AUBURN UNIVERSITY

SAMUEL GINN
COLLEGE OF ENGINEERING

Additive Manufacturing of Fatigue Resistant Materials by Establishing Structure-Property Relationships

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SAE Fatigue Design & Evaluation Committee
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Additive Manufacturing

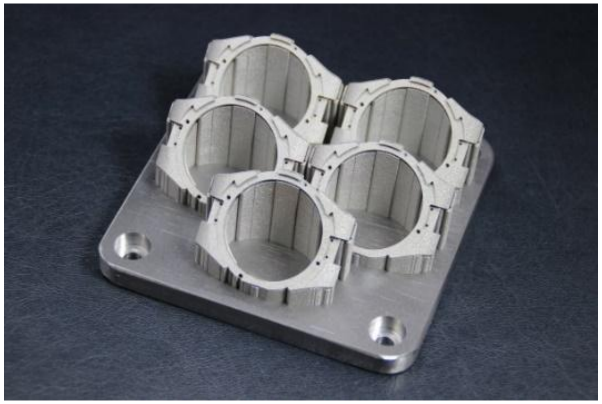
"A process of joining materials to make objects from 3D model data, usually layer upon layer…"
- ASTM Standard F2792-12a

- Directed energy deposition
- Powder bed fusion

dupress.com/articles/additive-manufacturing-3d-opportunity-in-aerospace/

Metals additive manufacturing

- Powder or wire feedstock
- Laser beam or electron beam energy source

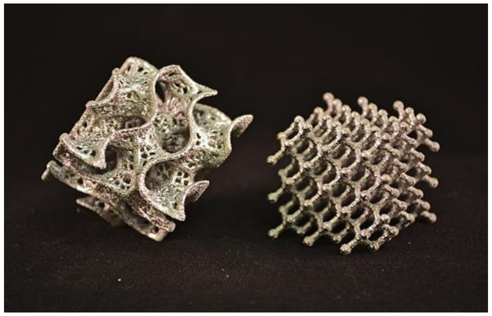


www.mtialbany.com/industries/additive-manufacturing/

www.bastech.com/2014/02/11/direct-metal-3d-printing-benefits-dental-lab/

Additive Manufacturing Benefits

additivemanufacturing.com/2015/09/22/eos-alphaform-produces-hip-implant-by-using-additive-manufacturing/



Metal 3D printed lattice structures made at CMU

https://en.wikipedia.org/wiki/USS_John_C._Stennis

Wider design space

Creating “tailored” properties

Customized parts (Per patient/per injury implants)

Light-weighting (lattice structures)

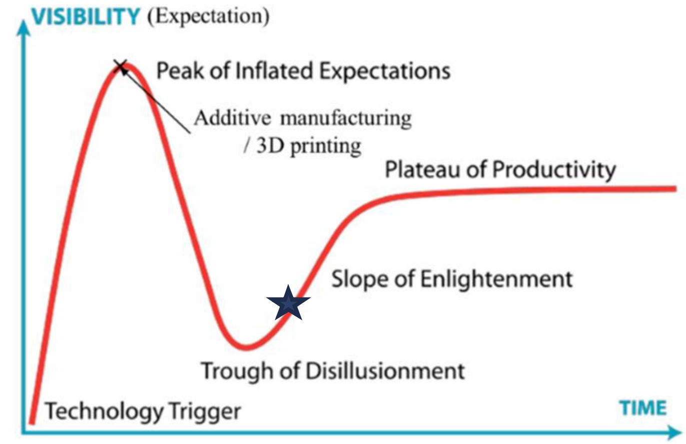
On demand fabrication (lower lead times)

Remote locations (Strategic supply lines, space exploration)

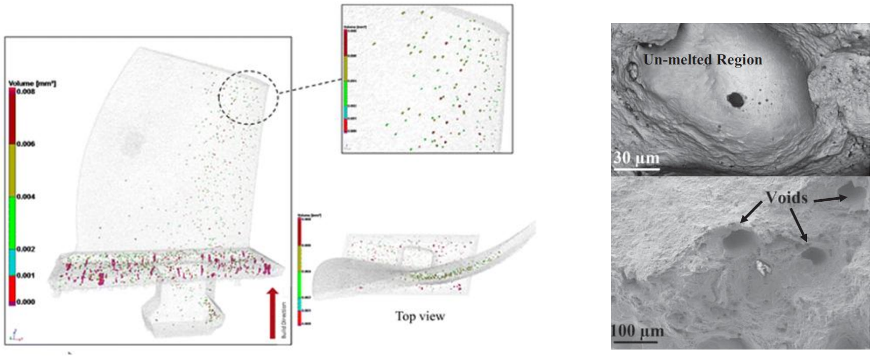
Repairing expensive parts

Additive Manufacturing Challenges

- AM parts are prone to having porosity and imperfections
- Structural integrity of AM parts is unknown
- Minimal standards and regulation for production and end-parts
- Certification needed
- Demand for an AM-trained workforce
- Industry-wide hesitation



Y. Huang, M.C. Leu, J. Mazumder, A. Donmez, "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations," ASME. *J. Manuf. Sci. Eng.* 137(1): 014001-014001-10, 2015.



M. Seifi, M. Gorelik, J. Waller, N. Shamsaei, et al. JOM (2017) 69: 439. doi:10.1007/s11837-017-2265-2

NCAME History

The National Center of Additive Manufacturing Excellence (NCAME) was established in 2017

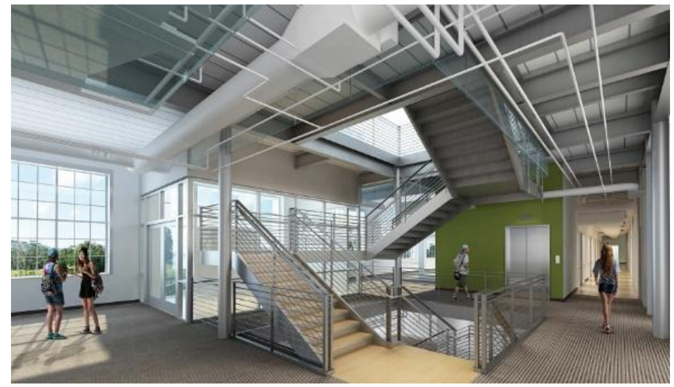
NASA recognized Auburn as its Strategic Academic Partner for Additive Manufacturing

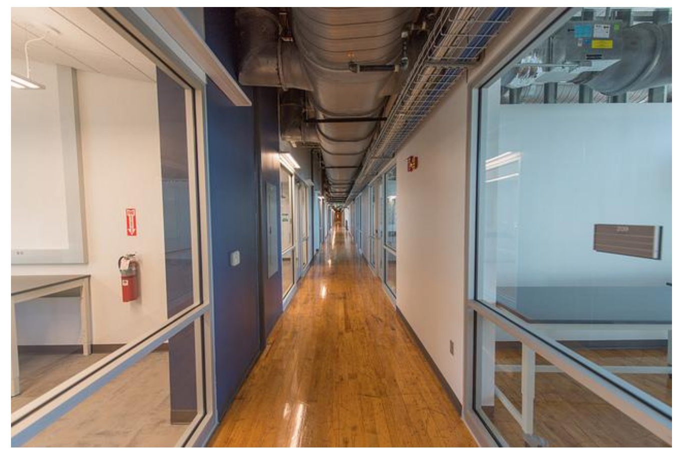
In 2018, through an international competitive search, Auburn was selected as one of the founding partners of ASTM Additive Manufacturing Center of Excellence (AM CoE)

NCAME Goals

- Conduct *fundamental* as well as *industry-relevant AM research* to support technology advancement.
- Perform *high-impact AM standards development* and the certification/qualification of AM products through collaboration with ASTM committees.
- Facilitate the exchange of ideas and information through *structured public/private partnerships* and by interacting with experts on a global scale.
- Innovate, promote and lead activities supportive of *workforce development.*

New Location



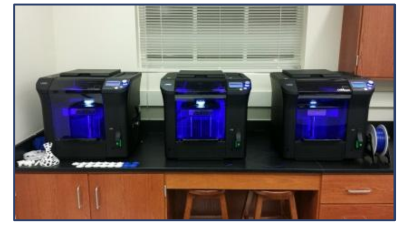


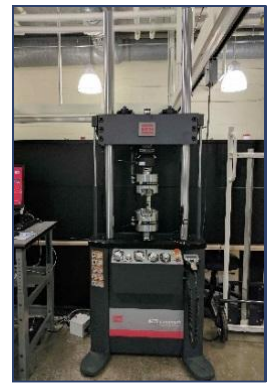
Gavin Engineering Research Laboratory

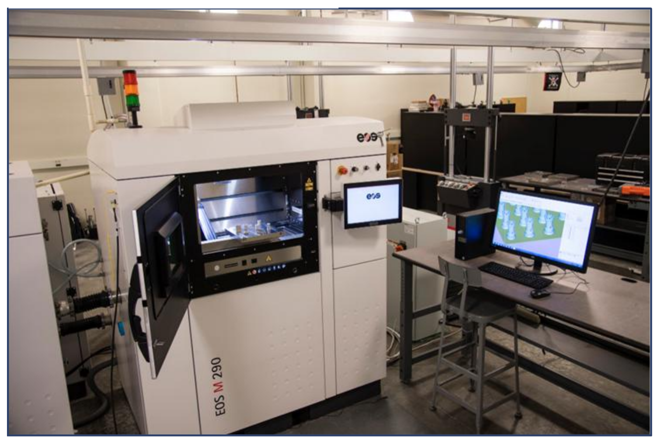
- 60,000 ft^2 laboratories & office spaces for additive manufacturing, polymers and composites – almost 1/3 of it belongs to NCAME

Auburn AM Experimental Setup

- Teaching equipment:
  - Multiple polymer-based 3D printers
- Research equipment:
  - EOS M290 X 3
  - Renishaw AM 250
  - Concept Laser MLAB 100R
  - Optomec LENS 750
  - Trumpf TruPrint 3000
  - Powder characterization
  - Microscopy center
  - Fatigue testing laboratory

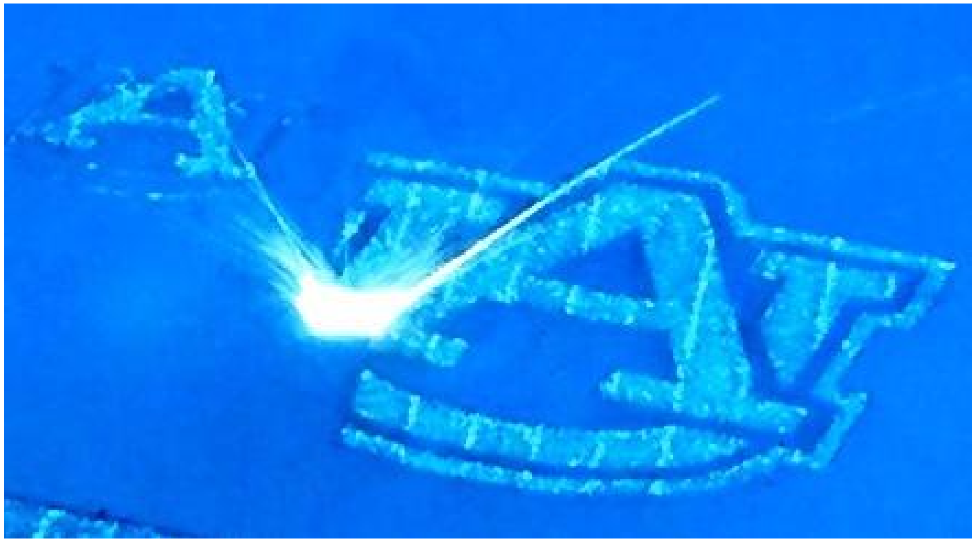




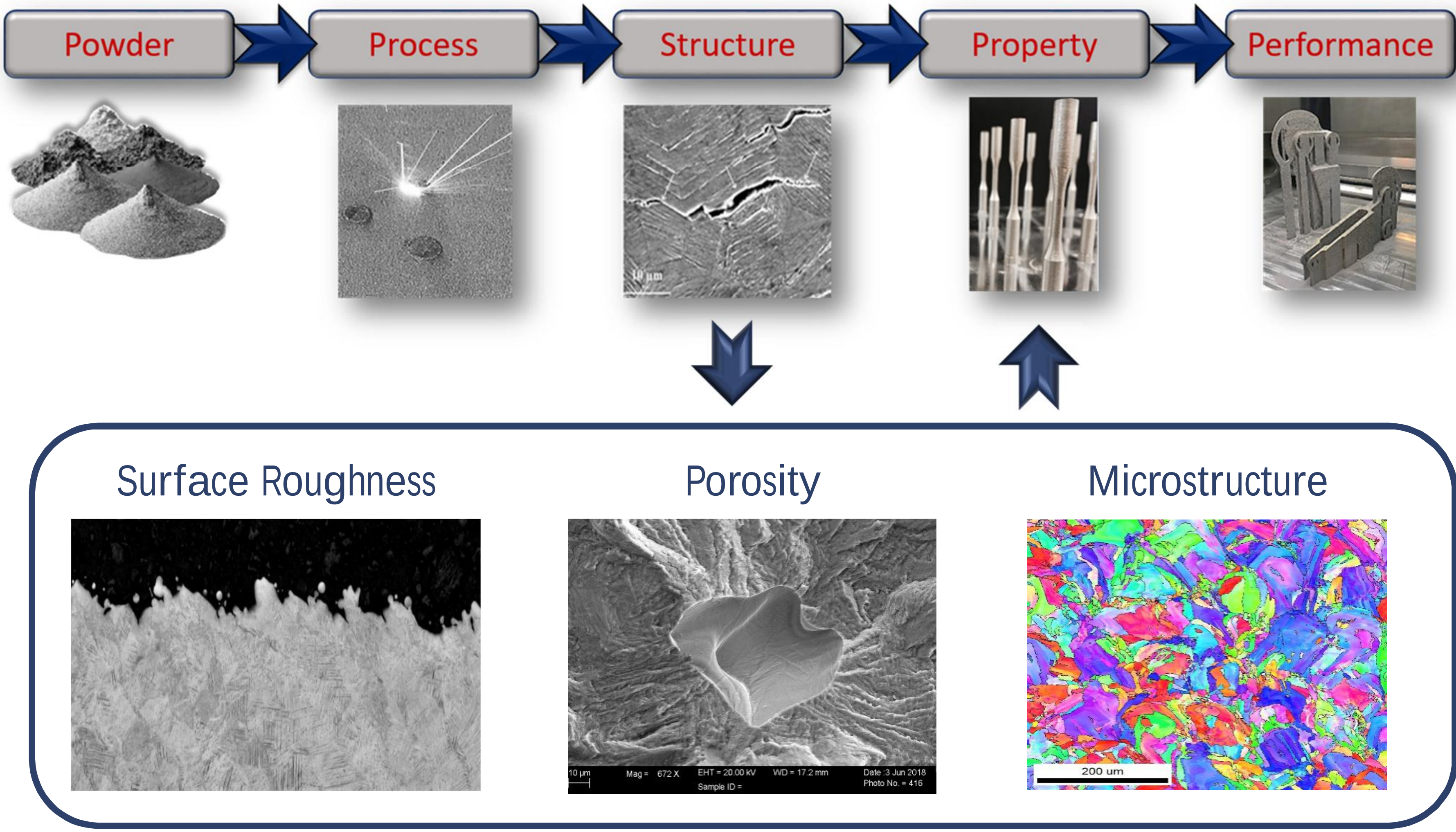


Outline

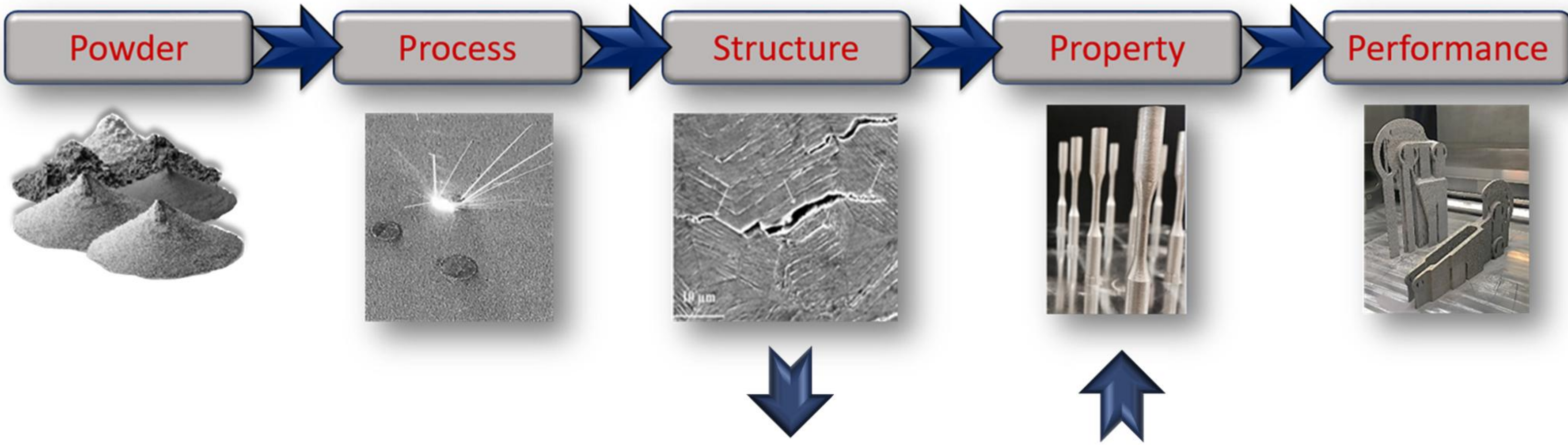
- Structure-Property Relationships
- Challenges
  - Surface Roughness
  - Internal Defects
  - Microstructure



