AUBURN UNIVERSITY

SAMUEL GINN
COLLEGE OF ENGINEERING

# Fatigue Behavior of Additive Manufactured Parts:

## *Influencing Factors & Process/Design Considerations*

SAE Fatigue Damage and Evaluation Fall Meeting
October 11th, 2018

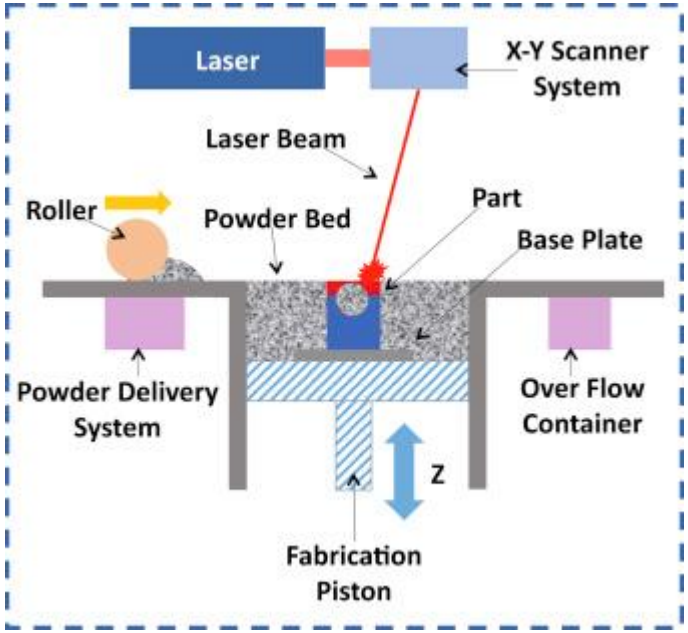
*Nima Shamsaei & Jonathan Pegues*

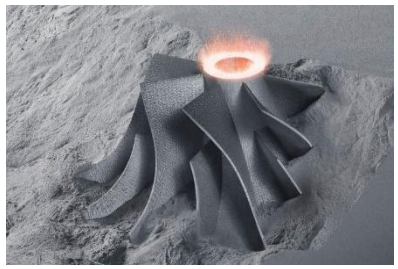
Department of Mechanical Engineering &
National Center for Additive Manufacturing Excellence (NCAME)

# Additive Manufacturing Benefits



- Additive manufacturing?
  - Layer-by-layer fabrication of complex parts
- Customize parts for specific applications
  - Biomedical, aerospace, automotive
- Wider design space
- Manufacture in remote locations
  - Submarines, battlefield, ships, space
- Economic stimulus
  - Restore U.S. leadership in manufacturing



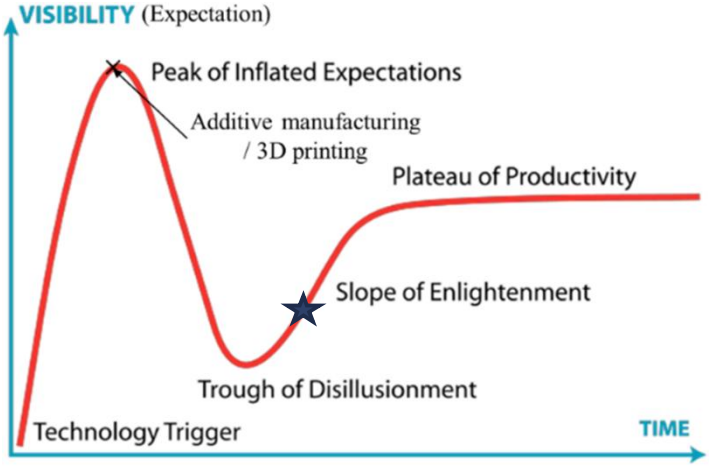



# The Challenges

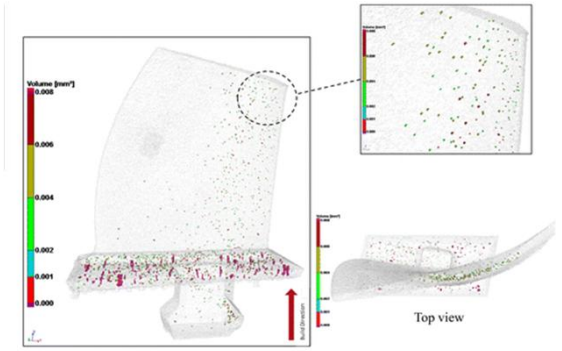
*"Would you fly in an additively manufactured airplane?"*

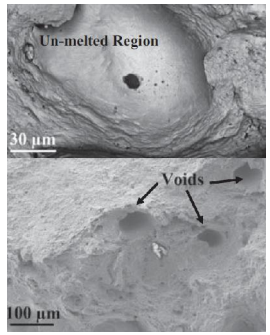


- AM parts are prone to having porosity and imperfections
- Structural integrity of AM parts not known
- Minimal standards and regulations for production and end-parts
- Certification needed
- Demand for an AM-trained workforce
- Industry-wide hesitation




Huang Y, Leu MC, Mazumder J, Donmez A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. ASME. *J. Manuf. Sci. Eng.* 2015;137(1):014001-014001-10. doi:10.1115/1.4028725.



