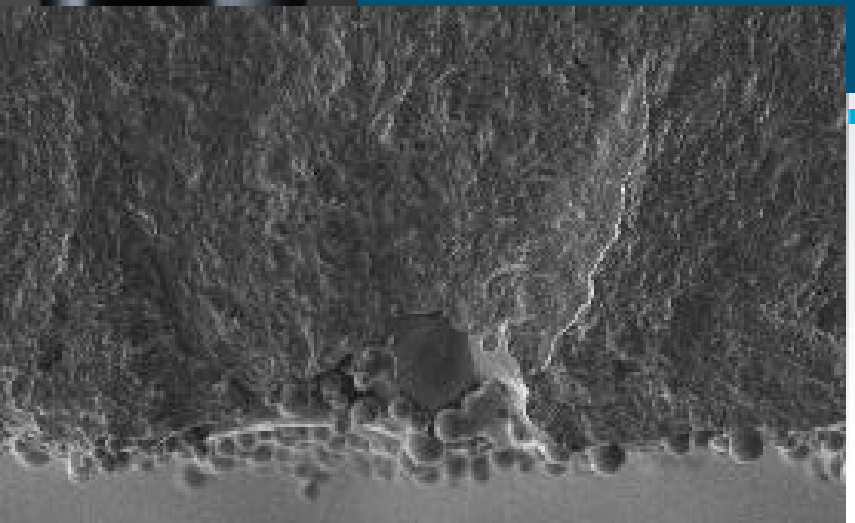

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Deformation Mechanisms in Hexagonal Metals II

Fatigue Behavior Of Additively Manufactured Ti-5553 (and Ti-6Al-4V)

Jay D. Carroll, Zachary Casias, Christopher Laursen, Philip Noell, John Emery

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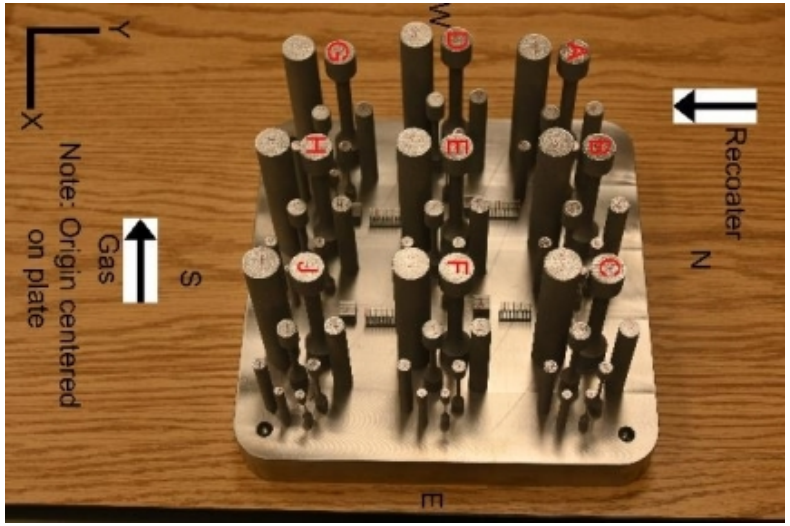
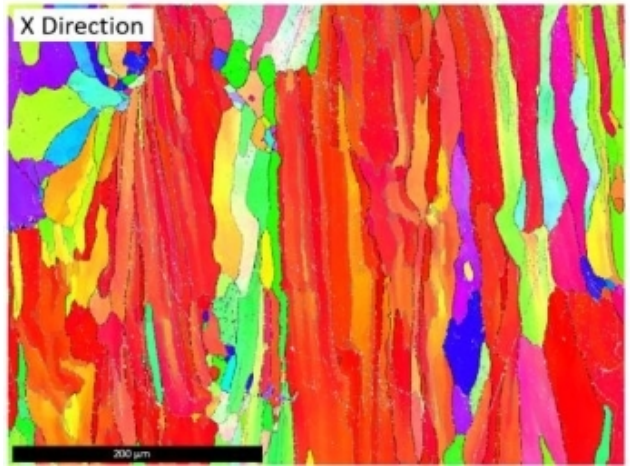
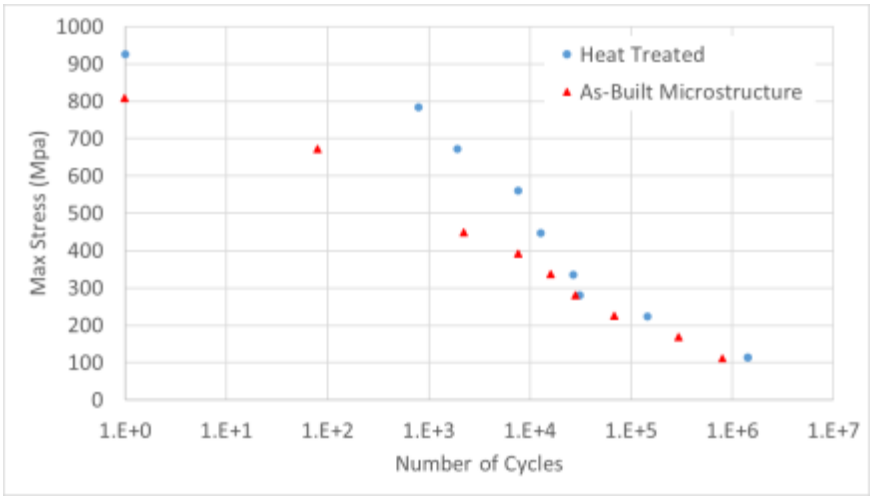
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Research Questions:

1. How does heat treatment affect AM Ti-5553 fatigue properties?
   - β vs α-β
2. Are AM Ti-6Al-4V fatigue lives size-dependent?
3. How do properties compare to literature?
   - More flaws in AM vs conventional processing
   - Effects of surface roughness







Ti-5553 vs Ti-6Al-4V

- **Ti-5553 near beta alloy**
  - **5% Al, 5% Mo, 5% V, 3% Cr, 0.5% Fe**
  - **Yield Strength ≈ 900 MPa**
  - **Ultimate Strength ≈ 1000 MPa**
  - **Some commercial use. Being explored as an AM alloy.**
- **Ti-6Al-4V alpha-beta alloy**
  - **6% Al, 4% V**
  - **Yield Strength ≈ 900 MPa**
  - **Ultimate Strength ≈ 925 MPa**
  - **Widespread commercial use and most common AM Ti alloy.**

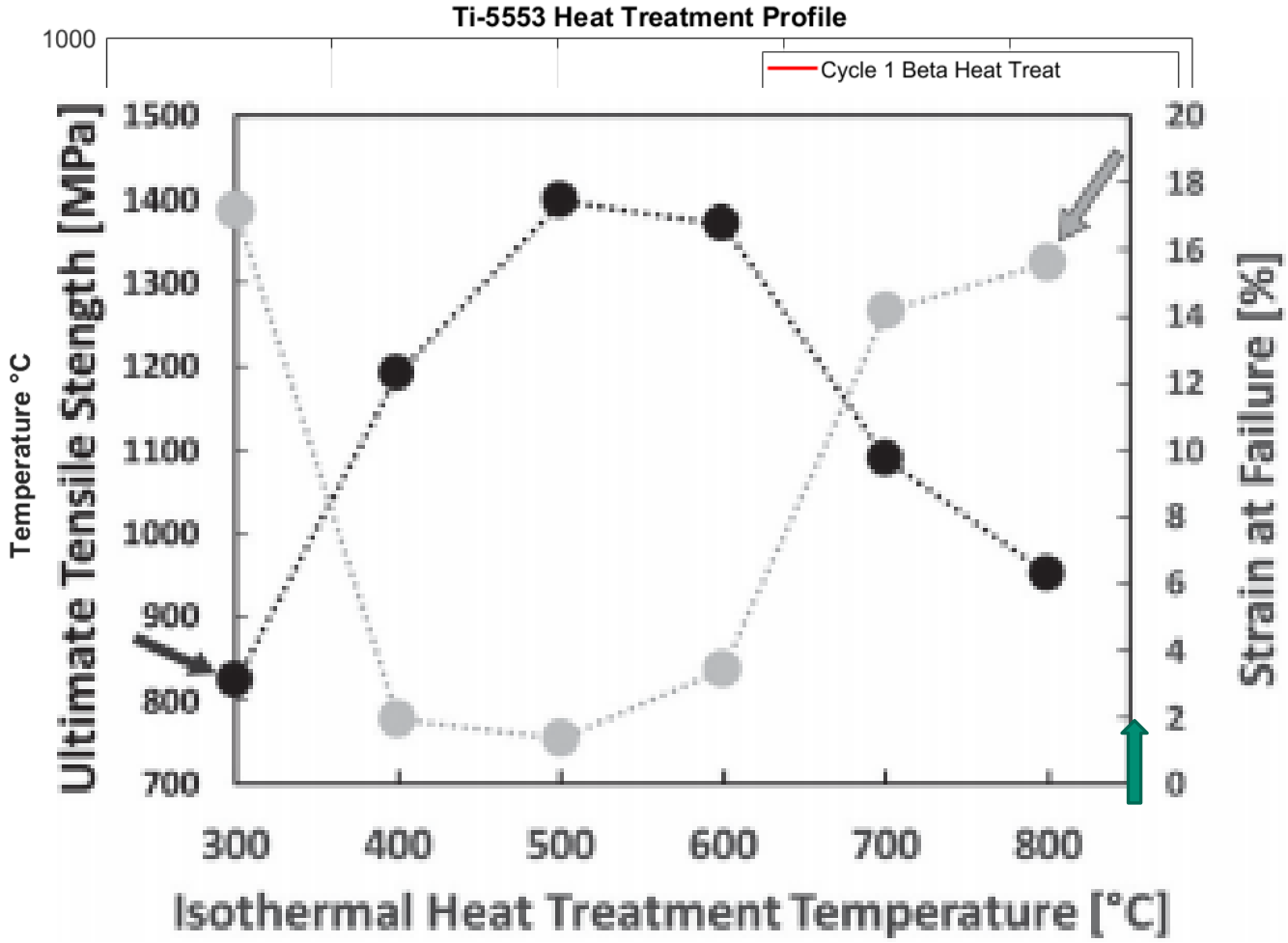
- **Why use Ti-5553 for additive manufacturing?**
  - **Lower elastic modulus in the beta (as-printed) condition.**
  - **Can resist hot cracking more than Ti-6Al-4V.**
  - **Can be heat treated to alpha-beta condition, high strength and good ductility**

Ti-5553 Heat Treatment

- **Elastic modulus can change by factor of 2 depending on α/β mixture!**

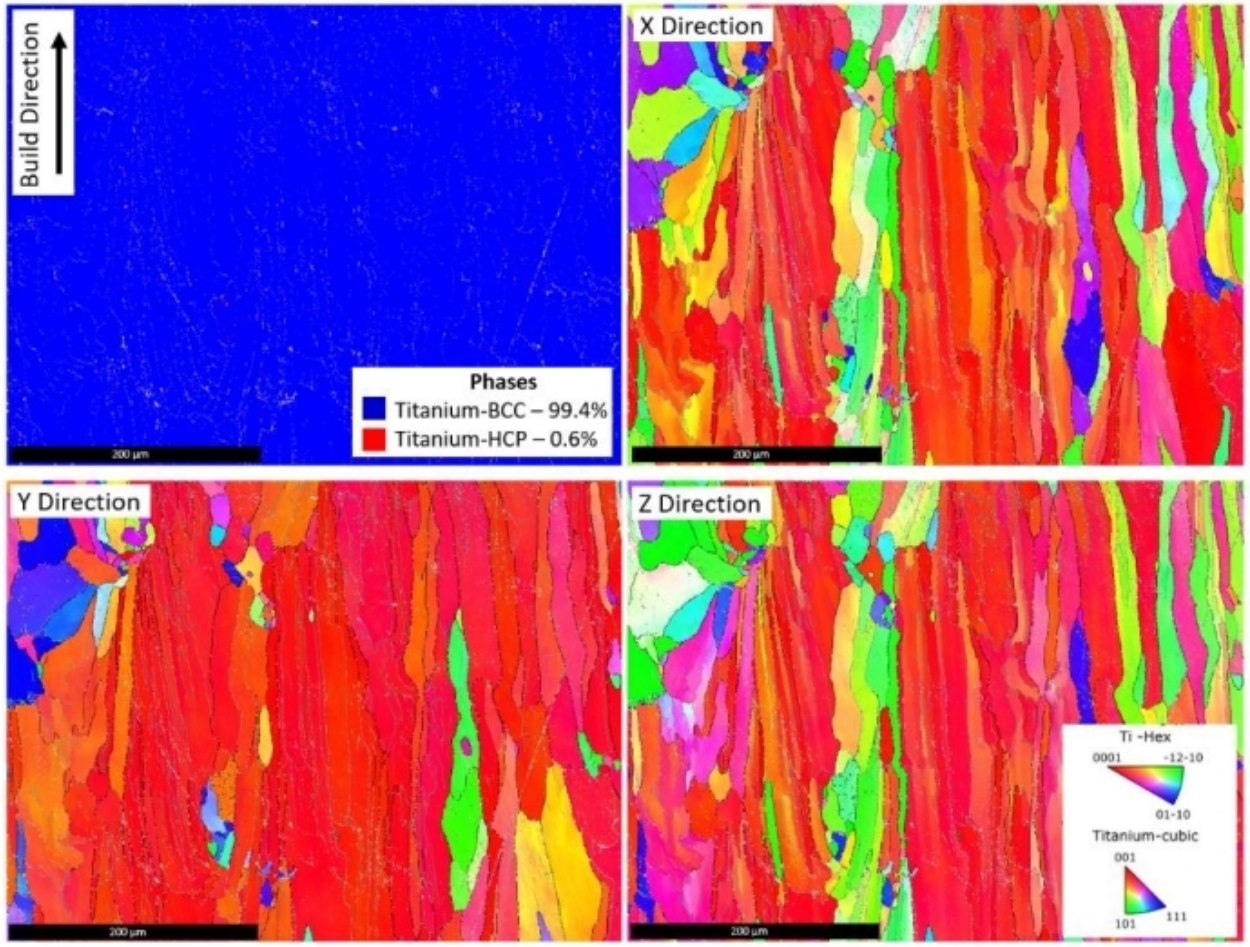
Carlton et al., Sci. Technol. Weld. Join. 24 (2019) 465-473

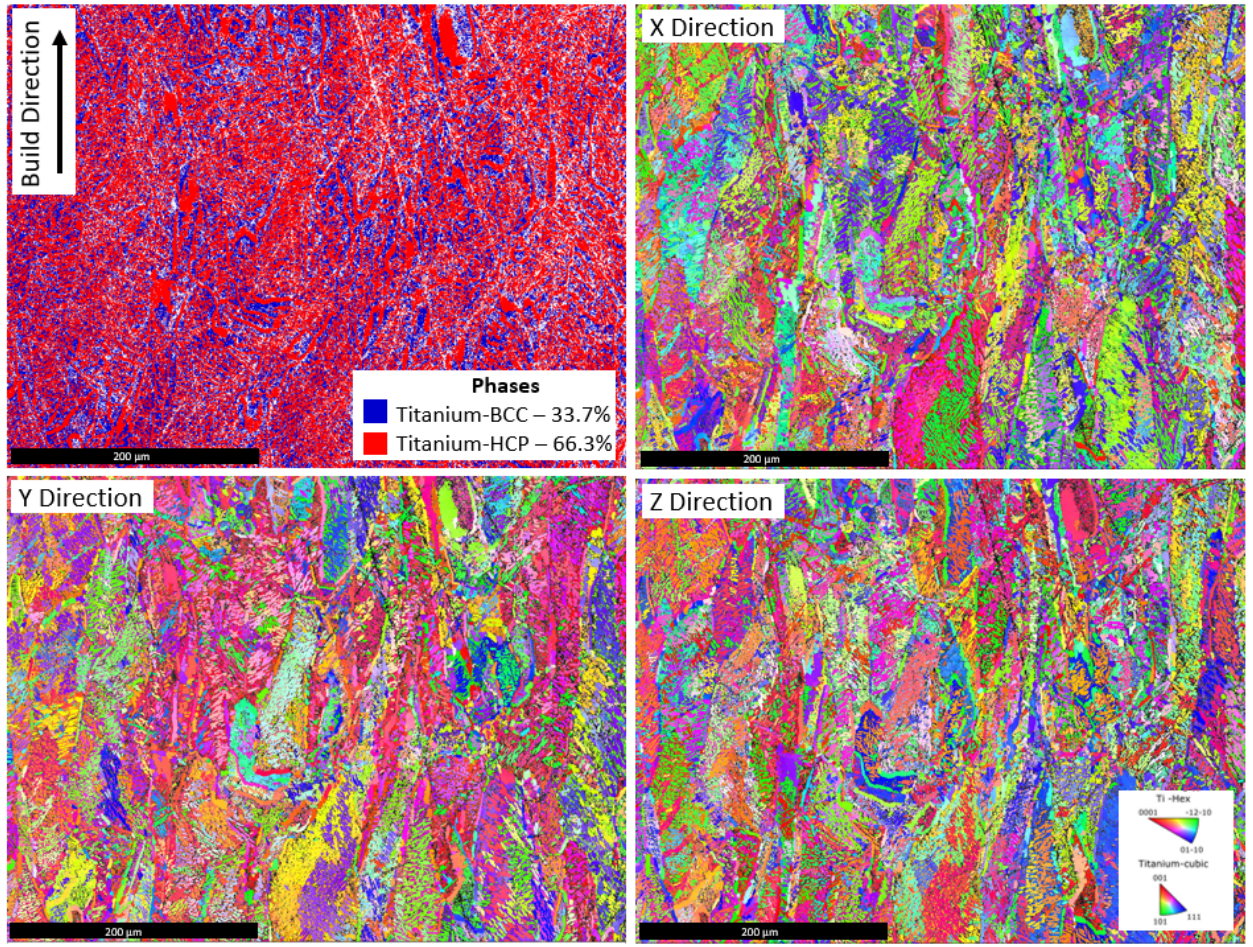
	Heat-treatment temperature (°C)		E (GPa)
Our as-built →	300	~100% β	48 ± 1
	400		66 ± 3
	500		98 ± 4
	600		97 ± 1
	700		92 ± 1
	800	25% α, 75% β	78 ± 4
Our heat treated (900°C) →	900	25% α, 75% β	91