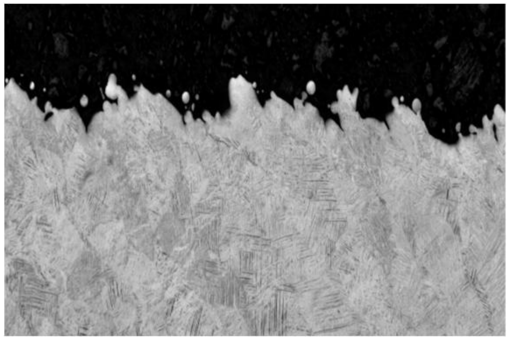
Research Focus



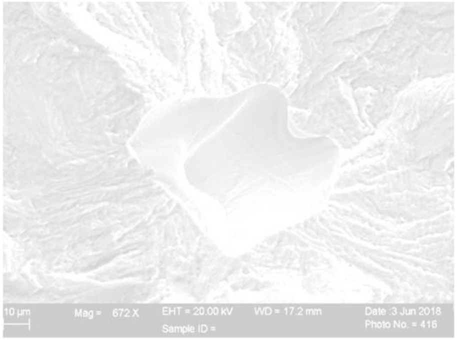
Surface Roughness



Surface Roughness



Porosity



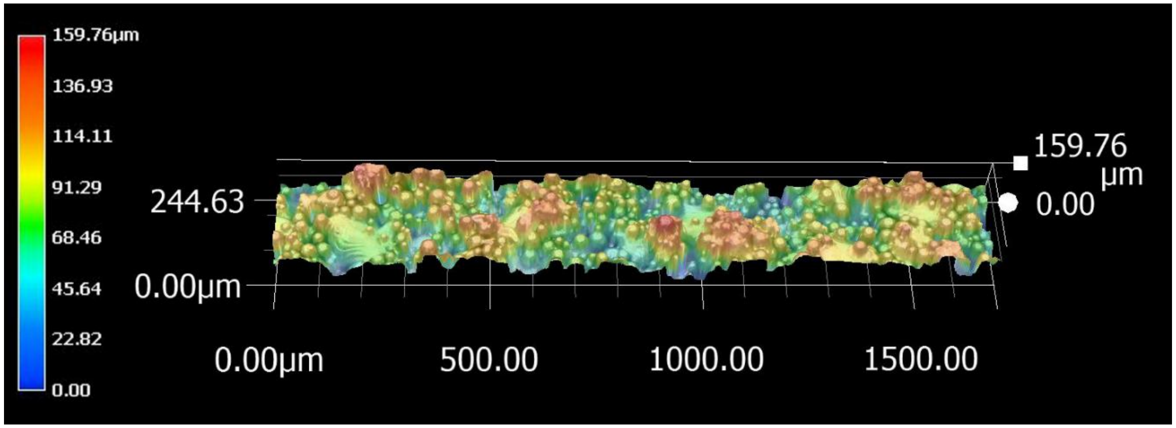
Microstructure

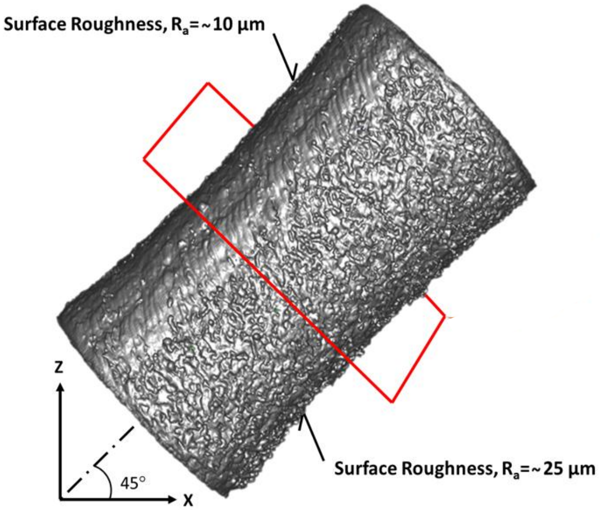
Challenge: Surface Roughness

Particles along the edge partially melt and fuse to the solid surface

For parts with overhangs and downward facing surfaces the effect of surface roughness is generally higher

LB-PBF Ti-6AL-4V





The arithmetic mean

$$R_a = \frac{1}{l_m}\int_0^{lm} |y|dx$$

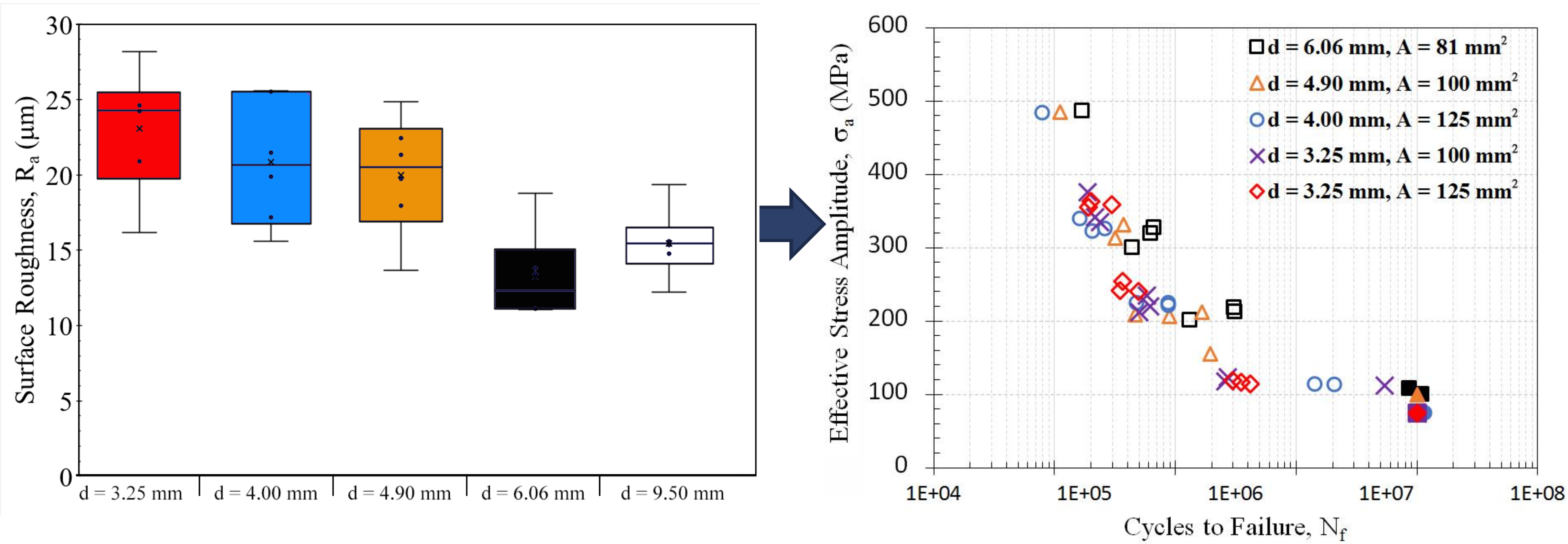
The max peak-to-valley

$$R_t = y_{max} - y_{min}$$

R_{zISO} – The 10-point height

$$R_{zISO} = \frac{1}{5}\left(\sum_{i=1}^{5}|y_{pi}| + \sum_{j=1}^{5}|y_{vj}|\right)$$

Challenge: Surface Roughness



Small diameters (d £ 4.90 mm) showed similar surface roughness

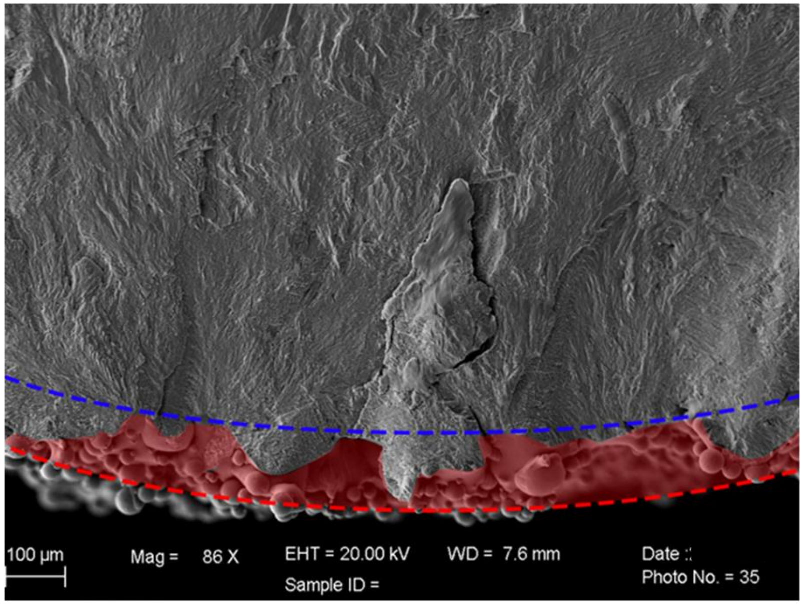
Larger diameters (d > 4.90 mm) showed lower surface roughness

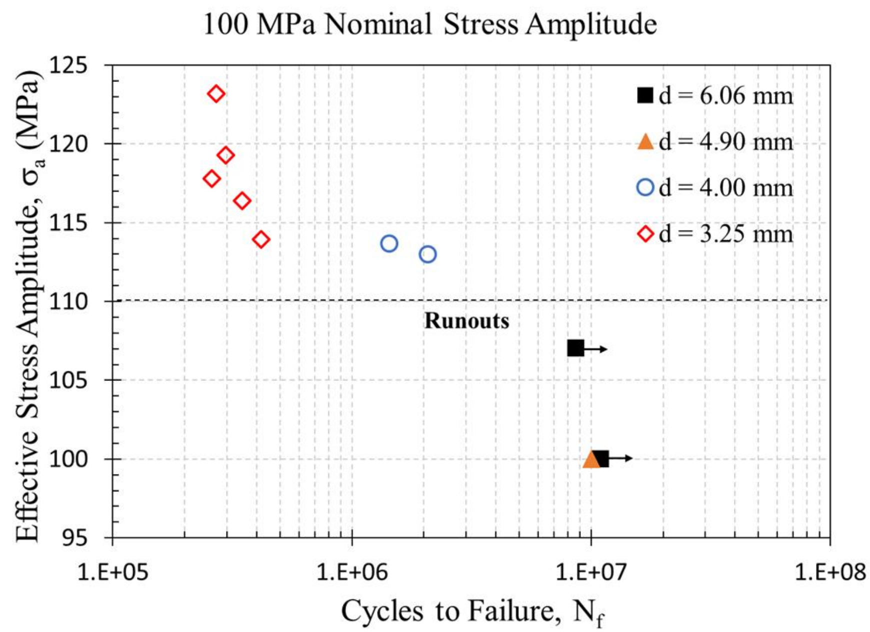
The lower mean roughness for the largest diameter resulted in improved fatigue resistance for all stress levels

J Pegues, M Roach, R S Williamson, & N Shamsaei, “Surface Roughness Effects on the Fatigue Strength of Additively Manufactured Ti-6Al-4V,” International Journal of Fatigue, International Journal of Fatigue, 116, 543-552, 2018.

Challenge: Surface Roughness

Diagonal As-Built LB-PBF Ti-6AL-4V





As gage diameter decreases the differences in nominal gage diameter & effective diameter increases

Applied stress amplitudes were greater for smaller diameter specimens resulting in the large scatter observed for high cycle fatigue data

J Pegues, M Roach, R S Williamson, & N Shamsaei, "Surface Roughness Effects on the Fatigue Strength of Additively Manufactured Ti-6Al-4V," International Journal of Fatigue, International Journal of Fatigue, 116, 543-552, 2018.

Defect Sensitive Modeling

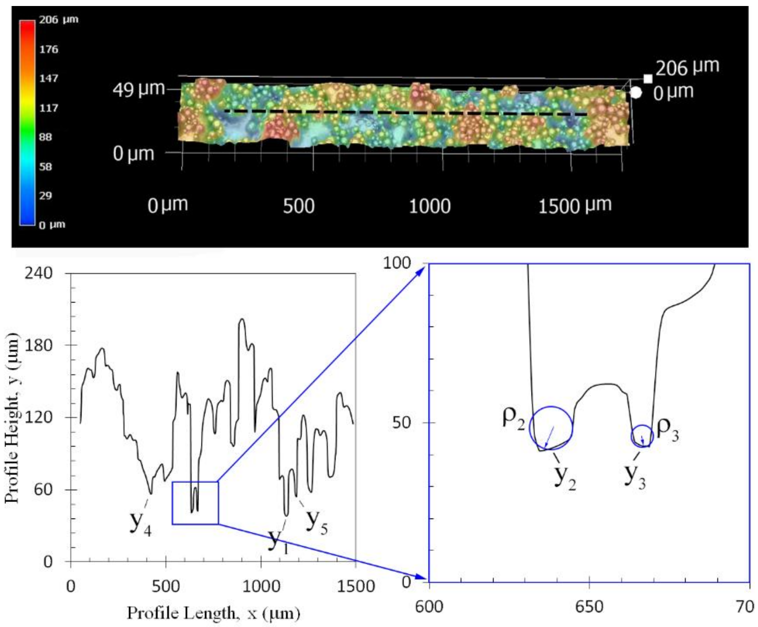
Reasonable stress-life predictions can be made for as-built surface conditions

