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The Effects of Post-Processing on Mechanical Properties and Corrosion Behavior of AM 316L Stainless Steel

Richard Fonda, Scott Olig, David Rowenhorst, Jerry Feng, Adelina Ntiros, Beth Stiles, Krystaufeux Williams, Roy Rayne, and Charles Hart

US Naval Research Laboratory

Codes 6350 and 6130

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Cross Platform Systems Development (CPSD) Program

Objective

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Objectives: Systematically determine the microstructure, corrosion behavior, and mechanical properties of AM 316L stainless steel in the as-built and post-processed conditions

Approach: Take advantage of the outstanding capabilities and expertise in microstructural characterization and corrosion behavior at NRL:

- **Advanced 2D and 3D microscopy techniques**
- **Corrosion testing**
- **Mechanical property testing**

316L AM Steel is *NOT* Stainless

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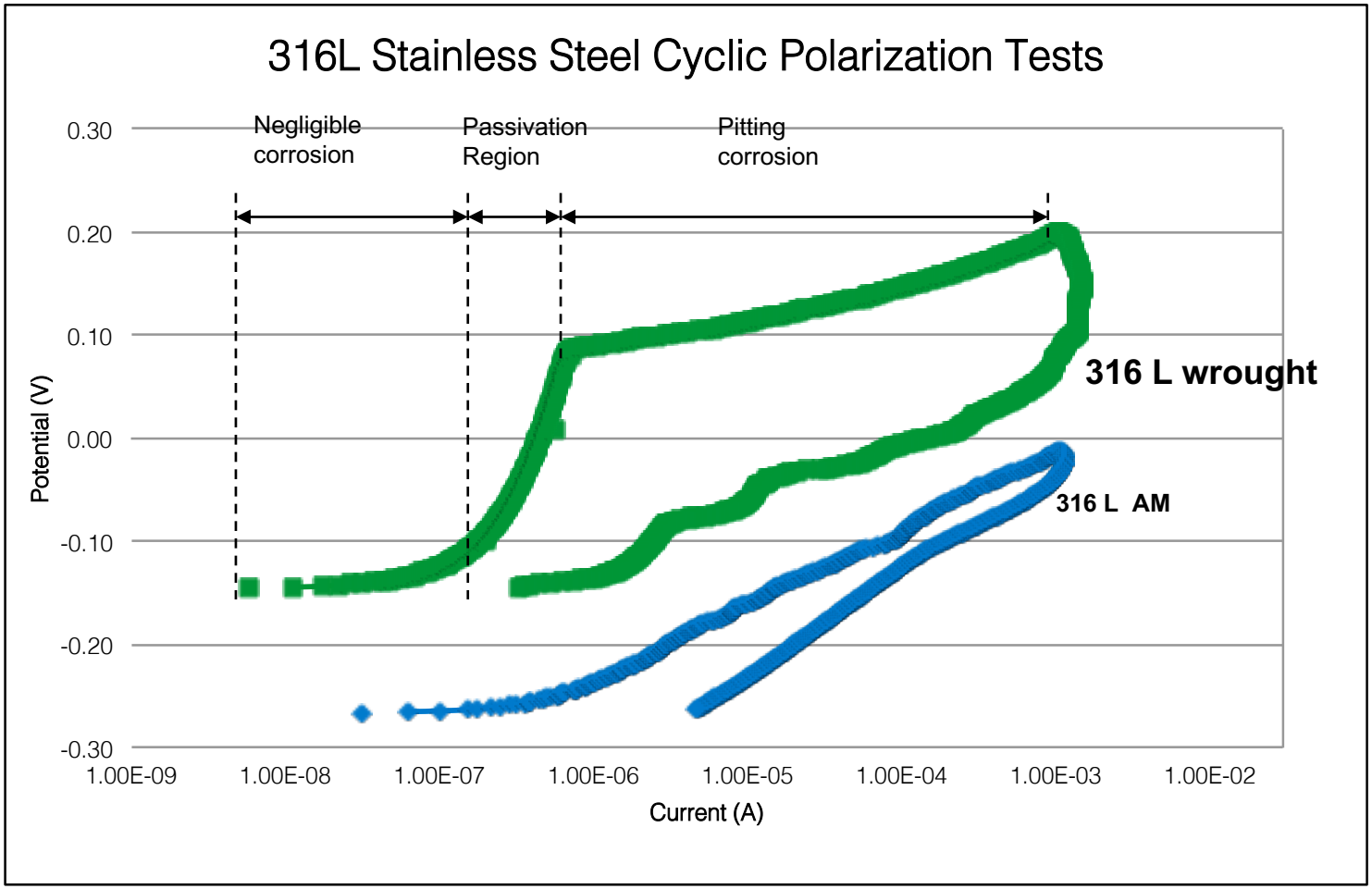
- As-built 316L sample does not exhibit any passivity
- AM sample corrodes three orders of magnitude faster than wrought sample at -100mV



Polarization response comparison, Courtesy Dr. J. Moran 6130

Porosity in As-Built Material

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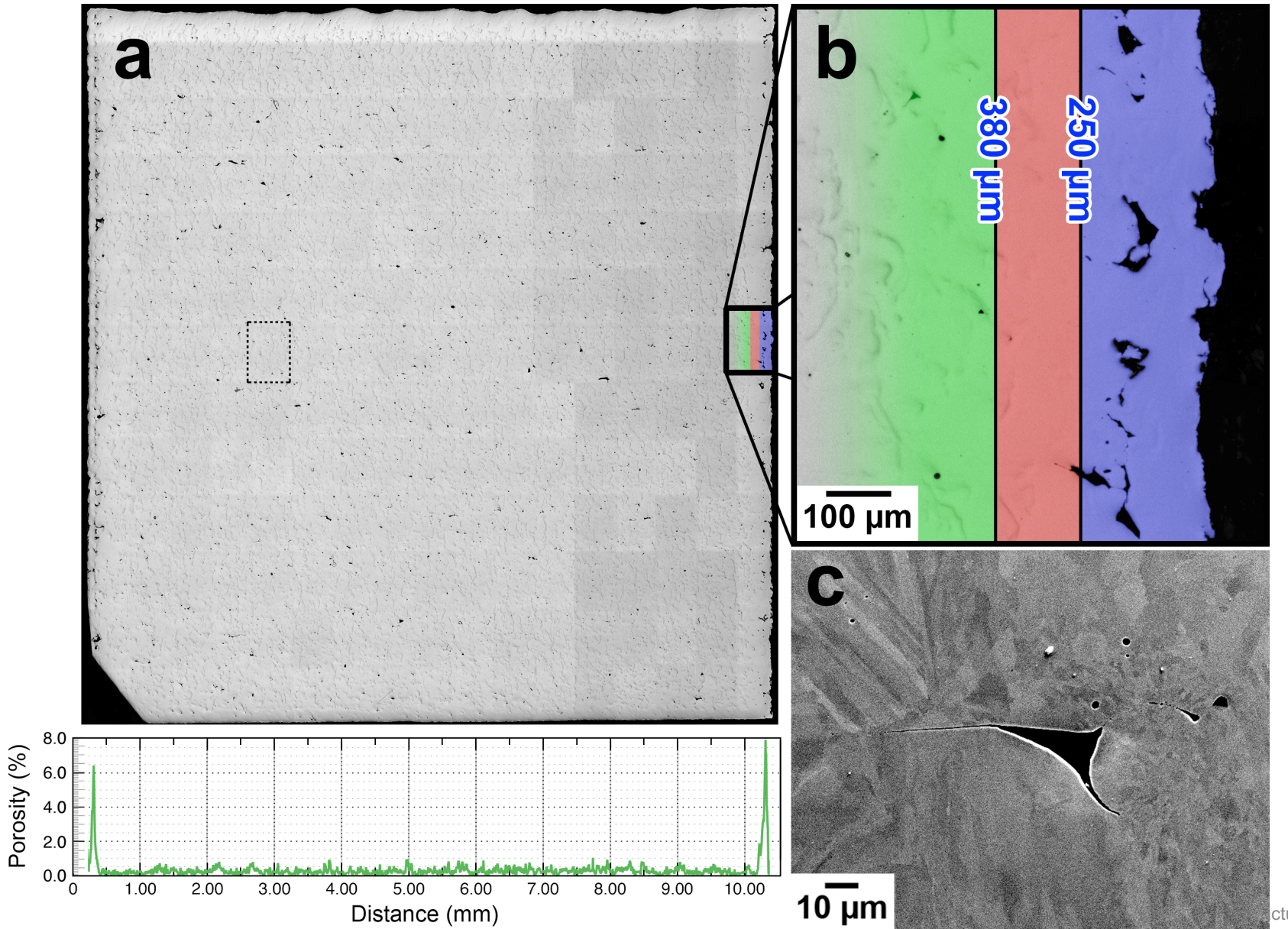
Both LOF and gas porosity present

Enhanced porosity between fill and border scans



Depth Effects of Corrosion

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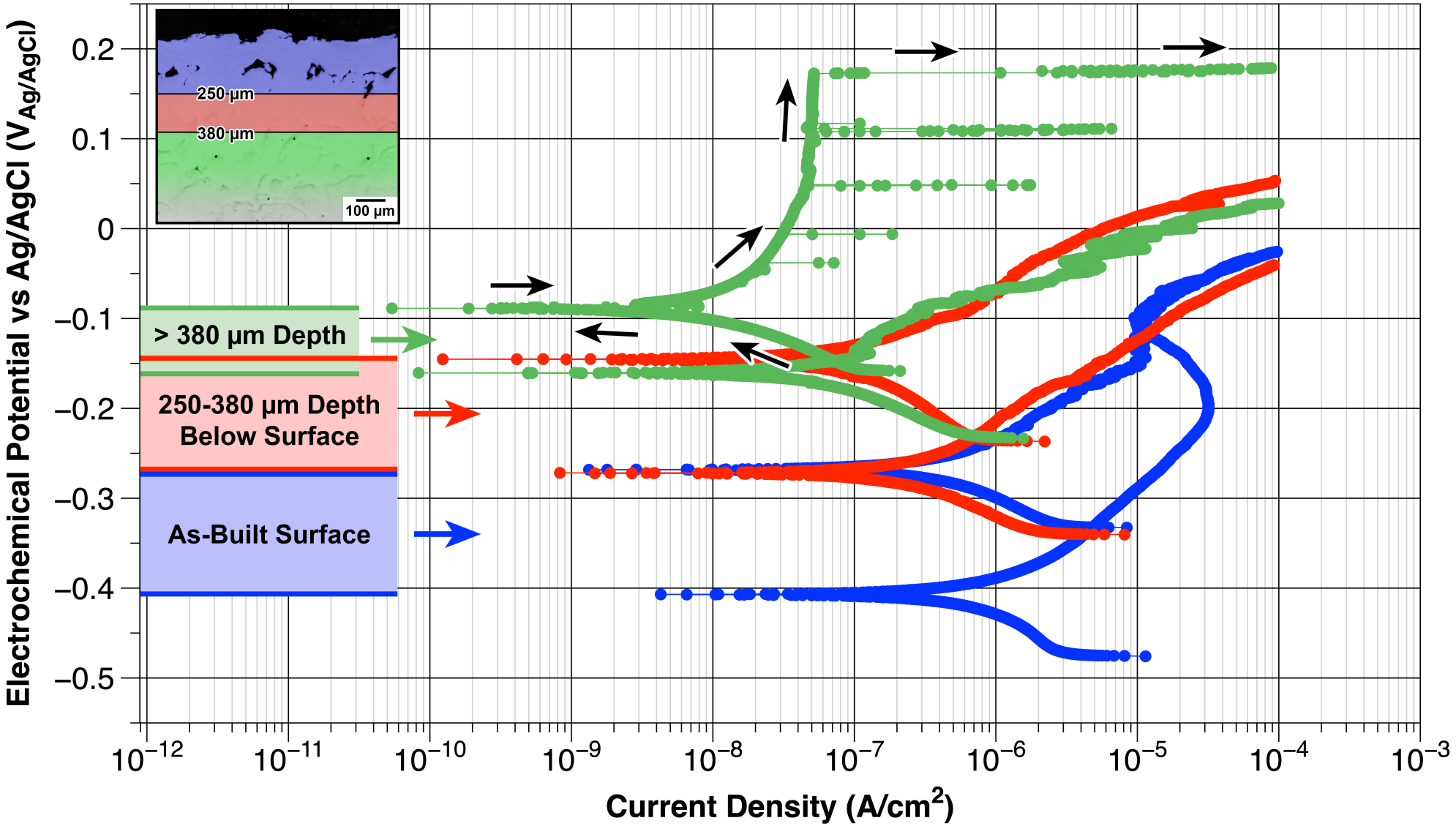
- No passivity at the as-built surface
- Passivity improves with distance from surface