AM Ti-5553 Microstructure

α = HCP (red)
β = BCC (blue)
ω = Hexagonal (detrimental, not detected)



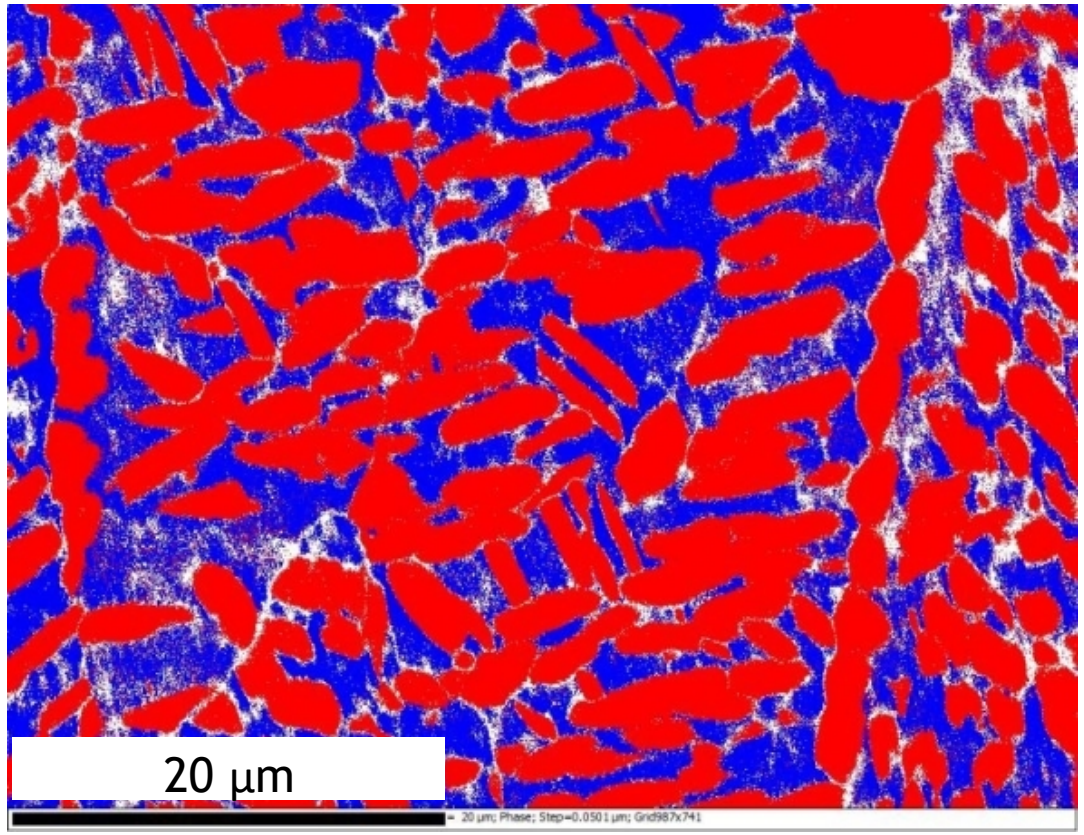


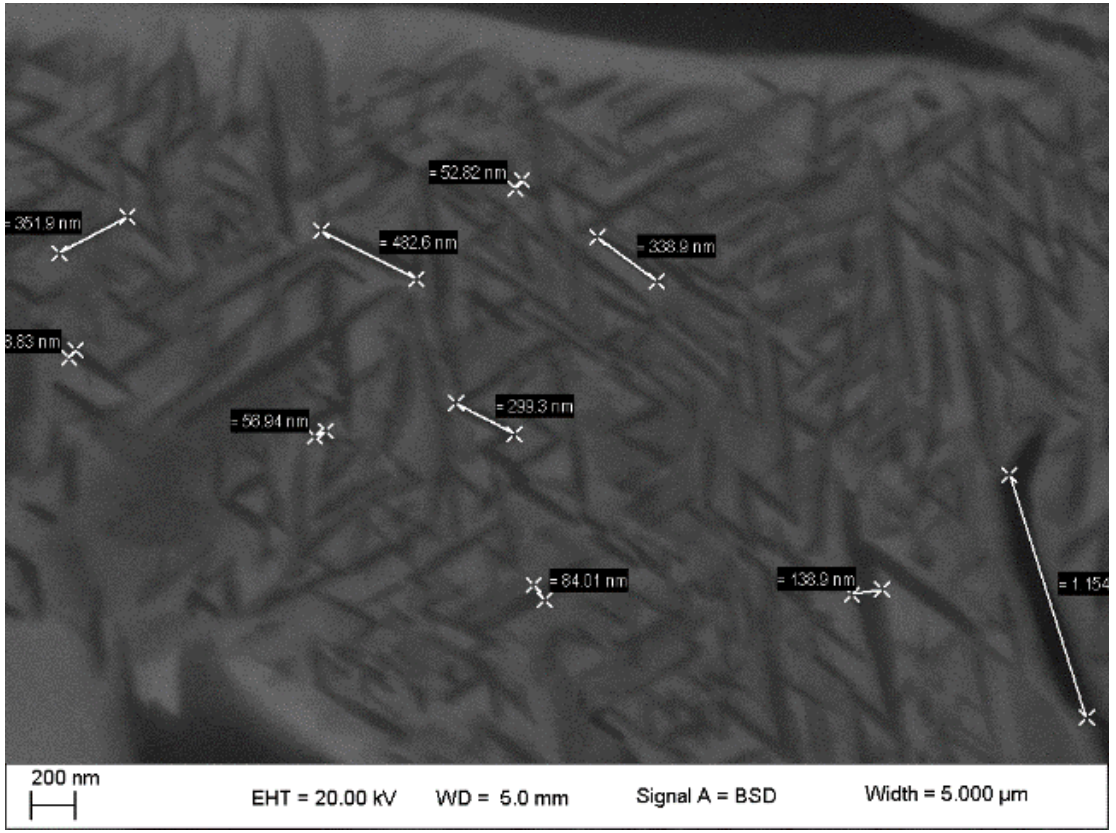
- **As-printed has columnar microstructure, pure BCC with [100] in the build direction.**
- **Heat treated has 33% Beta and 67% alpha in laths at several size scales:**
- **~ 7 x 1 µm and ~300 x 50 nm.**

AM Ti-5553 Microstructure

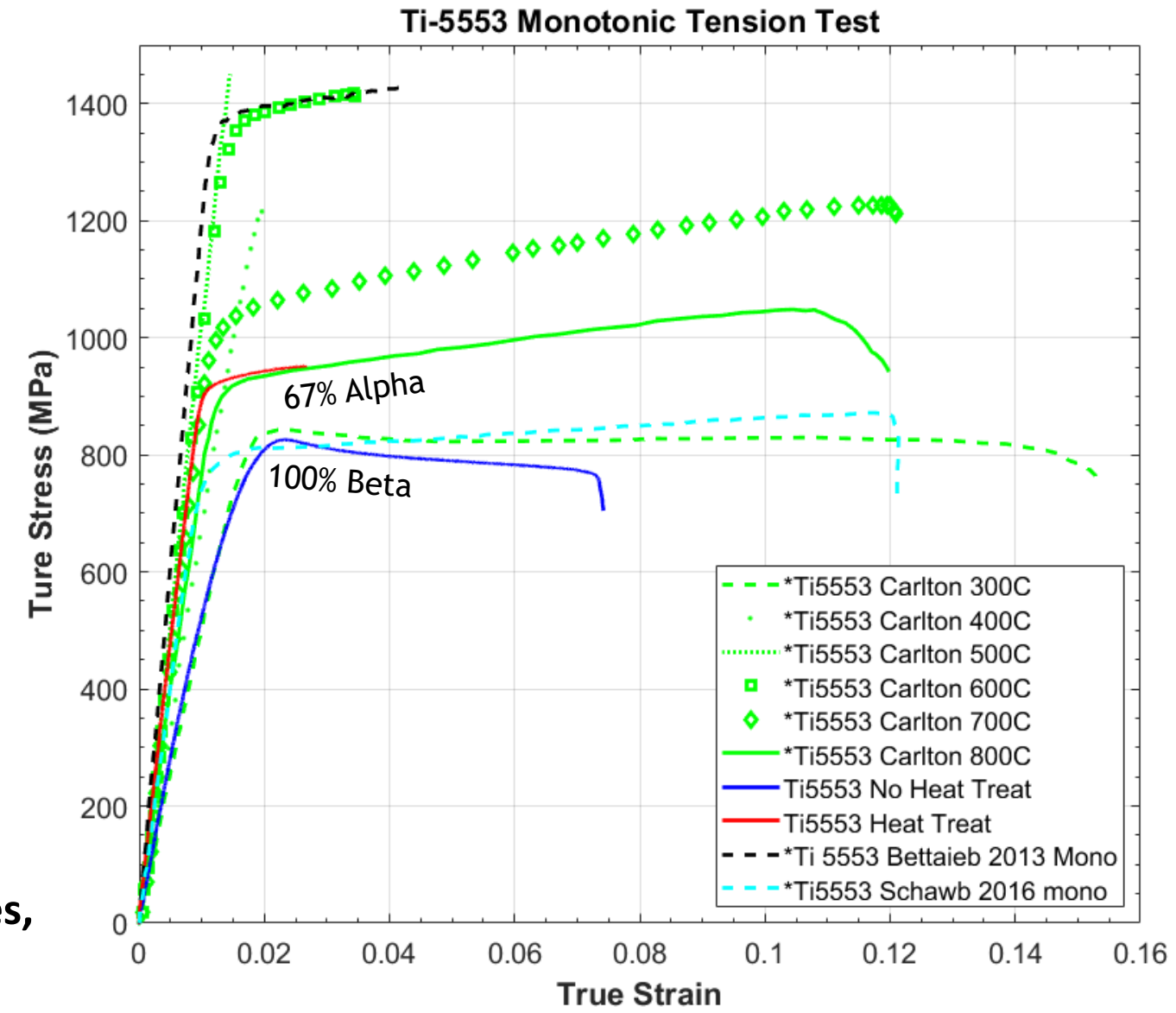
α = HCP (red)
β = BCC (blue)
ω = Hexagonal (detrimental, not detected)

- **Heat treated Ti-5553 has 33% β and 67% α in laths at several size scales:**
- **Fine α laths ~ 7 x 1 µm**
- **Coarse α laths ~300 x 50 nm.**



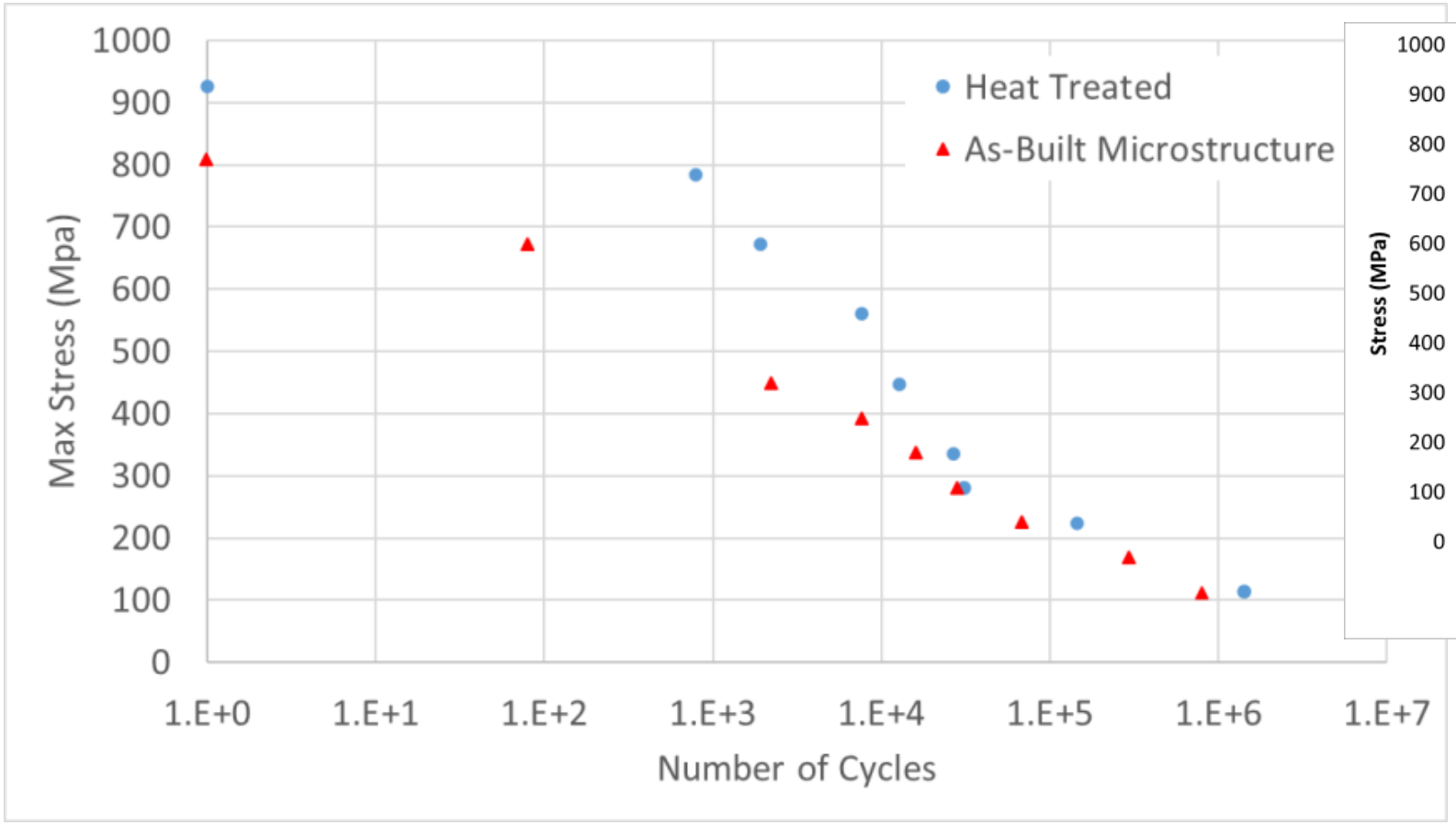


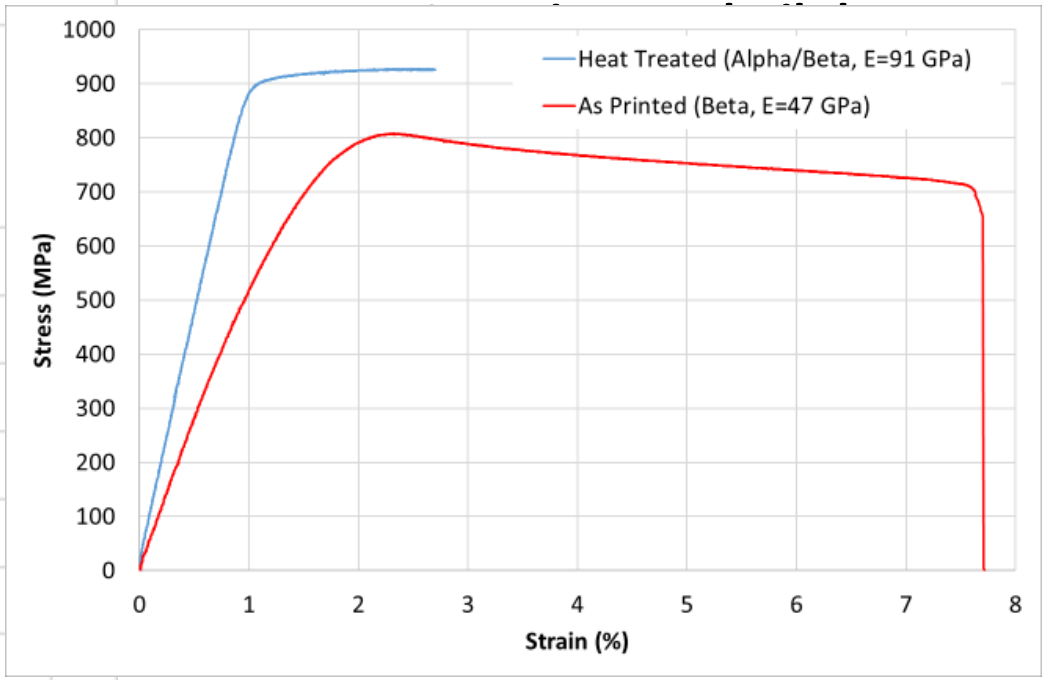
This AM Ti-5553 is inline with published values