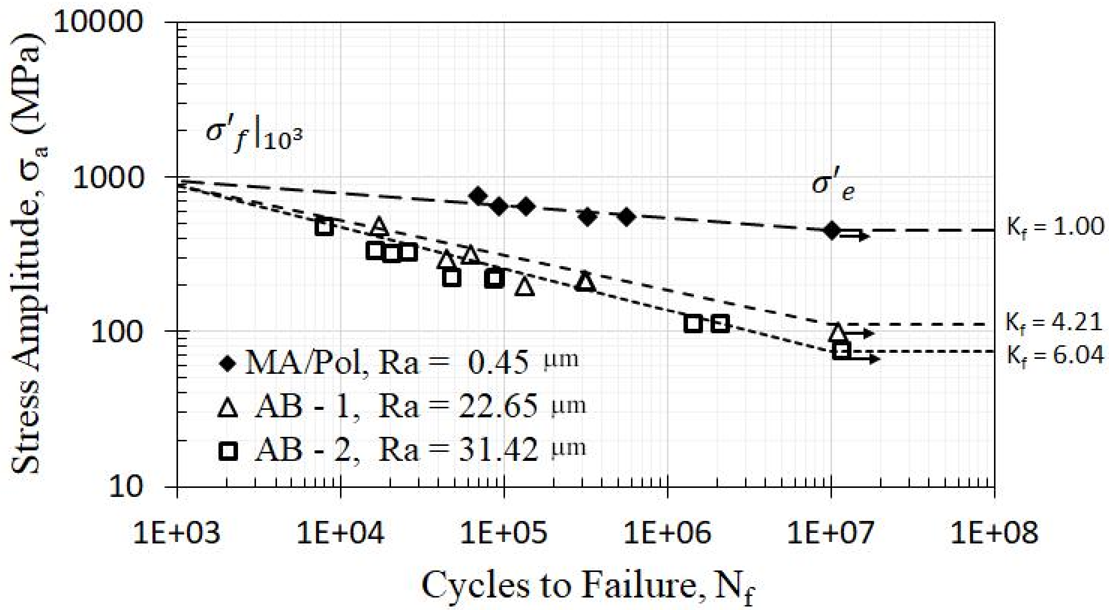
Predictions are non-conservative

$$\bar{K}_t = 1 + n\left(\frac{R_a}{\bar{\rho}_{10}}\right)\left(\frac{R_t}{R_{zISO}}\right)$$

$$q = 1/(1 + \gamma/\bar{\rho}_{10})$$

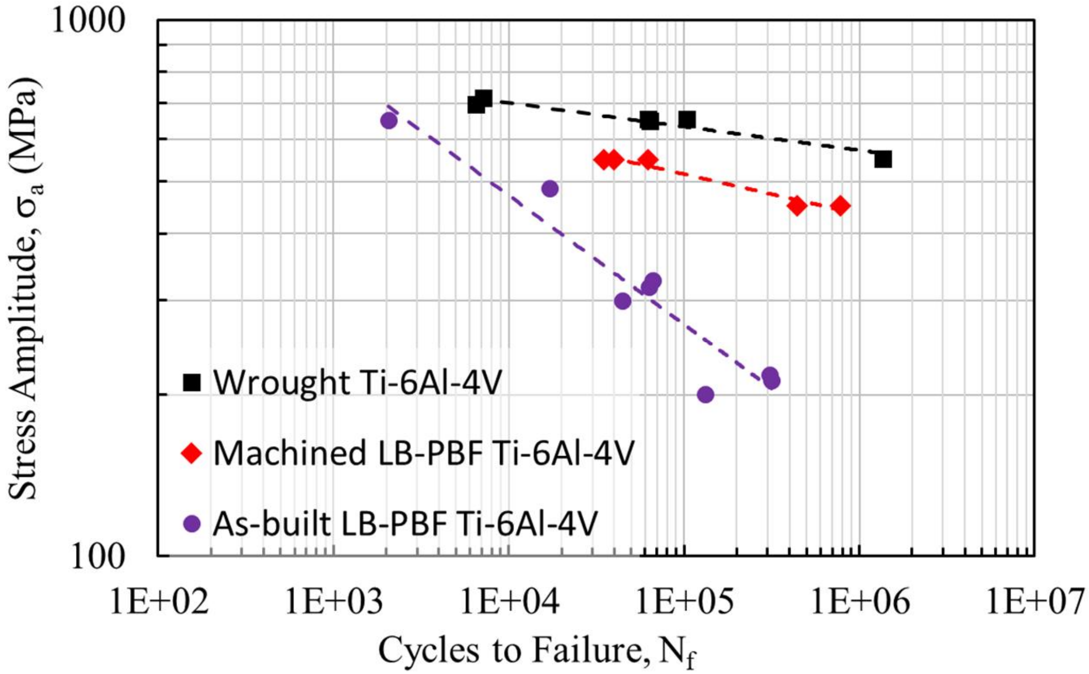
$$\bar{K}_f = 1 + q(K_t - 1)$$





J Pegues, N Shamsaei, M Roach, & R S Williamson, "Prediction of the Fatigue Stress Concentration Factors for As-built Ti-6Al-4V Surfaces" Materials Design & Processing Communications, Material Design & Processing Communications, e36, 2019.

Improving Surface Finish

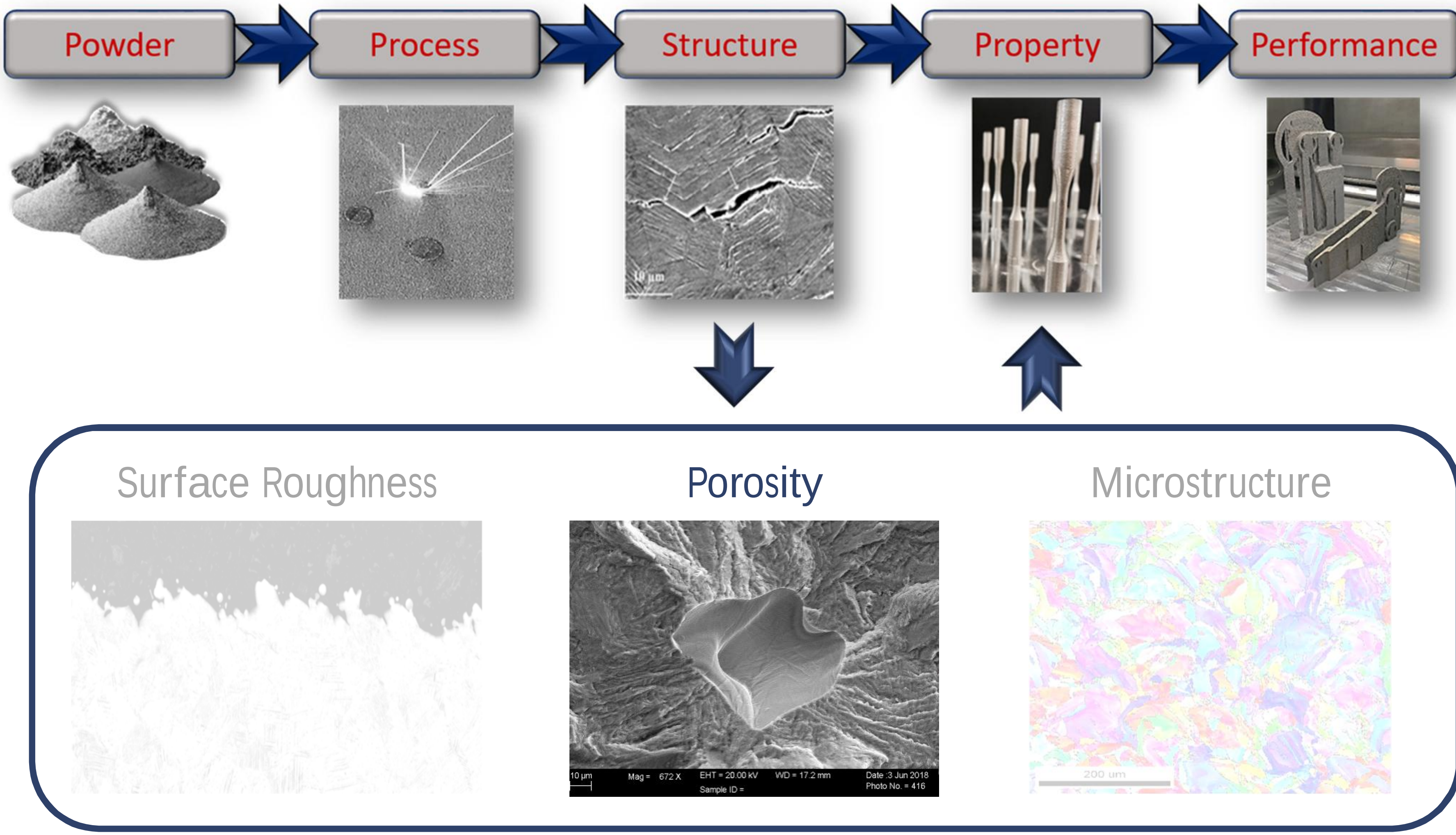


Machining the as-built surface can improve the fatigue resistance of AM materials

The high cycle fatigue performance is typically still lower than its wrought counterpart

- J Pegues, M Roach, R S Williamson, & N Shamsaei, "Surface Roughness Effects on the Fatigue Strength of Additively Manufactured Ti-6Al-4V," International Journal of Fatigue, International Journal of Fatigue, 116, 543-552, 2018.
- J Pegues, M Roach, R Williamson, N Shamsaei, "Volume Effects on the Fatigue Behavior of Additively Manufactured Ti-6Al 4V Parts," Solid Freeform Fabrication, 2018

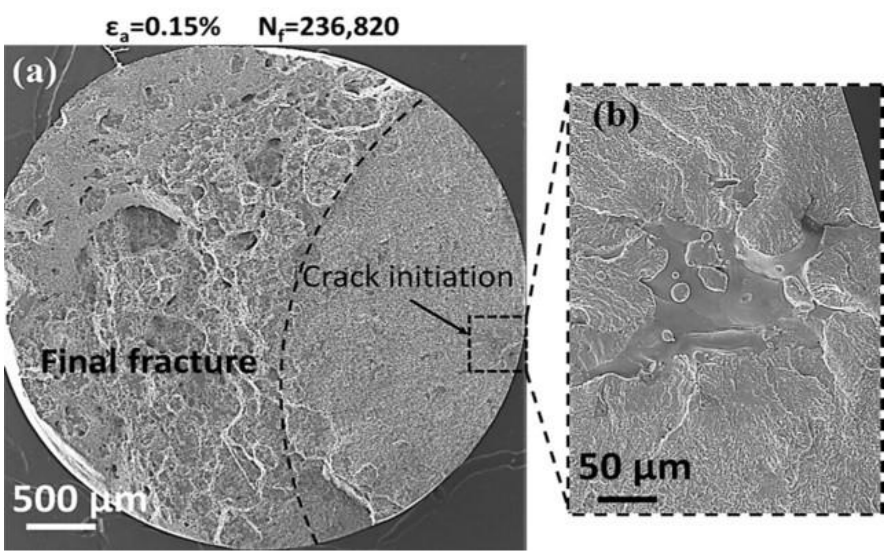
Porosity


Powder
Process
Structure
Property
Performance
Surface Roughness
Porosity
Microstructure

Porosity Sources and Types

Lack of fusion:

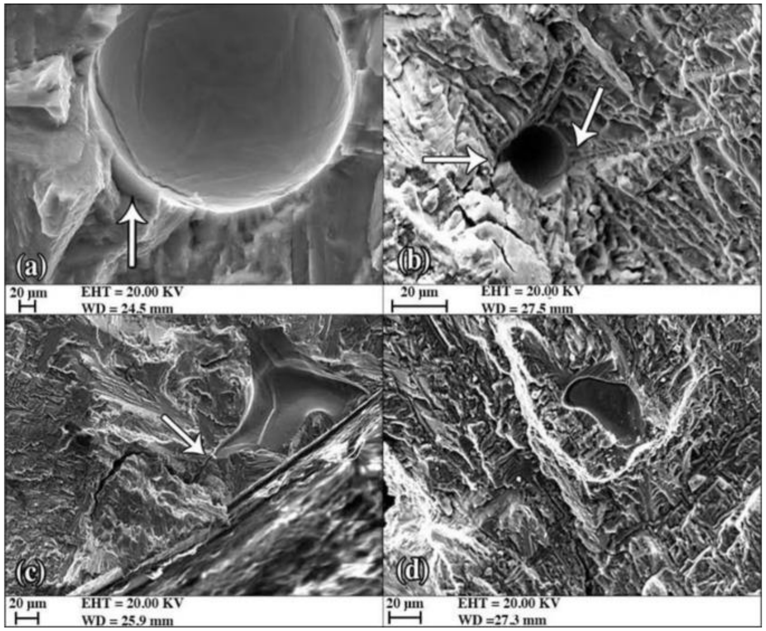
- Incomplete melting
  - Flat, slit shaped



A Yadollahi, N Shamsaei. (2017) IJF, 98: 14-31.

Entrapped gas pore:

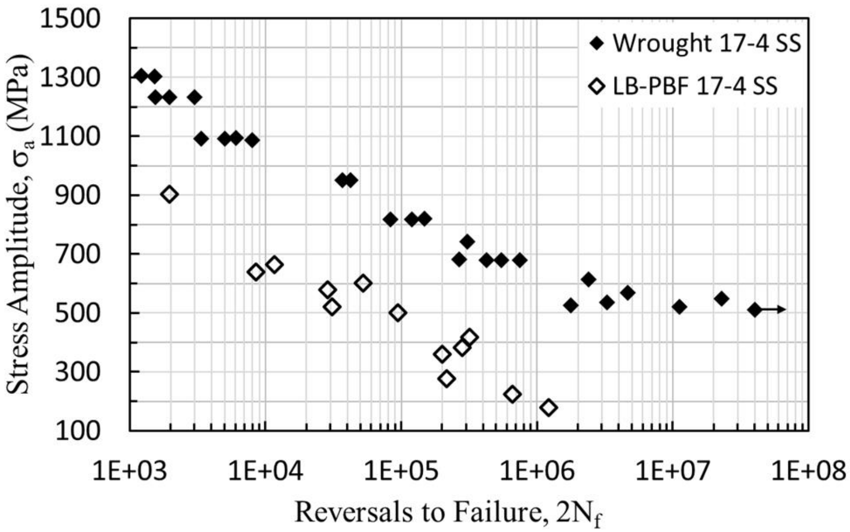
- Poor powder distribution
- Overheating (keyhole mode)
  - Spherical

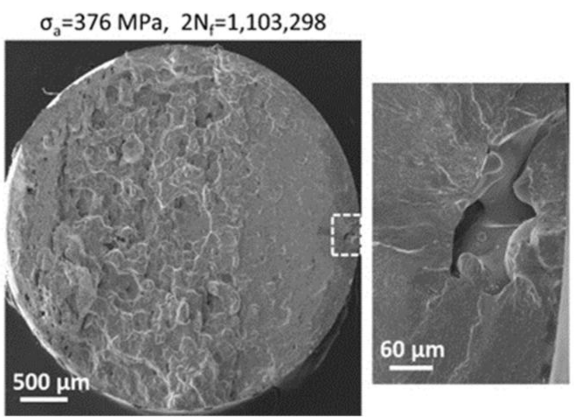


AJ Sterling, B Torries, N Shamsaei, SM Thompson, DW Seely. (2016) MSEA, 655: 100-112.

Fatigue of AM Materials - Porosity

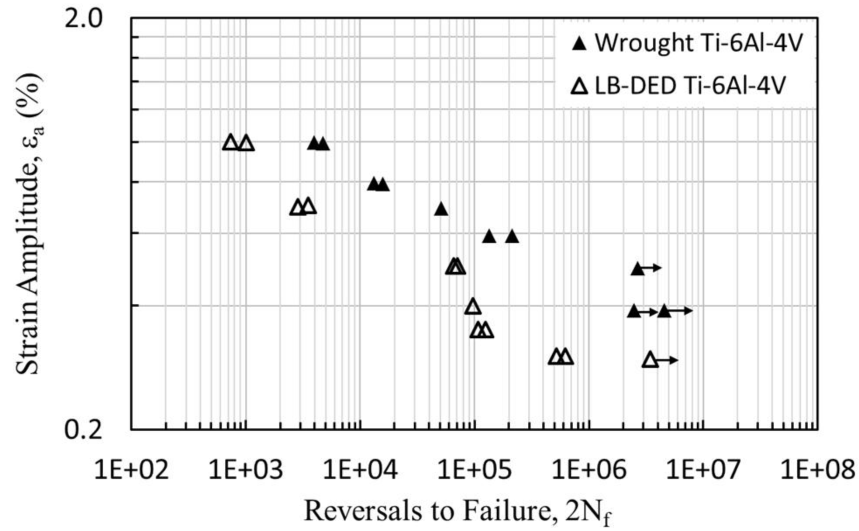
Machined / Polished

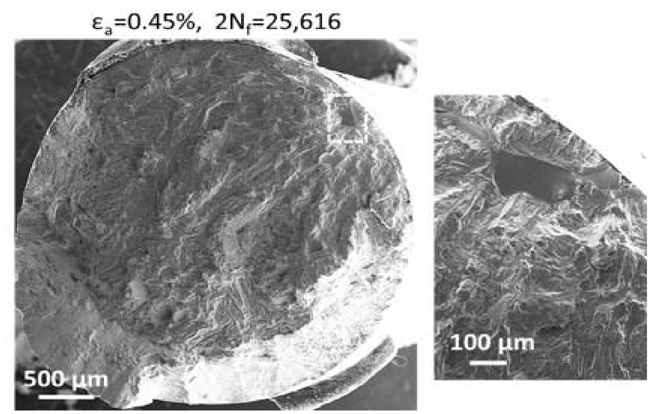




A Yadollahi, N Shamsaei. (2017) IJF, 98: 14-31.