As-Built Microstructure

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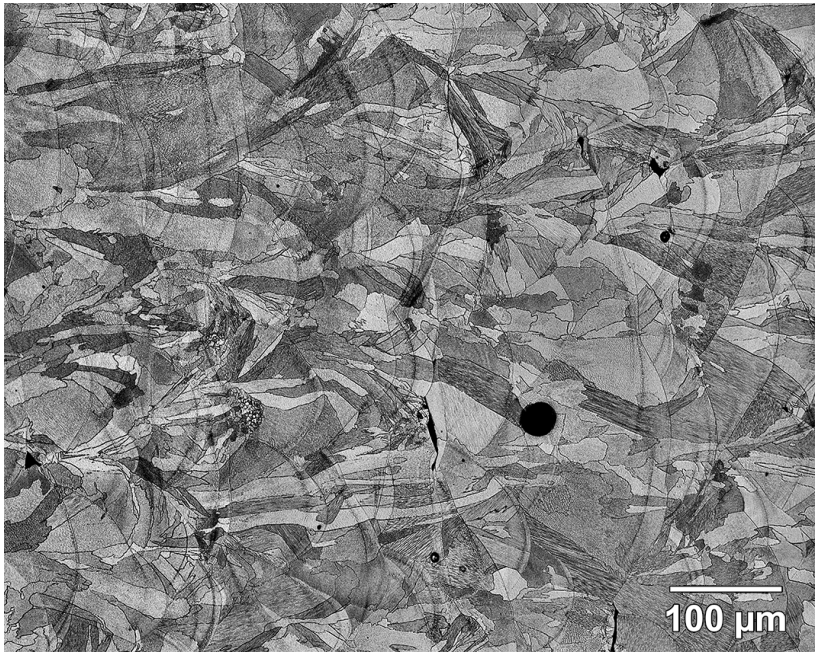
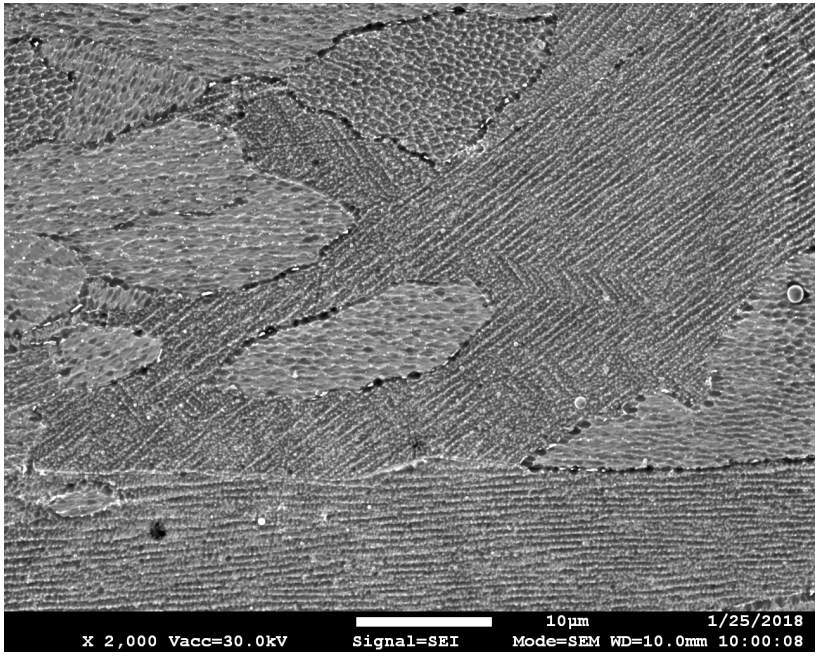
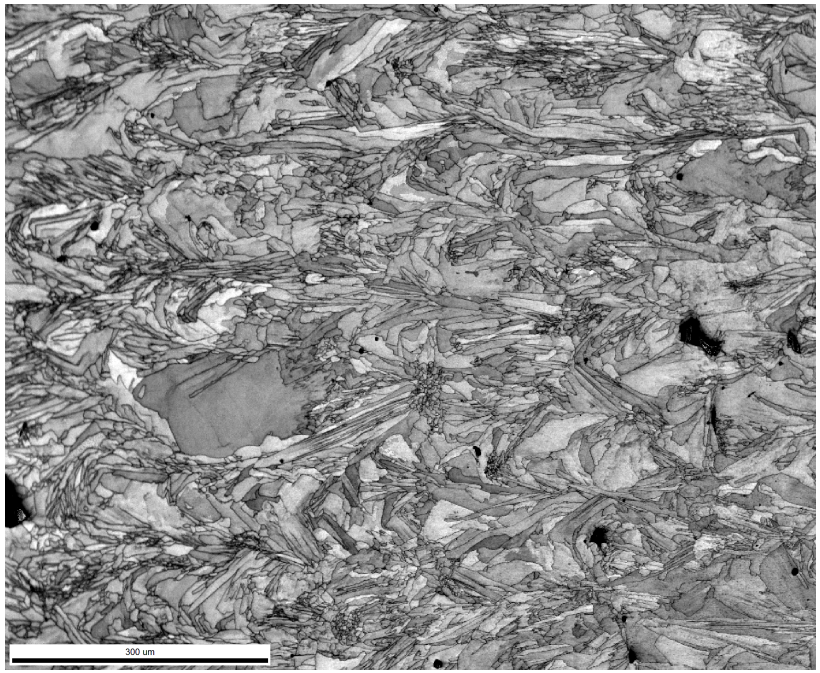
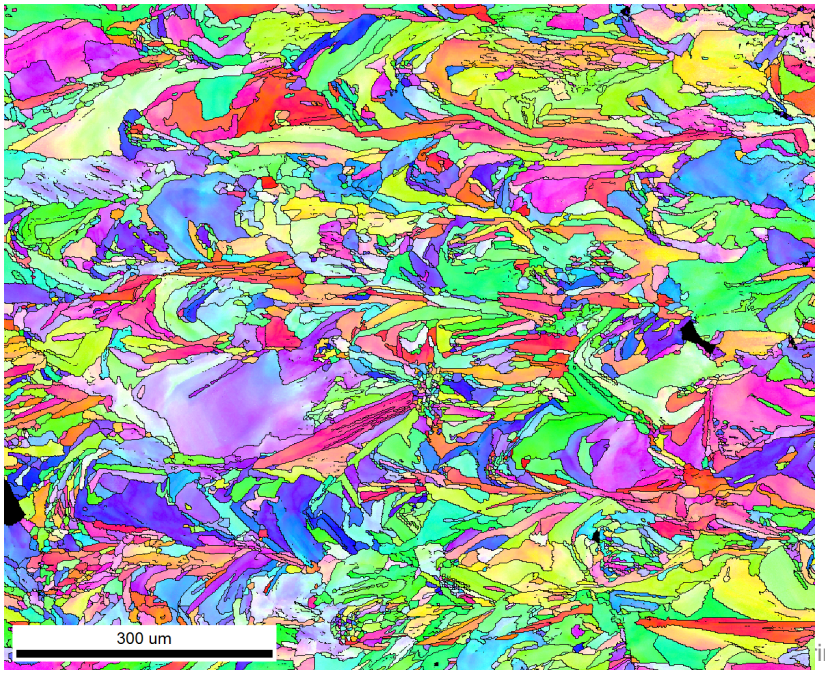
Standard L-PBF Appearance









Samples

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- **As-Received Sample:**
  - 316L Stainless Steel
  - EOS M270
  - Stress Relief: 790 °C, 1 h
- **Additional Heat Treatments:**

500 °C, 1h	**1100 °C, 1h**
700 °C, 1h	**1200 °C, 1h**
800 °C, 1h	**1300 °C, 1h**
900 °C, 1h	**1300 °C, 15h**
1000 °C, 1h	

- **HIP Treatments—15 ksi (100 Mpa):**

1000 °C, 3h	**1100 °C, 3h**	**1200 °C, 3h**

Microhardness Variations

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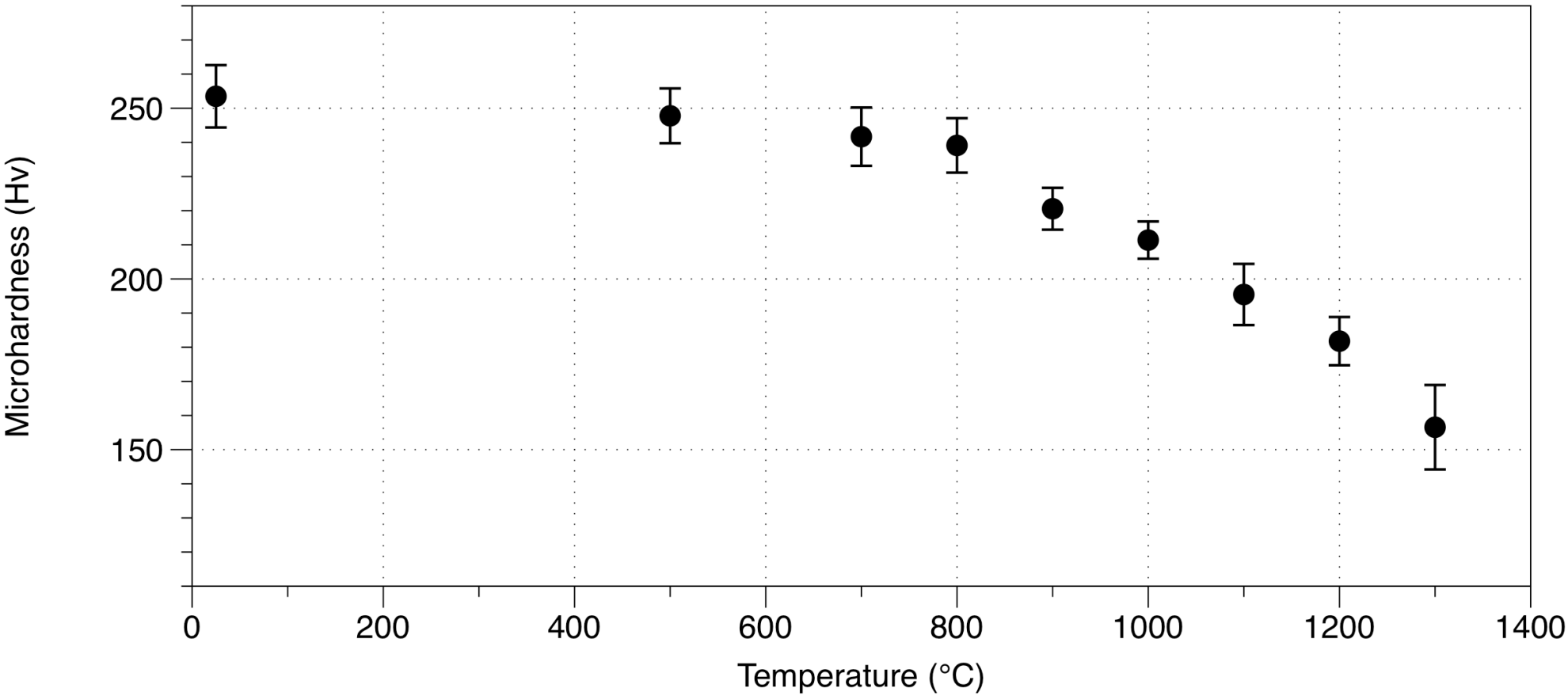