- **Strengths are in-line with published values, but ductilities are lower.**

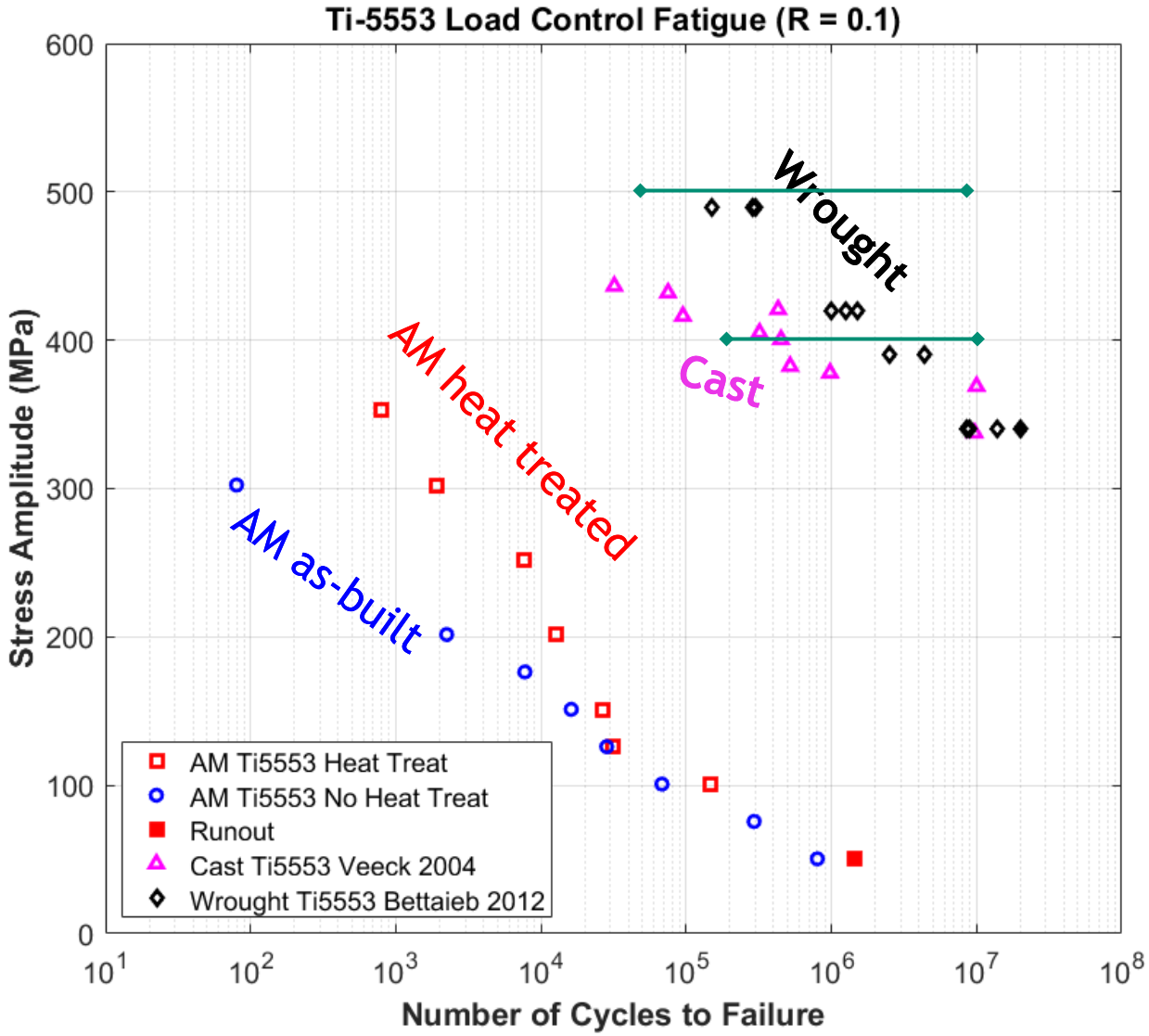
AM Ti-5553 Stress Life Fatigue Curves





- **Steep drop-off in fatigue strengths with no clear threshold.**
- **Similar behavior in high cycle fatigue regime (>10,000 cycles).**
- **Heat-treated experiences more microplasticity in the LCF regime leading to shorter lifetimes.**

This AM Ti-5553 has fatigue lives far below published values for wrought and cast Ti-5553.



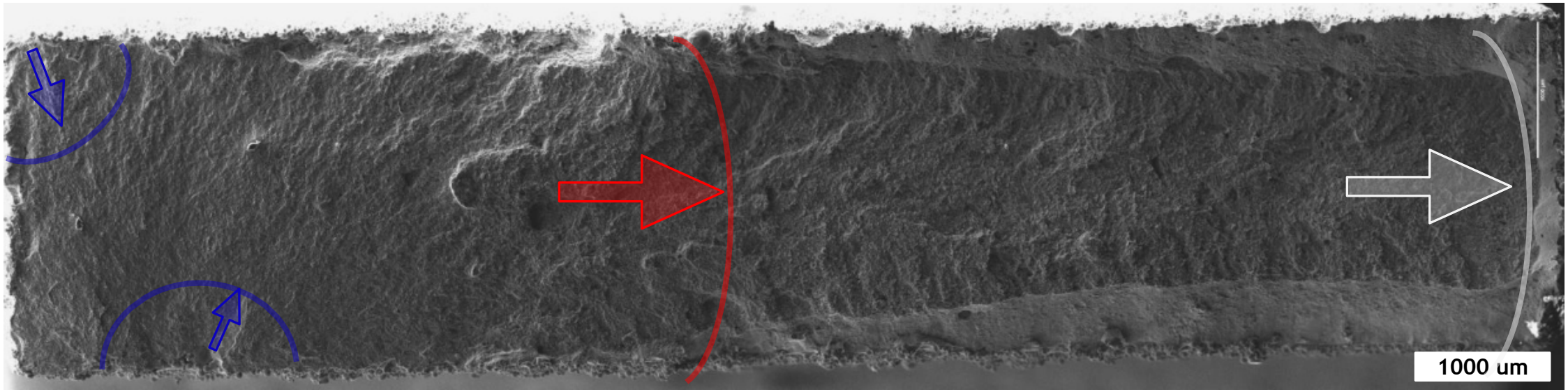
- **This AM Ti-5553 has fatigue properties far below conventionally processed Ti-5553.**
- **Is it inherent to AM or just our AM.**
- **Yasin also tested AM Ti-5553 in fatigue, at R=-1, round, heat treat to 900C.**

Possible causes:

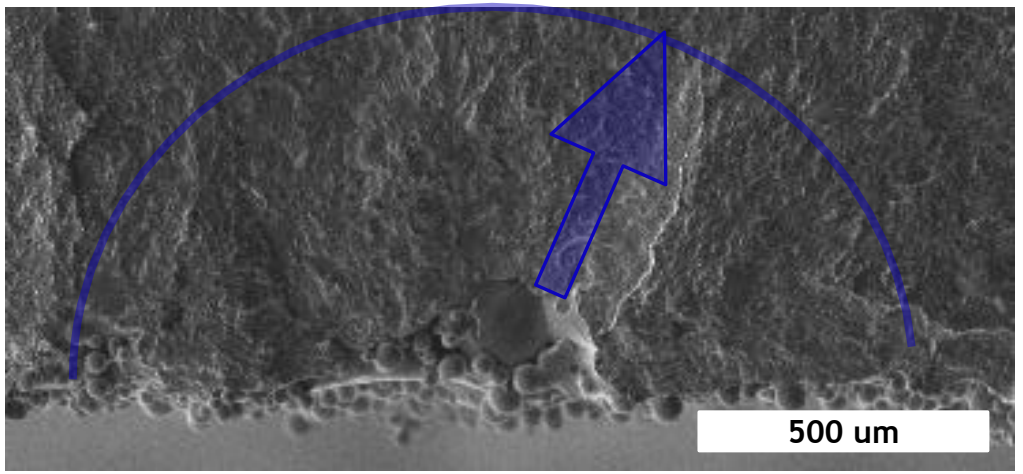
- **Coarse alpha from excessive heat treatment.**
- **Flaws from AM.**
- **Surface roughness and aspect ratio of sample.**

Bettaieb et al., Mat Sci Eng A, 2012
Veeck et al., J. Advanced Mat, 2005
Yasin et al. Proc Struct Integ., 2022

AM Ti-5553 fatigue nucleates at near-surface voids

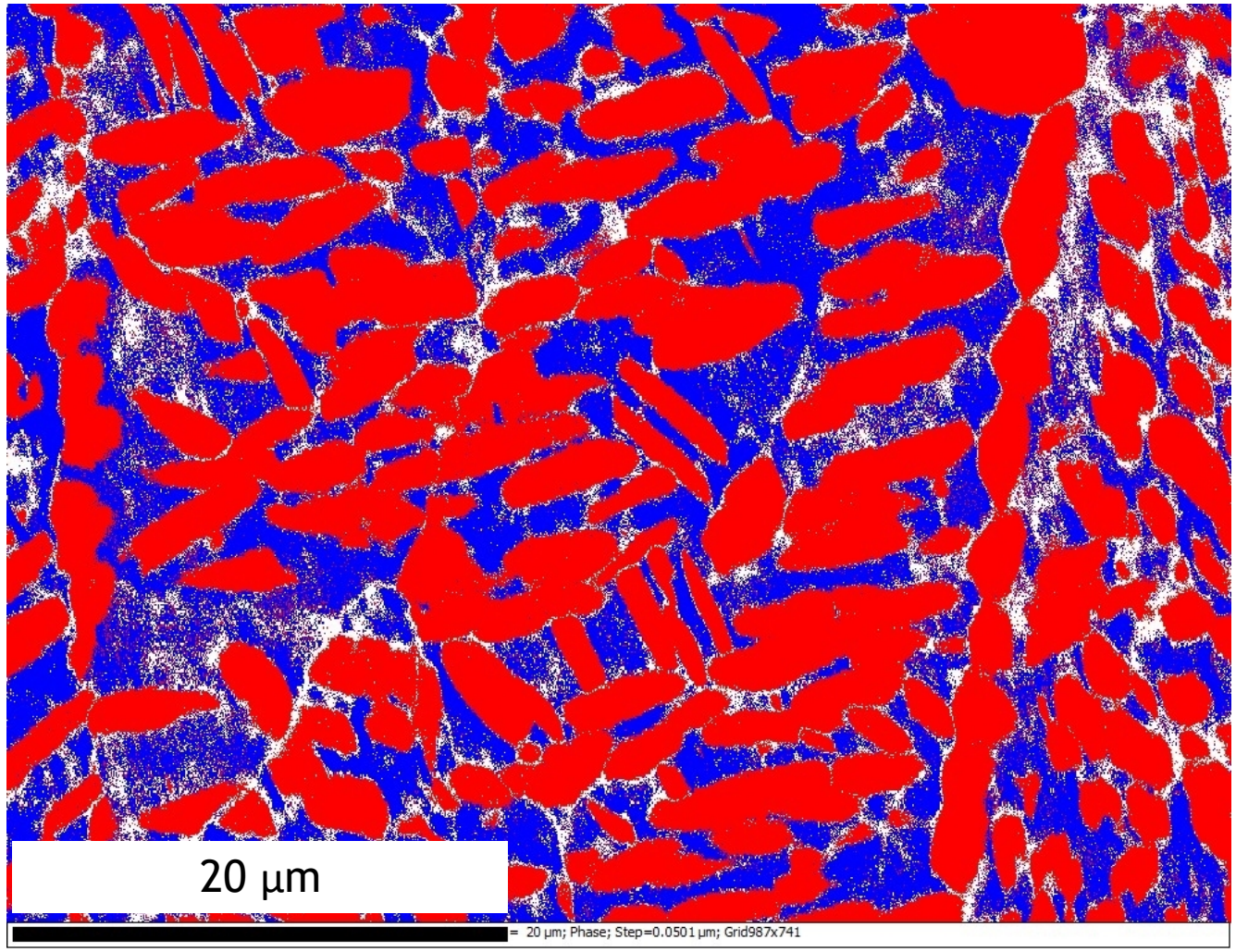


- **Fracture surfaces show failure dominated by surface defects.**
- **Machining specimens could remove near-surface voids and lead to artificially high fatigue strengths.**



Lower fatigue strength of AM Ti-5553

α = HCP (red)
β = BCC (blue)



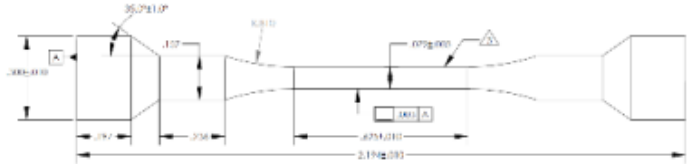
Possible causes:

- **Coarse alpha from excessive heat treatment.**
- **Flaws from AM.**
- **Surface roughness and aspect ratio of sample.**