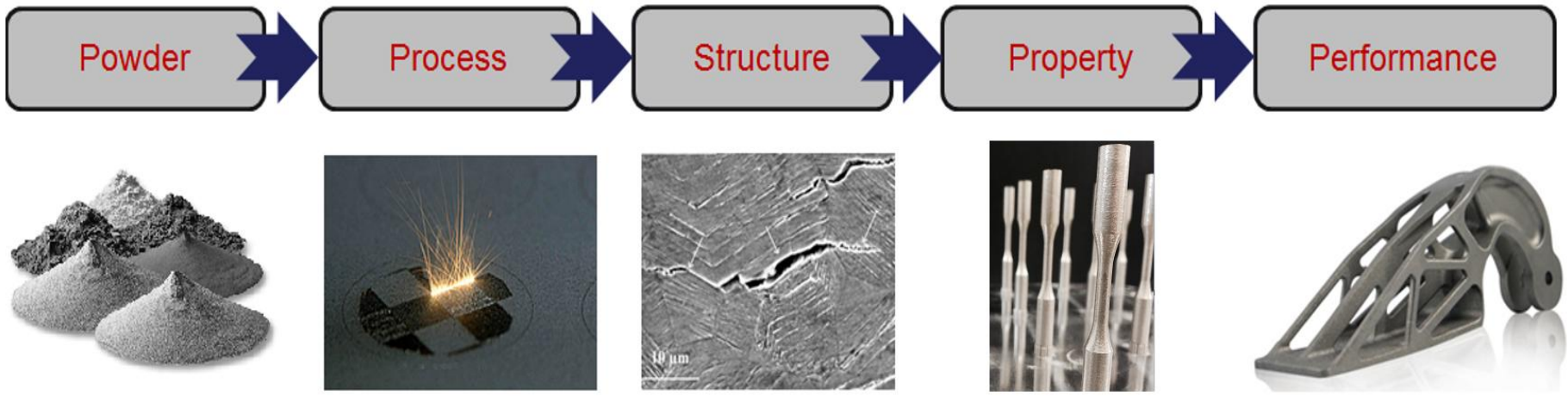

Seifi, M., Gorelik, M., Waller, J., Shamsaei, N., et al. JOM (2017) 69: 439. doi:10.1007/s11837-017-2265-2

# Research



- Challenge: The powder-process-structure-property-performance relationships of AM parts are not well-understood. This lack of understanding delays the adoption of this technology

- Our research focus is to better understand such key relationships



# The Challenges (It Ain't Easy)

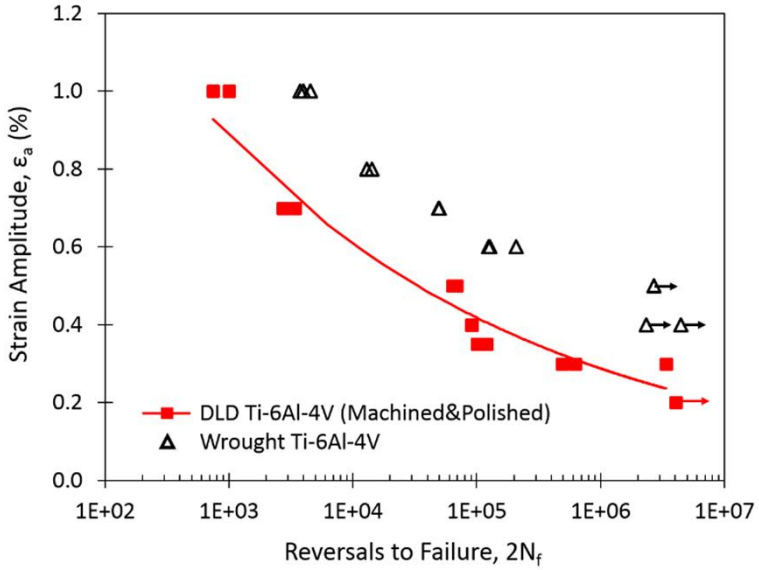


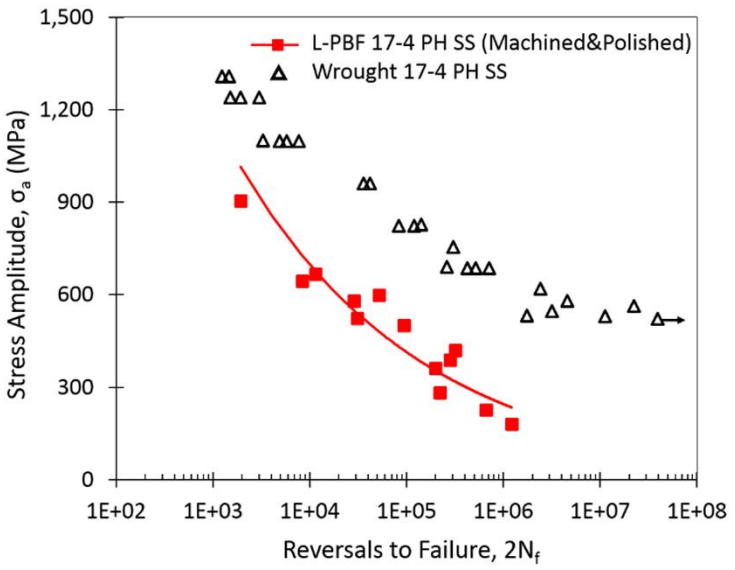
Some challenges of fabricating parts with acceptable structural integrity using additive manufacturing technology:

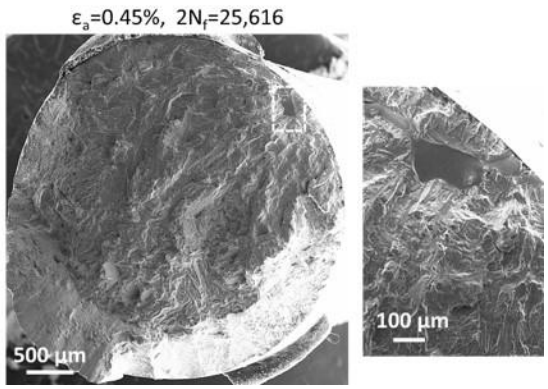
- *Shorter fatigue life*
  - *Process-induced defects*
- *Powder quality*
- *Proper post-processing methods (heat treatment, etc.)*
- *Anisotropy and layer orientation*
- *Surface roughness*
- *Time interval, geometry, and size effect*

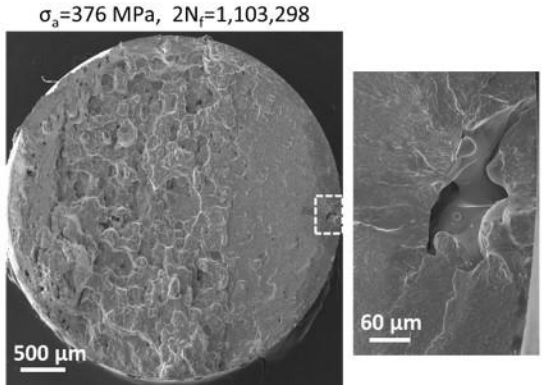
# Challenge: Shorter Fatigue Life





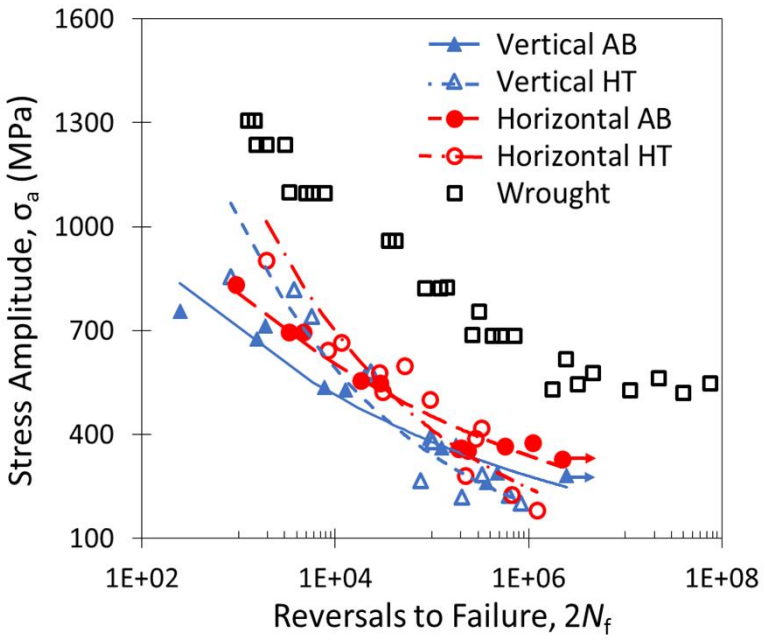

AJ Sterling, B Torries, N Shamsaei, SM Thompson, DW Seely, "Fatigue behavior and failure mechanisms of direct laser deposited Ti–6Al–4V," Materials Science and Engineering: A, 655: 100-112.

A Yadollahi and N Shamsaei, "Additive Manufacturing of Fatigue Resistant Materials: Challenges and Opportunities," International Journal of Fatigue, 98: 14-31, 2017.

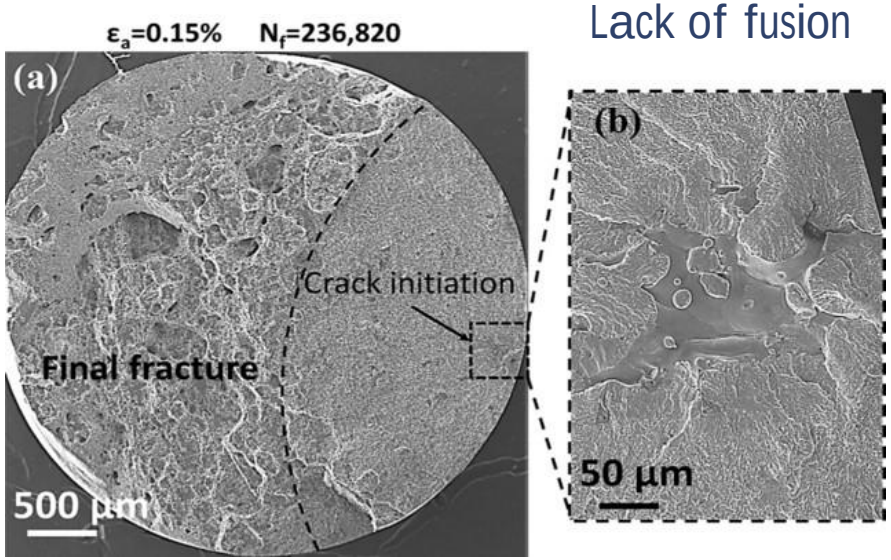
# Challenge: Shorter Fatigue Life



Machined L-PBF 17-4 PH SS




Lack of fusion




(Wrought data from NASA)