- **Heat treat for 1 hour at various Temps**
  - ➢ **Slight decrease up to 800 °C**
  - ➢ **Steeper decrease above 800 °C**

Changes in Cell Structure

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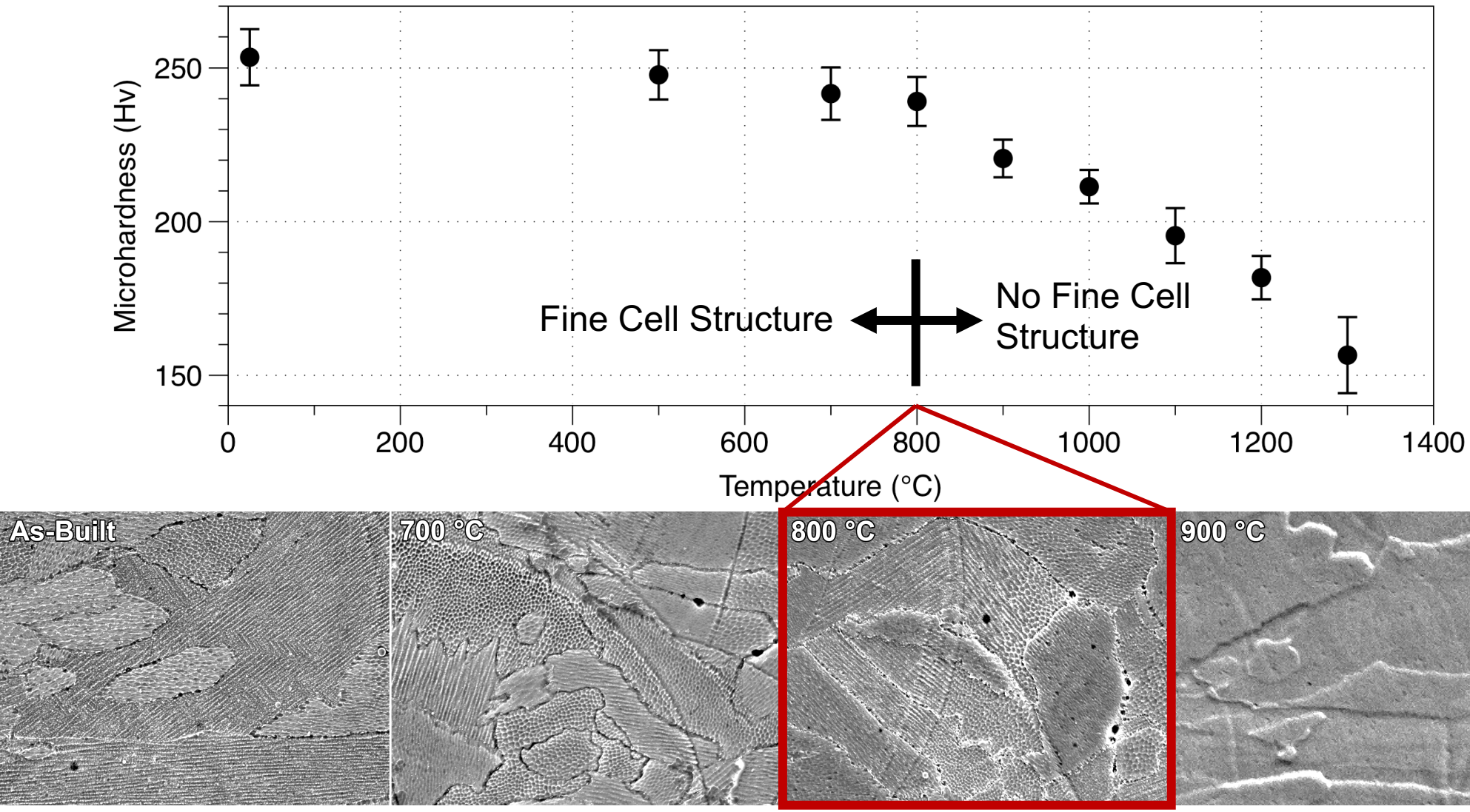
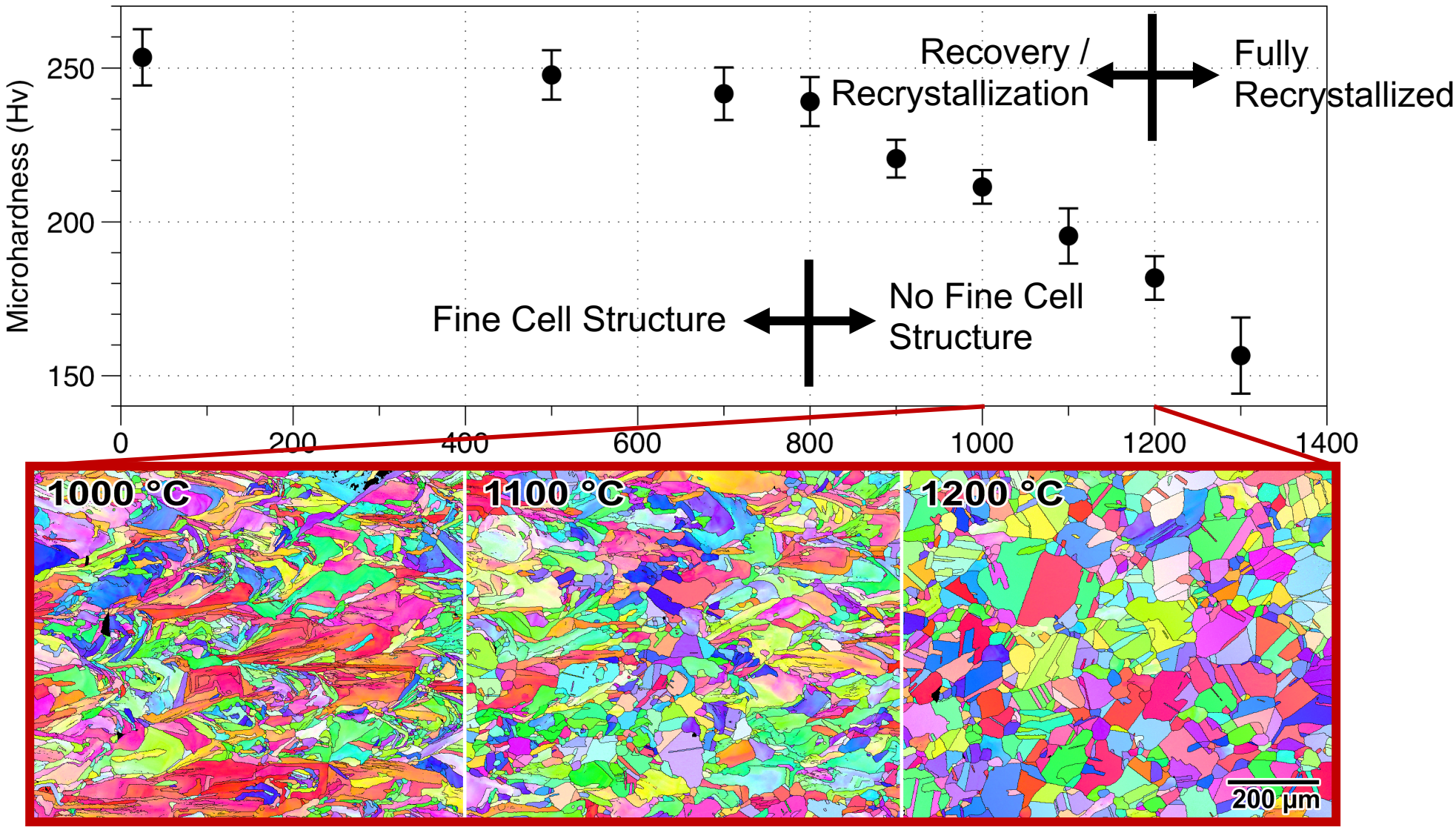


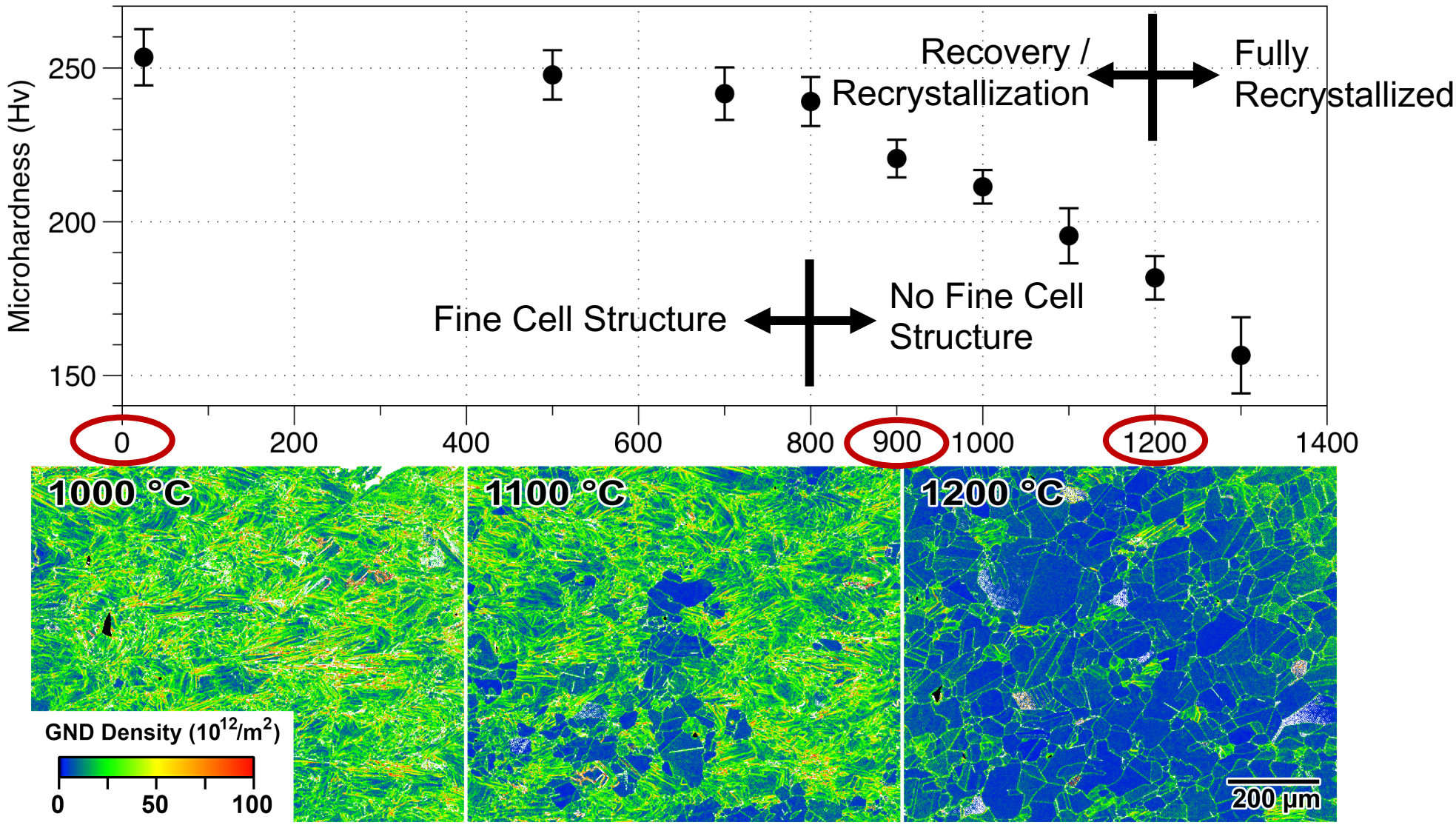
- **Cell structure evident below 800 °C**
- **Associated with higher strength and better corrosion resistance**
- **Completely absent at 900 °C and above**