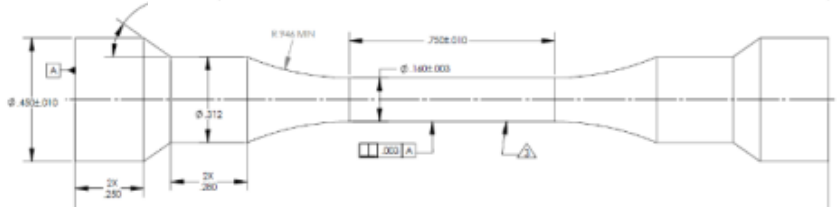
Ti-6Al-4V

AM Ti-6Al-4V Tensile/fatigue samples

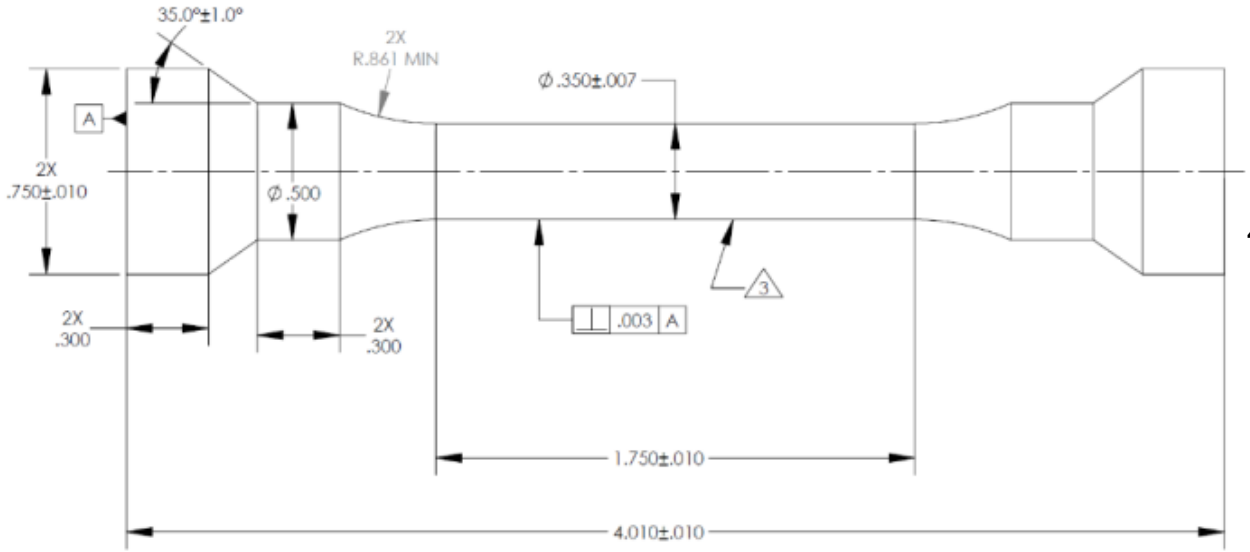
- **Annealing heat treatment at 704°C for 2 hrs in vacuum <10^{-5} torr. Cooling rates of 5°Cmin.**



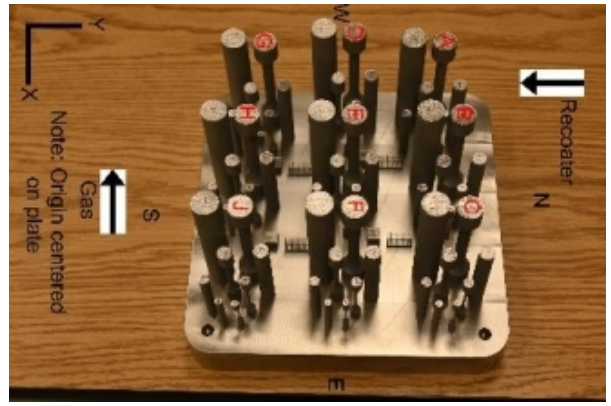
R6
15.9 mm long x 2mm dia



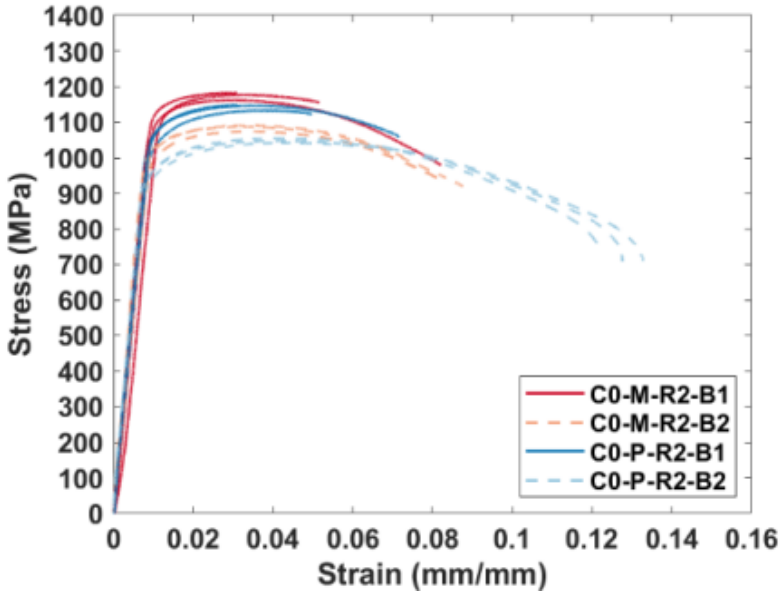
R4
19 mm long x 4.1 mm dia

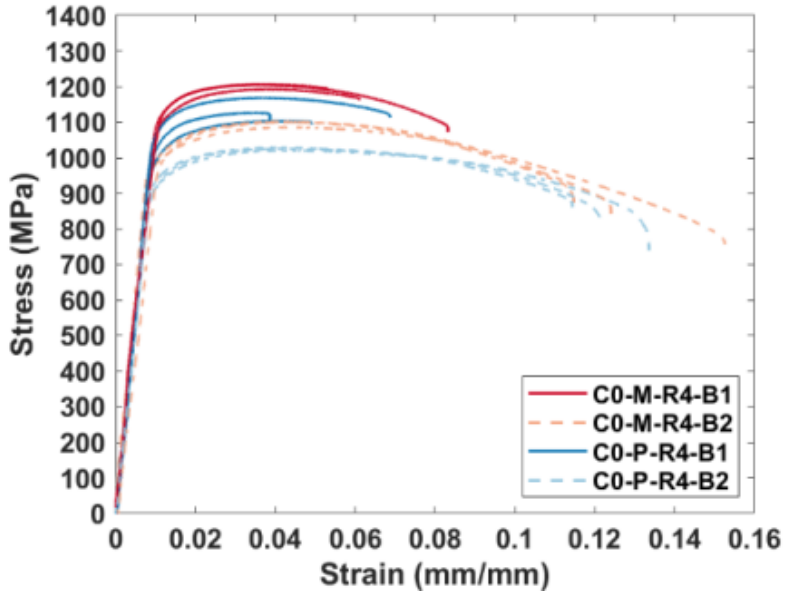


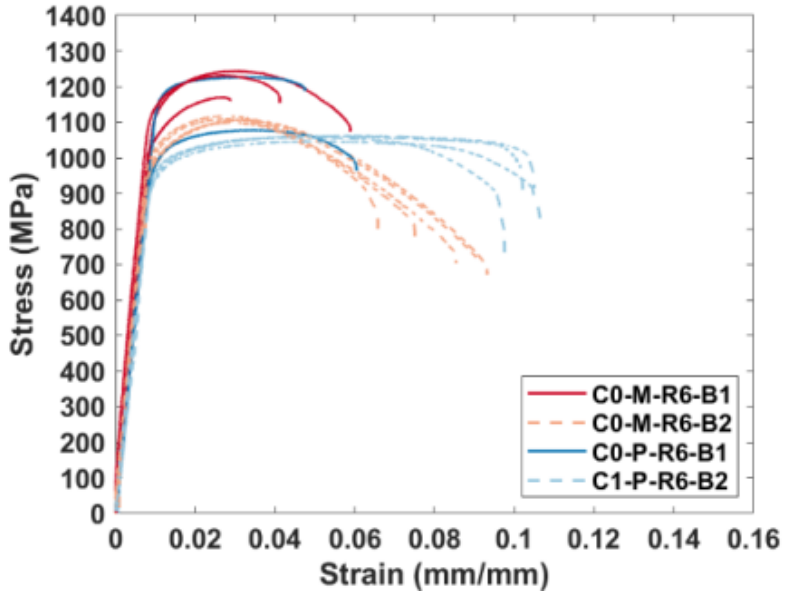
R2
45 mm long x 8.9 mm dia



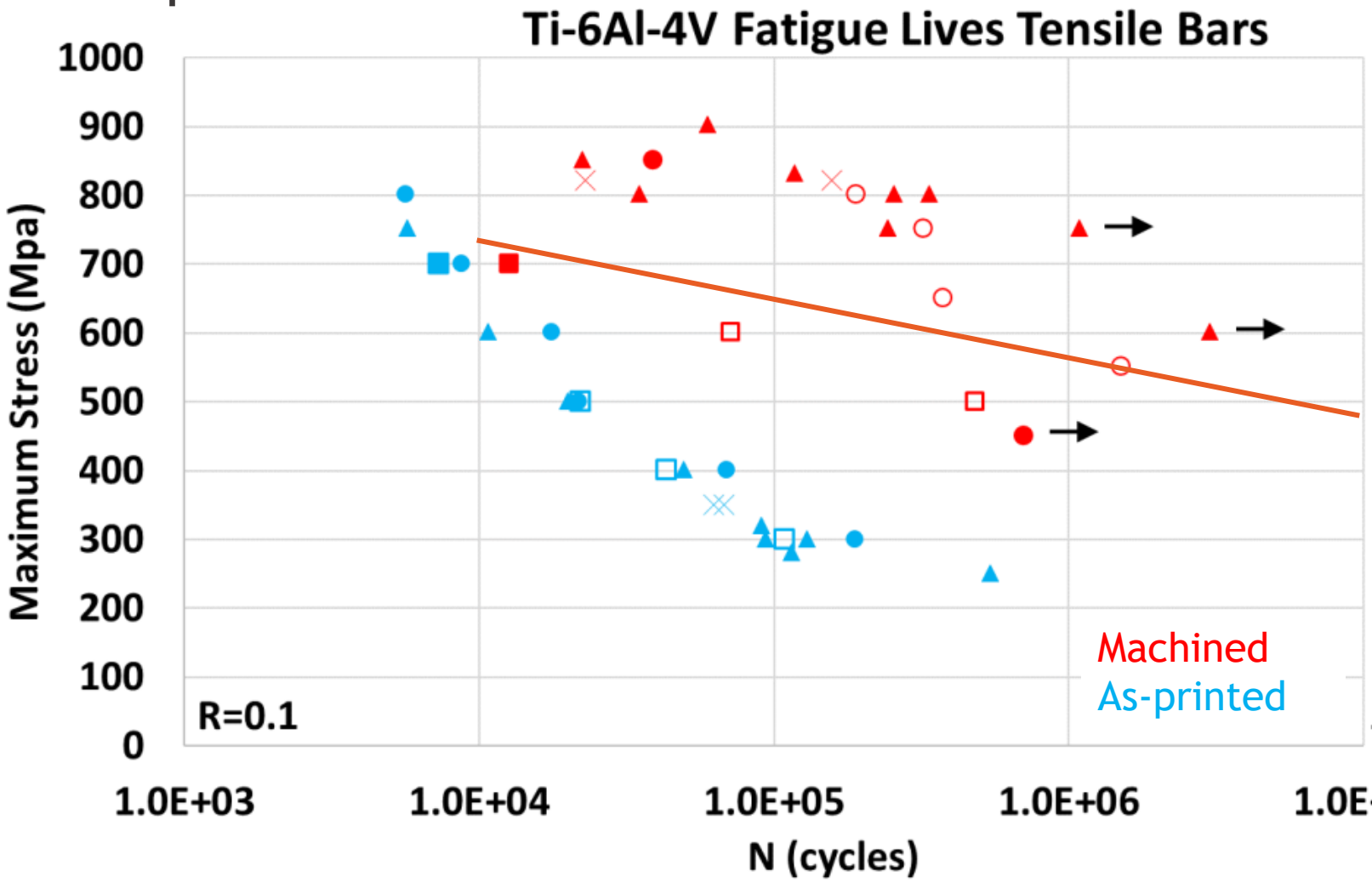
AM Ti-6Al-4V Tensile Results



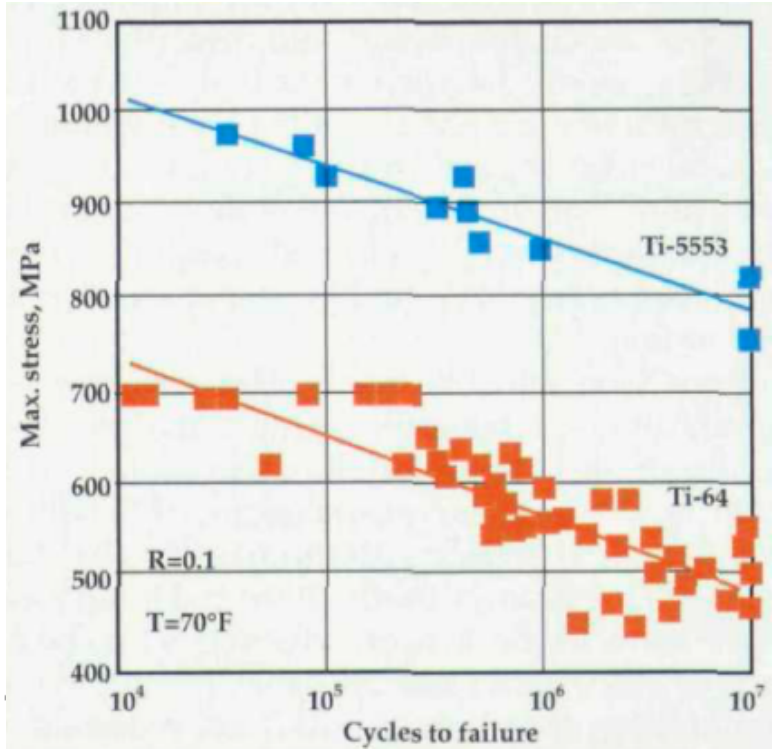




AM Ti-6Al-4V fatigue lives appears to be size-independent

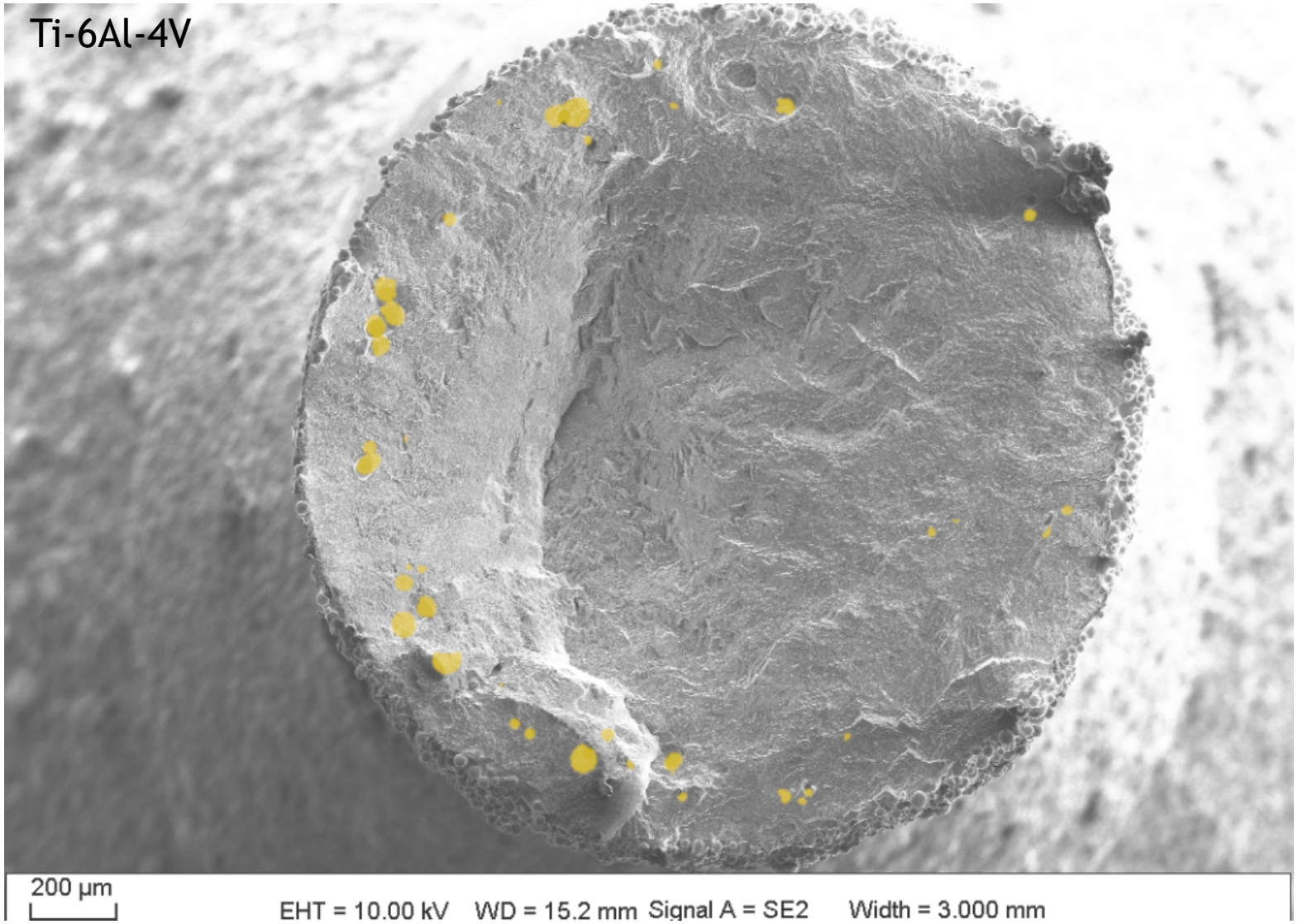


Veeck et al., J. Advanced Mat, 2005
Cast and machined



- **Machined specimens outperform AM surfaces.**
- **Specimens with AM surfaces are much more predictable.**
- **No measurable size effects between as-printed R2, R4, R6 samples**

