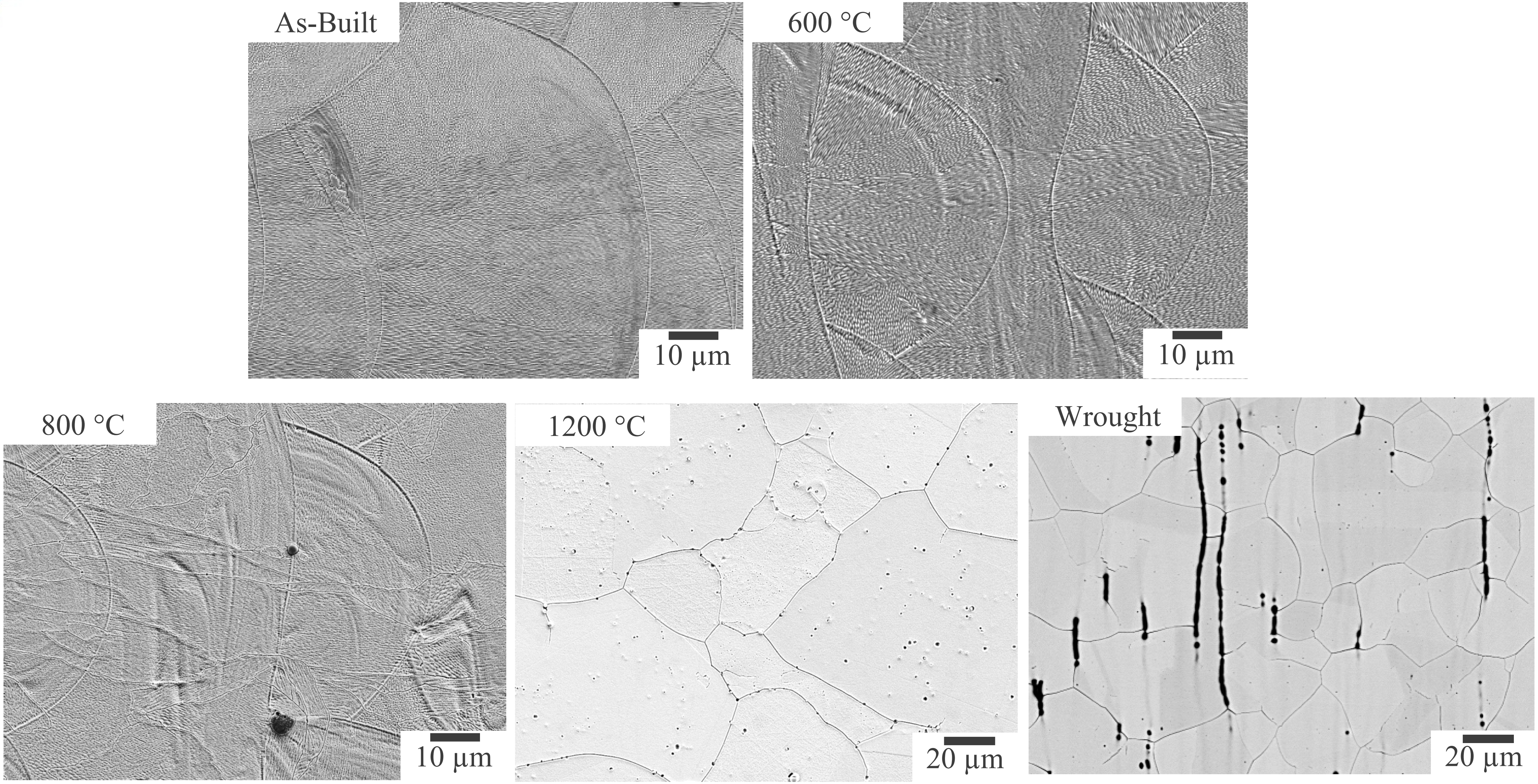
15 mm, 800 °C
σ_{xx} = +70 MPa



15 mm, 1200 °C
σ_{xx} ~ 0 MPa

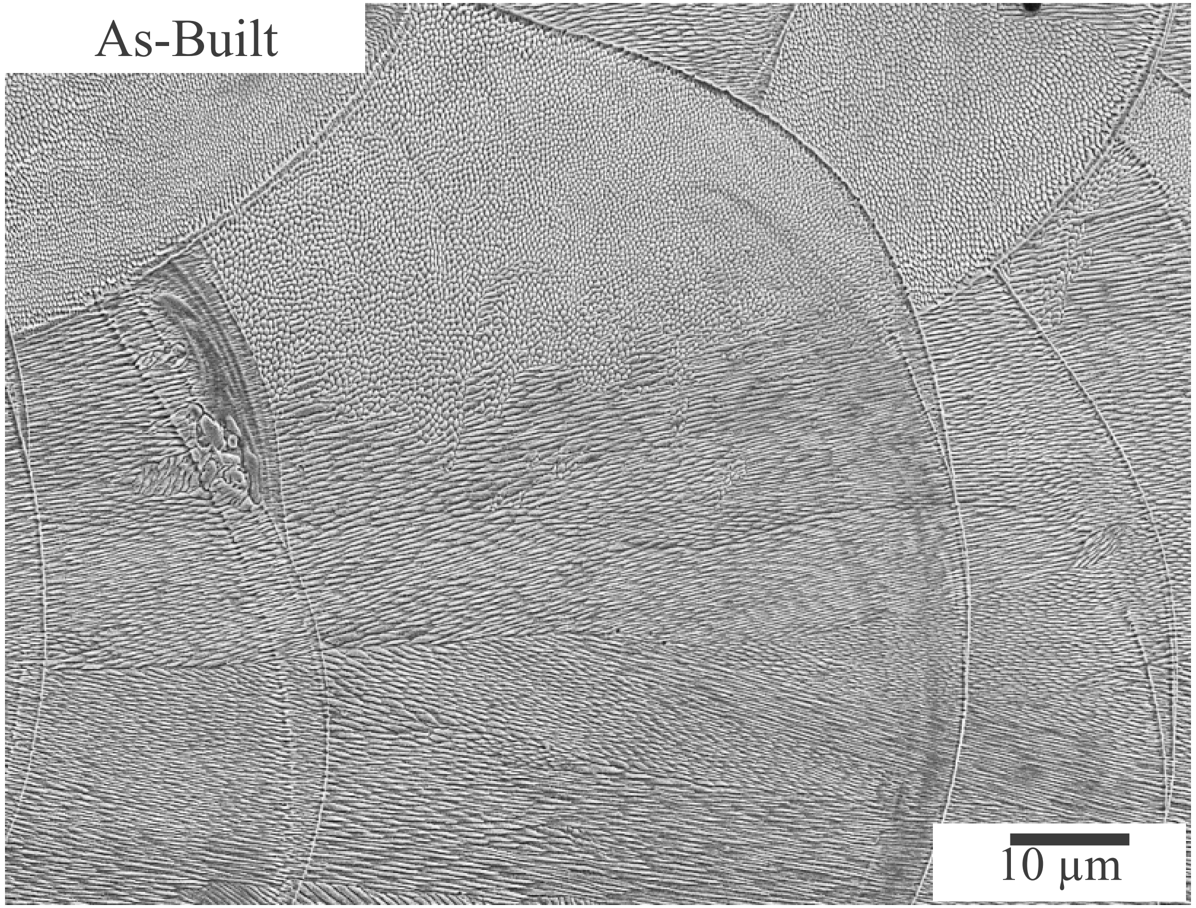