Grain Evolution



- **Recovery / Recrystallization occurs from 1000-1200 °C**
- **Difficult to discern from IPF maps**

Recrystallization



- **Recovery / Recrystallization occurs from 1000-1200 °C**
- **More evident in Geometrically Necessary Dislocation maps**
- **Three characteristic temperature regimes**

Evolution with Temperature

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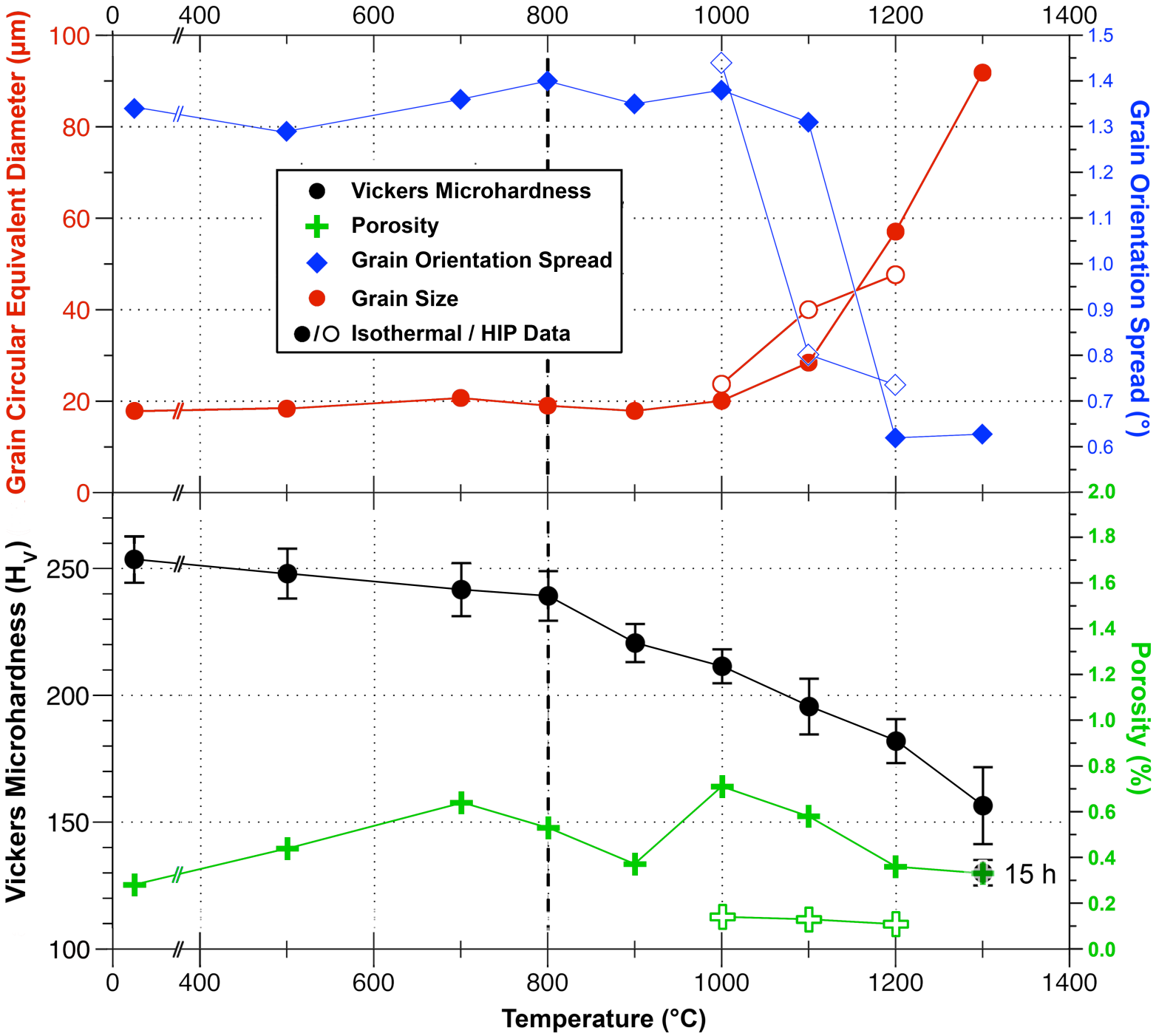

Corrosion of Bulk AM 316L

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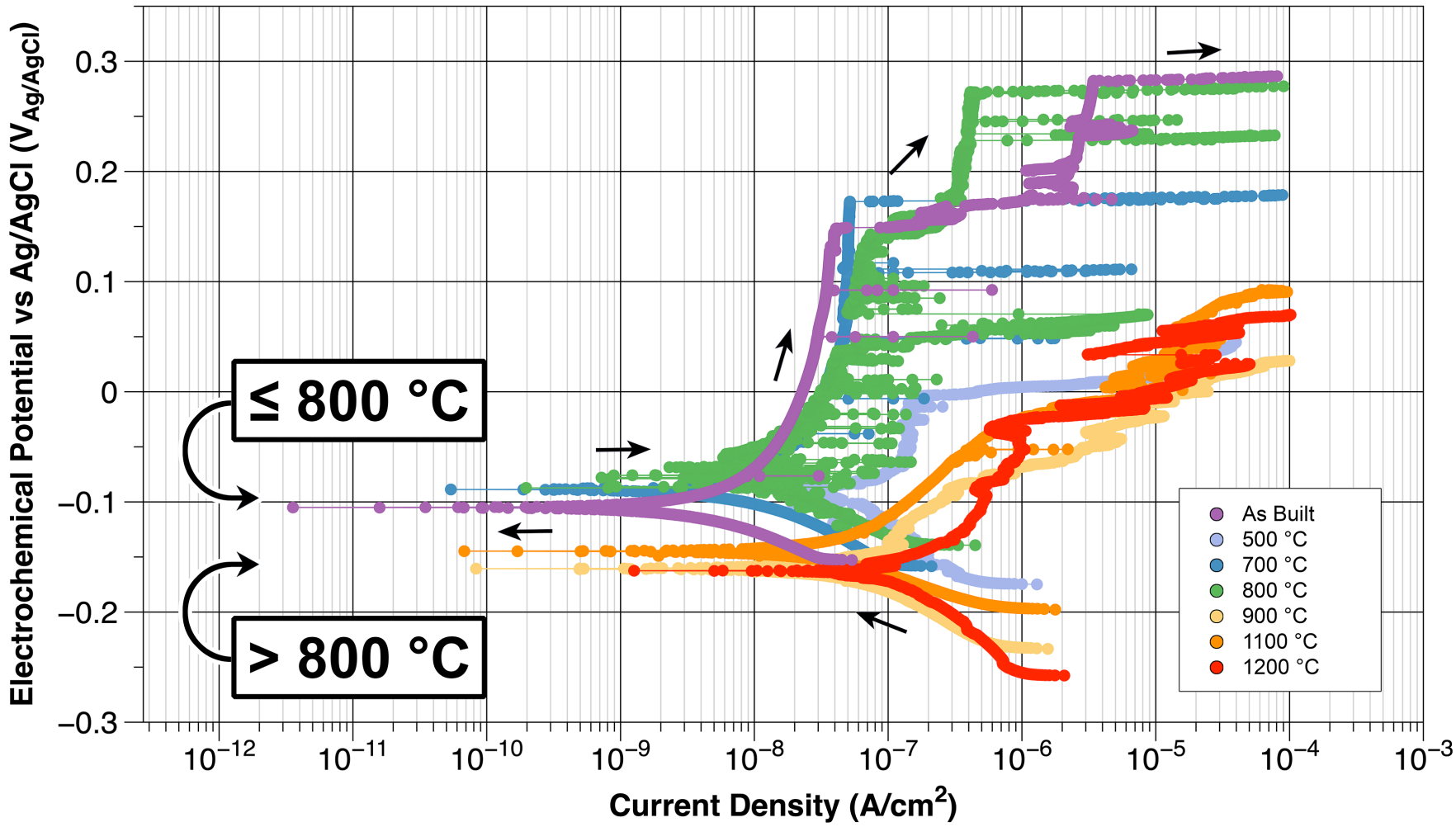

- **Passive behavior of build interior up to 800 °C**
- **Corrosion is enhanced / passivity lost above 800 °C**

Corrosion of Bulk HIP AM 316L

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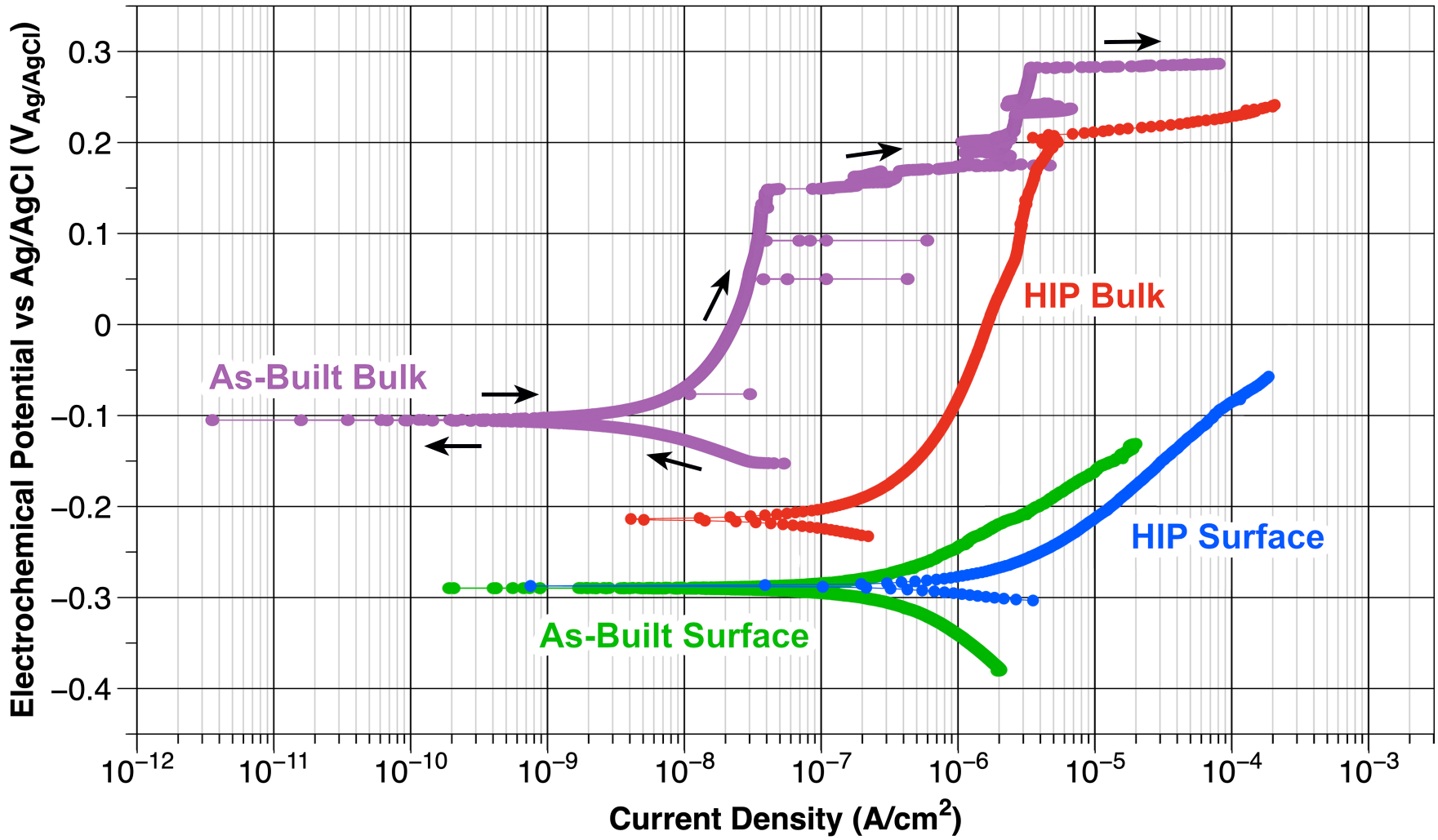