Machined / Polished





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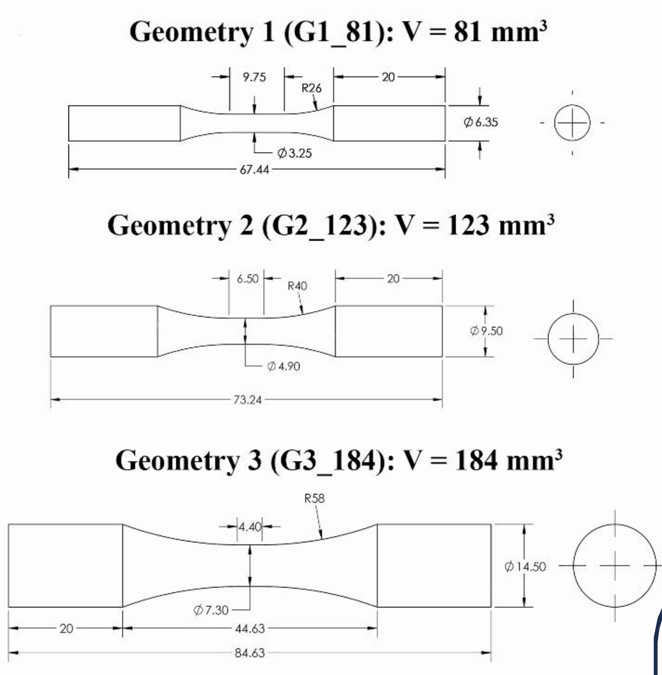
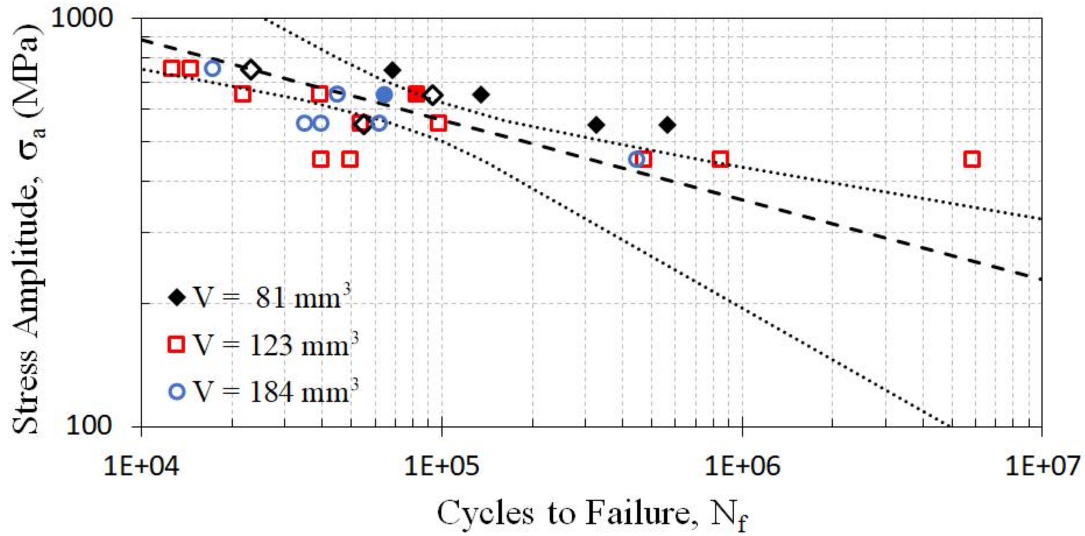
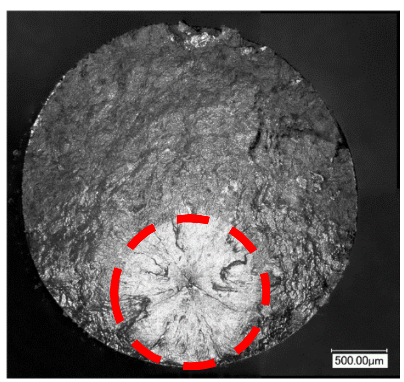
Fatigue of AM Materials - Porosity



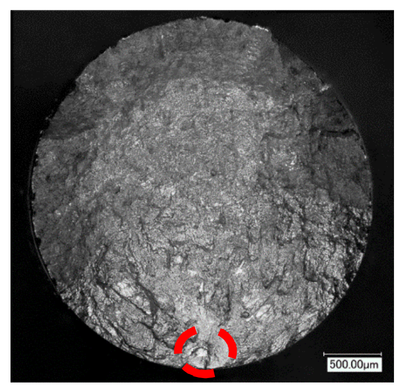


G1_81: s_a = 550 MPa

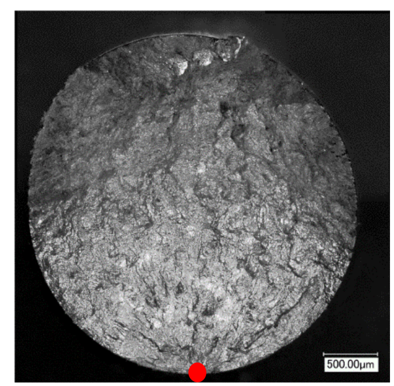
N_f = 564,102



N_f = 326,816

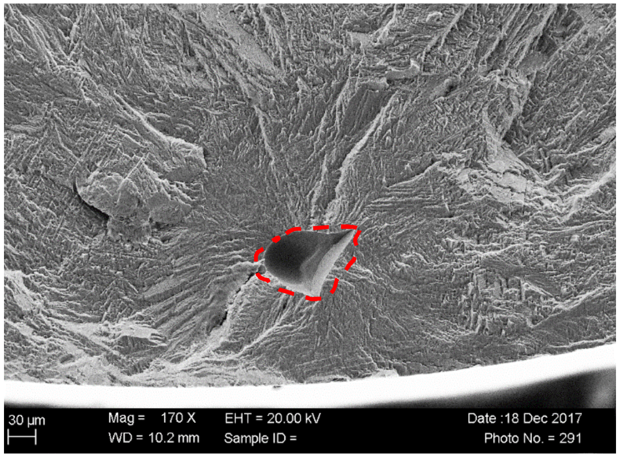


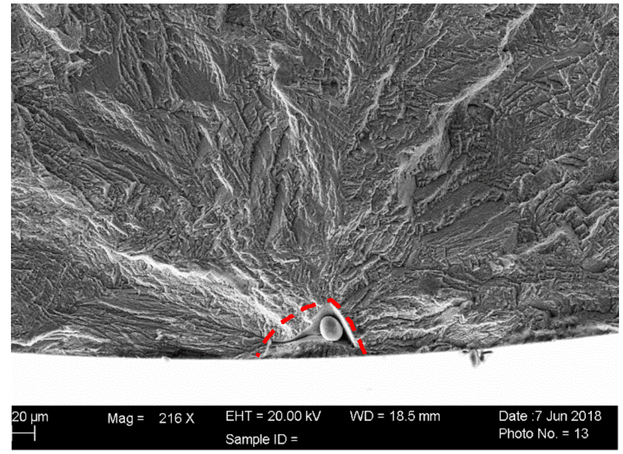
N_f = 55,151



J Pegues, M Roach, R Williamson, N Shamsaei, "Volume Effects on the Fatigue Behavior of Additively Manufactured Ti-6Al 4V Parts," Solid Freeform Fabrication, 2018

Fatigue of AM Materials - Porosity



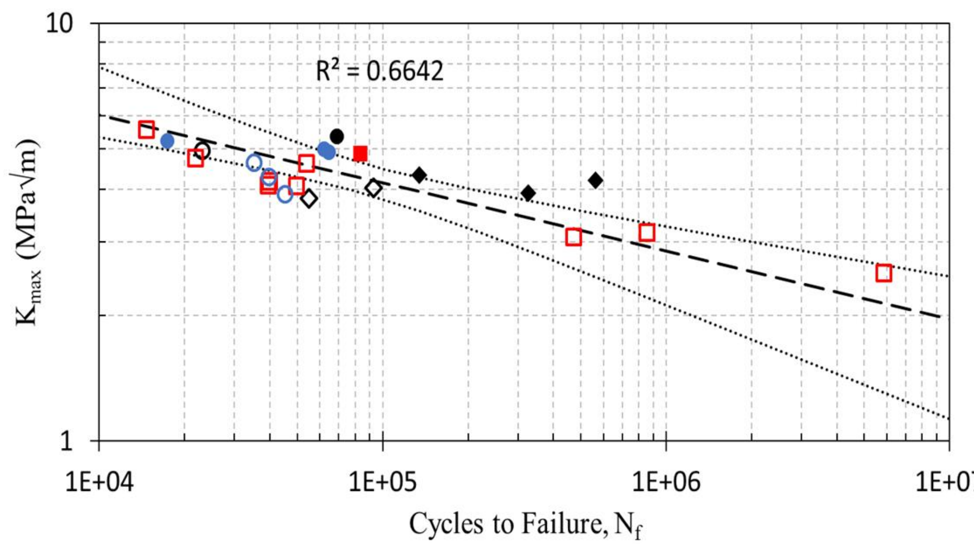


$$K_{Imax} = Y\sigma_{max}\sqrt{\pi\sqrt{area}}$$

Y = 0.65 for surface cracks
0.50 for sub-surface cracks

s_{max} = Peak stress

$\sqrt{area}$ = 2D projection of defect area on the loading plane



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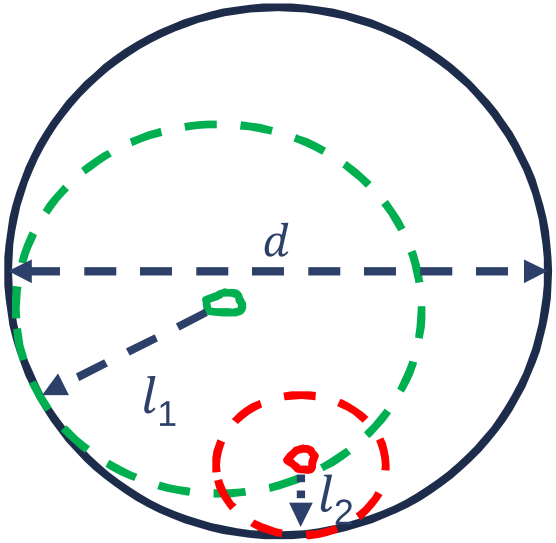
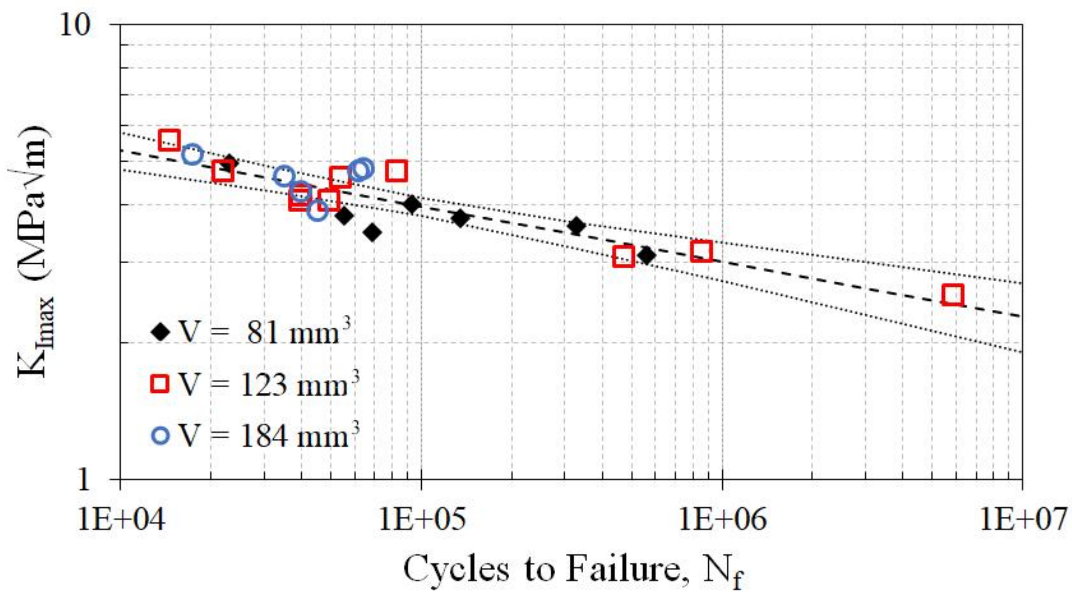
Fatigue of AM Materials - Porosity



The shape function was adjusted by adding a distance from the surface ratio based on gage diameter:

$$K_{Imax} = \left(\frac{d - l_i}{d}\right) Y \sigma_{max} \sqrt{\pi \sqrt{area}}$$



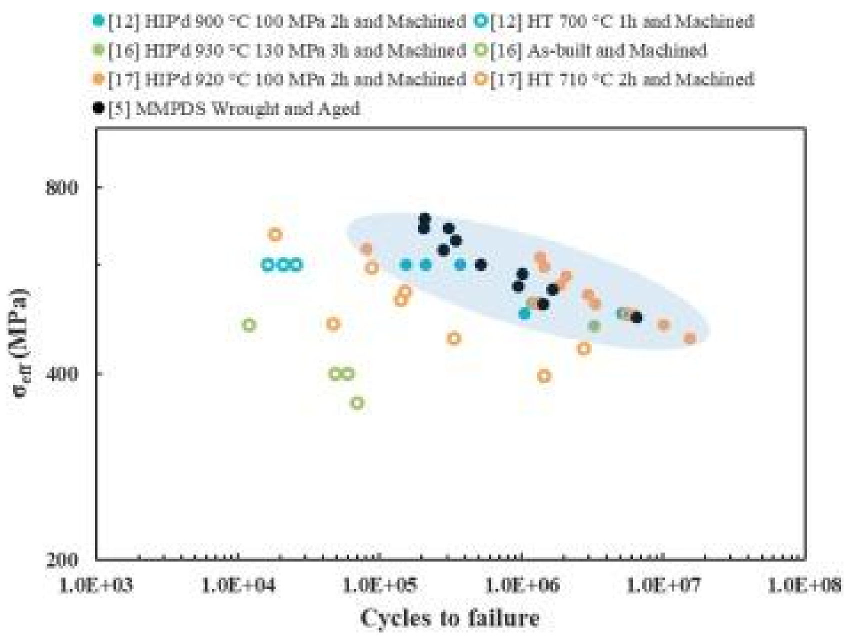
This approach showed better correlation for the embedded defects

May be useful in determining defect criticality for a given defect size a distribution – requires NDI

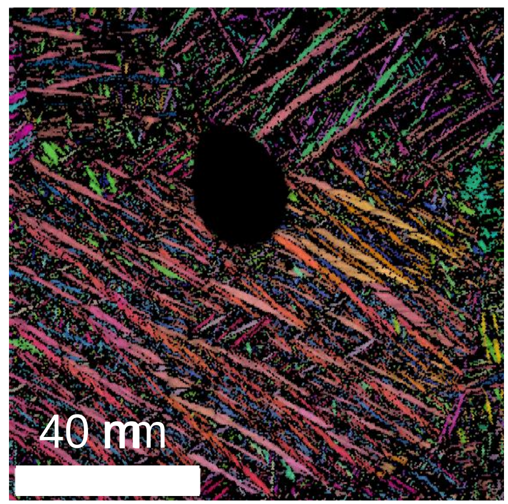
J Pegues, M Roach, R Williamson, N Shamsaei, "Volume Effects on the Fatigue Behavior of Additively Manufactured Ti-6Al 4V Parts," Solid Freeform Fabrication, 2018

Changing the Failure Mechanisms

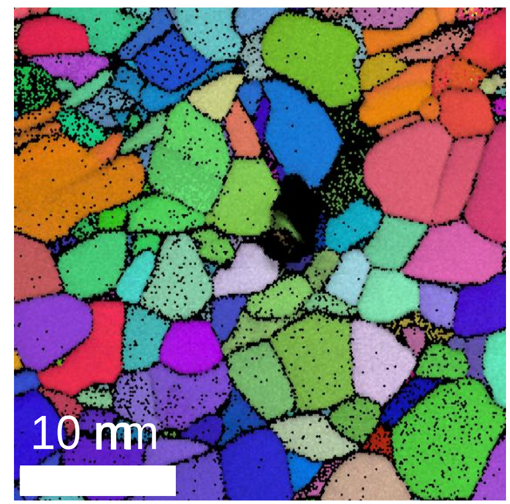
Subjecting AM Ti-6Al-4V to hot isostatic pressing (HIP) has shown the ability to improve the fatigue performance comparable to wrought