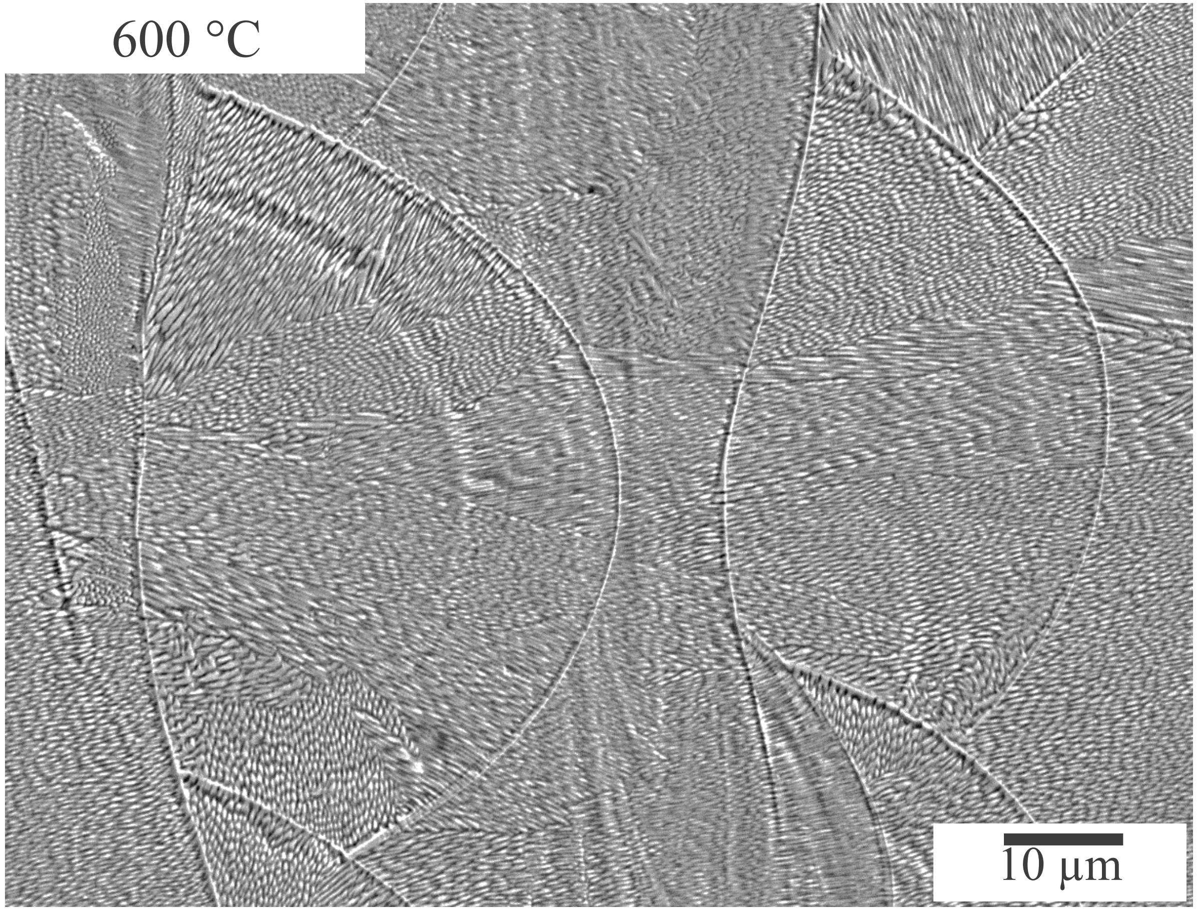
Heat Treated Etched Microstructure



Heat Treated Etched Microstructure