- Enhanced corrosion rate after HIP
- Passive / non-passive behavior retained

Effect of T on Porosity Fraction

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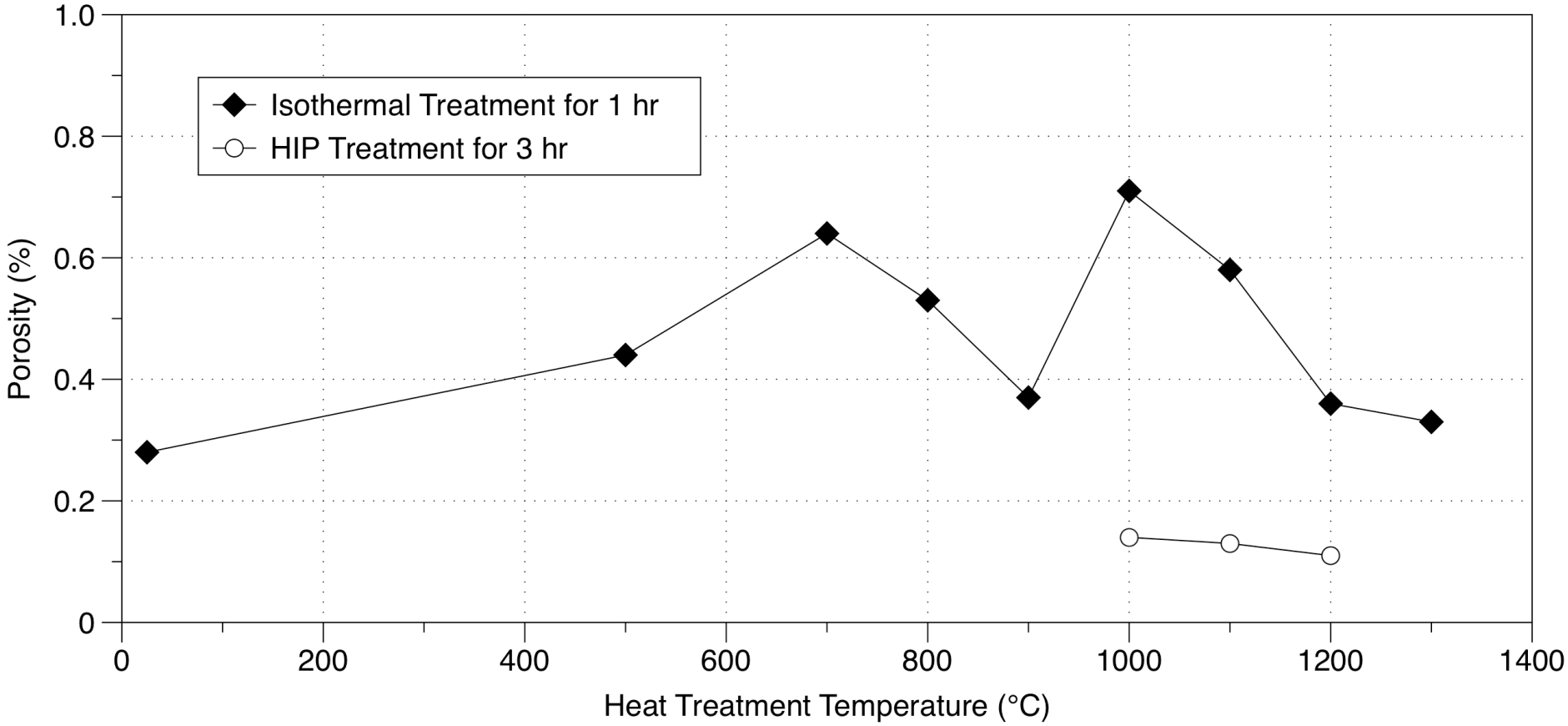

- **Heat treatments alone do not change pore volume fraction**
- **HIP treatments reduce pore volume fraction by ~2/3**

Effect of HT on Pore Morphology

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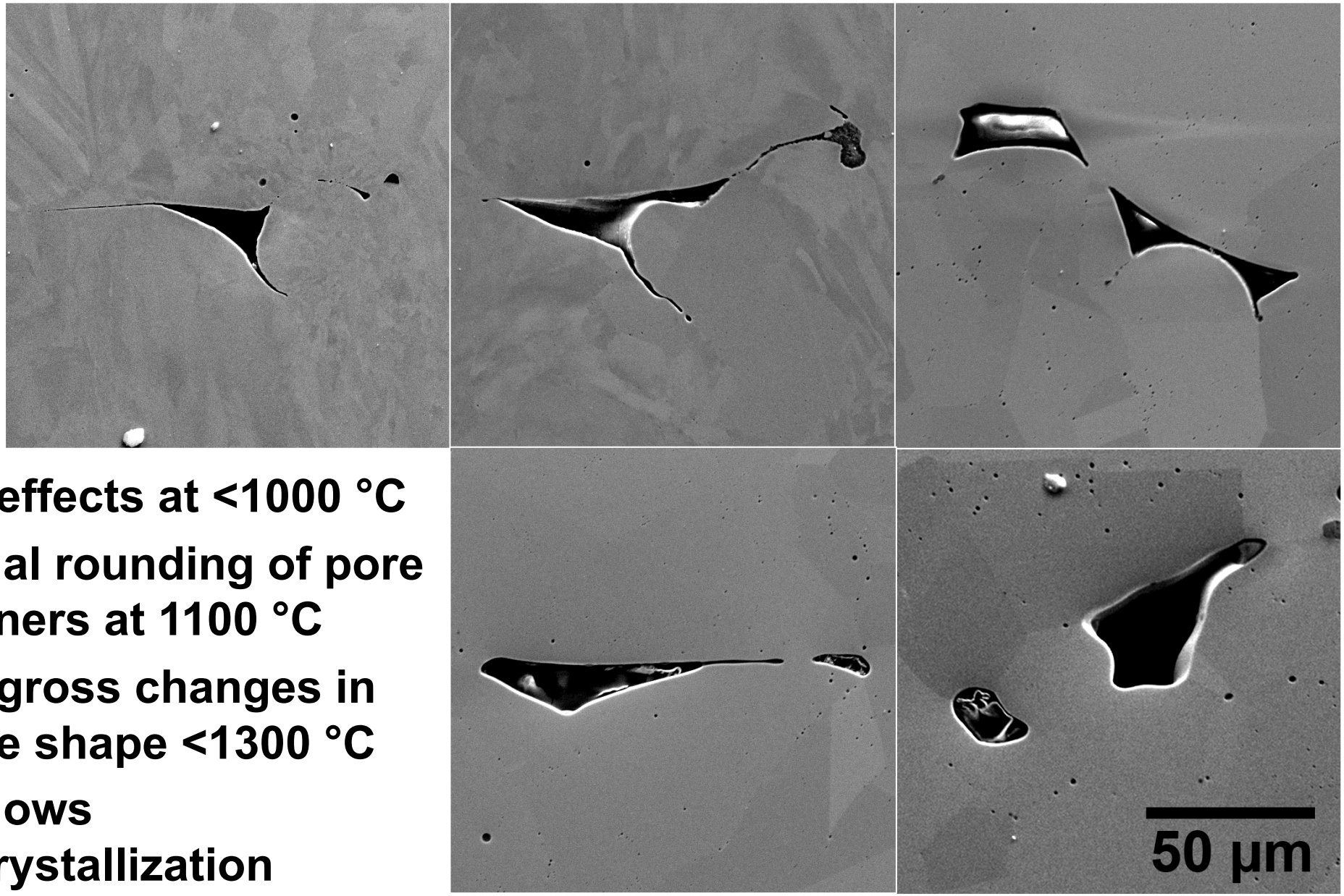
As-received | 1100 °C, 1 hr | 1200 °C, 1 hr



- **No effects at <1000 °C**
- **Initial rounding of pore corners at 1100 °C**
- **No gross changes in pore shape <1300 °C**
- **Follows recrystallization behavior**

1300 °C, 1 hr | 1300 °C, 15 hr

Effects of HIP on Porosity

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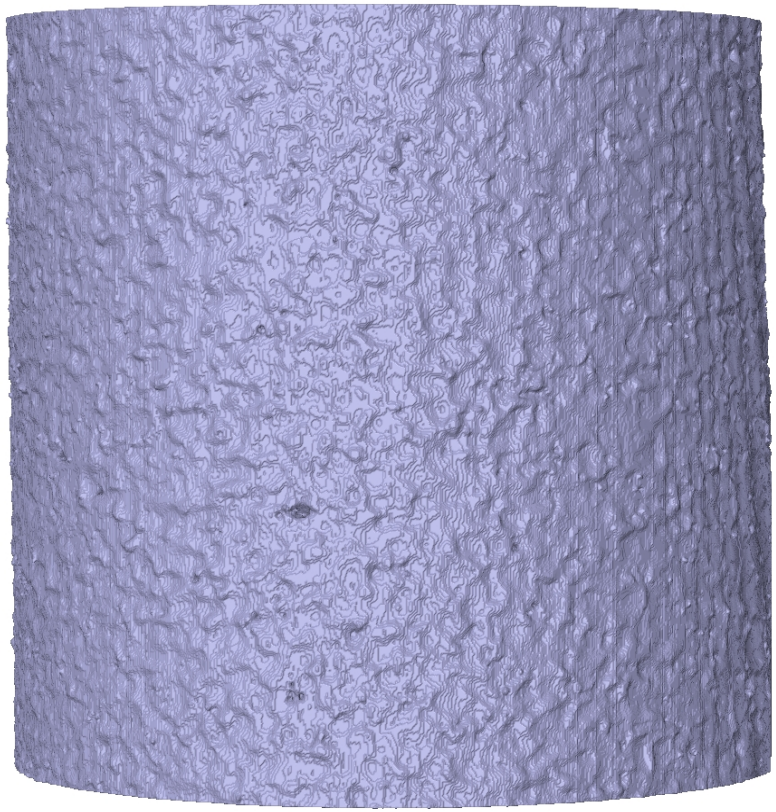
As-Built



1.0 mm

HIP

0.75 mm

LOF pores removed by HIP; small pores remain

New Build Parameters

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Further analysis of four characteristic structures

- **EOS M290 at JHU-APL**
- **EOS StainlessSteel 316L**
- **Porosity <0.1%**

Parameters

- **Power: 195 W**
- **Laser Speed: 1083 mm/s**
- **Layer thickness: 0.02 mm**
- **Hatch Distance: 0.09 mm**
- **Stripe width: 5 mm**
- **Stripe overlap: 0.12 mm**