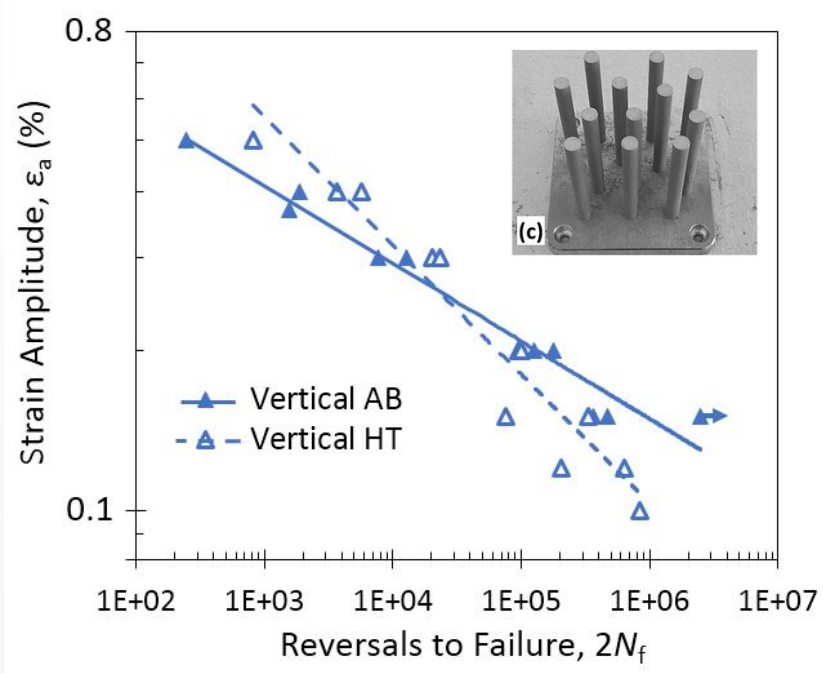
- *Much shorter fatigue lives for AM specimens (99.2% density)*
- *Cracks initiate from near surface defects*

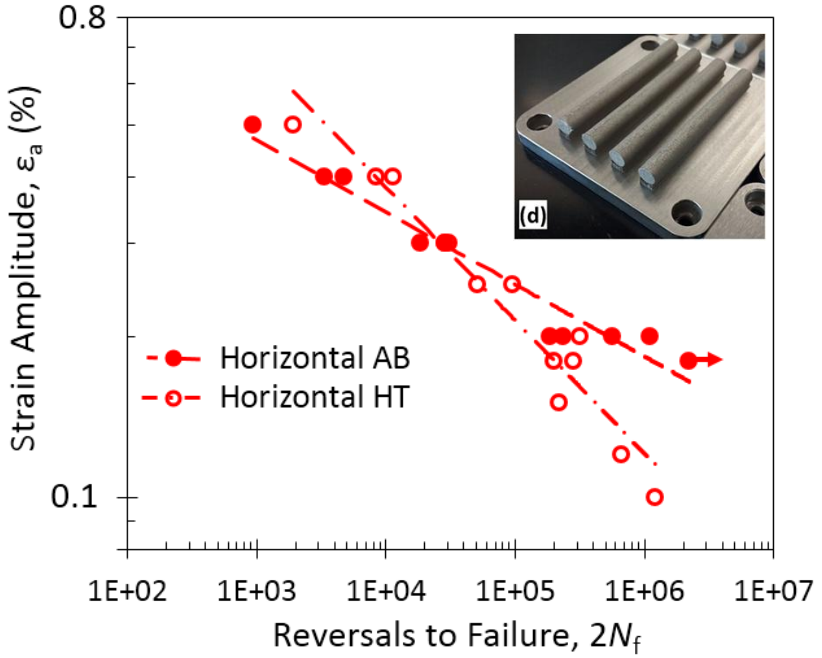
A Yadollahi, N Shamsaei, SM Thompson, A Elwany, L Bian, "Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel," International Journal of Fatigue, Vol. 94, pp. 218-235, 2017.

# Challenge: Heat Treatment



Machined L-PBF 17-4 PH SS



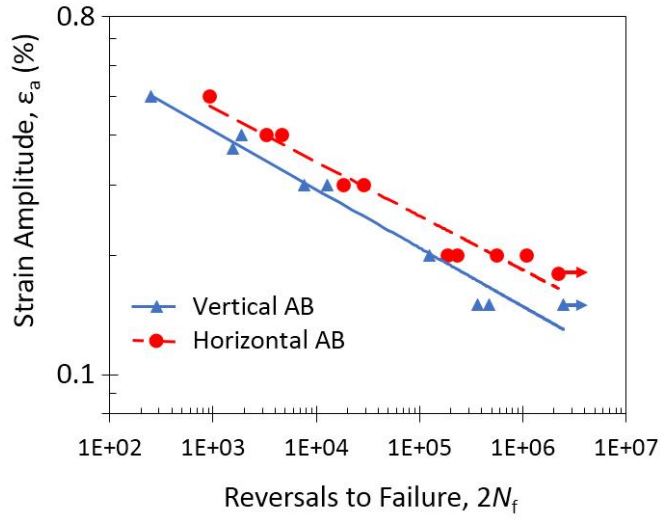

- *Heat treatment did not improve fatigue resistance in long life regime*
- *Heat treatment procedures may need to be revised for AM parts*

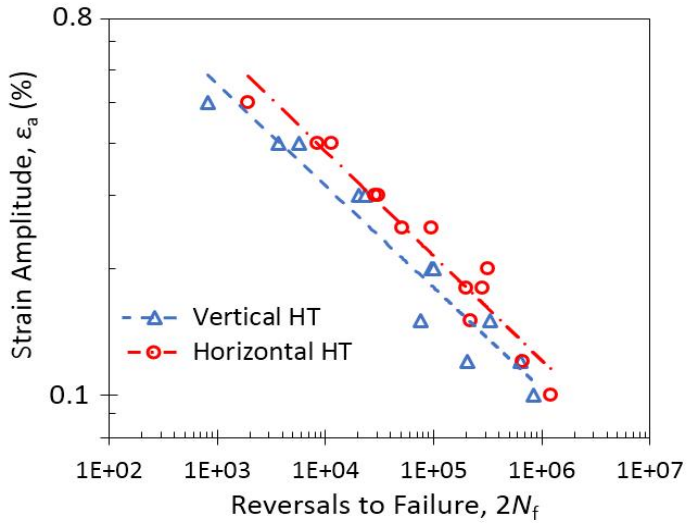
A Yadollahi, N Shamsaei, SM Thompson, A Elwany, L Bian, "Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel," International Journal of Fatigue, Vol. 94, pp. 218-235, 2017.