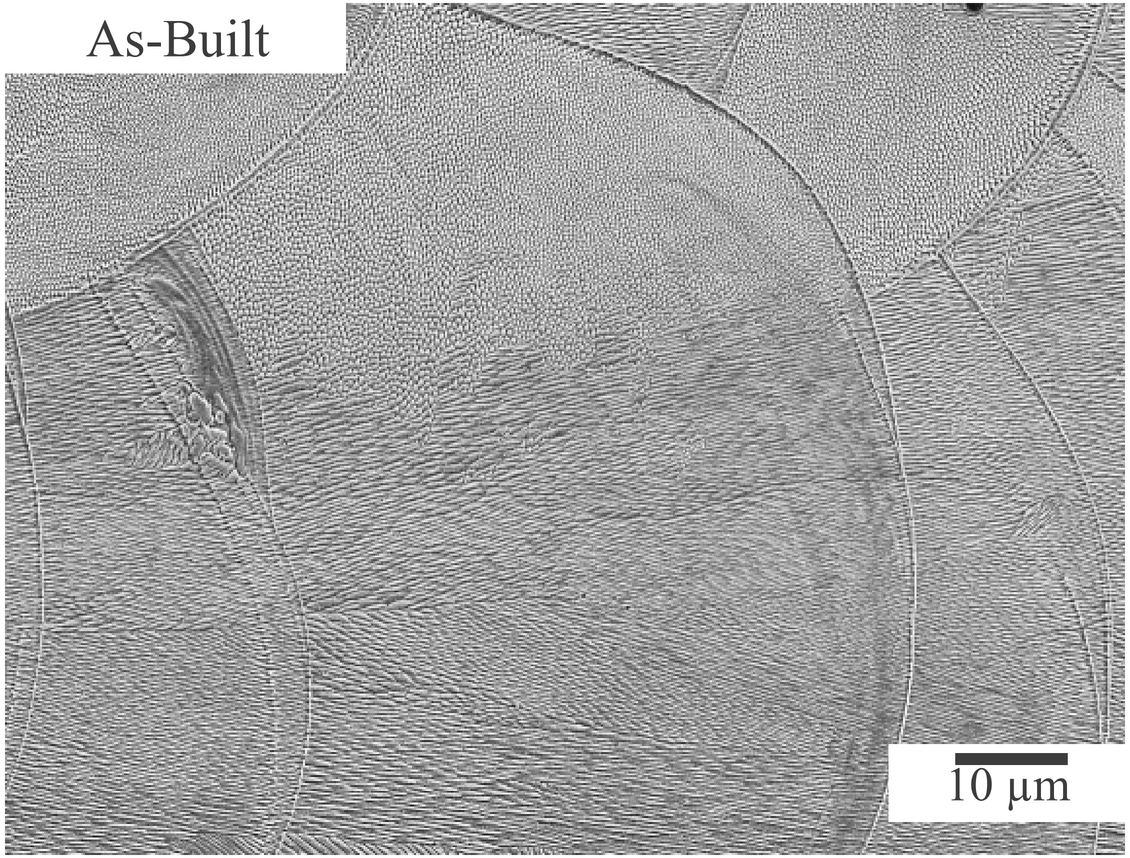
As-built & 600 °C look similar
- preferential attack at cell boundaries
- some melt pool boundaries