AM Ti-6Al-4V size independence may be related to voids at the contour-fill interface



- **Machined specimens significantly outperform as-printed specimens, but with more noise.**
  - **Enough voids in as-printed to make lives deterministic?**
- **Voids near surfaces due to interface between contour pass and fill hatch.**

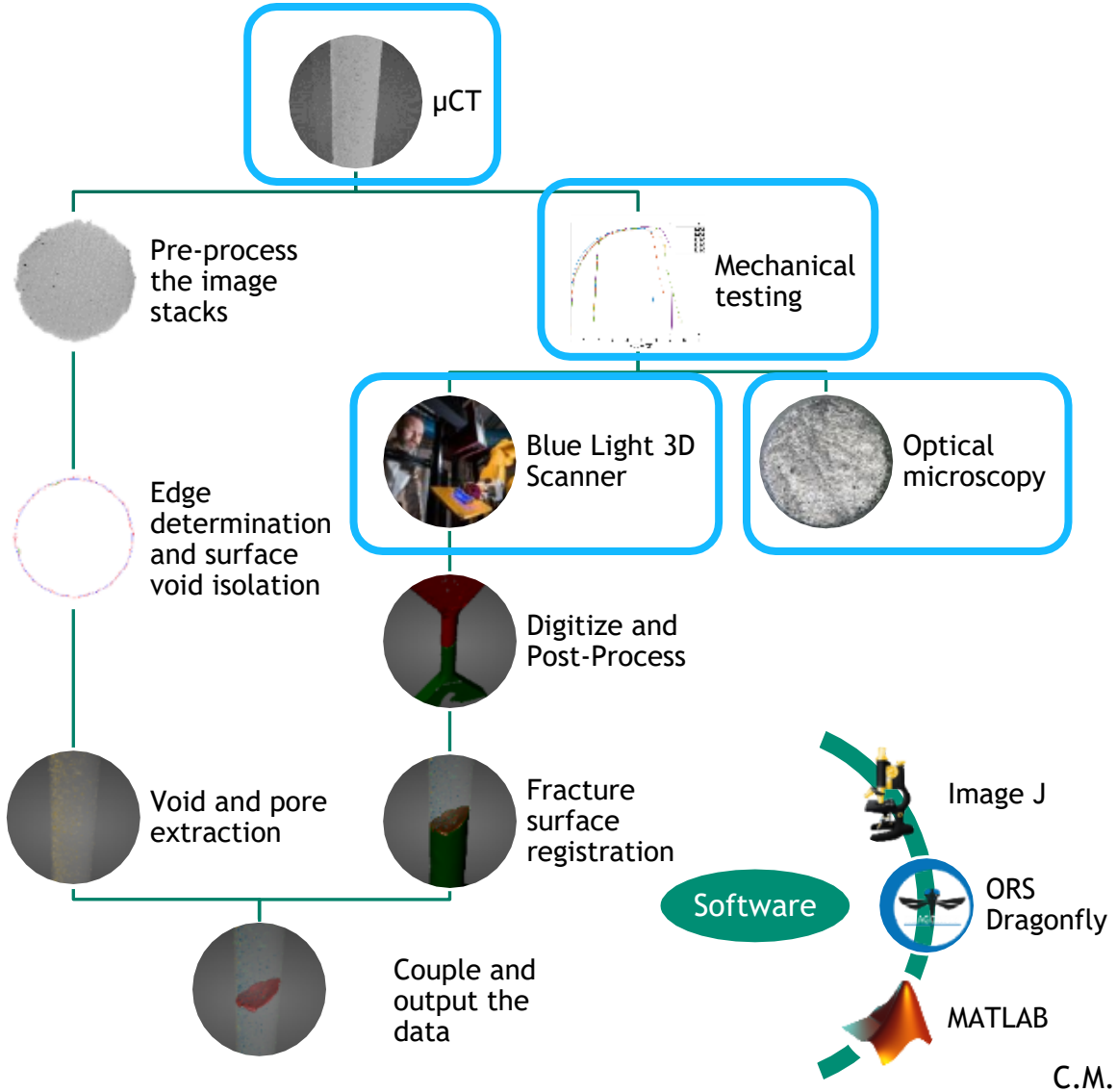
Conclusions

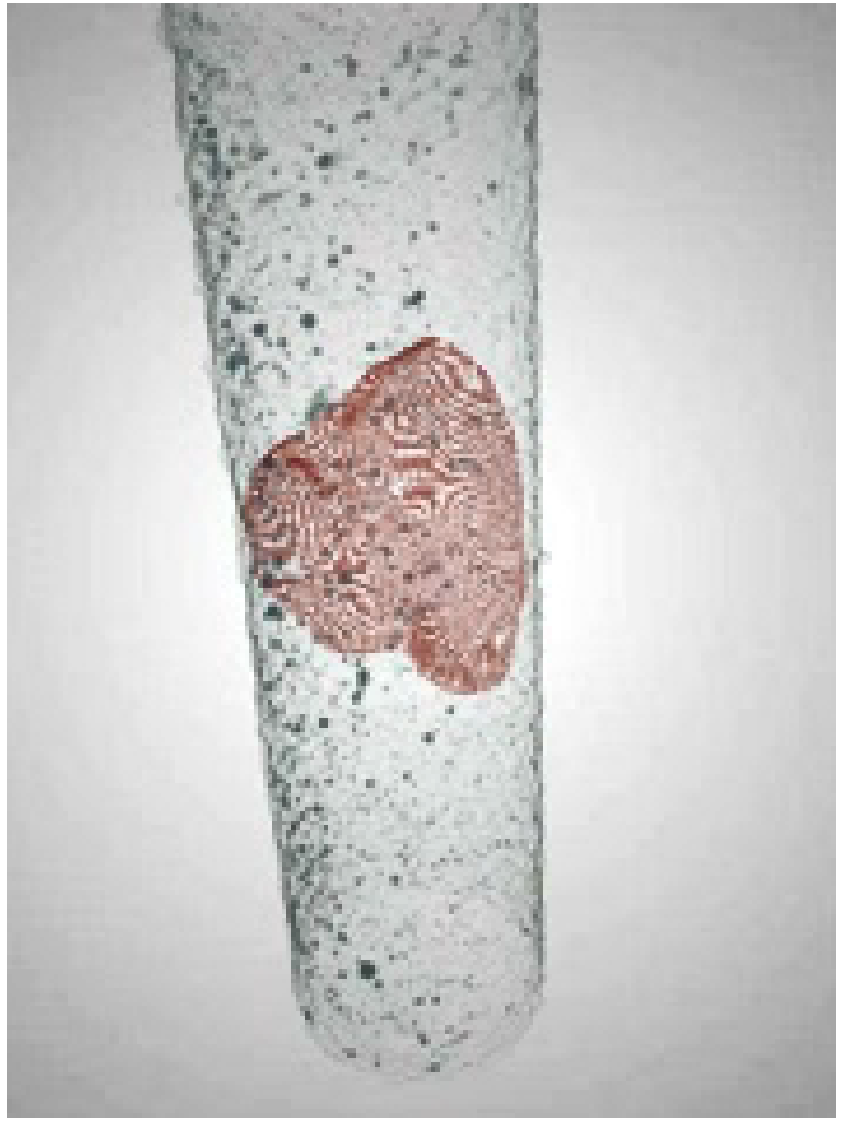
- **Some of the first measurements of fatigue of AM Ti-5553.**
- **Pure beta vs 75% alpha 25% beta alloys exhibited equivalent fatigue lives in high cycle fatigue.**
  - **In low cycle fatigue, alpha/beta appears to outperform pure beta.**
- **Ti-6Al-4V fatigue lives were independent of specimen size**
  - **Increasing void probability with increasing size balances with increased surface crust with decreasing size.**

Future work: can we attribute failure location to specific defects?

Heat treated AlSi10Mg, tension

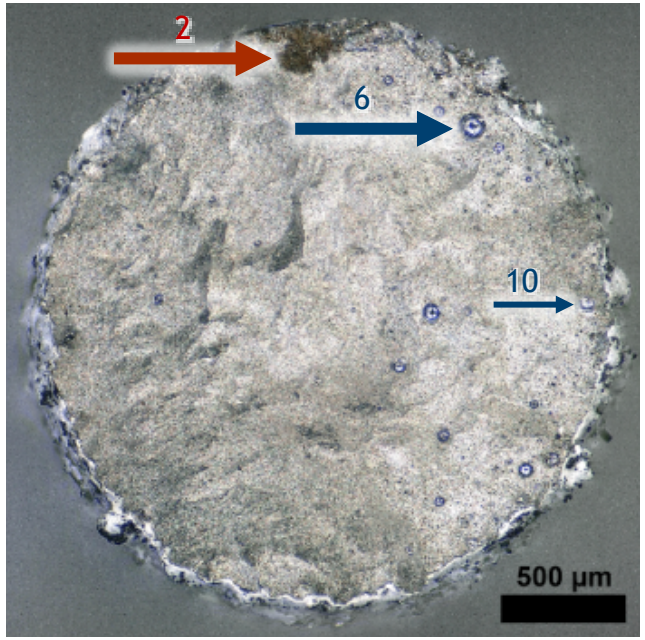
Ex-situ Correlation of Computed Tomography and Fracture Location

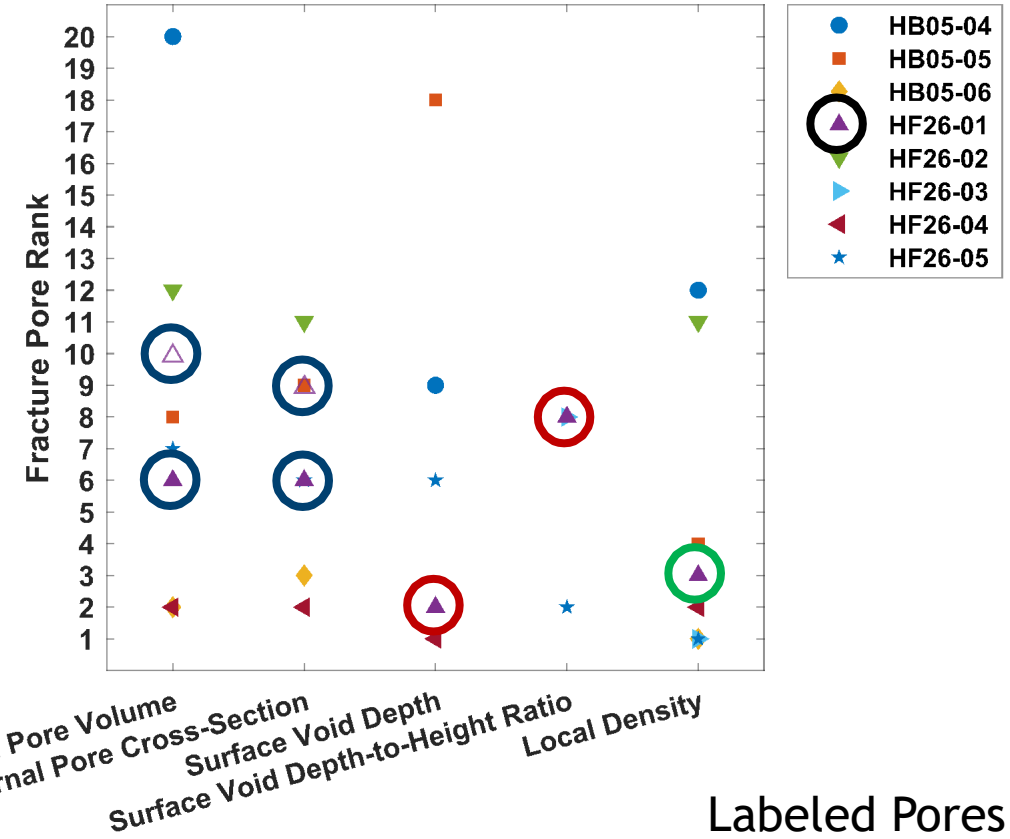


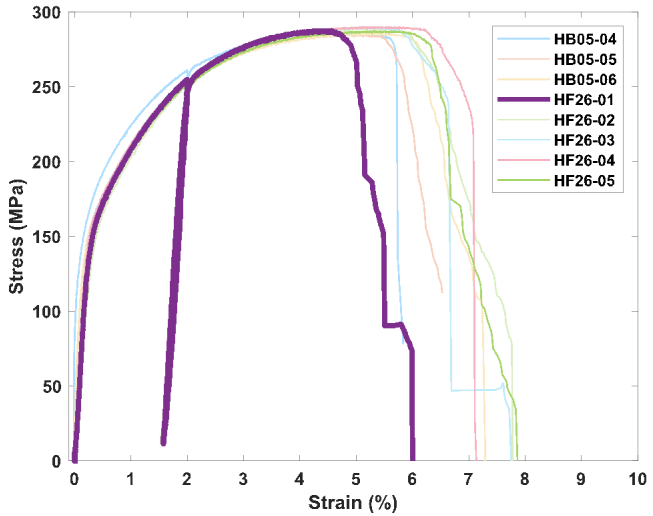


C.M. Laursen, P.J. Noell, J.D. Carroll, "Ex-situ Correlation of Fracture Location to Internal Defects in AM AlSi10Mg via micro Computed Tomography", *In Preparation*

Failure of specimen HF26-01 was largely determined by surface void depth.







Labeled Pores:17,503

HF26-05	Internal Pore Volume	Internal Pore Cross-Section	Surface Void Depth	Surface Void Depth-to-Height	Local Density
Rank	6	6	2	8	3
Pore Label	83322	83322	83964	7520	1297
Fracture Value	730,294 µm^3	10,522 µm^2	168.8 µm	9.49	99.727 %
Peak Value	2,045,810 µm^3	24,204 µm^2	197.1 µm	16.67	99.687 %

Acknowledgements

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Dale Cillessen, Jessica Buckner