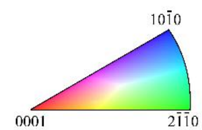


Non-HIP: LB-PBF Ti-6Al-4V



HIP: LB-PBF Ti-6Al-4V

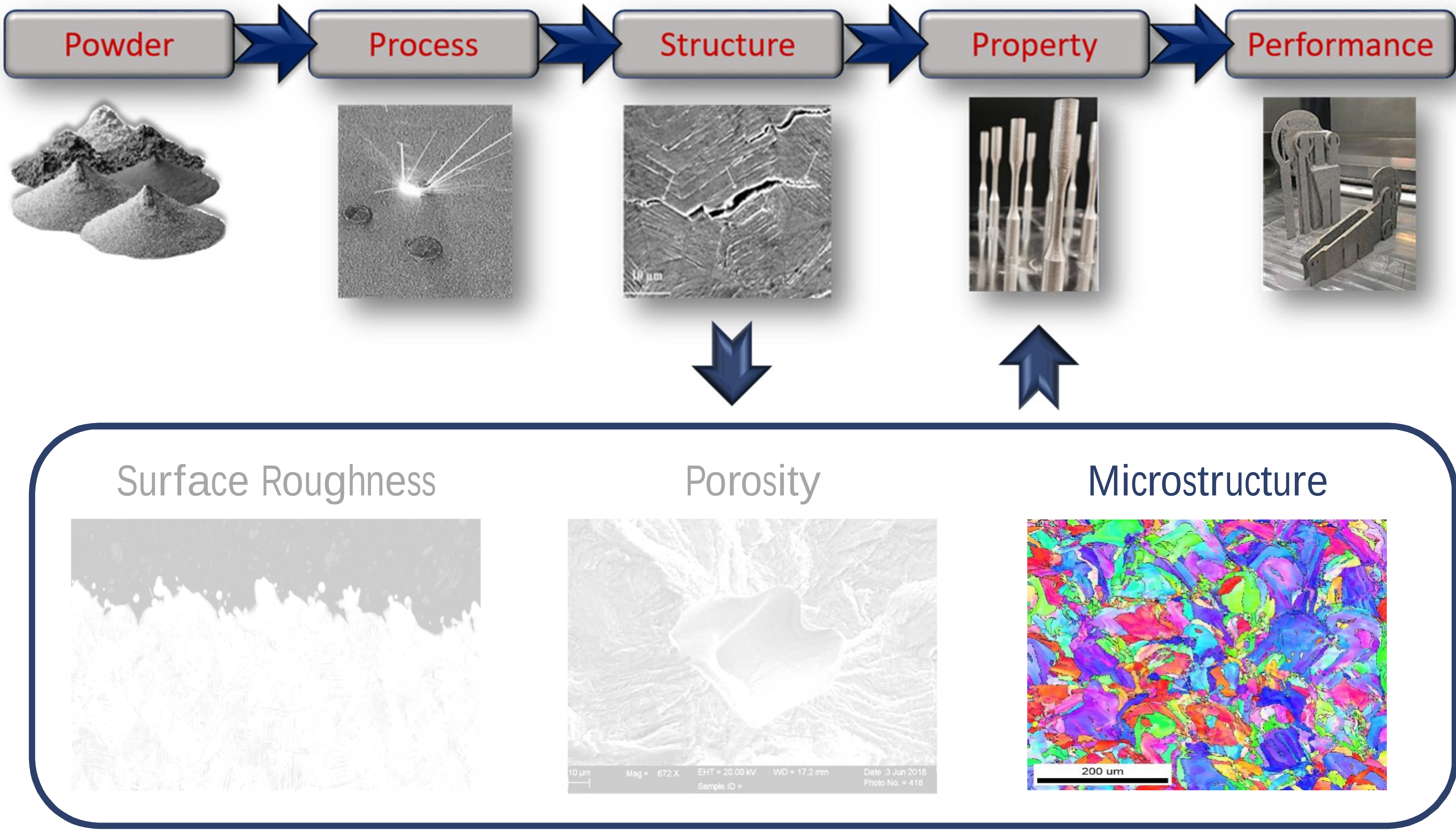




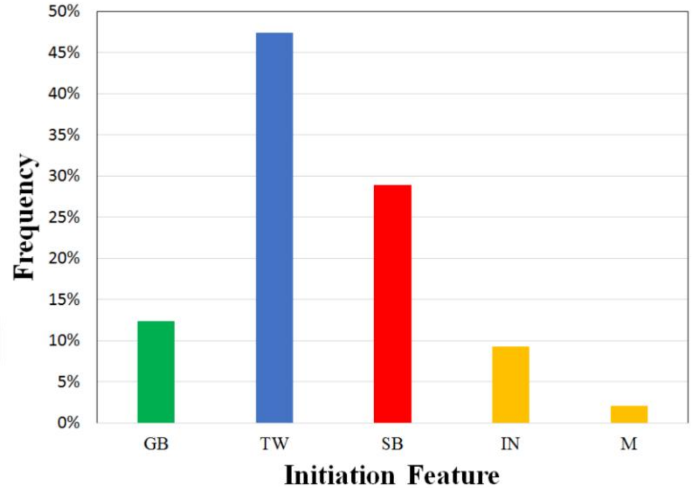
Size of the defects are reduced and the microstructure near the pores became more equiaxed

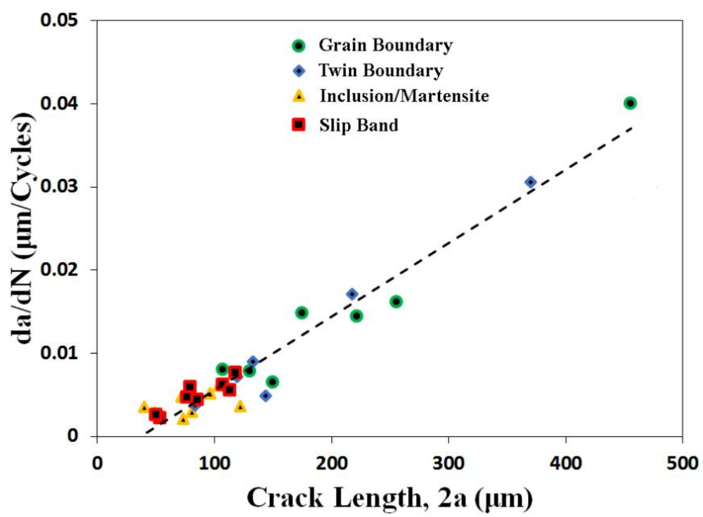
P. Li, D.H. Warner, J.W. Pegues, M.D. Roach, N. Shamsaei, N. Phan, "Investigation of the mechanisms by which hot isostatic pressing improves the fatigue performance of powder bed fused Ti-6Al-4V," International Journal of Fatigue, 2019.

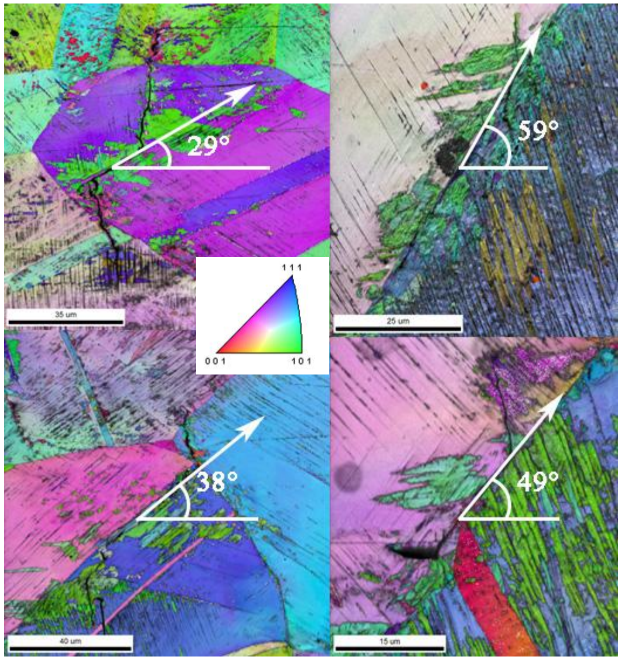
Microstructure

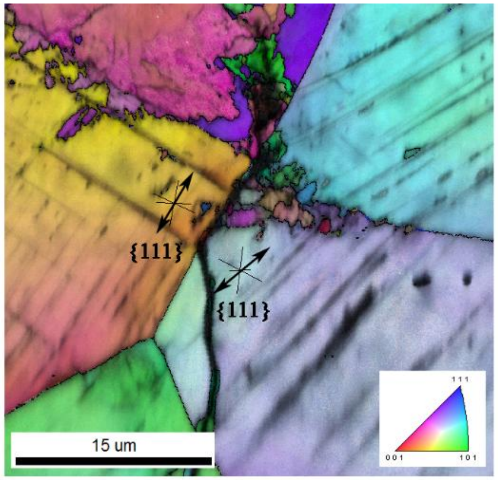


Fatigue Behavior – Wrought 304L SS









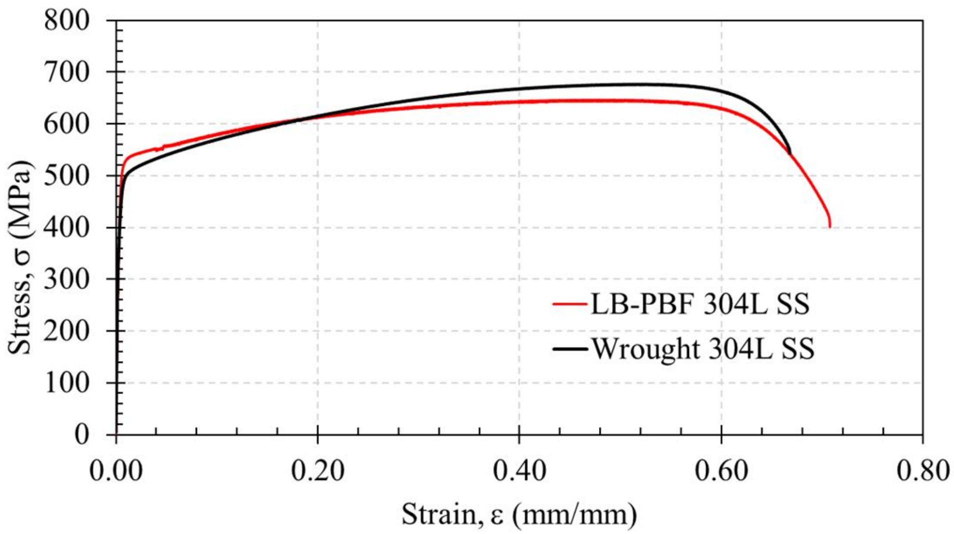
Crack initiation occurred mostly at twin boundaries

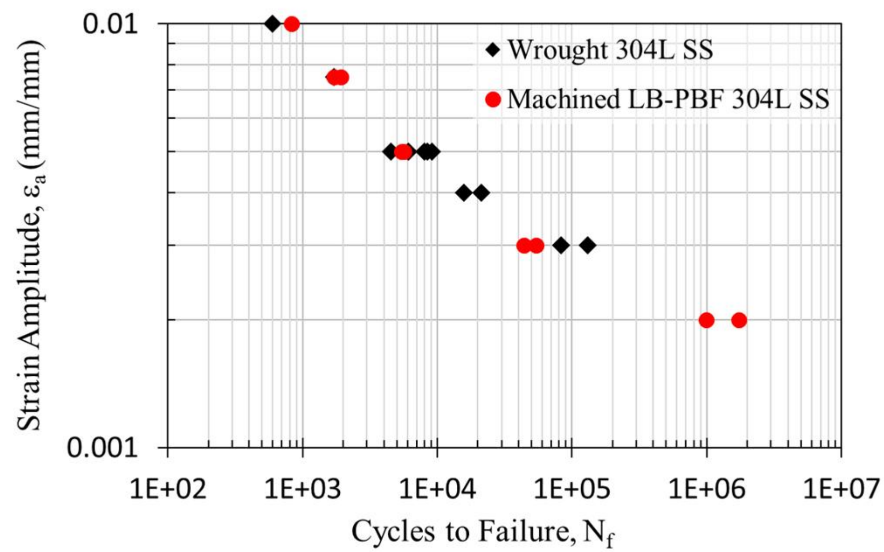
Cracks that originated at other features typically showed little growth

Pegues, J. W., Roach, M. D., & Shamsaei, N. (2017). Influence of microstructure on fatigue crack nucleation and microstructurally short crack growth of an austenitic stainless steel. Materials Science and Engineering: A, 707, 657-667.

304L Stainless Steel – AM vs. Wrought

304L SS surprisingly shows less sensitivity to defects (surface roughness and porosity) than other AM materials



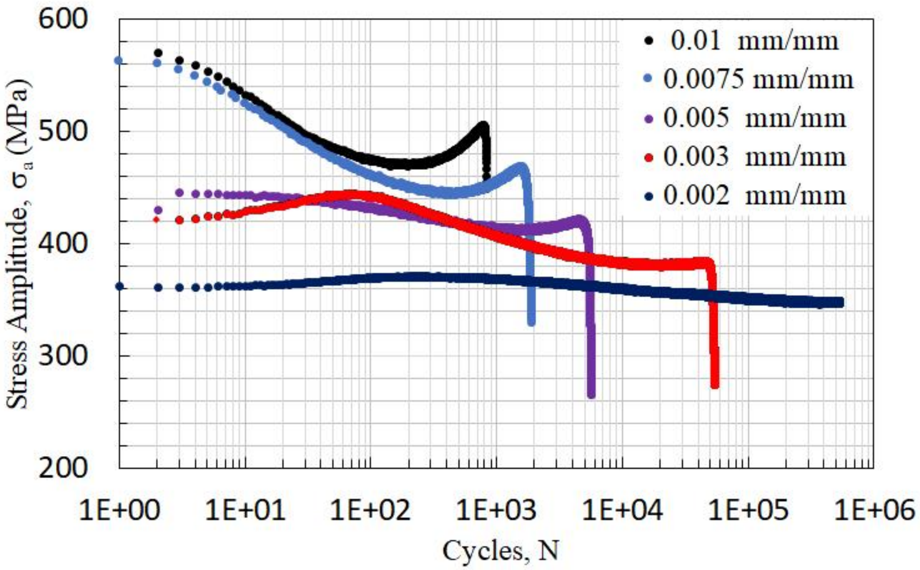


304L SS	S_y (MPa)	S_u (MPa)	EL (%)	*e_f (mm/mm)
Wrought	400	677	67	0.002
LB-PBF	450	647	71	0.002

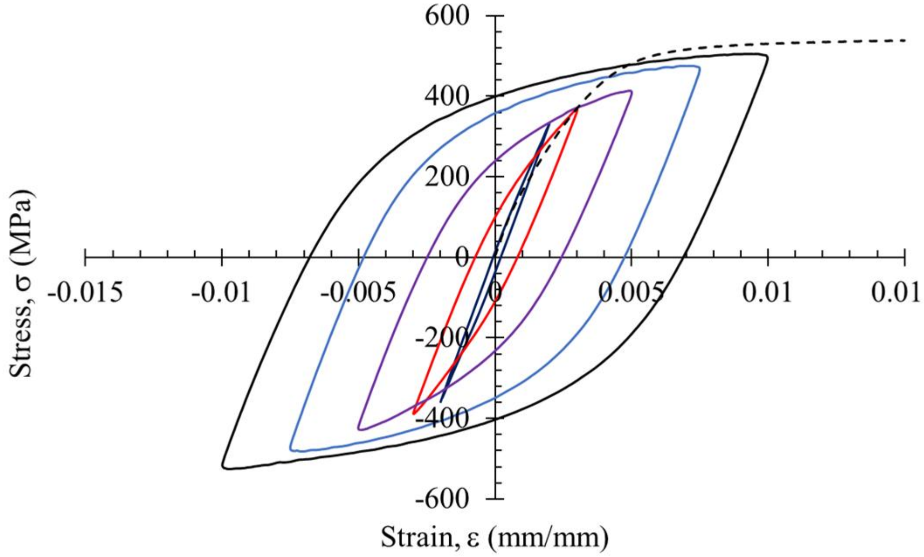
*e_f fatigue strength at N_f = 10^6 cycles

Cyclic Deformation Behavior

Machined/Polished LB-PBF 304L SS



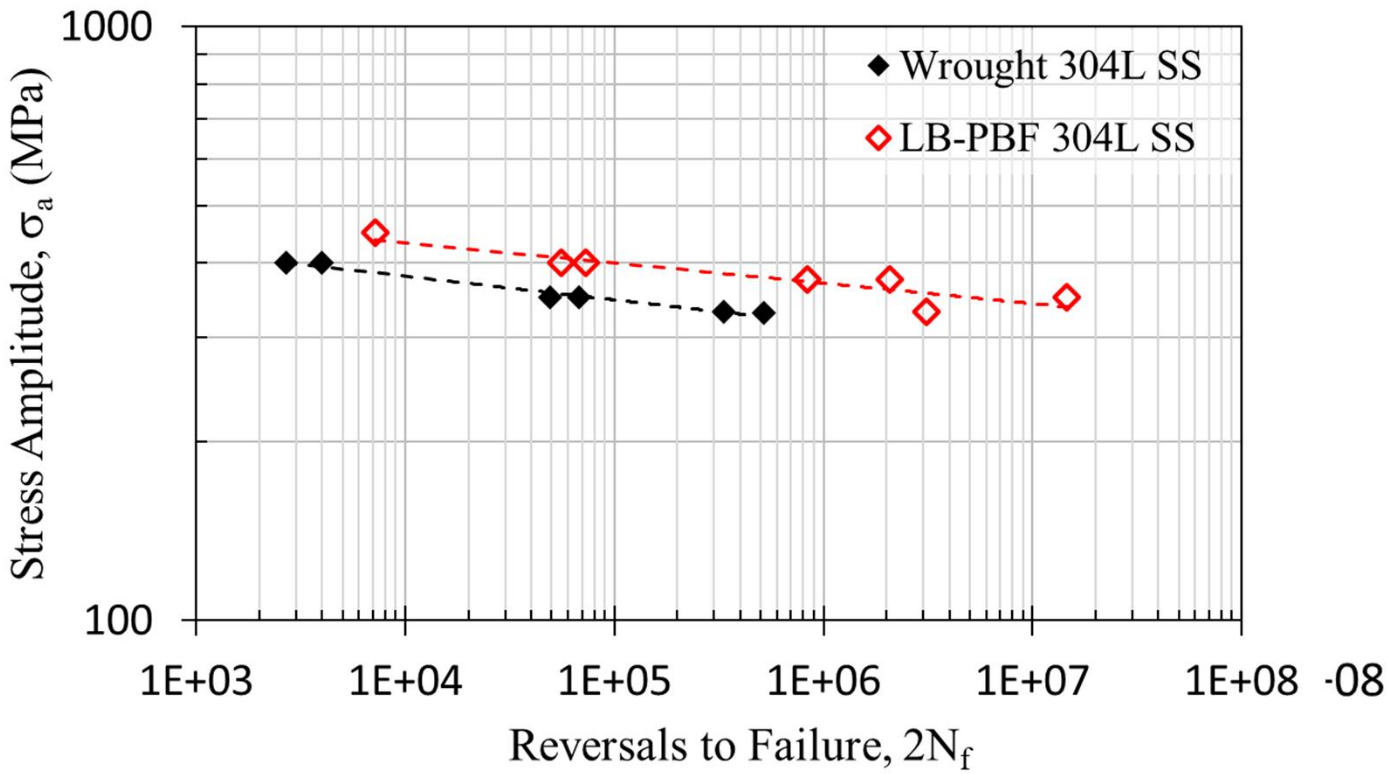
Half Life



Stress Response

- 3 stages
  - Initial work hardening, cyclic softening, secondary hardening
- Larger strain amplitudes showed significant secondary hardening