# Challenge: Anisotropy (Build Orientation)

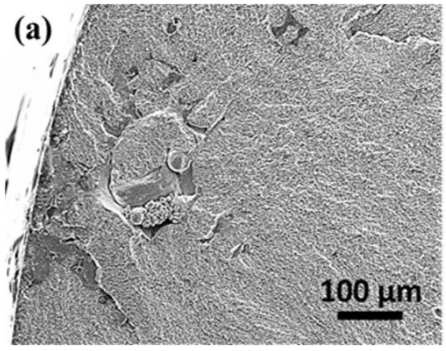


Machined L-PBF 17-4 PH SS

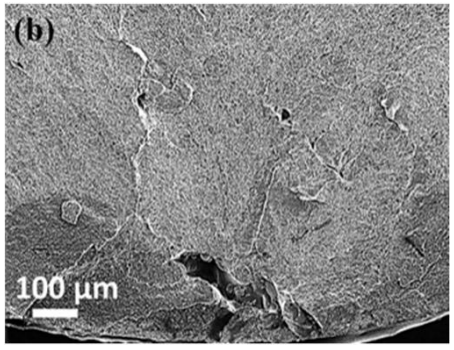


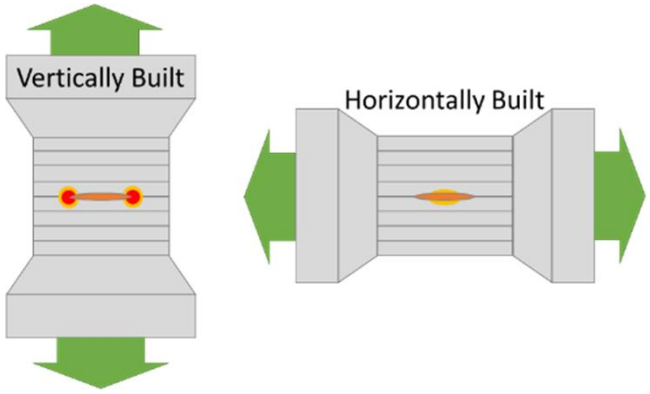




Vertical




Horizontal

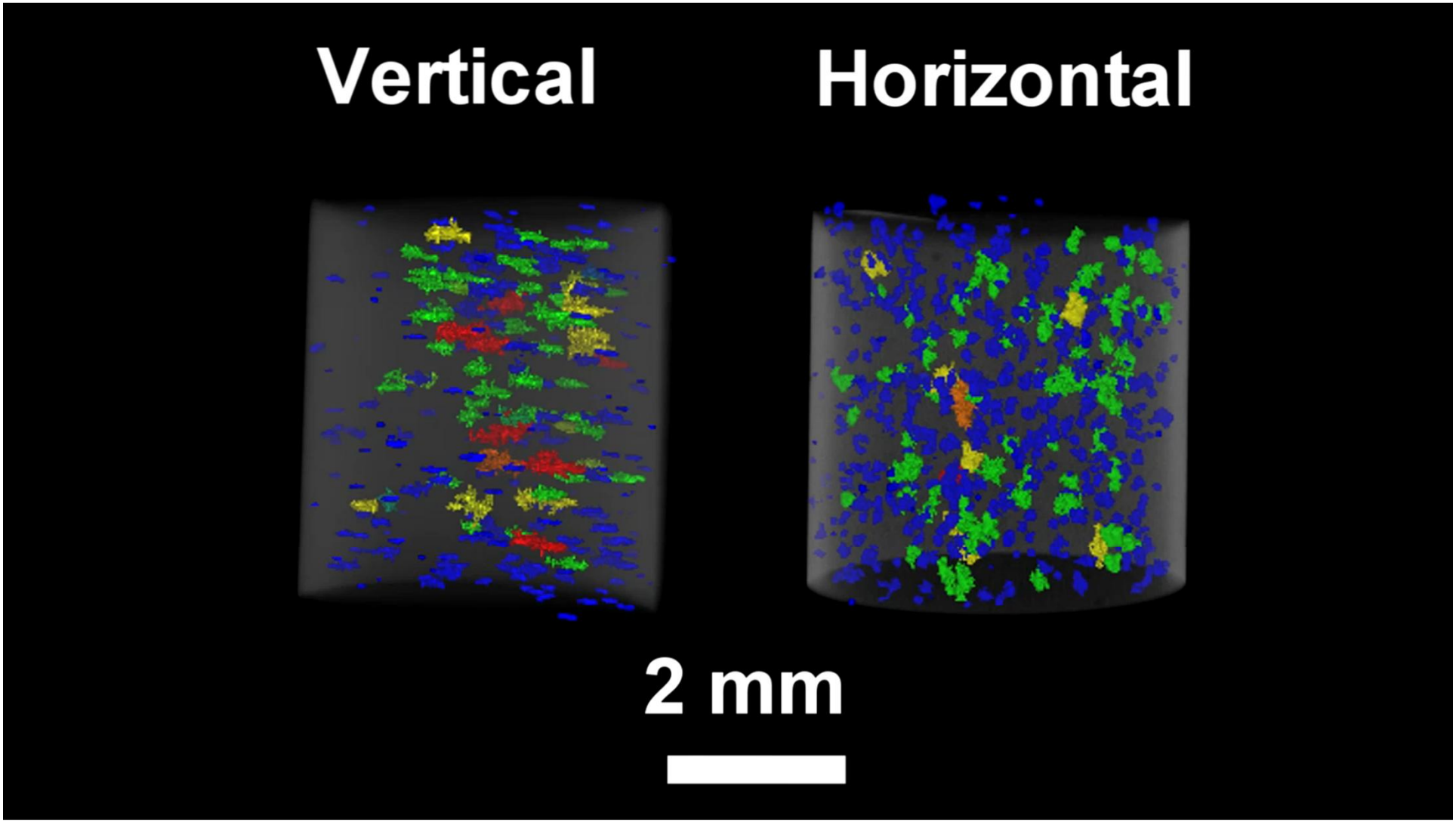



A Yadollahi, N Shamsaei, SM Thompson, A Elwany, L Bian, "Effects of building orientation and heat treatment on fatigue behavior of selective laser melted 17-4 PH stainless steel," International Journal of Fatigue, Vol. 94, pp. 218-235, 2017.

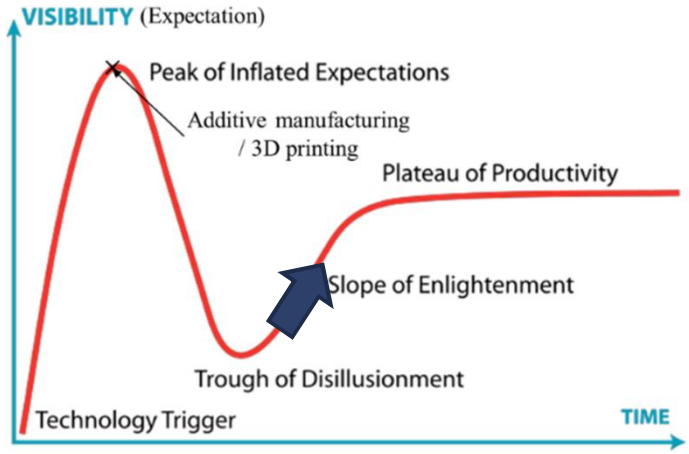
# Challenge: Anisotropy (Build Orientation)