Characteristic Microstructures

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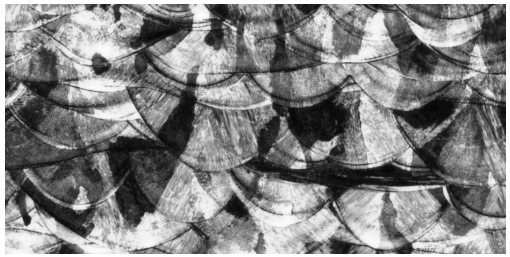
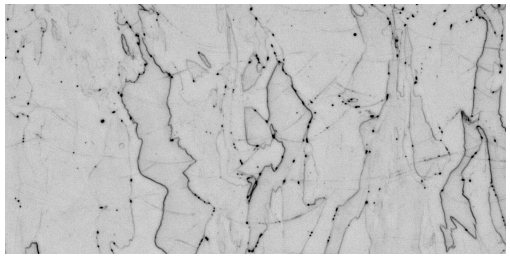
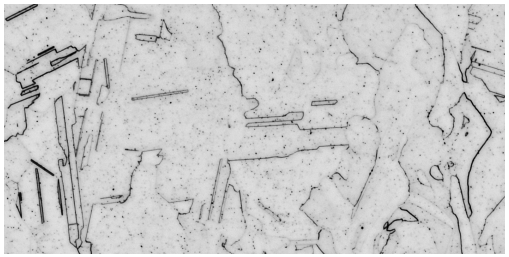
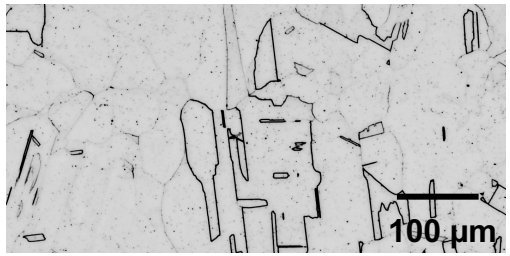
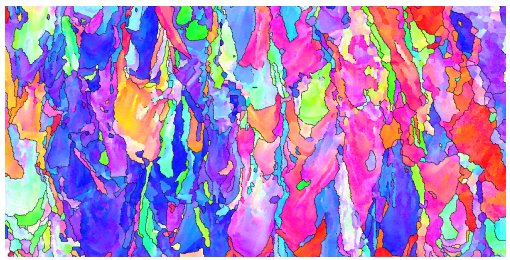
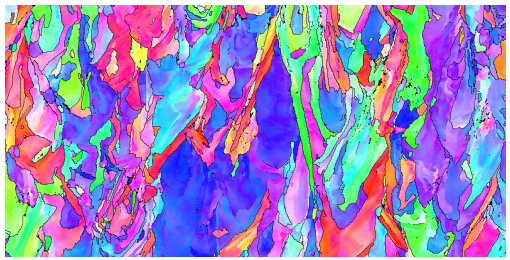
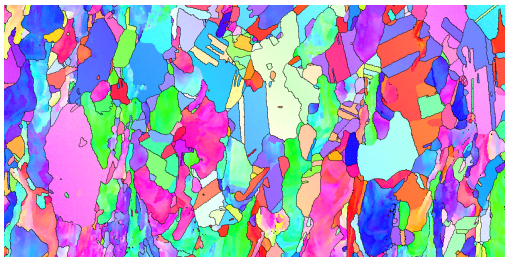
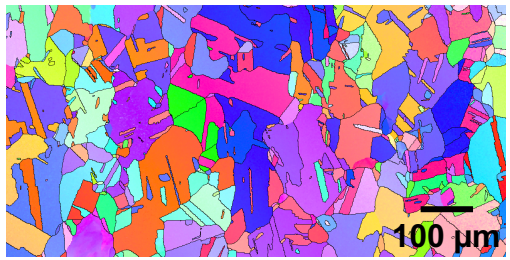
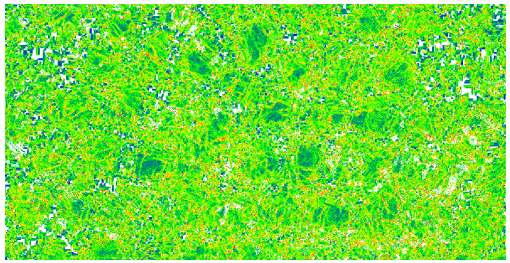
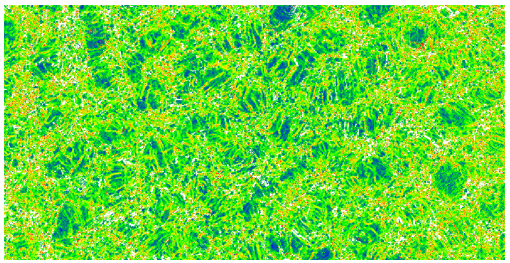
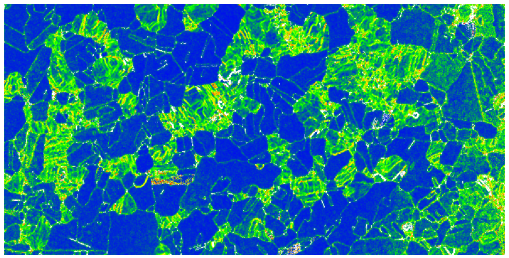
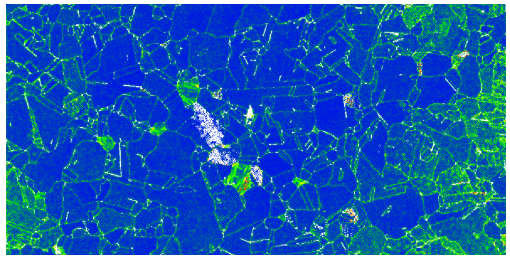
As-Built	Annealed	Recrystallized	HIPed
			
			
			
As-Built	**900 °C, 1h**	**1200 °C, 1h**	**HIP: 1204 °C, 4h**
Fine cell structure	**No cell structure**	No cell structure	No cell structure
As-built grain structure	As-built grain structure	**70% recrystallized grain structure**	**Fully recrystallized grain structure**
Few precipitates	Few precipitates	**Fine precipitates**	**Fine precipitates**

Tensile Testing

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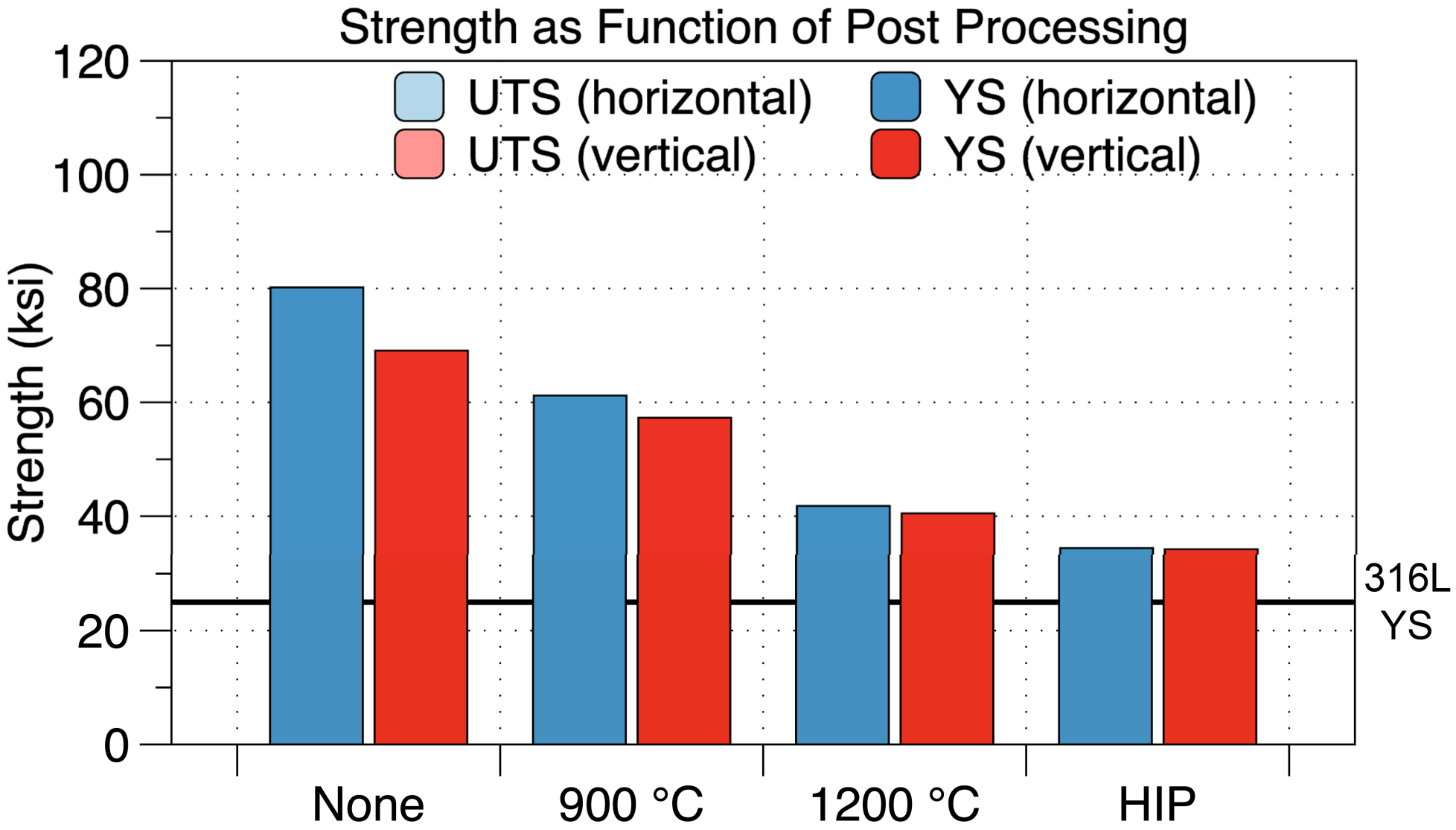
- YS decreases with processing temperature
- All samples exceed 316L specifications