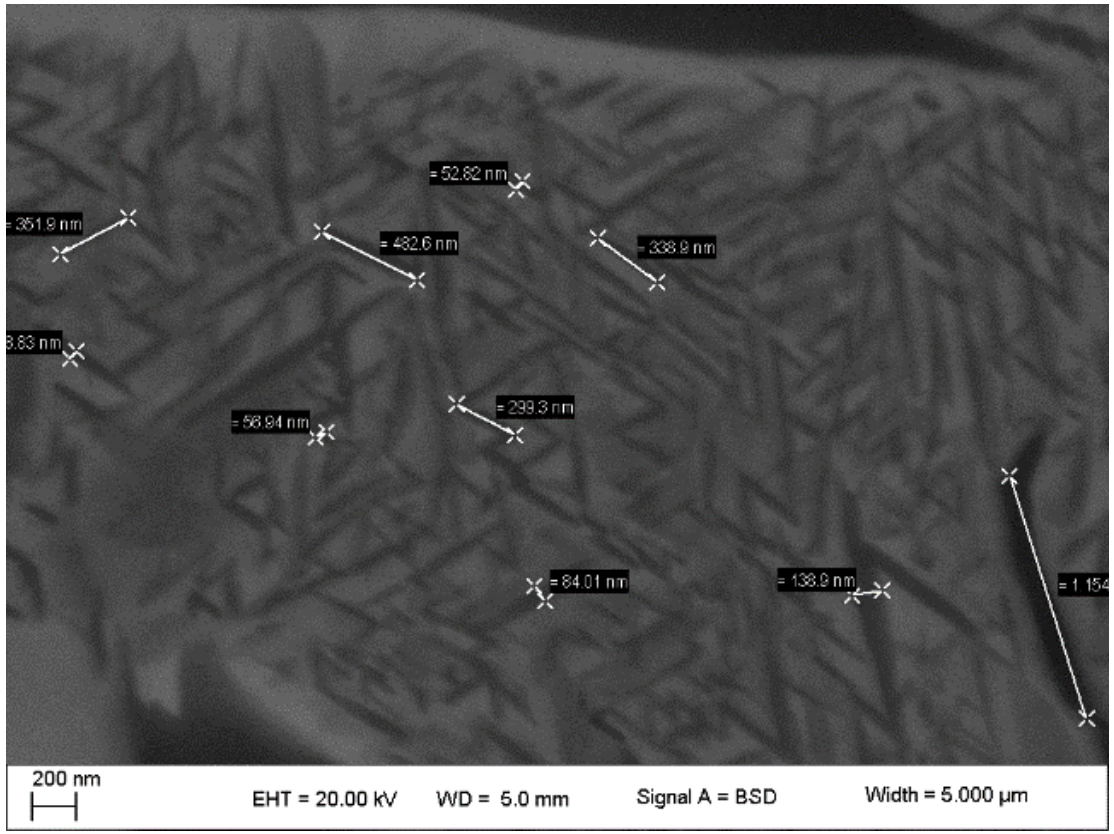
National Security Campus

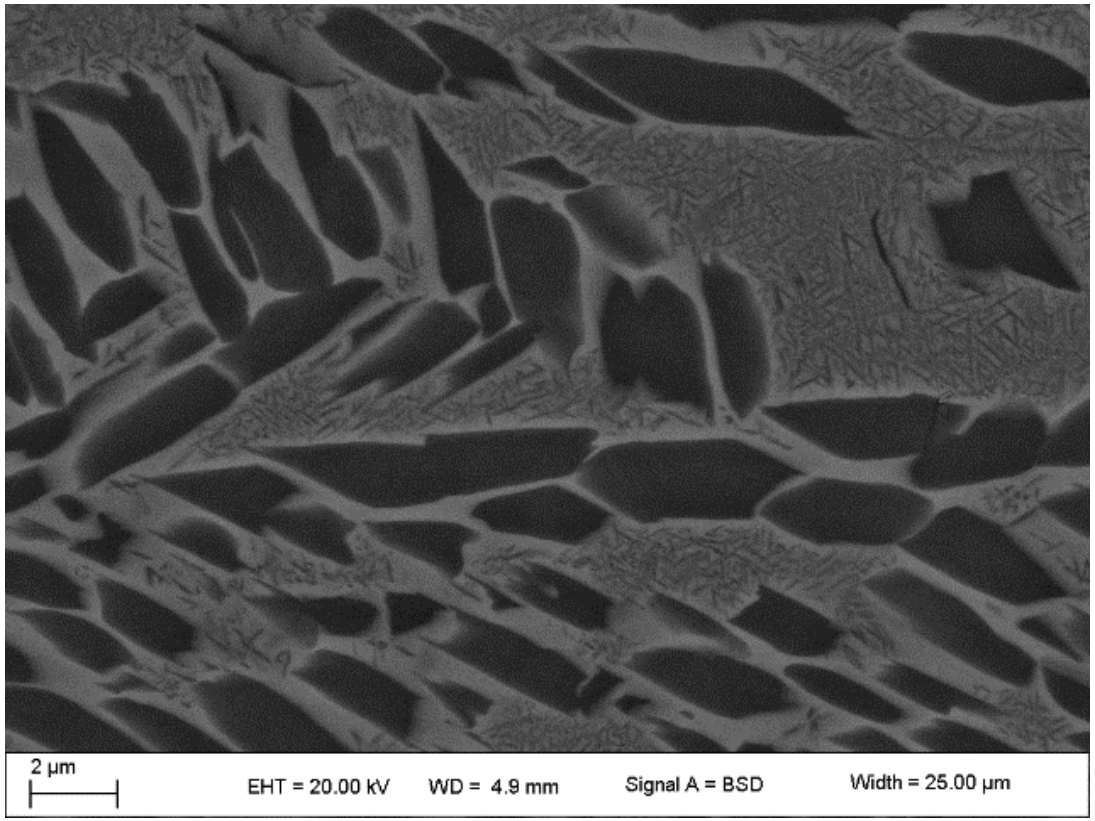
Ben Brown, Andy Deal

Authors: Jay D. Carroll, Zachary Casias, Christopher Laursen, Philip Noell, John Emery

Extra Slides

High resolution images of alpha laths in AM Ti-5553





CT relate voids to fracture?

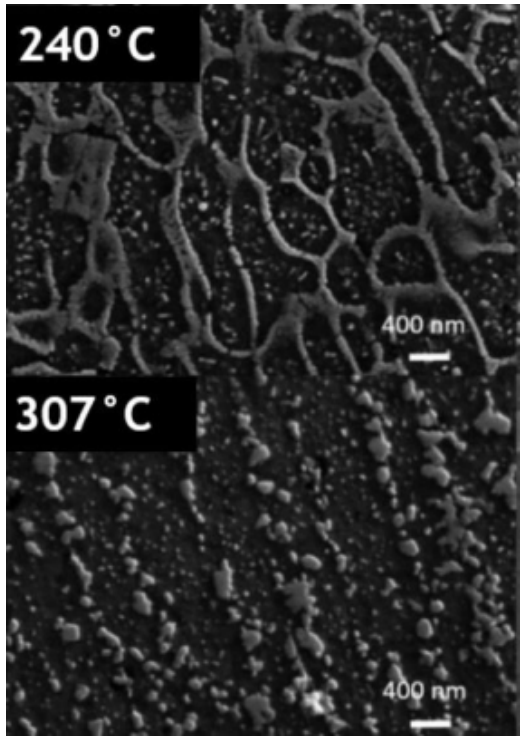
Heat treated AlSi10Mg, tension

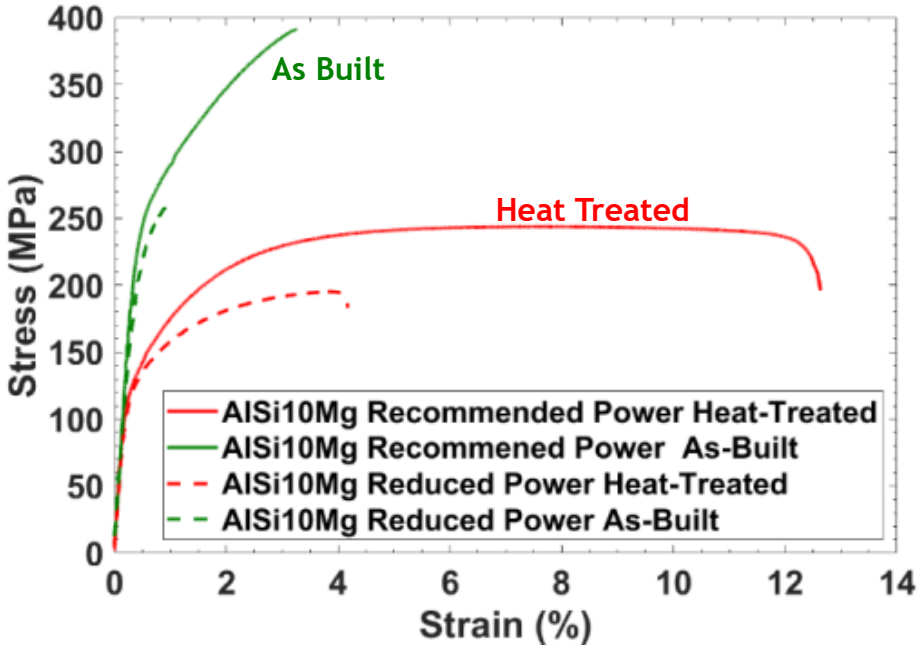
Research Questions:

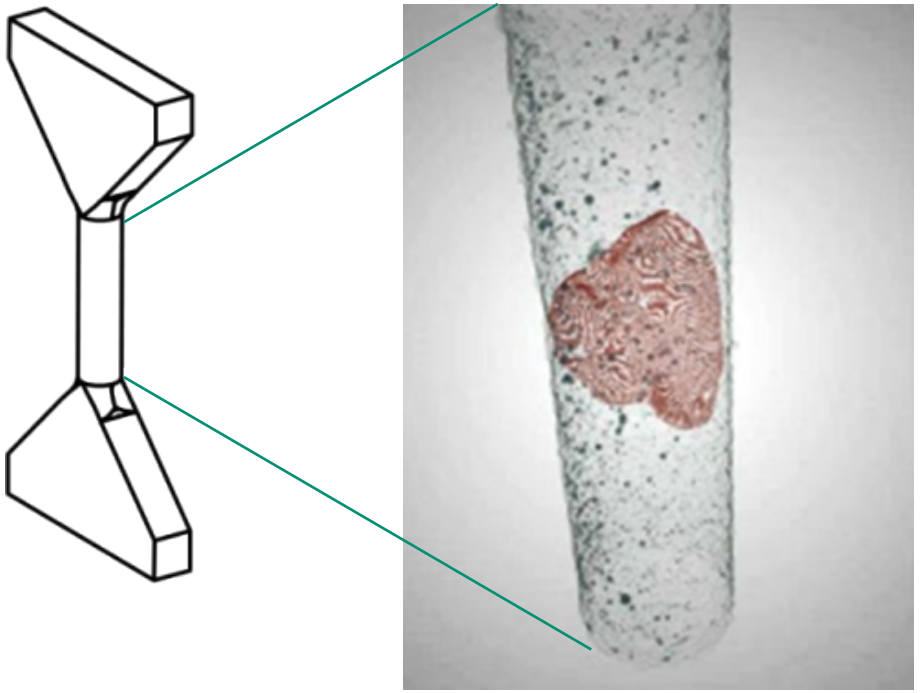
Sandia National Laboratories

AlSi10Mg

1. **What is the effect of heat treatment on mechanical properties?**
2. **What is the effect of porosity on mechanical properties?**
3. **Can we attribute failure location to specific defects?**

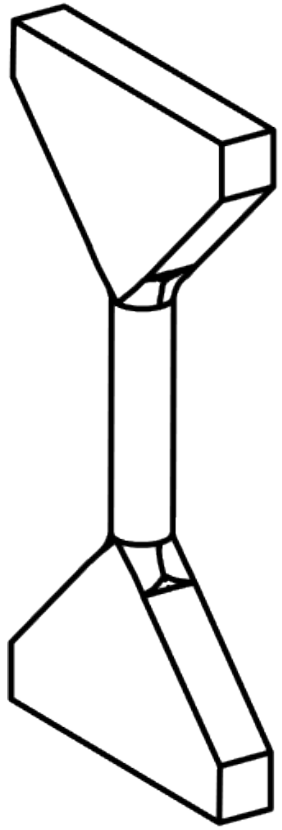


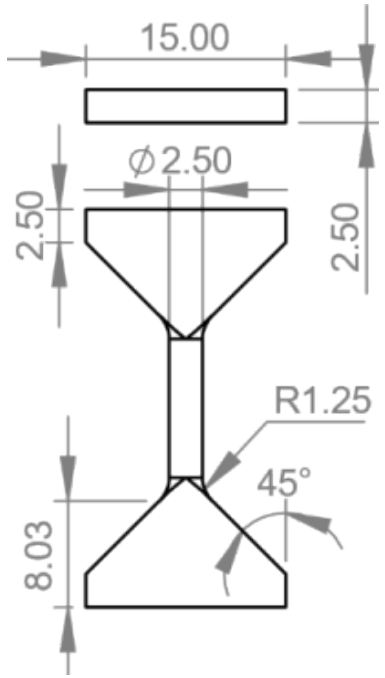




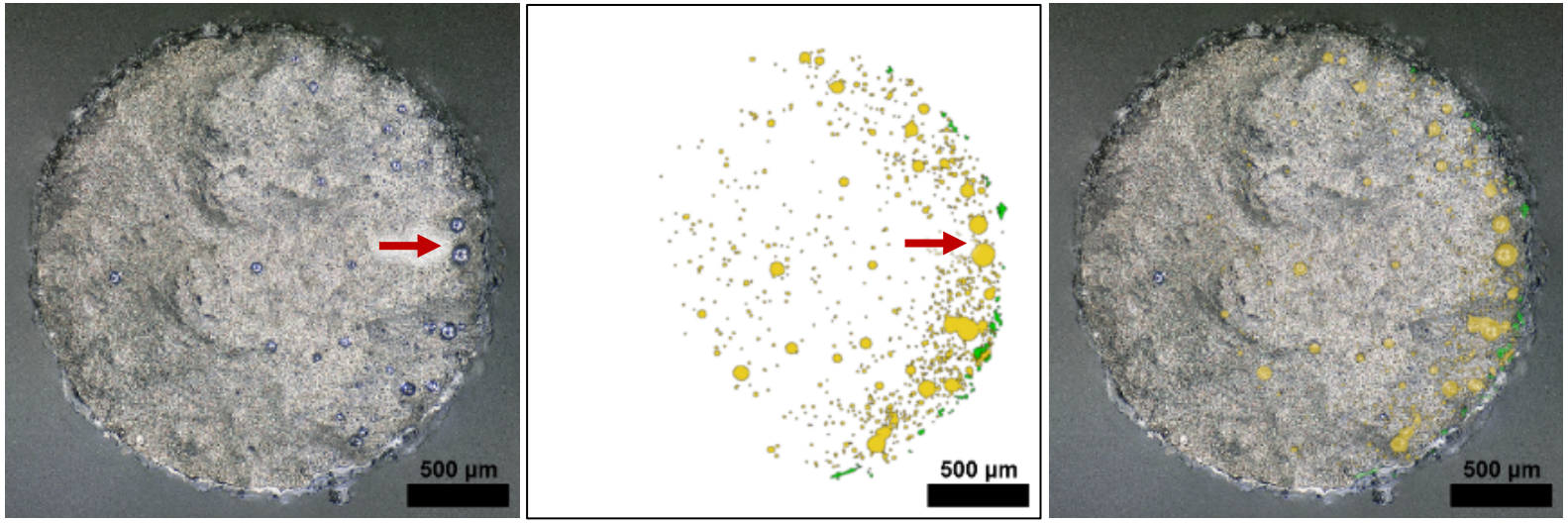
Verify pores mapped to fracture surface match fracture surface

- **Fracture surface is not planar.**
- **Pores are considered on the fracture surface if within ±50 µm.**
- **Visually verified alignment.**