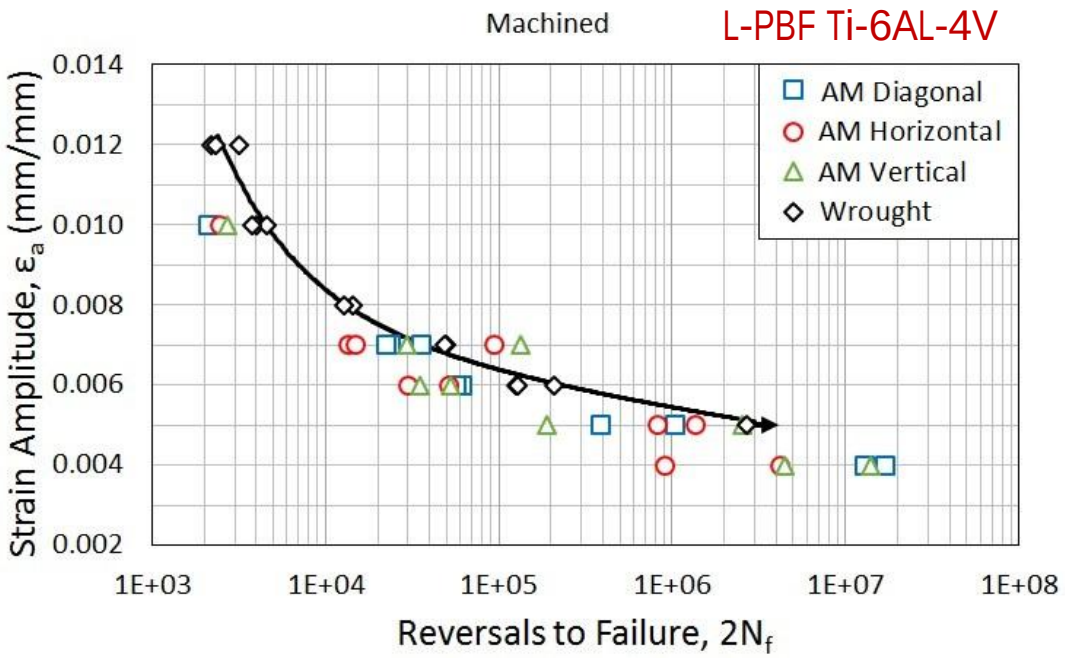


# Challenge: Anisotropy





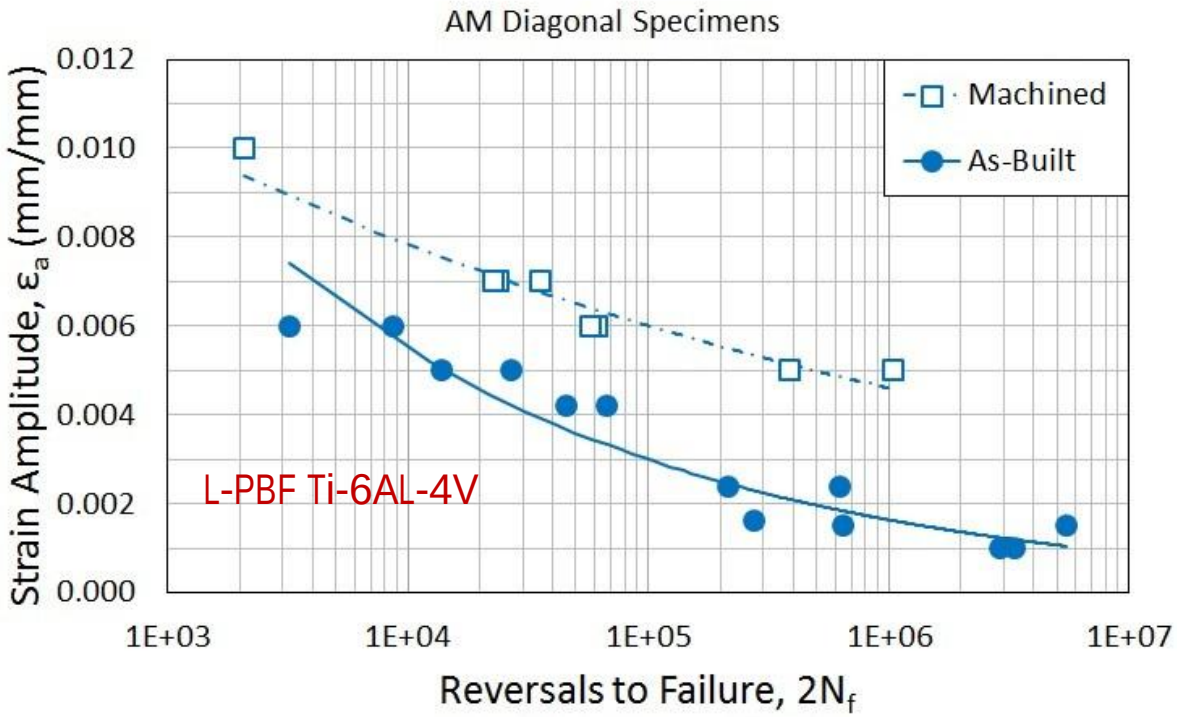

Huang Y, Leu MC, Mazumder J, Donmez A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. ASME. *J. Manuf. Sci. Eng.* 2015;137(1):014001-014001-10. doi:10.1115/1.4028725.




- Anisotropy also depends on material and equipment