Tensile Testing

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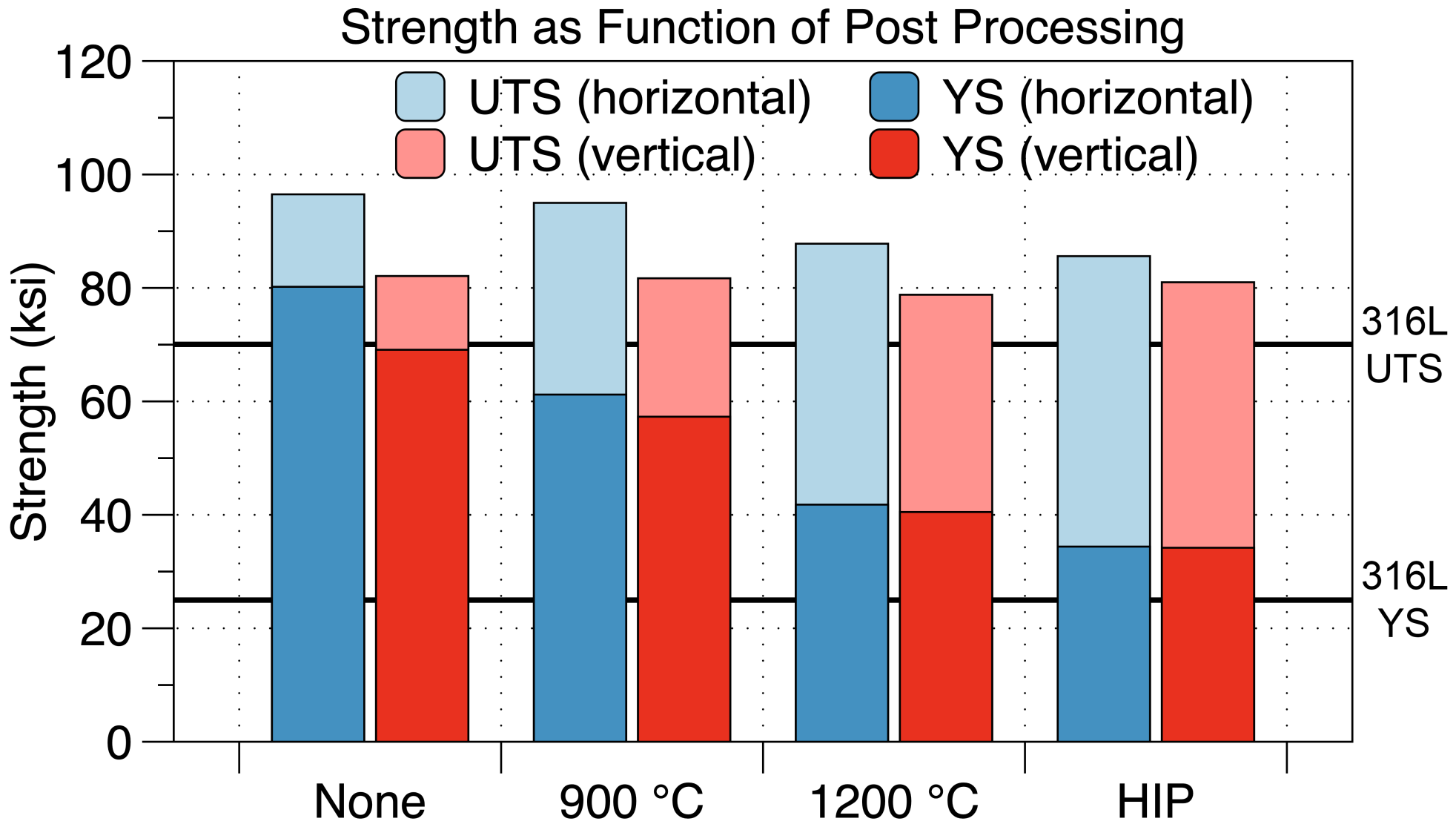
- **UTS shows only slight decrease with Temp**
- **All samples exceed 316L specifications**



Elongation

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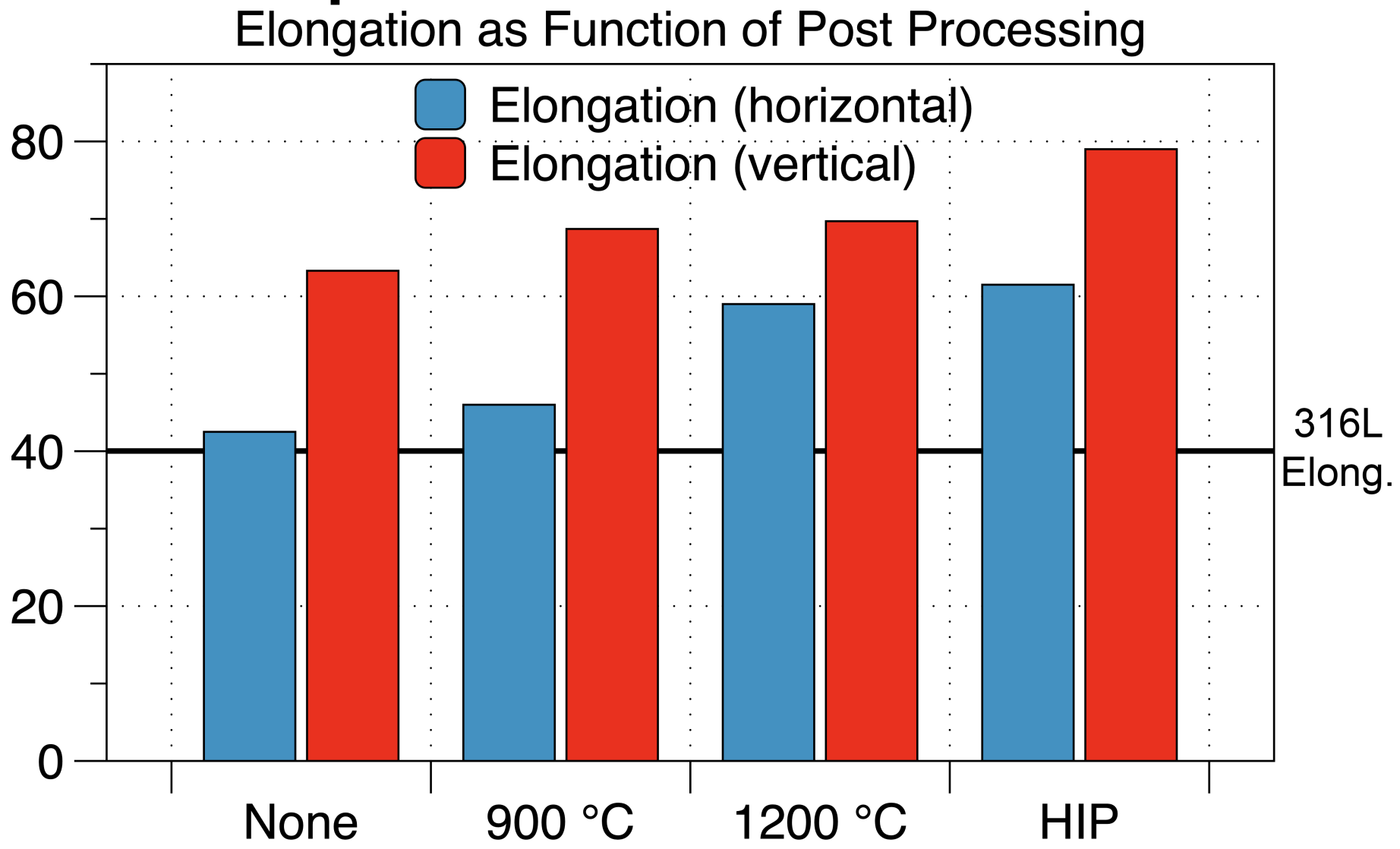
- **Elongation increases with processing temp**
- **Vertical samples more ductile than horizontal**



Rotate Bending Fatigue

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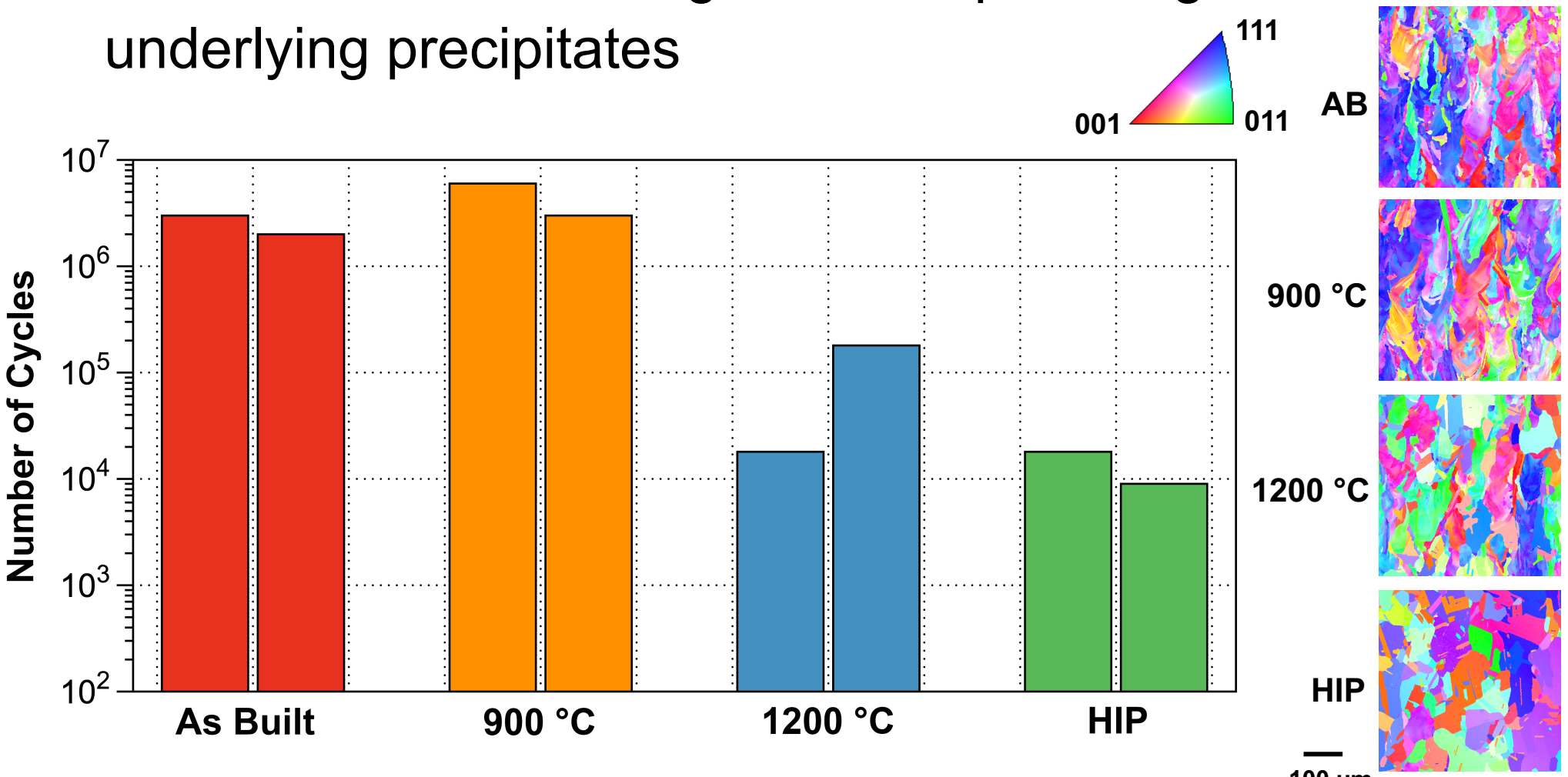
- **Fatigue life degrades with recrystallization**
  - Vertical sample orientation (along BD)
  - Evolution from vertical grains to equiaxed grains with underlying precipitates