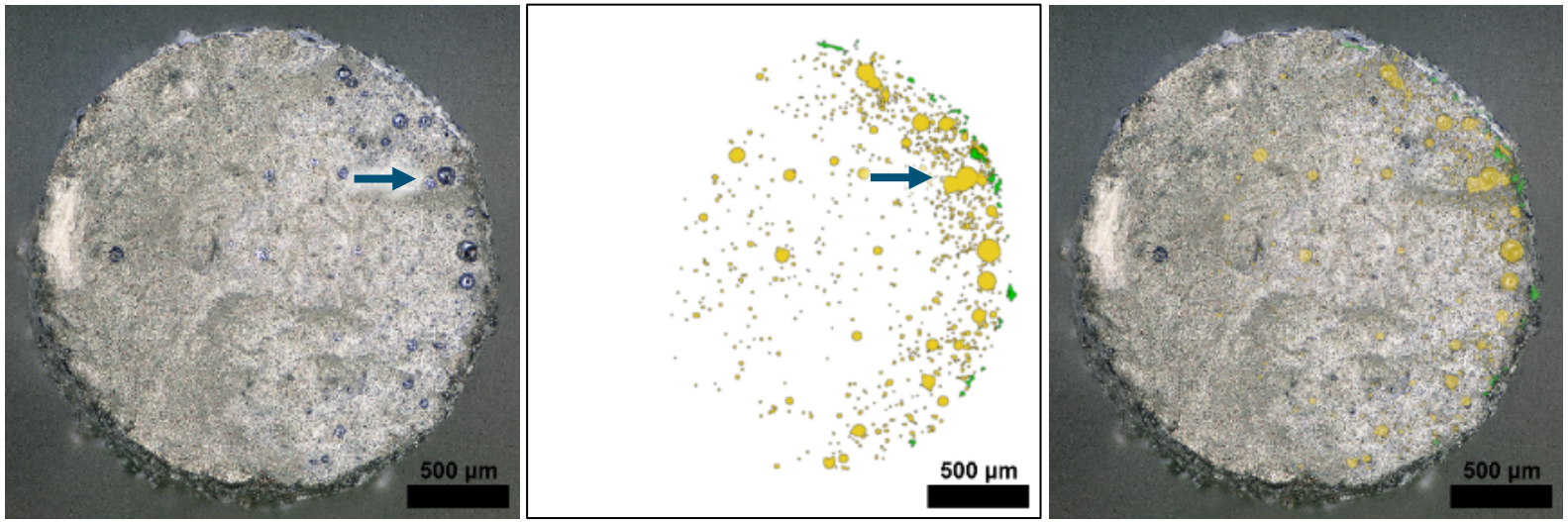




Top Fracture Surface

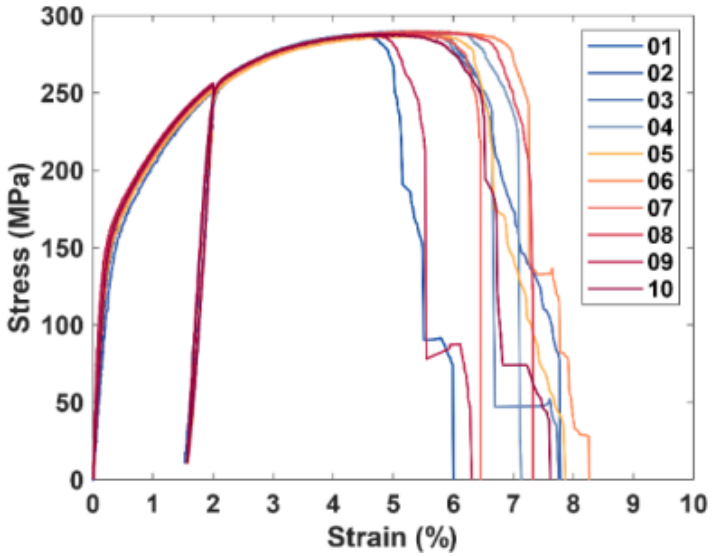


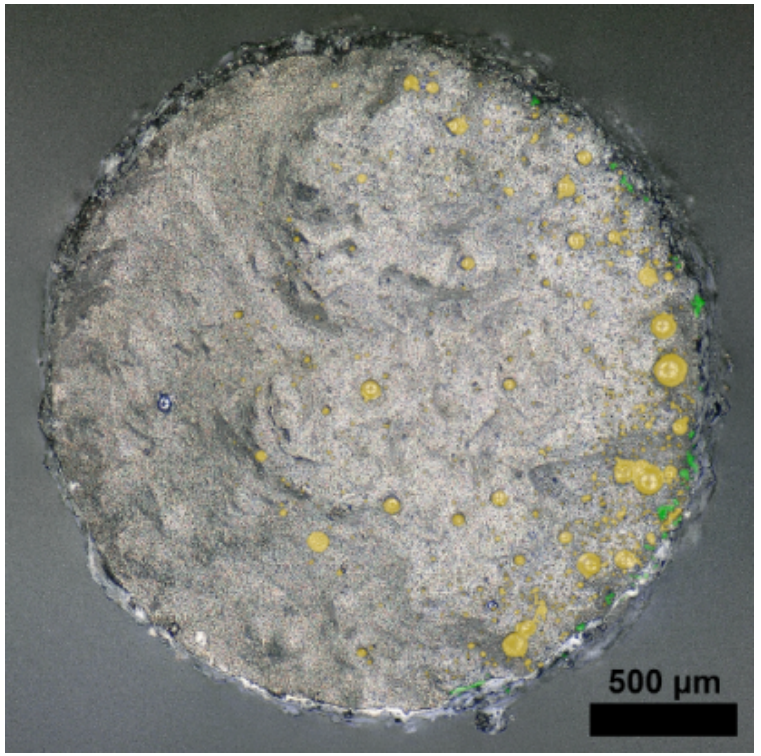
Bottom Fracture Surface

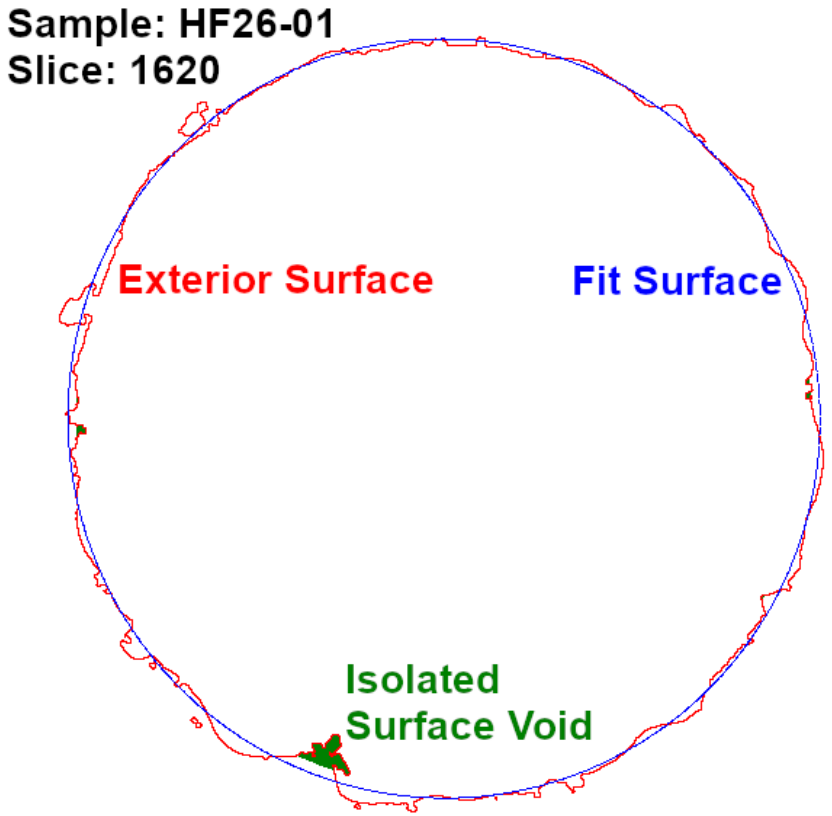


Surface flaws and internal pores are primary two features of interest.

- 10 tensile bars
- Internal pores
- Surface flaws





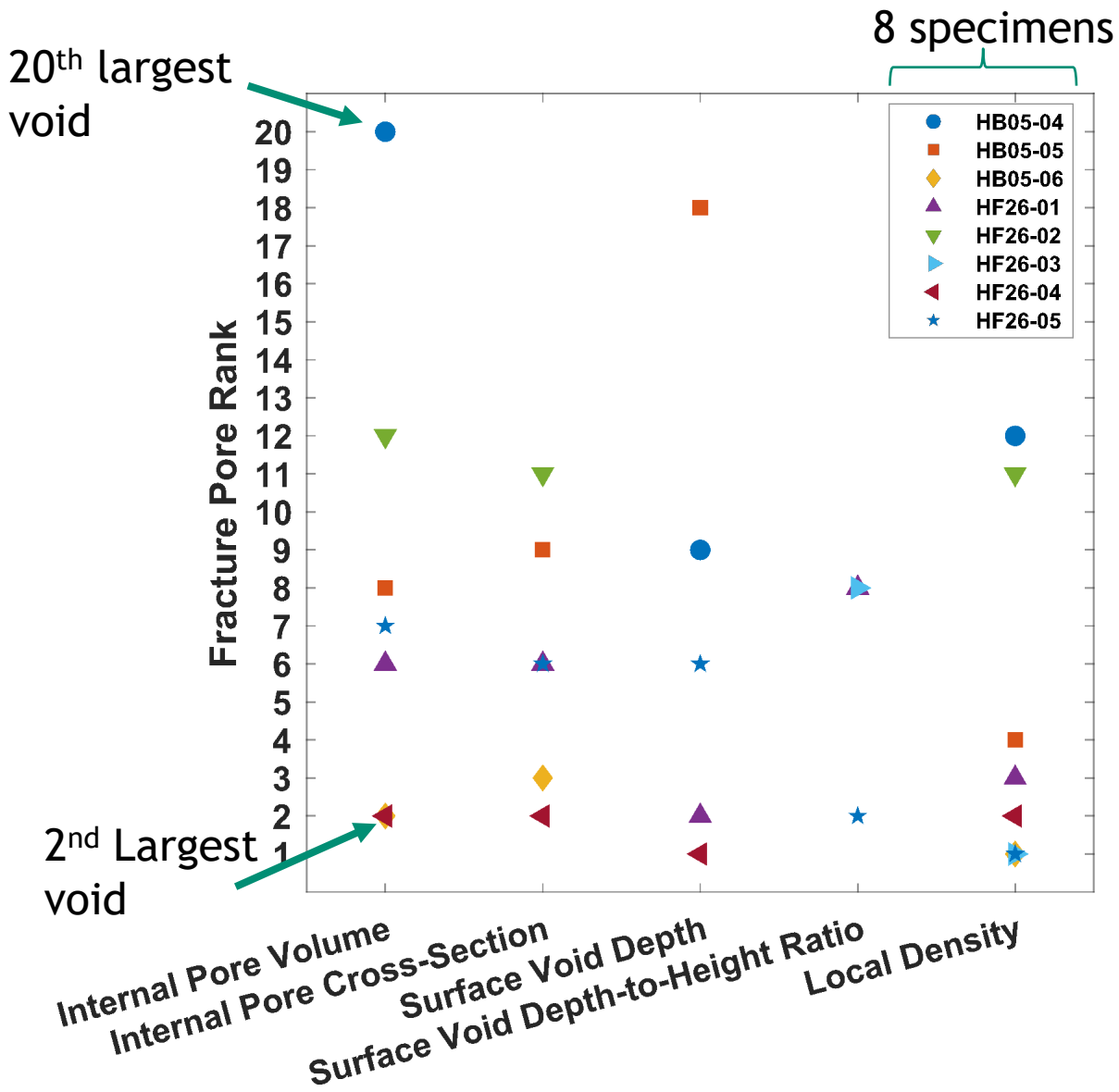


Identify dominant parameters leading to fracture by ranking.

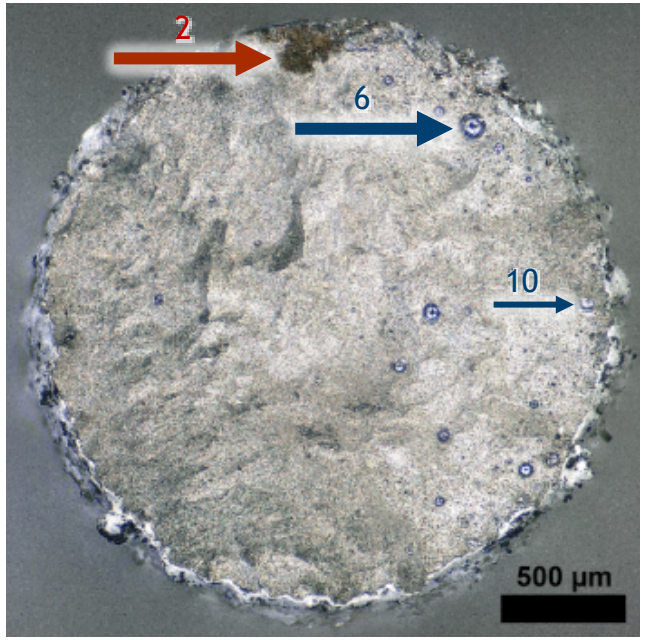
- **Rank flaws on several metrics.**
- **Dominant parameters will have many high-ranked features on the fracture surface.**

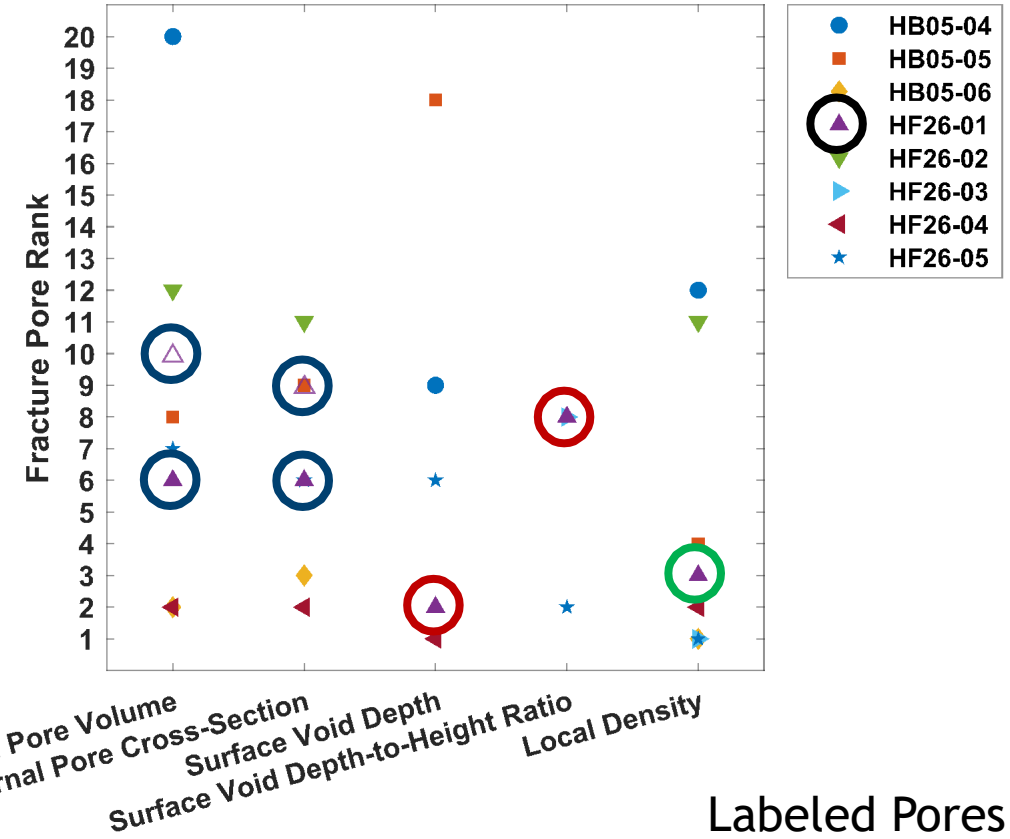
Parameters

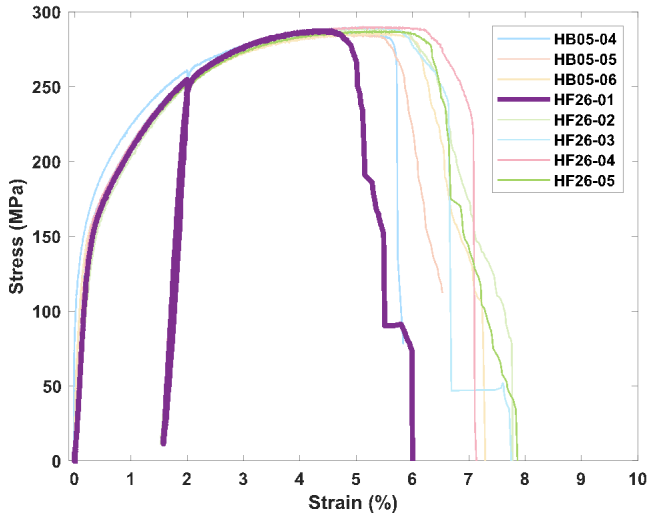
- **Largest pore volume on fracture surface**
- **Largest cross-sectional area of internal pores**
- **Deepest surface Void**
- **Sharpest surface void (height-to-depth ratio)**
- **Lowest regional density (200µm thick slices, ~100 per specimen)**



Failure of specimen HF26-01 was largely determined by surface void depth.