- Fatigue life can also improve significantly

# Challenge: Surface Roughness





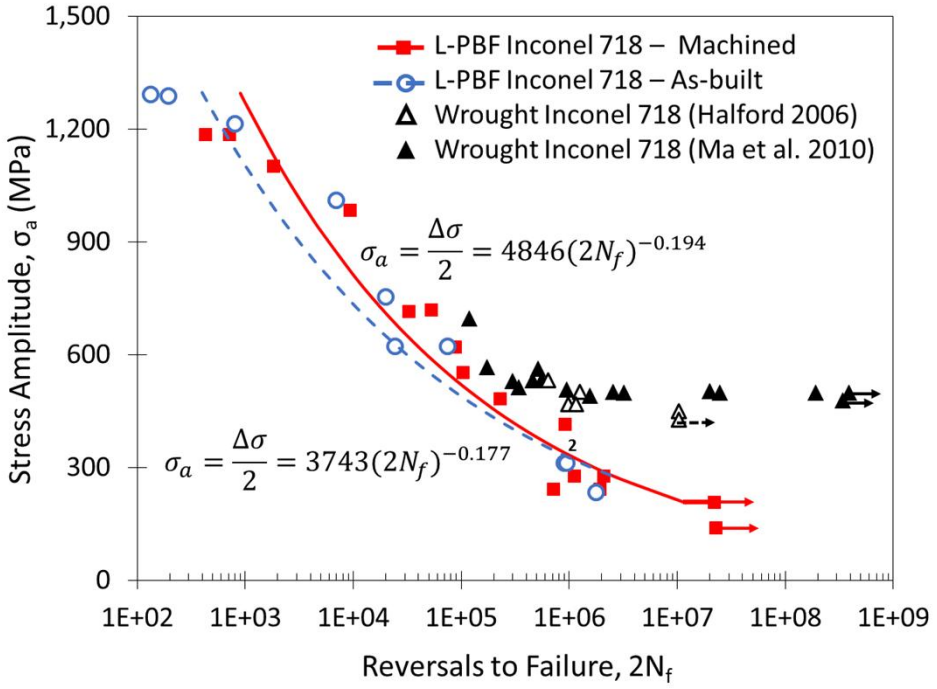

- Applications in which post process machining is not applicable
- Fatigue life may be affected drastically by surface roughness, which is typical to AM processes
- However, the promise of AM is to minimize post-processing steps