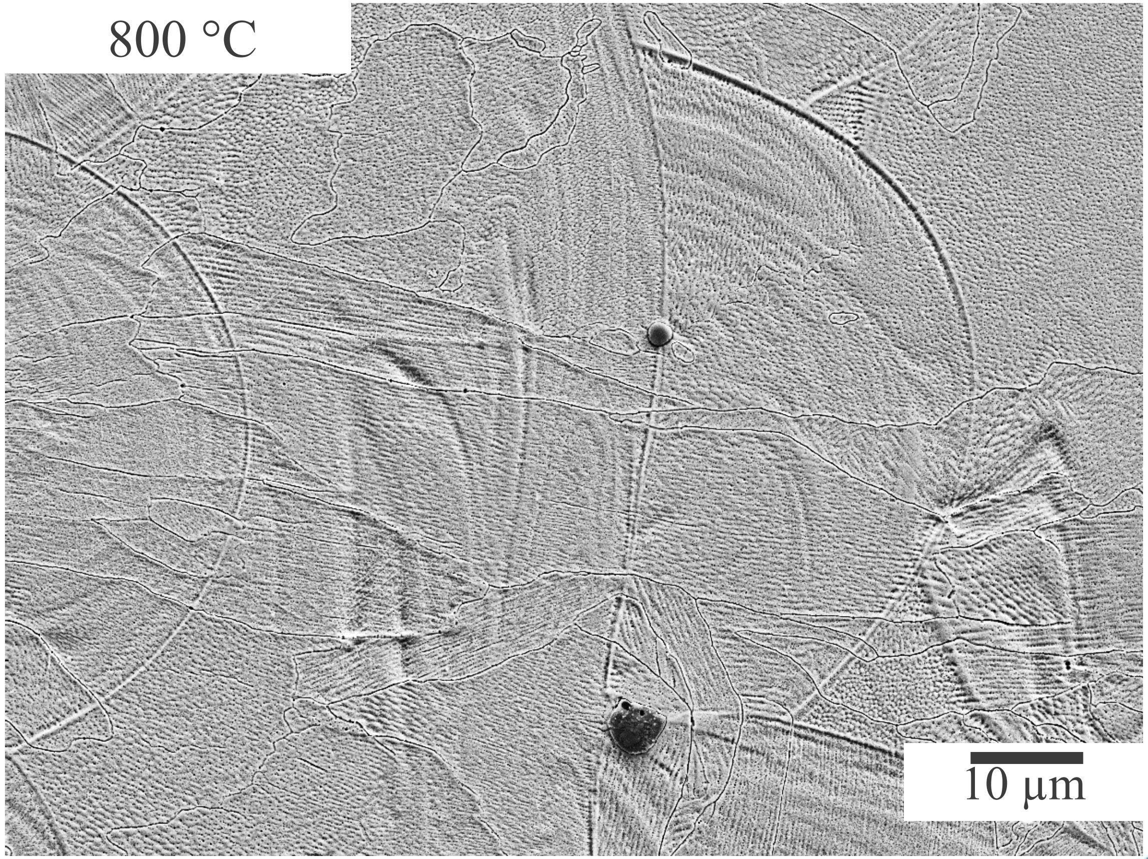




Heat Treated Etched Microstructure

800 °C
- attack at cell boundaries & melt pool boundaries
- more grain boundaries visible (indicates recovery)