Stress-Life Fatigue Behavior 304L SS

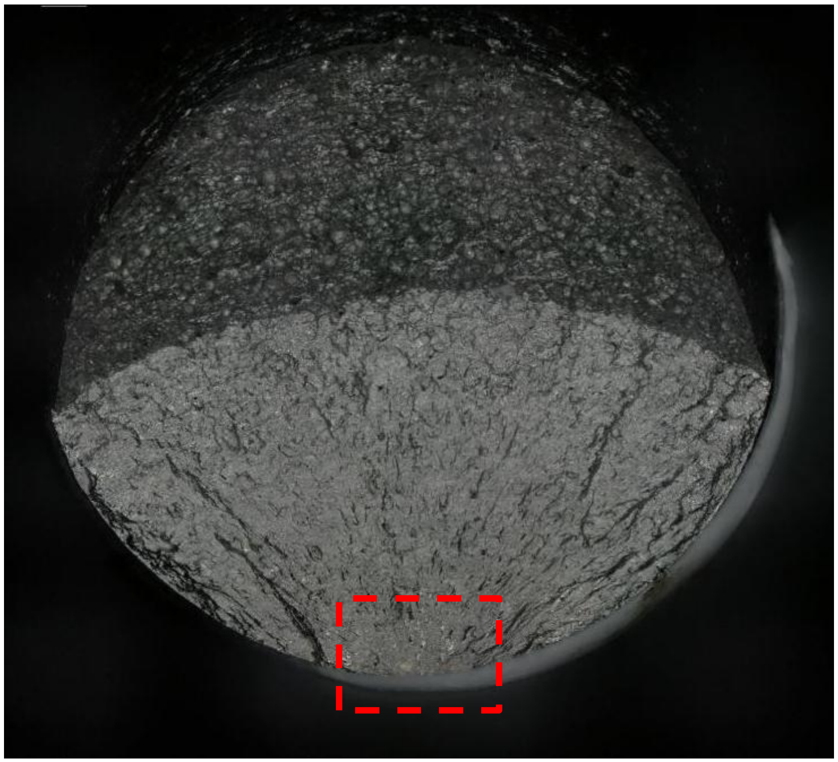


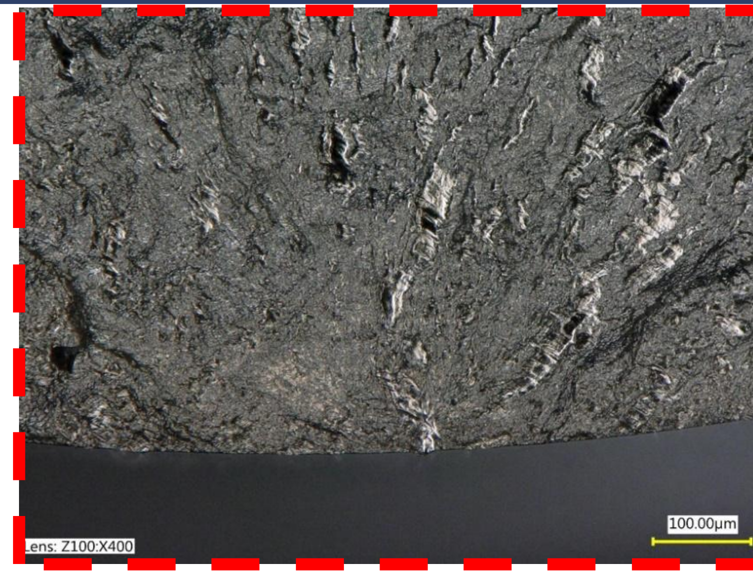
Stress-life of machined AM specimens is similar to the wrought

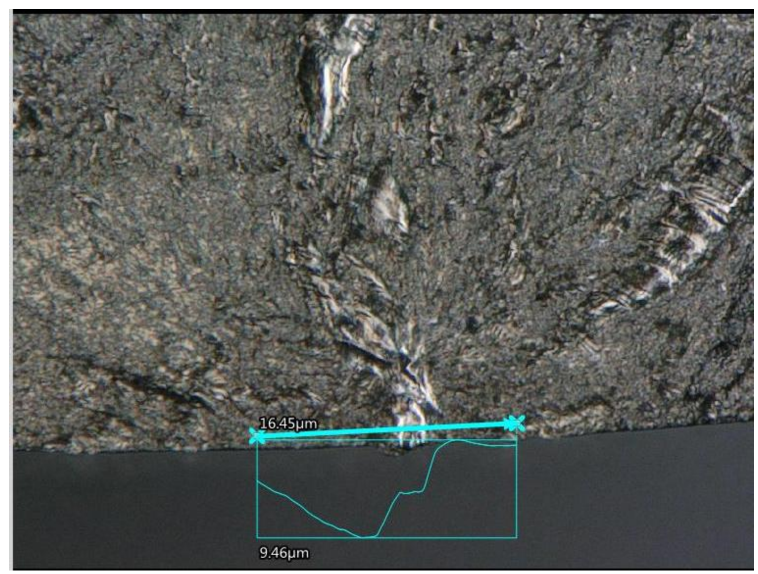
One to two orders of magnitude improvement across all stress levels

Fractography

s_a = 400 MPa, N_f = 36,562 Cycles







Cracks did not initiate at pores

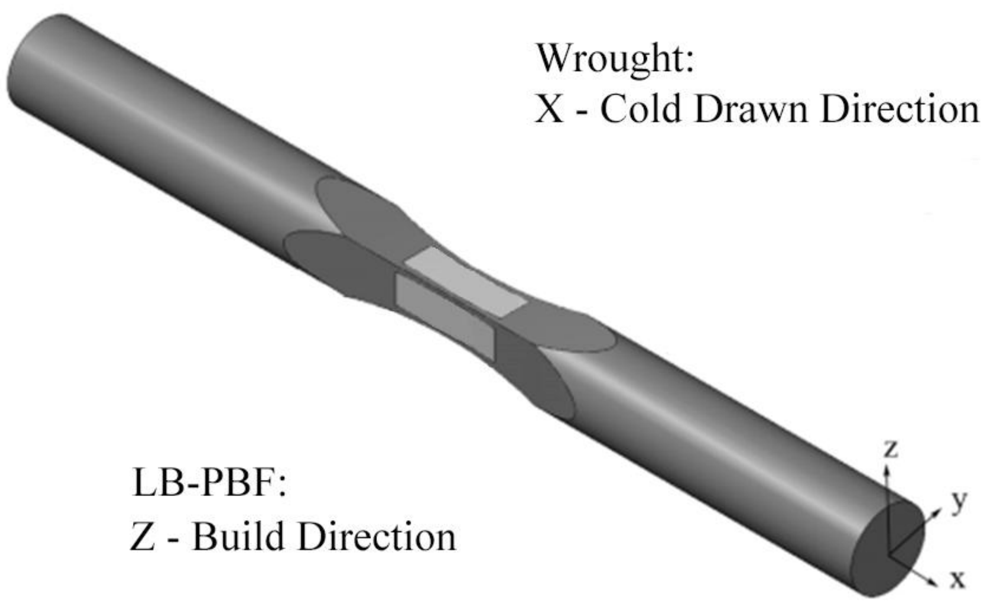
Crack initiation profiles indicated cracks initiated at microstructural features

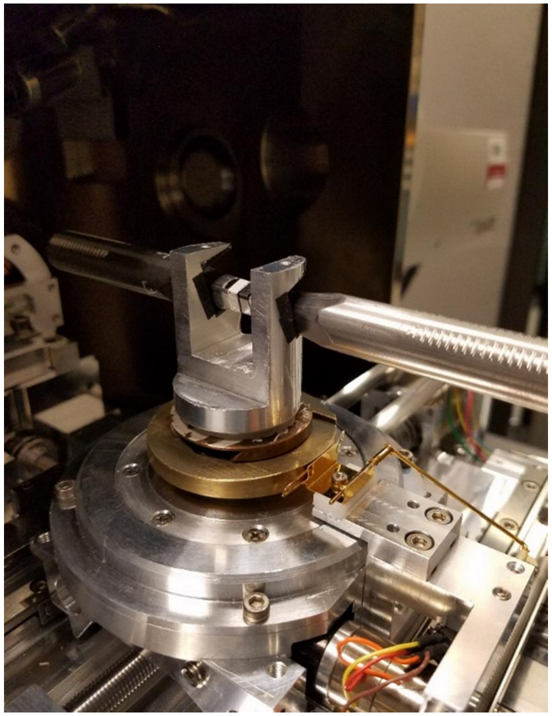
Experimental Methods

Square gage crack initiation specimens were machined from horizontally fabricated rods and electropolished

CI specimens were subjected to interrupted fatigue testing

During interruptions the specimens were imaged using electron backscatter diffraction

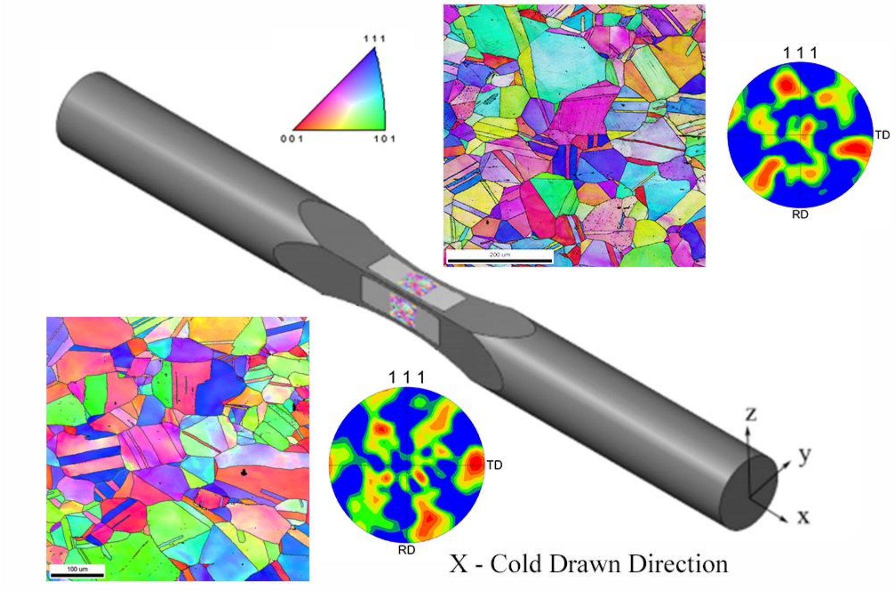




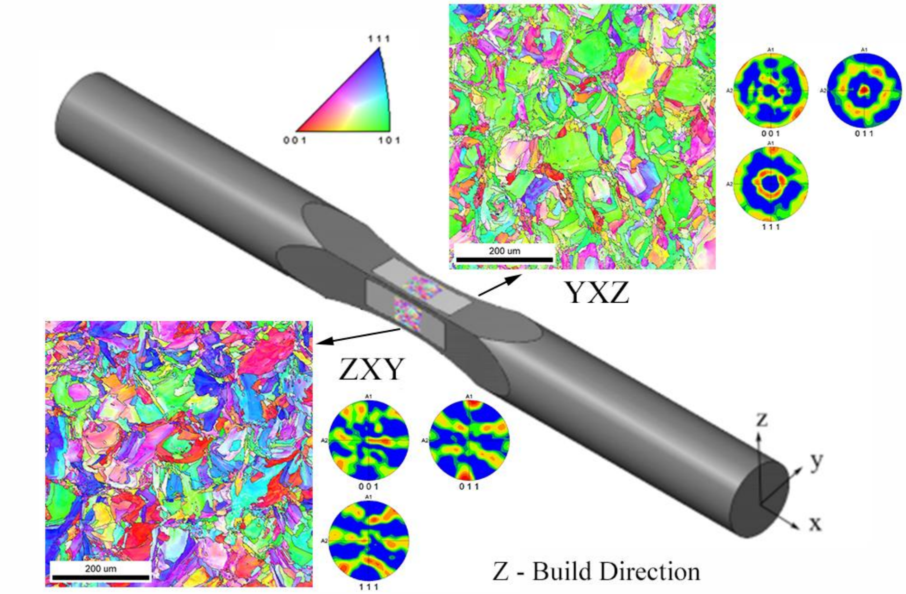
Microstructural Characterization

Distinct 011 fiber texture for the plane perpendicular to the build direction (YXZ)

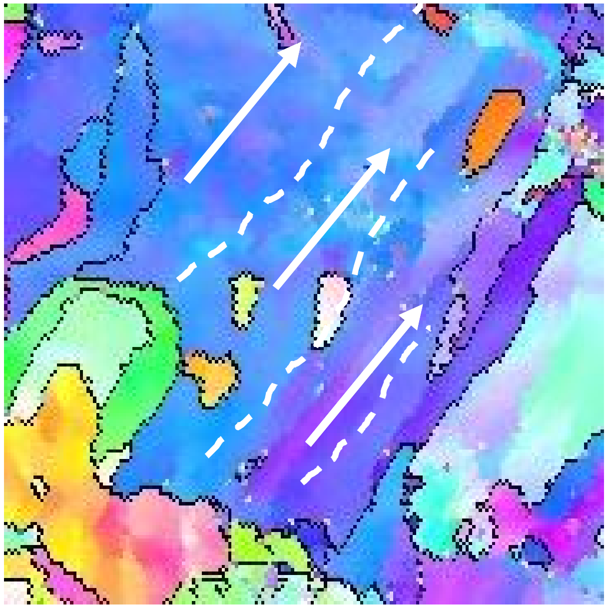
Wrought 304L SS
Cold Drawn and Annealed

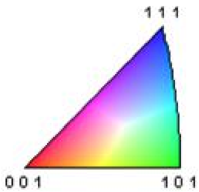


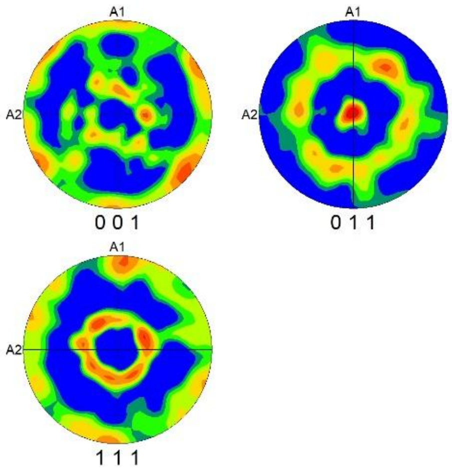
LB-PBF 304L SS
Stress Relieved

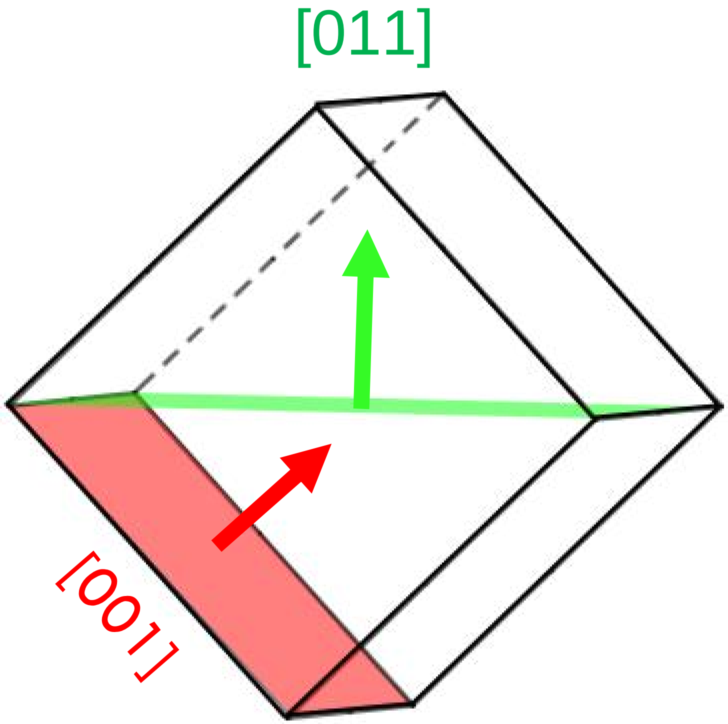


LB-PBF 304L Microstructure









The easy dendritic growth along [001] occurs at an angle resulting in the 011 fiber texture