Corrosion at Transverse Surface

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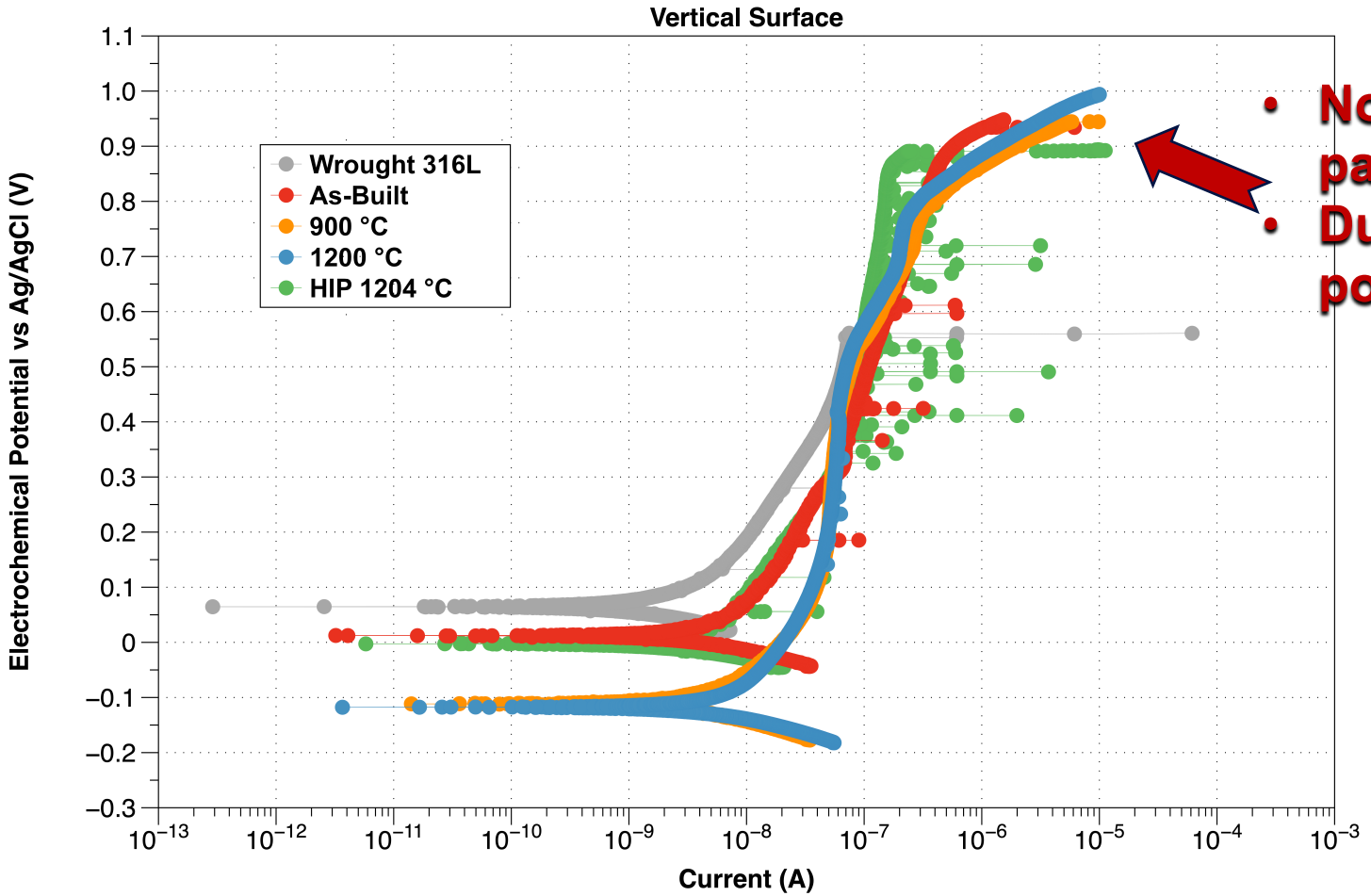
- **AM has better passivity than the wrought 316L**
- **HIP sample has transients in passivation regime**
  - reflect individual isolated corrosion events (precipitates?)
- **Difference in OCP due to defects/matrix comp?**



- **No loss of passivity >800°C**
- **Due to low porosity?**

Corrosion at Build Plane

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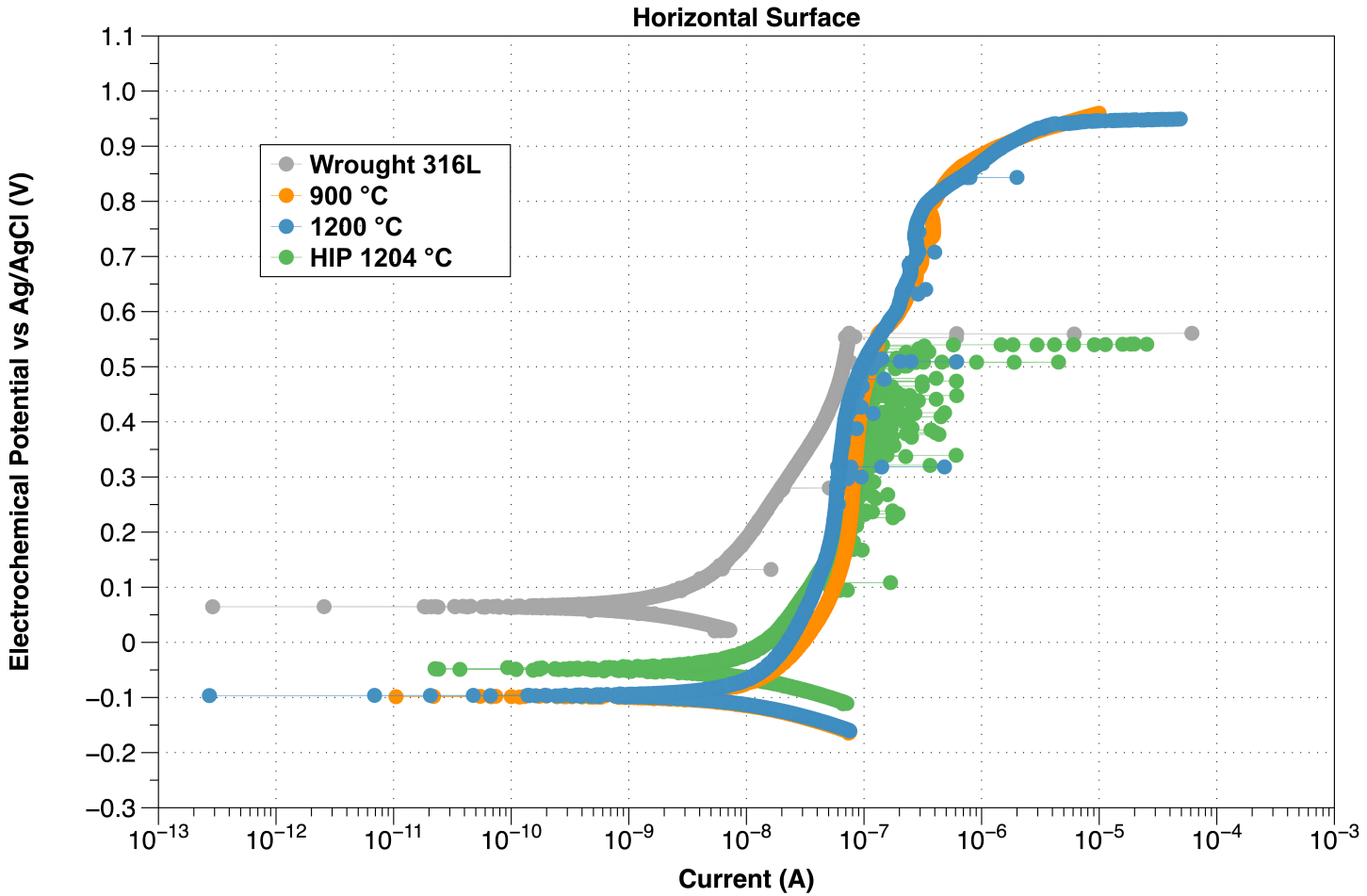
- **Generally similar to transverse surface**
- **More transients observed in HIP sample**
  - Leads to earlier breakdown of surface (ppts?)



Onset of Crevice Corrosion

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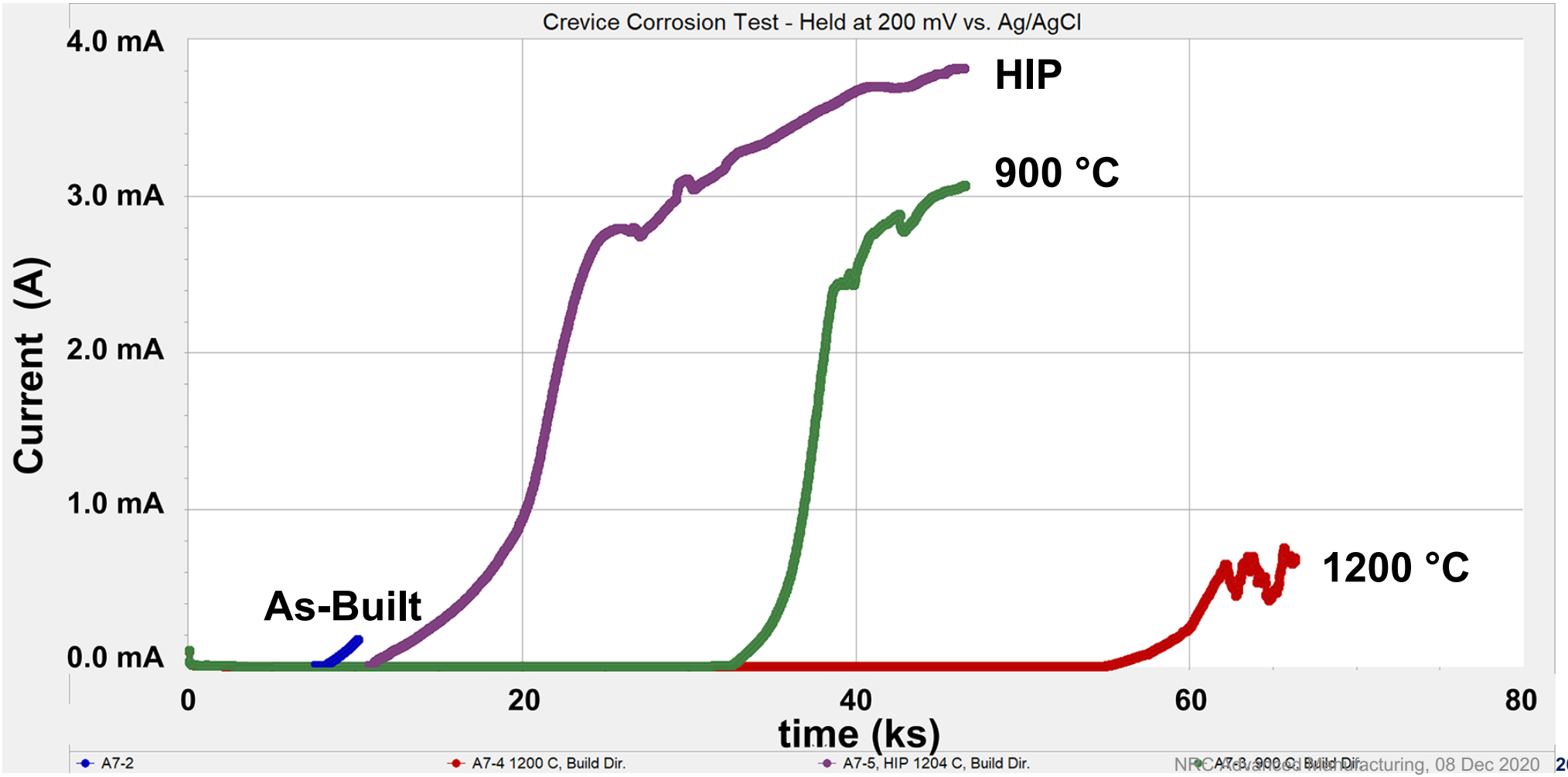
- **Delayed onset from AB ⇨ 900°C ⇨ 1200°C due to coarsening of microstructure scale**
- **Accelerated CC of HIP condition: precipitates?**



Summary

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- **Corrosion** enhanced at surface due to porosity
- **Three distinct microstructural regimes:**

  As-Built < 800 °C < **Annealed** < 1200 °C < **Recrystallized**
- **Microhardness** decreases with increasing temperature
- **Porosity fraction** does not evolve with temperature
  - HIP reduces porosity by ~2/3 by closing LOF pores
- **Yield Strength:** ~3x the 316L specification
  - decreases with processing temperature
- **UTS**: slight decrease due to recrystallization/ppt
- **Elongation:** increases with processing temperature
- **RB Fatigue**: ~100x decrease with recrystallization
- **Corrosion:** HIP-induced precipitation causes increased frequency of transients and rapid onset of crevice corr.
- **Crevice corrosion** resistance improves at 900 °C & 1200 °C
- **All AM structures exceed 316L specifications for YS, UTS, and elongation**

Thank you!