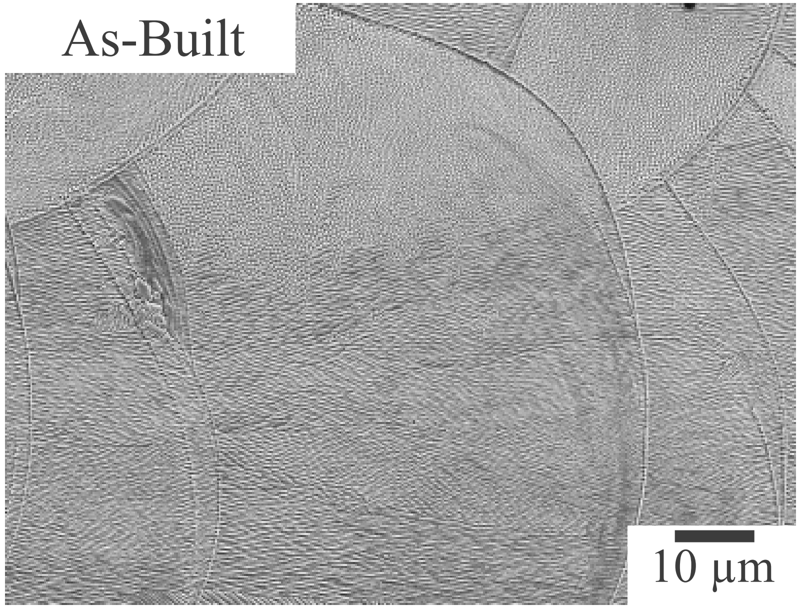


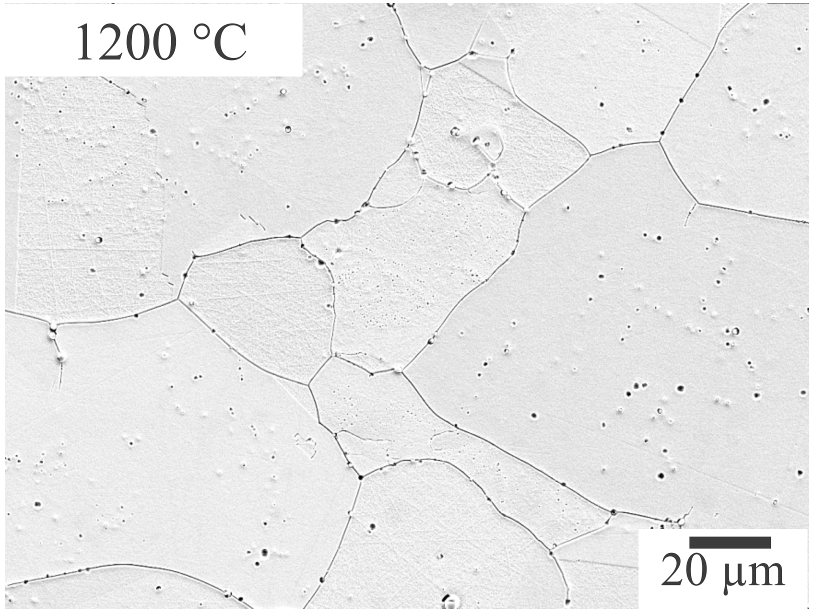


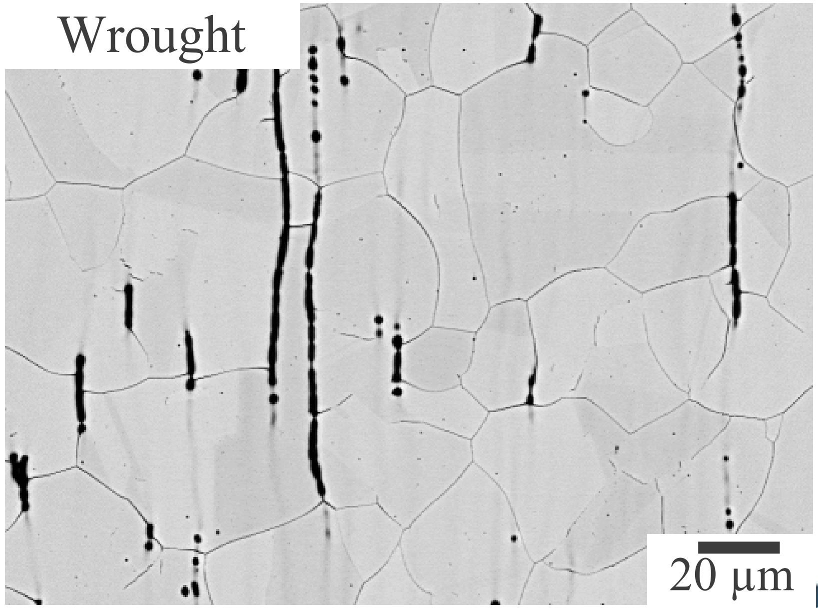
Heat Treated Etched Microstructure

1200 °C

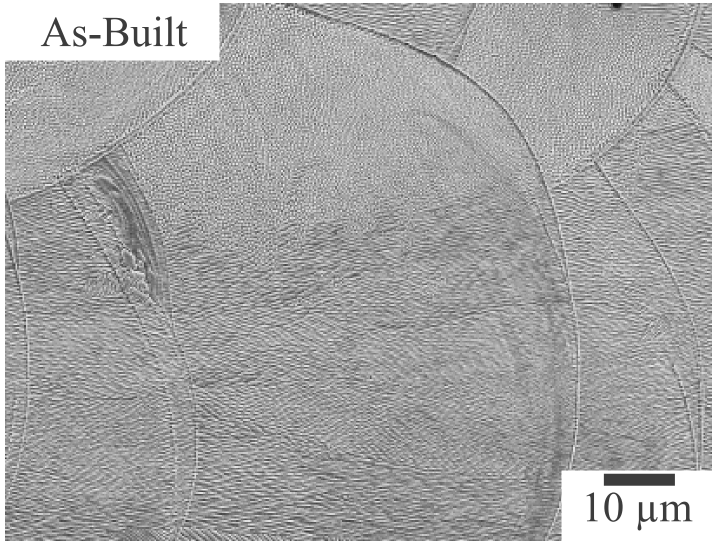
- No visible cell boundaries or melt pool boundaries
- Lots of grain boundaries visible-similar to wrought