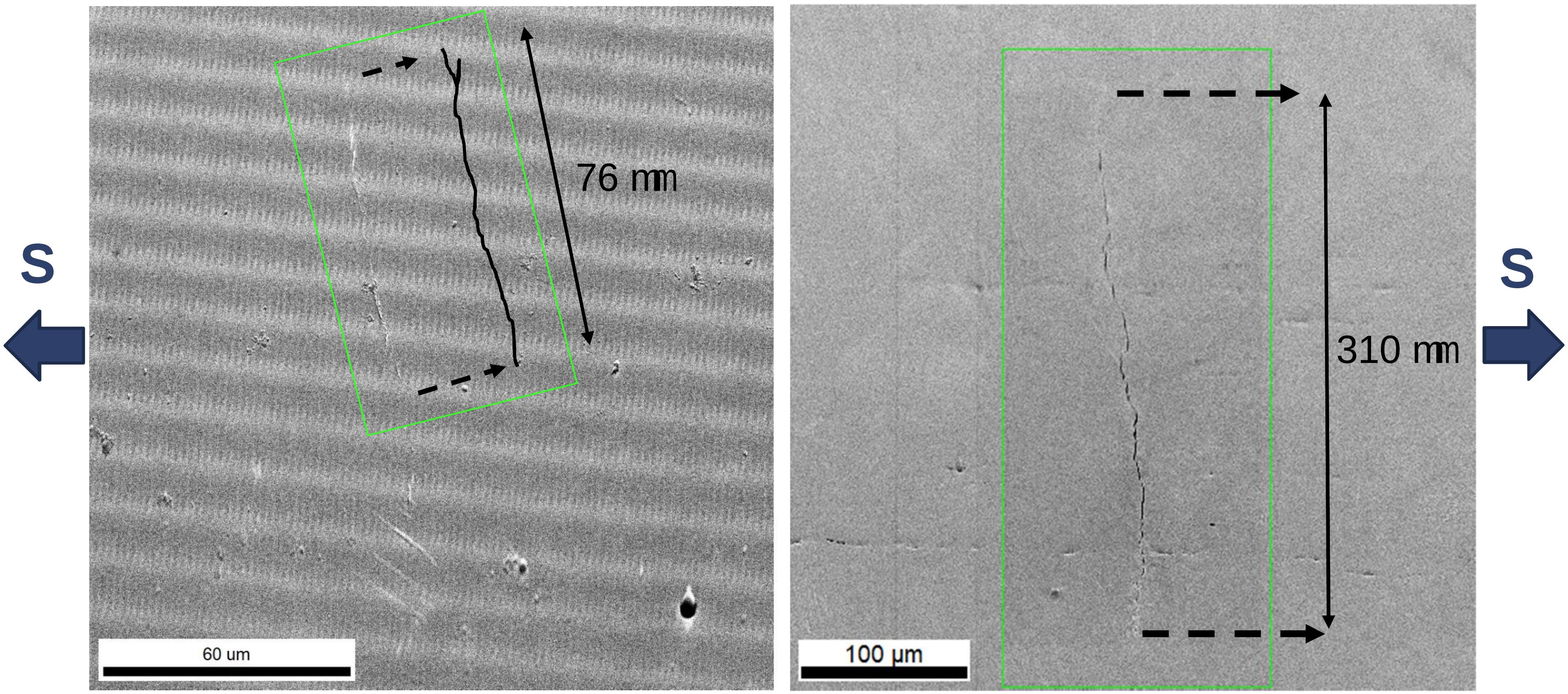
Crack Initiation – AM 304L SS

Machined/Polished LB-PBF 304L SS

s_a = 330 MPa, N = 100,000 cycles

Machined/Polished Wrought 304L SS

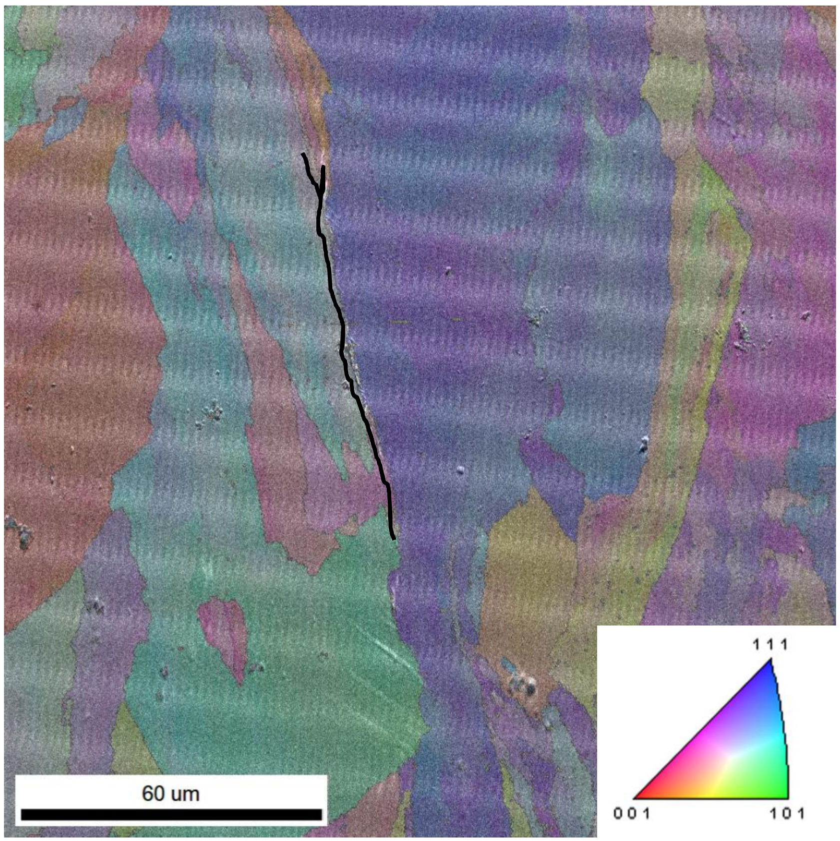
s_a = 330 MPa, N = 35,000 cycles



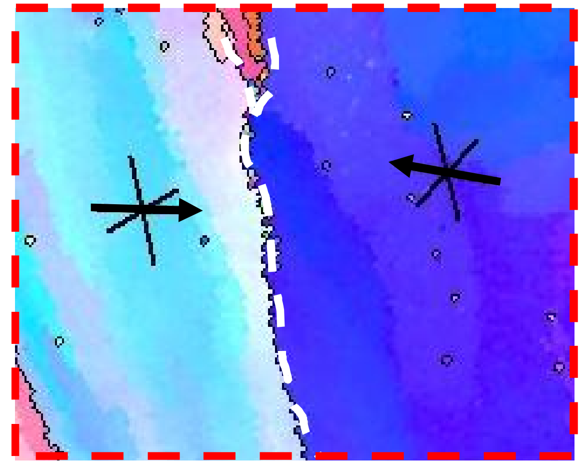
Crack Initiation – AM 304L SS

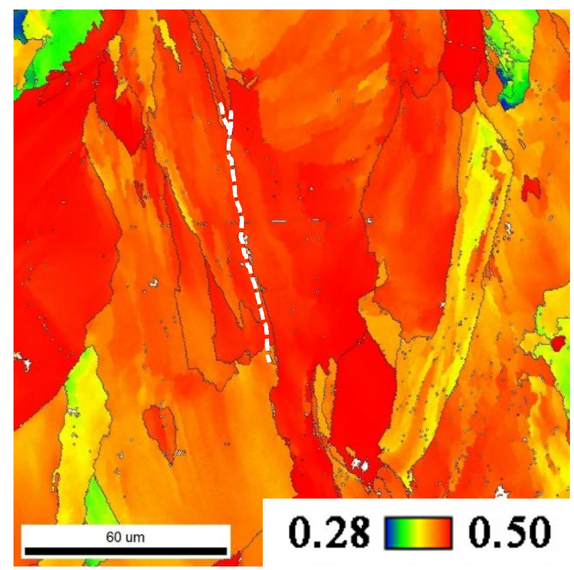
s_a = 330 MPa, N = 100,000 cycles

S



S



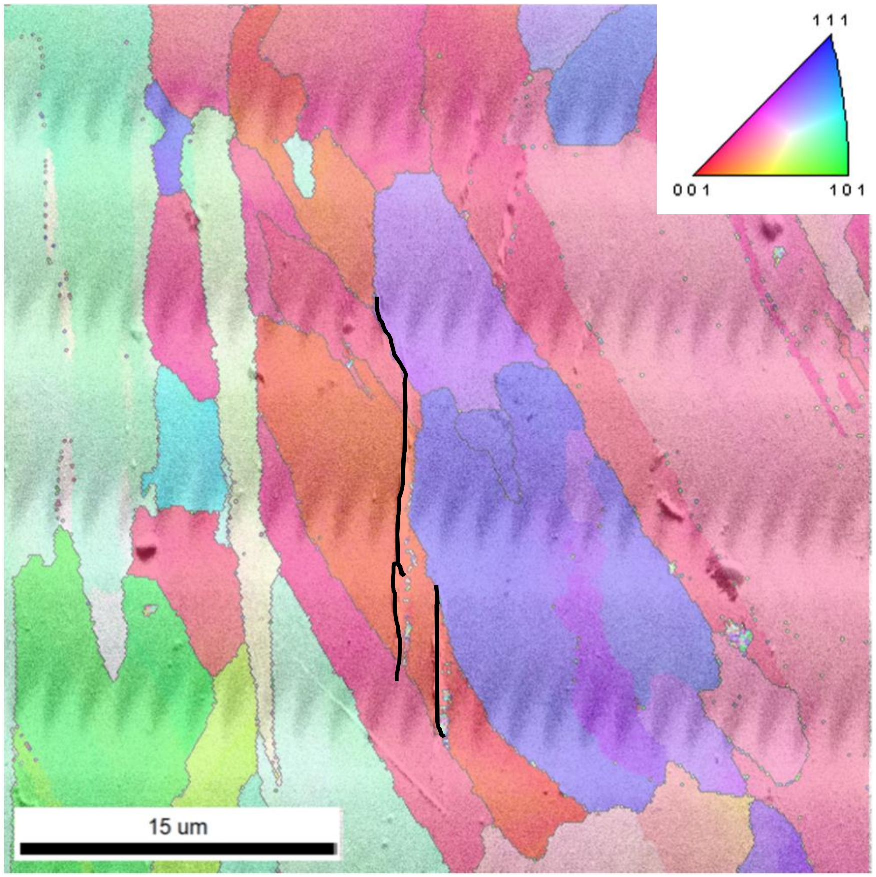


Misorientation(p1)	Misorientation(p2)	Sigm...	Deviation	Plane(p1)	Plane(p2)
51.43@[12 -13 -2]	51.43@[12 -13 -2]	-	-	[9 -7 2]	[-10 7 2]

Crack Initiation – AM 304L SS

s_a = 330 MPa, N = 100,000 cycles

S



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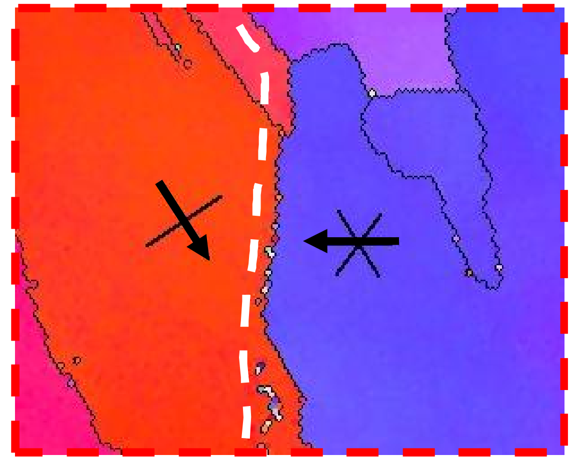
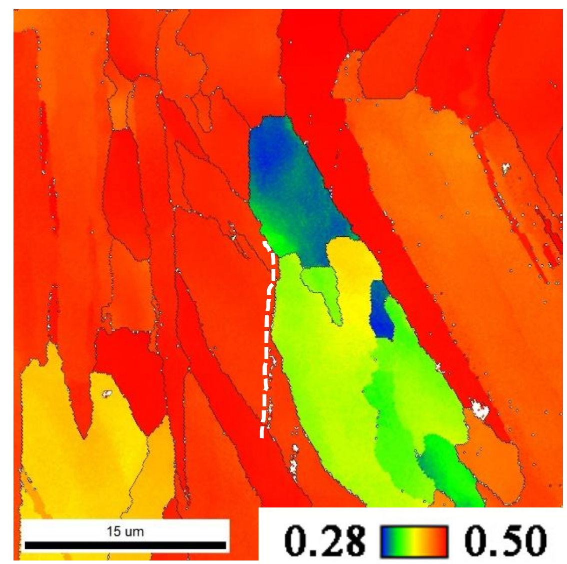
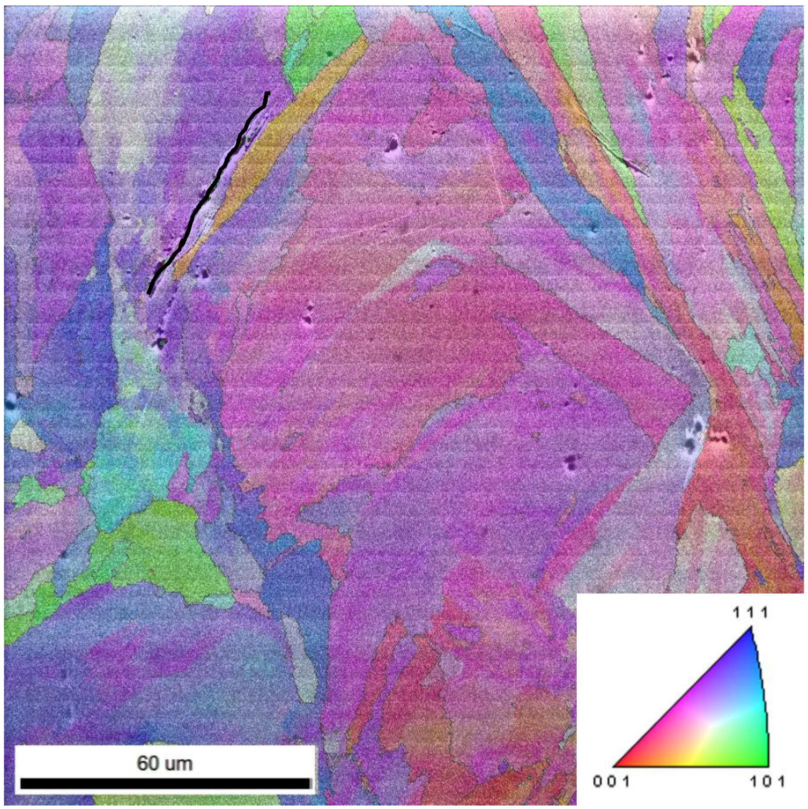




Misorientation(p1)	Misorientation(p2)	Sigm...	Deviation	Plane(p1)	Plane(p2)
49.60@[-6 2 -7]	49.60@[-6 2 -7]	-	-	[-19 -1 16]	[-5 9 -7]