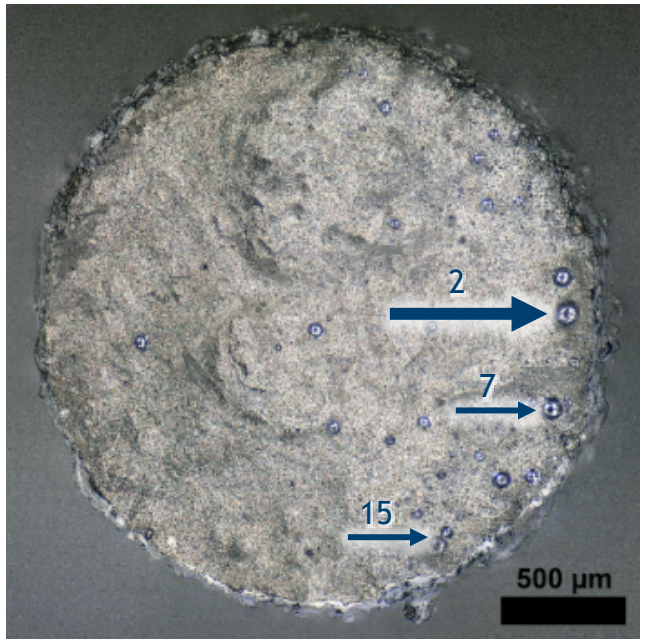


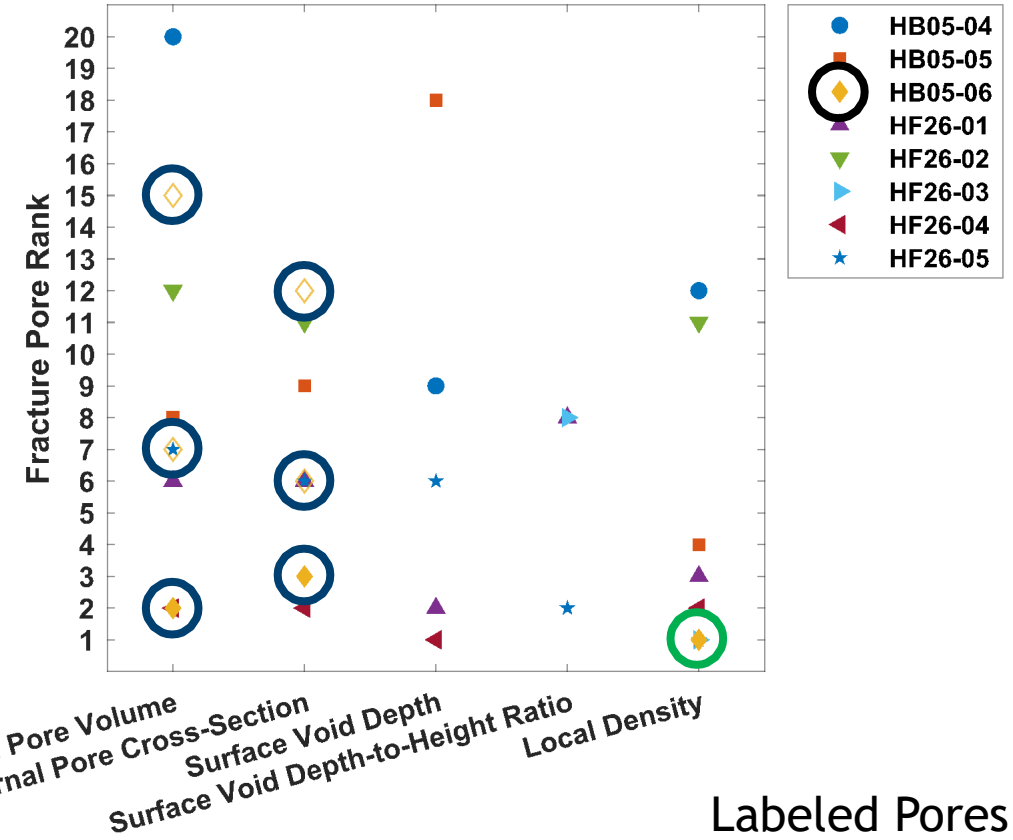


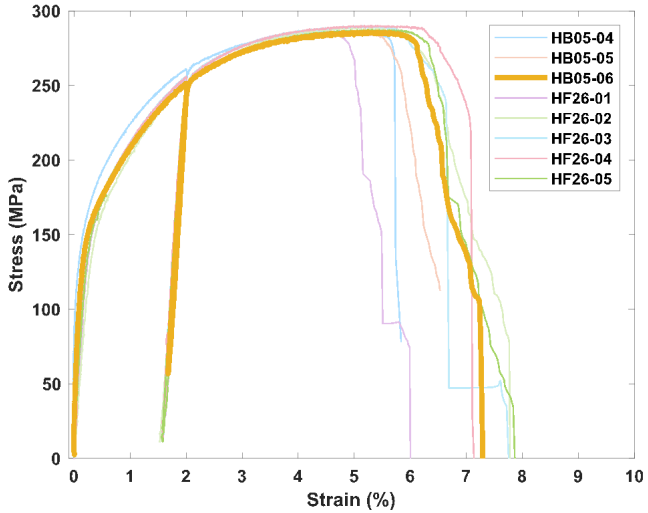
Labeled Pores:17,503

HF26-05	Internal Pore Volume	Internal Pore Cross-Section	Surface Void Depth	Surface Void Depth-to-Height	Local Density
Rank	6	6	2	8	3
Pore Label	83322	83322	83964	7520	1297
Fracture Value	730,294 µm^3	10,522 µm^2	168.8 µm	9.49	99.727 %
Peak Value	2,045,810 µm^3	24,204 µm^2	197.1 µm	16.67	99.687 %

Failure of specimen HB05-06 was largely determined by local density and several large pores.



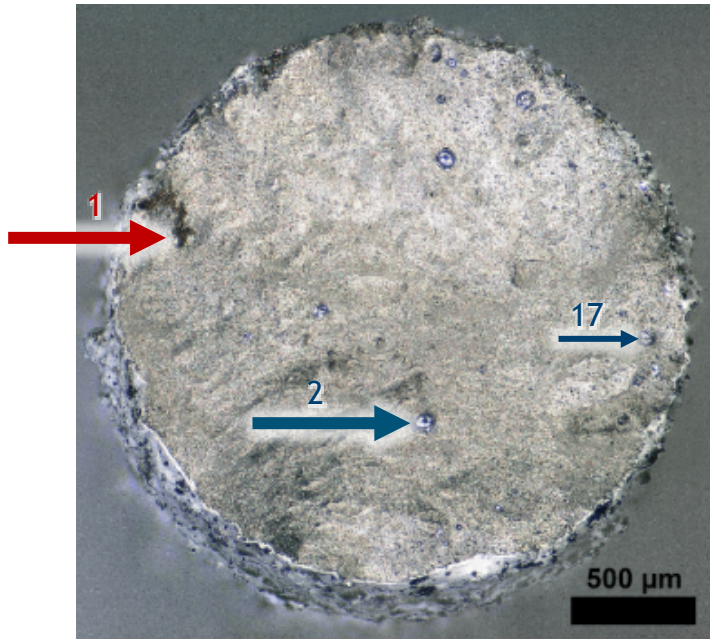


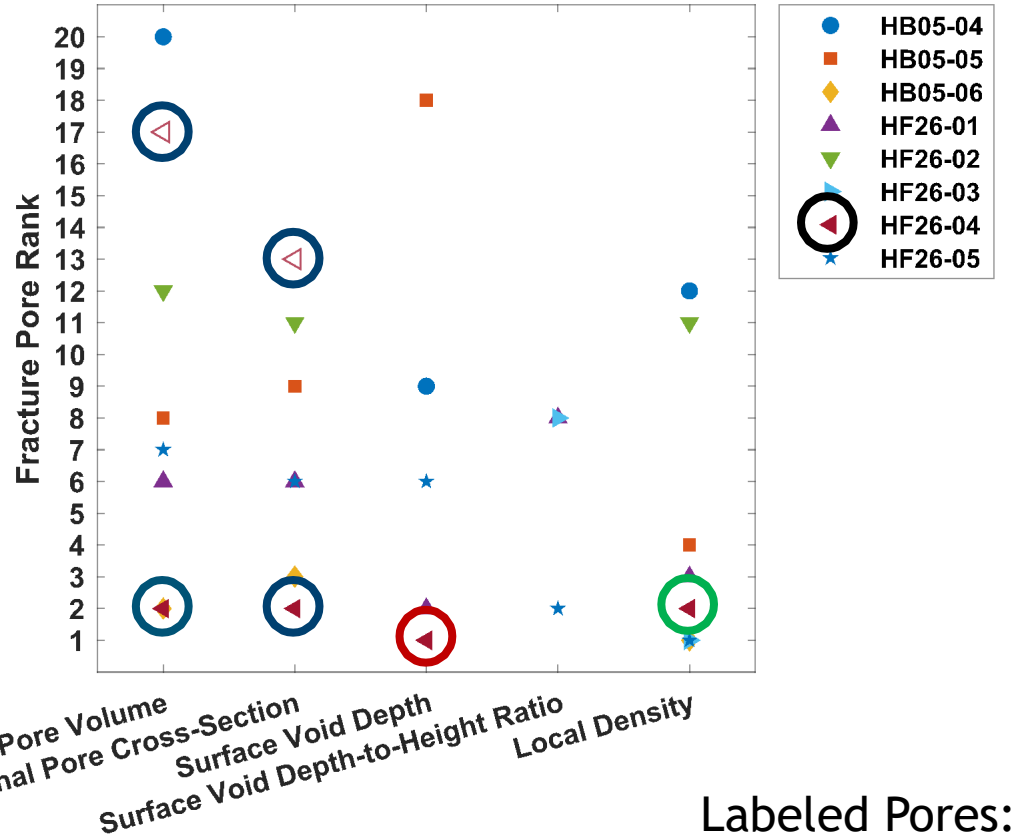


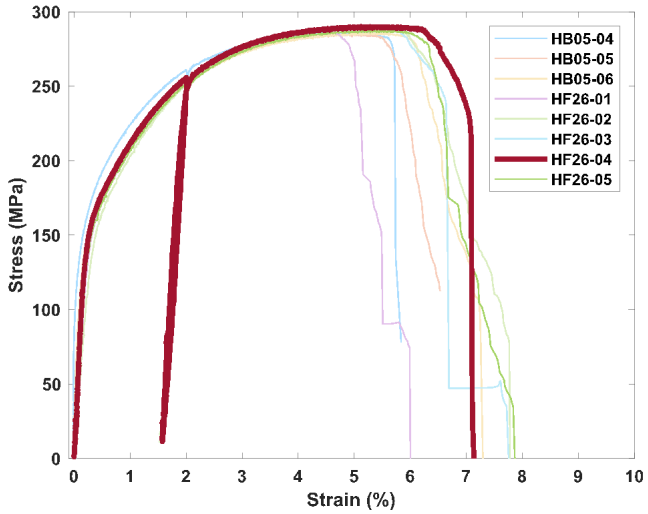
Labeled Pores:85,420

HF26-05	Internal Pore Volume	Internal Pore Cross-Section	Surface Void Depth	Surface Void Depth-to-Height	Local Density
Rank	2	3	77.5	47	1
Pore Label	41030	41030	43203	45059	1617
Fracture Value	1,113,681 µm³	12,081 µm²	72.2 µm	9.23	99.402 %
Peak Value	1,447,799 µm³	13,191 µm²	128.0 µm	20.25	99.402 %

Failure of specimen HF26-04 was caused by many factors: a large surface flaw, several large internal voids, and low local density.







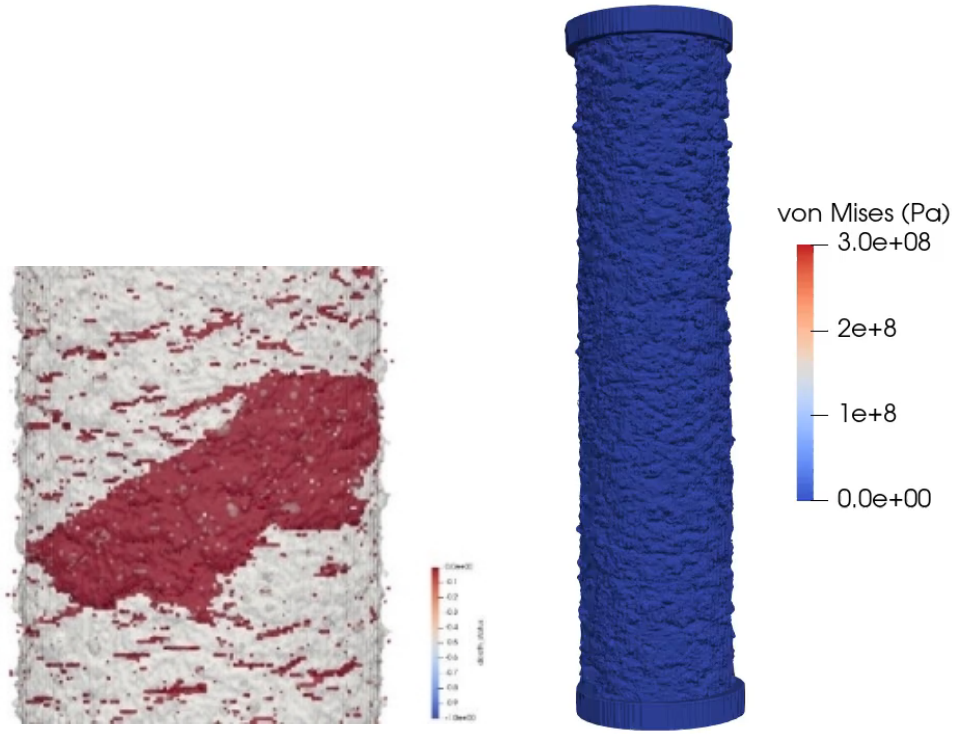
Labeled Pores:14,939

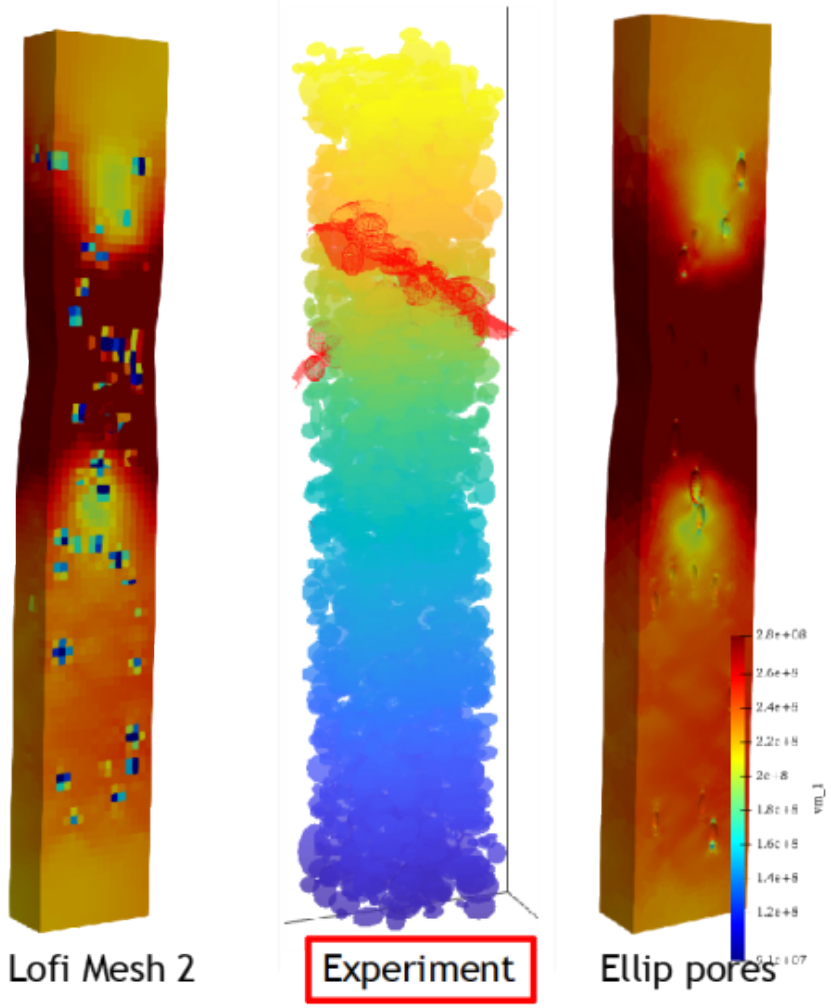
HF26-05	Internal Pore Volume	Internal Pore Cross-Section	Surface Void Depth	Surface Void Depth-to-Height	Local Density
Rank	2	2	1	43.5	3
Pore Label	7565	7565	9480	8040	1156
Fracture Value	580,576 µm^3	12,975 µm^2	264.4 µm	5.66	99.786 %
Peak Value	880,867 µm^3	14,514 µm^2	264.4 µm	15.68	99.783 %

C.M. Laursen, P.J. Noell, J.D. Carroll, "Ex-situ Correlation of Fracture Location to Internal Defects in AM AlSi10Mg via micro Computed Tomography", *In Preparation*

Future and ongoing work

1. **Hierarchical finite element model to better understand interactions between pores.**
2. **Machine learning on large, rich datasets to gain predictive capabilities. (See Kyle Johnson, 3:45 Session VIII, 207A).**
3. **Apply lessons learned to component qualification.**





Courtesy of John Emery