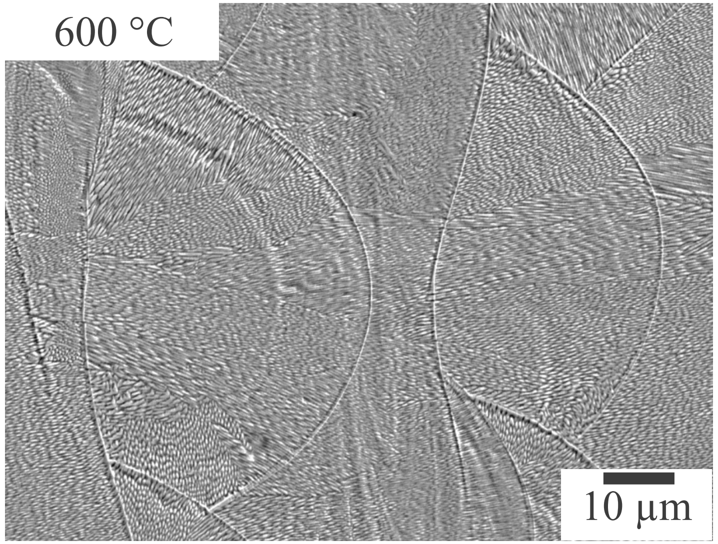




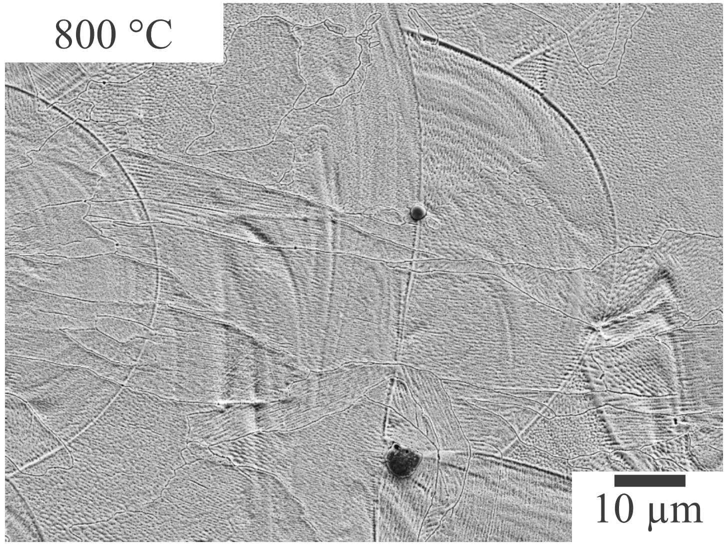


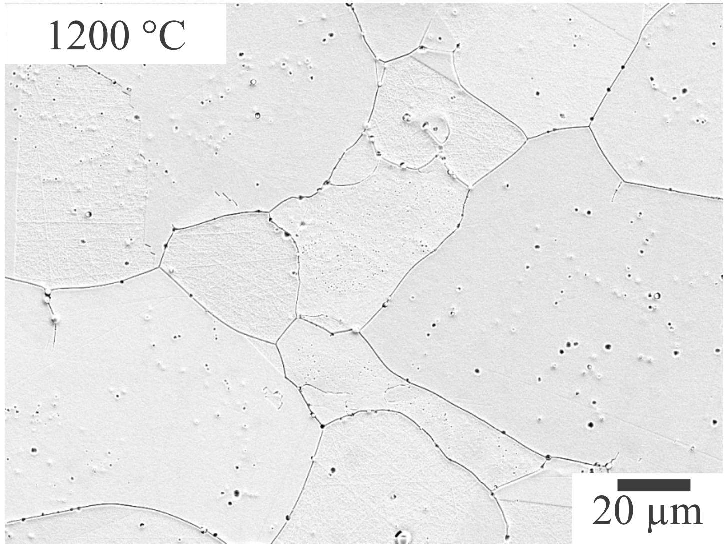
Heat Treated Etched Microstructure

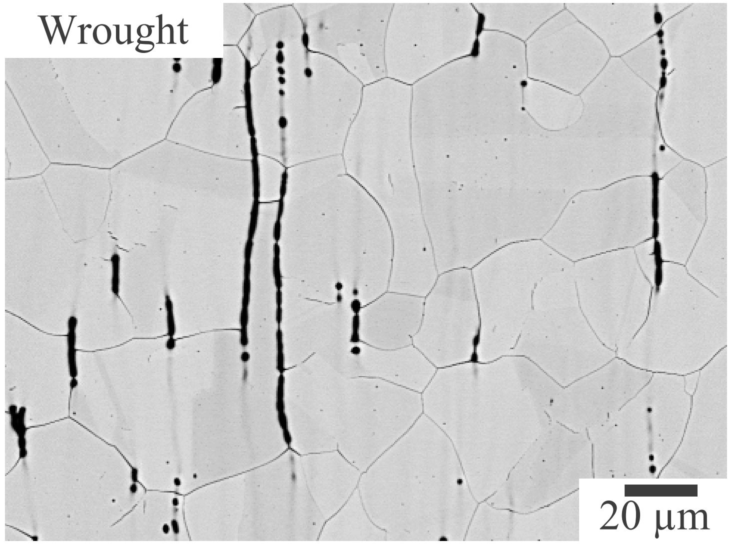




800 °C has no cracking
but isn't completely recrystallized

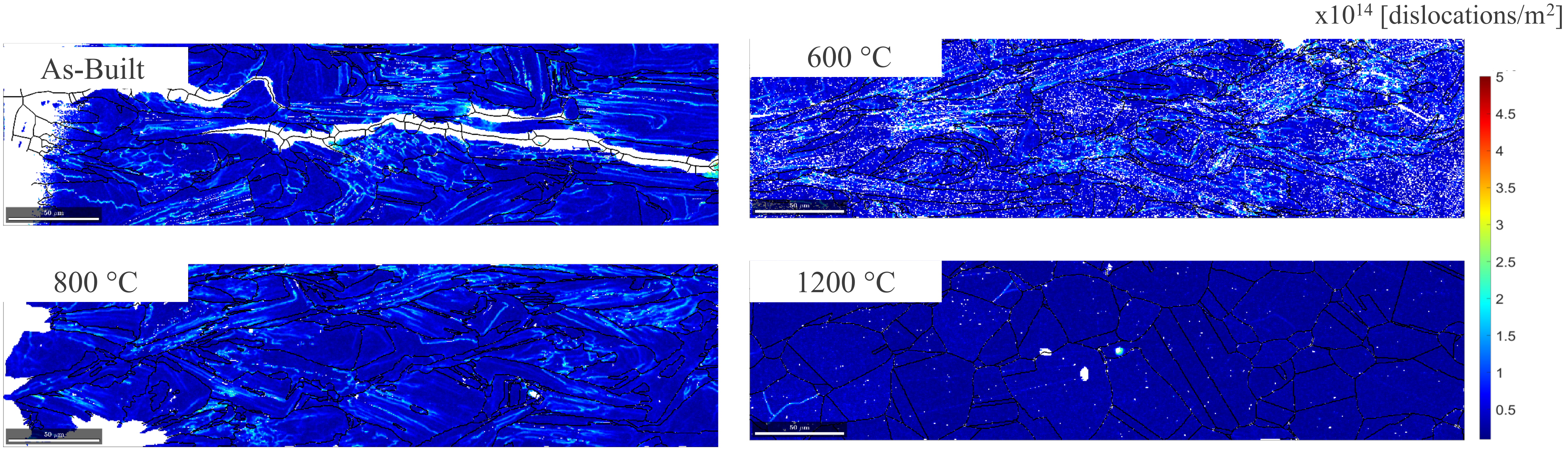






Geometrically Necessary Dislocation (GND) Density

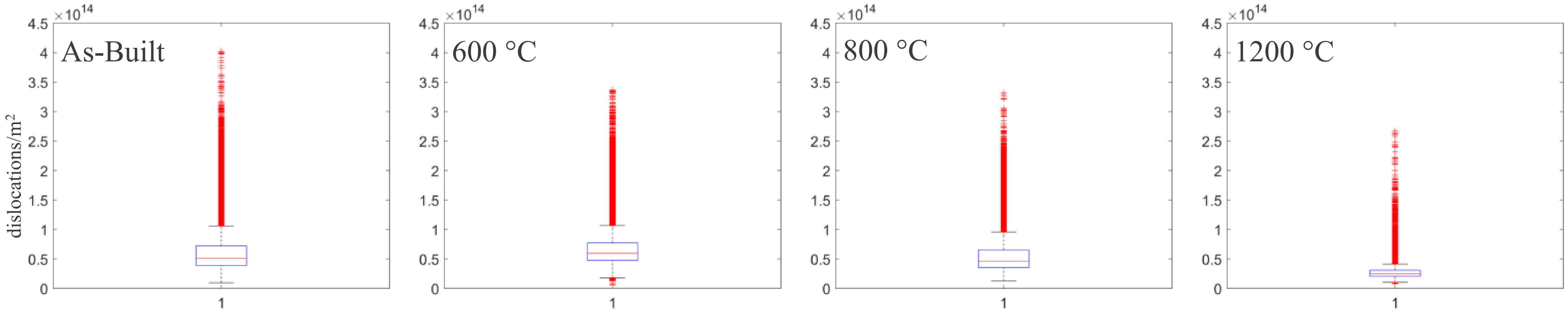
600 °C minimal change in GND compared to as-built
800 °C lower GND density (not recrystallization)
1200 °C density similar to fully annealed wrought



Geometrically Necessary Dislocation (GND) Density

Possible impacts of large local dislocation density at cell boundaries

- high localized stress
- cause H-trapping



Conclusions

- Reducing sample thickness & heat-treatments are effective ways of controlling residual stress
- All as-built showed SCC susceptibility regardless of thickness
- Distribution of stress affects distribution of cracking
- Residual stresses from melt tracks can be enough to affect SCC
- 800 °C & 1200 °C for 1 hour eliminated SCC susceptibility. EBSD, GND analysis suggest a reduction in dislocation density (not just reducing tensile stress) reduces SCC susceptibility