Crack Initiation – AM 304L SS

s_a = 330 MPa, N = 100,000 cycles



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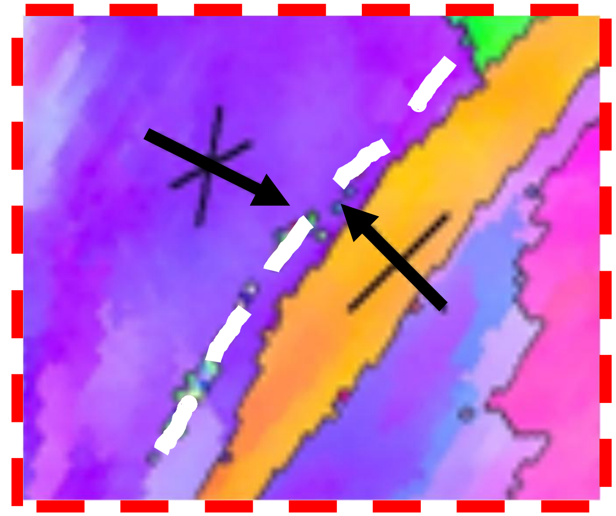
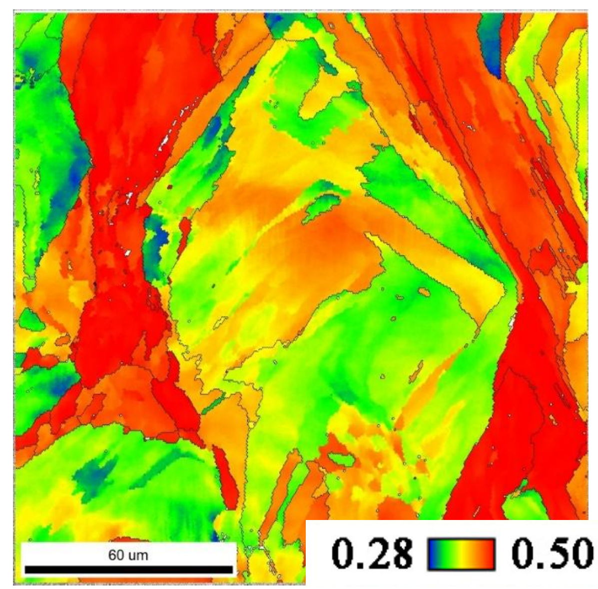
S



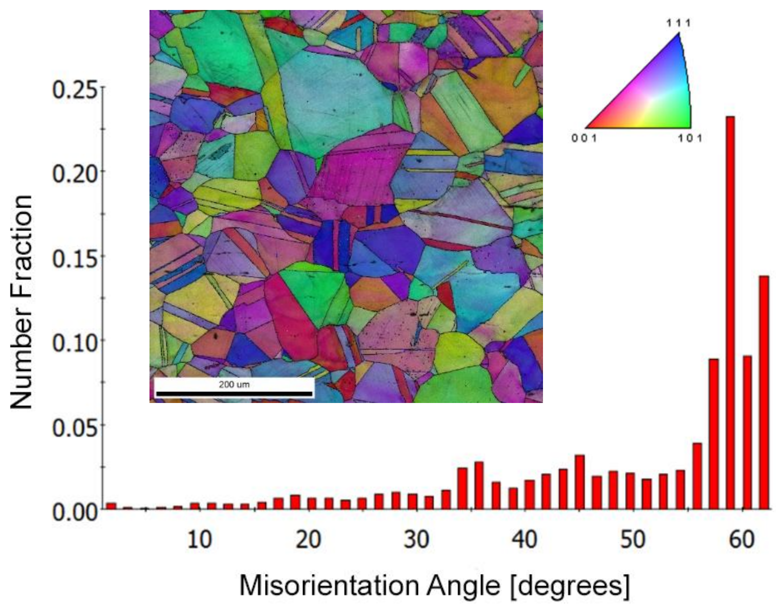


Misorientation(p1)	Misorientation(p2)	Sigm...	Deviation	Plane(p1)	Plane(p2)
56.50@[-9 10 -9]	56.50@[-9 10 -9]	3	4.22	[4 5 -12]	[-15 -4 3]

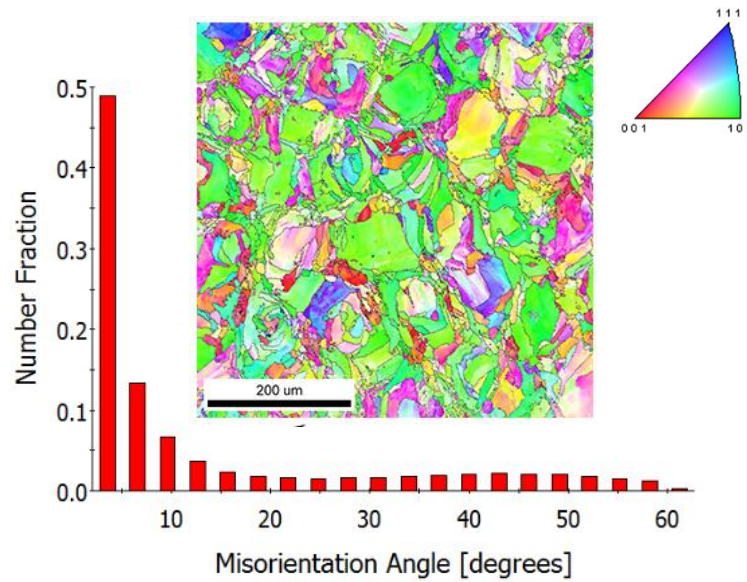
Orientation Effects on CI

- Grain size of LB-PBF 304L SS is much finer than its wrought counterpart
- Twin boundary density is much lower for LB-PBF 304L SS
- Leveraging AM's ability to tailor microstructure can lead to improved fatigue resistance

Wrought 304L SS

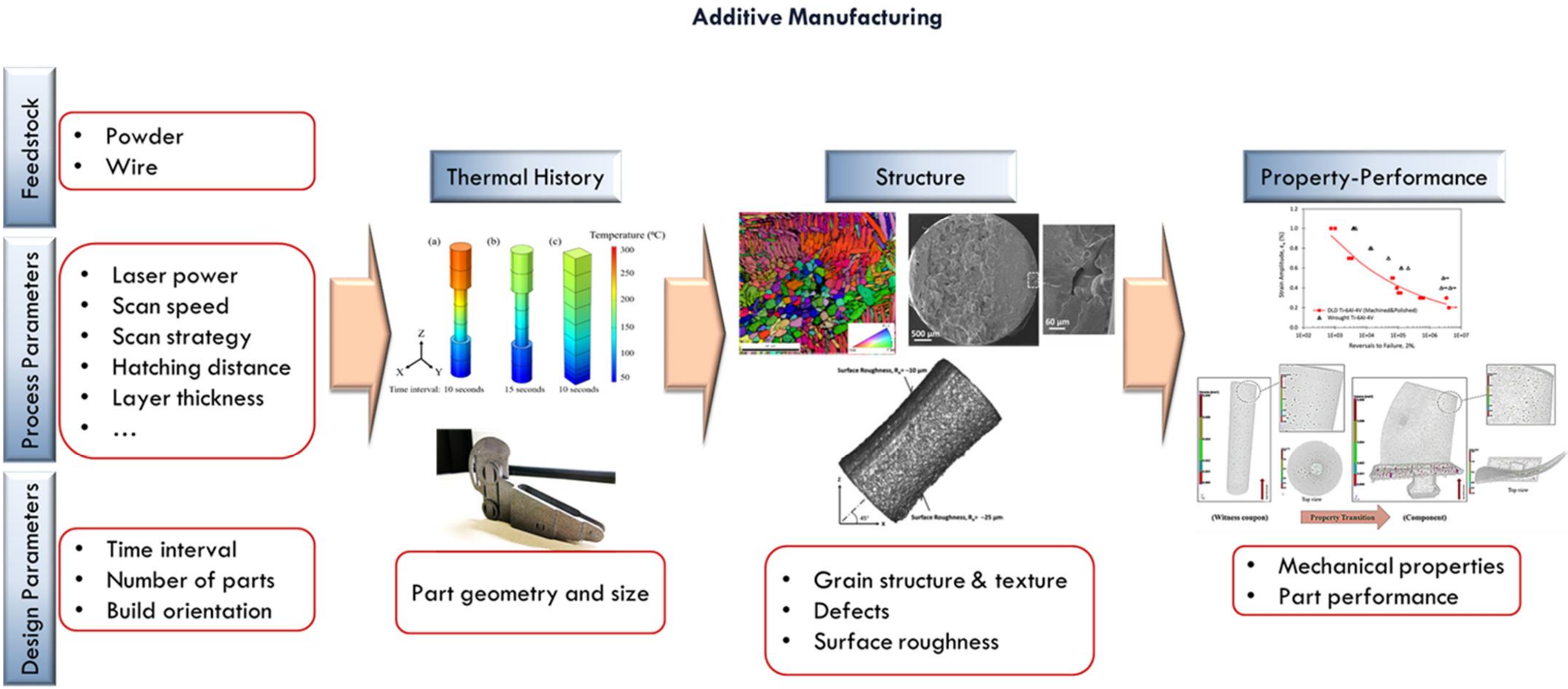


LB-PBF 304L SS



J.W. Pegues, S. Shao, N. Shamsaei, J.A Schneider, R.D. Moser, "Cyclic strain rate effect on martensitic transformation and fatigue behaviour of an austenitic stainless steel," Fatigue & Fracture of Engineering Materials & Structures, 40(12), 2080-2091, 2017.

Process-Structure-Property Relationships



Summary

- Additive Manufacturing provides opportunities and risks.
- Fatigue resistance is one of the major challenges against the widespread adoption of this technology.
- Establishing property-performance relationships as they are affected by process-structure relationships is vital.
- Additive manufacturing of more fatigue resistant materials and parts may be possible by better understanding the feedstock-process-structure-property-performance relationships.

JP10

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First and foremost, special thanks to my advisor Dr. Nima Shamsaei for guidance throughout my graduate studies

SAE Fatigue Design and Evaluation Committee

All of my lab mates at NCAME

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Thank you all for your attention!

Jonathan Pegues
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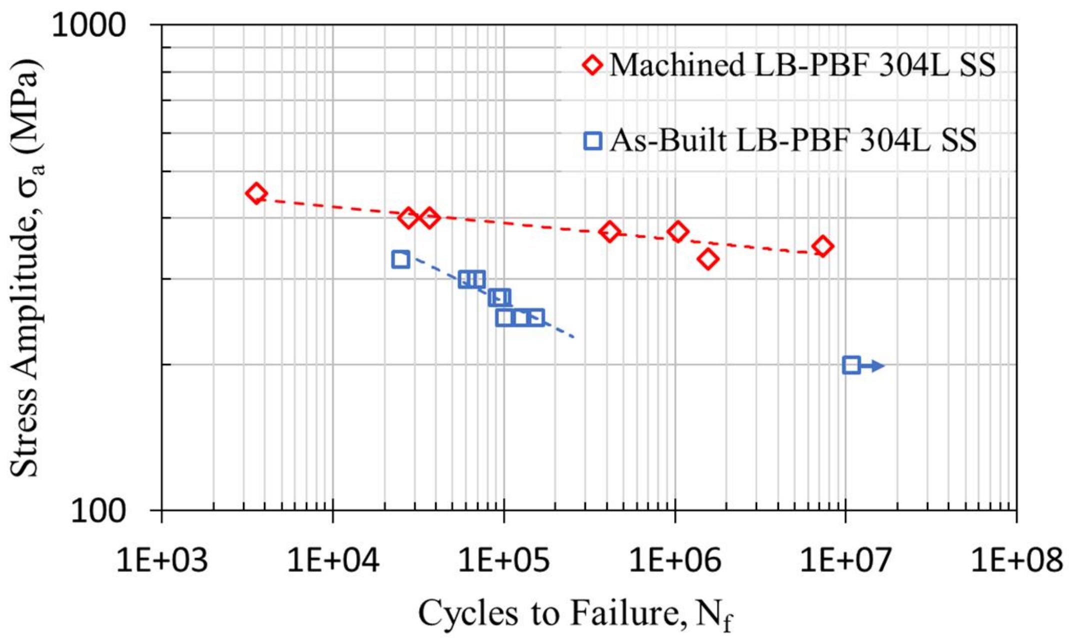
JP10 add AU

Jonathan Pegues, 4/5/2019

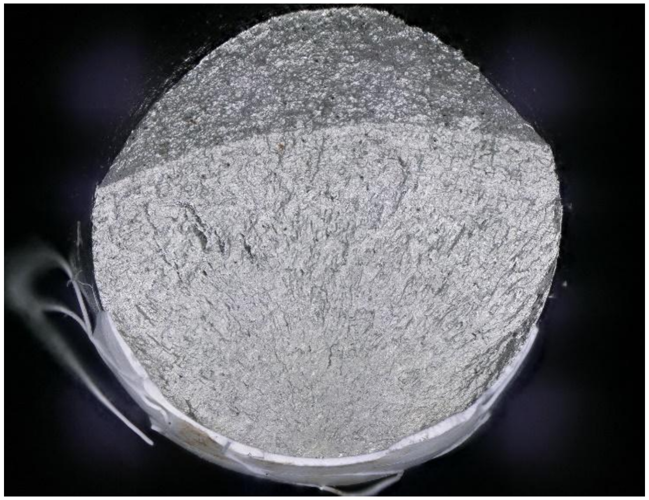

THIS IS TRADITION.
THIS IS SPIRIT.
THIS IS PASSION.
THIS IS AUBURN.

Challenge: Surface Finishing & Machining

Machining the surface and polishing can lead to orders of magnitude improvement in fatigue resistance

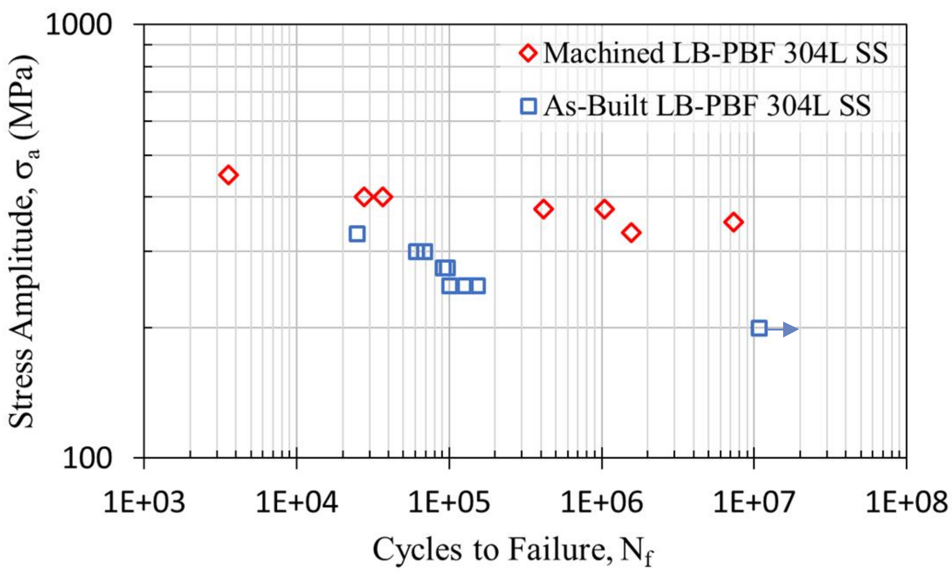


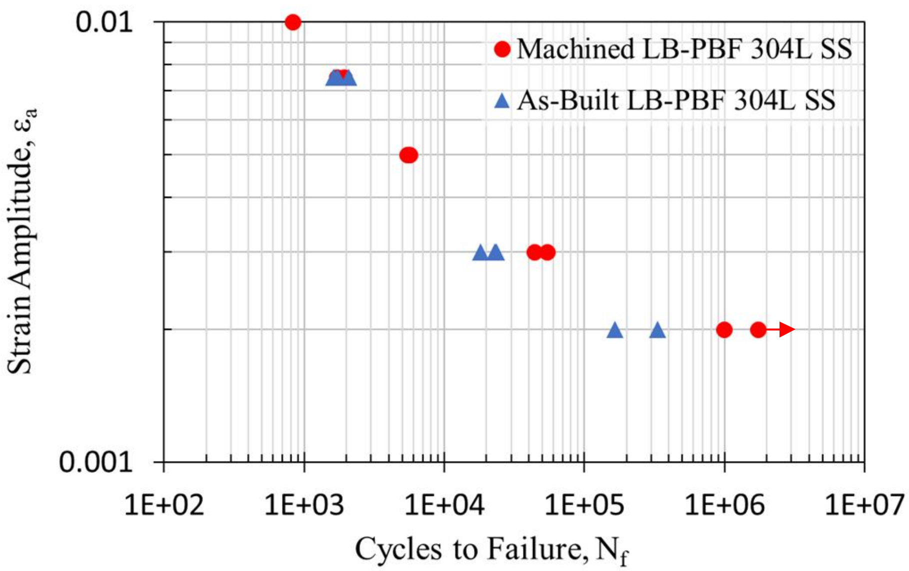
Machined LB-PBF 304L SS



As-Built LB-PBF 304L SS

Surface Roughness 304L SS





The effects of surface roughness on fatigue behavior can depend on material and loading types