Future Work

Develop heat treatment specific to AM materials

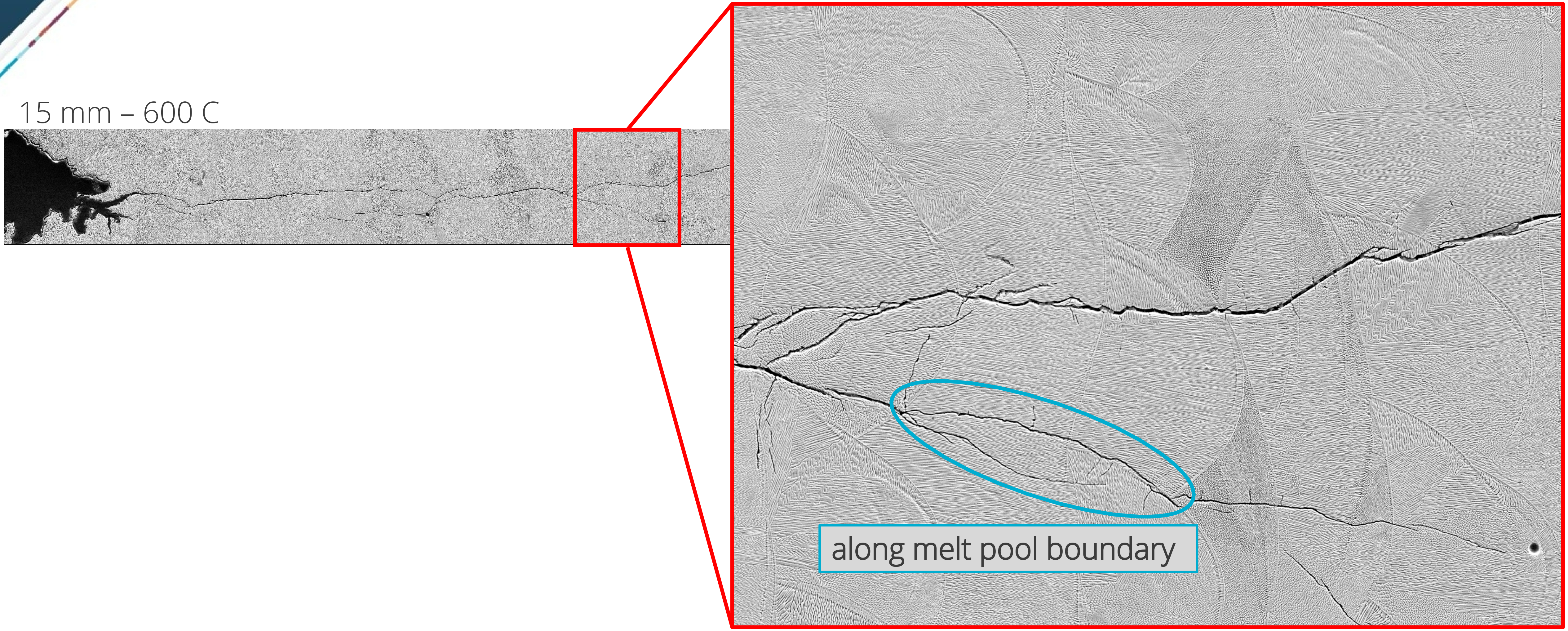
- Control residual stress
- Address sensitization, segregation at melt pool boundaries

Further examine effects of residual stress

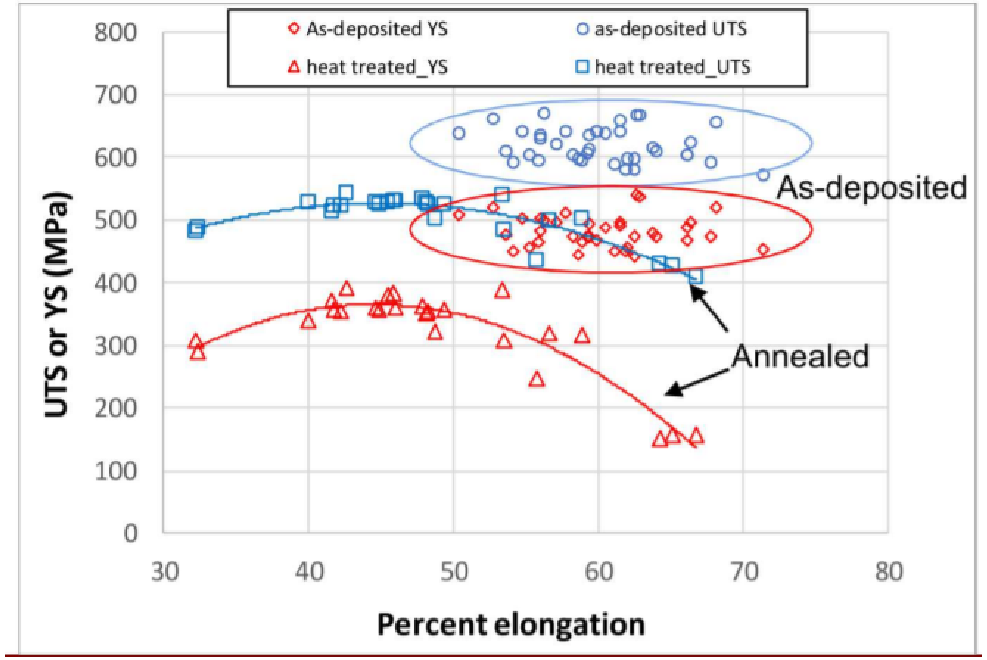
- Residual stress in build direction

Thank you!

15 mm – 600 C



Standard way to remove residual stress is heat treatment.
AM metals react differently to heat treatment than wrought.
Heat treatment can decrease beneficial mechanical properties (yield strength) that would otherwise be a benefit stemming from the as-printed AM microstructure.



D. Susan 2018-12051C