# Challenge: Surface Roughness

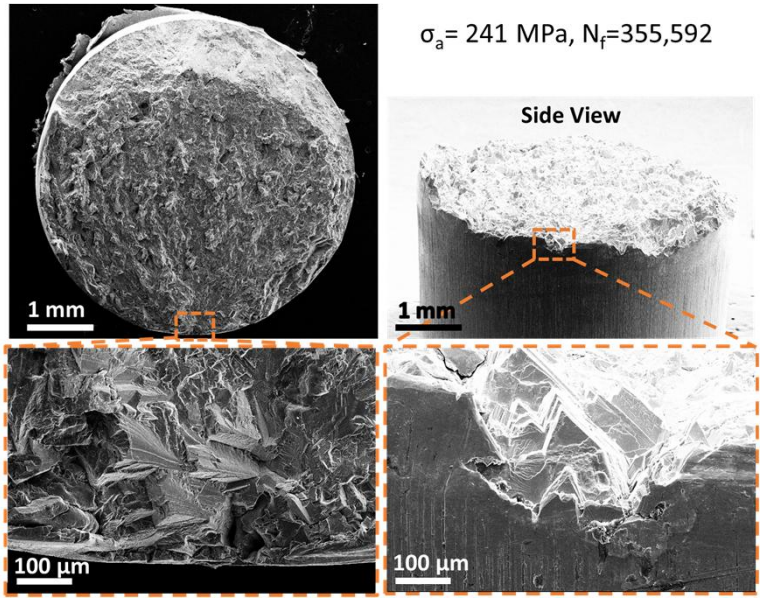


*Effect of Surface Finish*

L-PBF Inconel 718

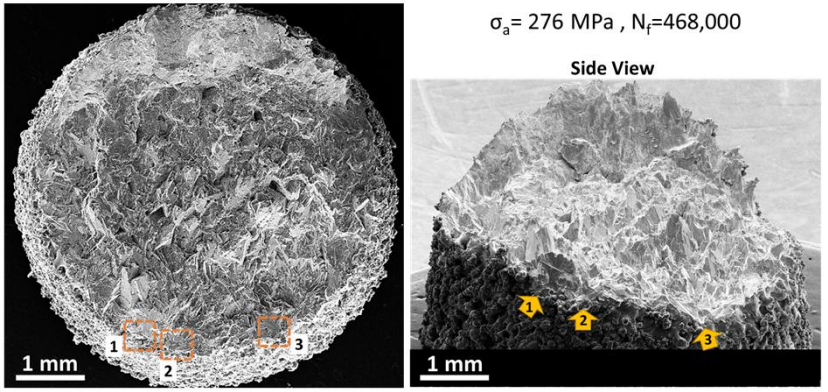



Machined




$\sigma_a$= 241 MPa, $N_f$=355,592

As-built



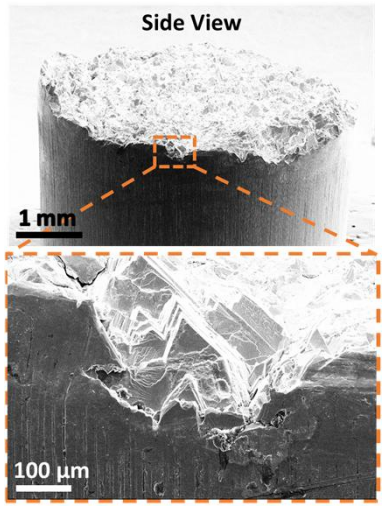

$\sigma_a$= 276 MPa , $N_f$=468,000

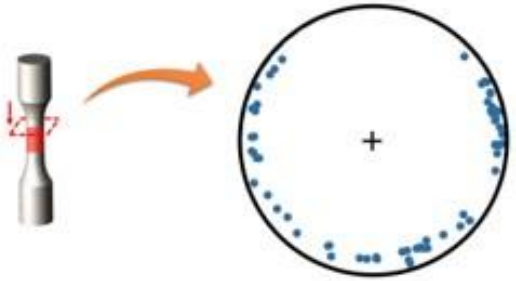
# Challenge: Machining Depth

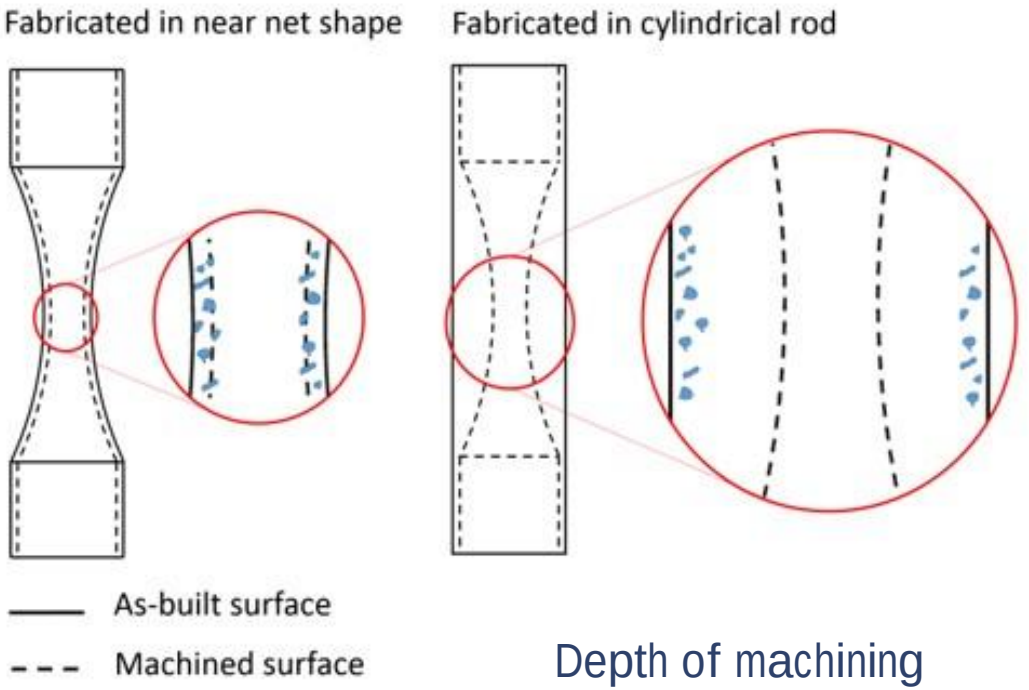


Machined
L-PBF Inc 718

$\sigma_a$= 241 MPa, $N_f$=355,592



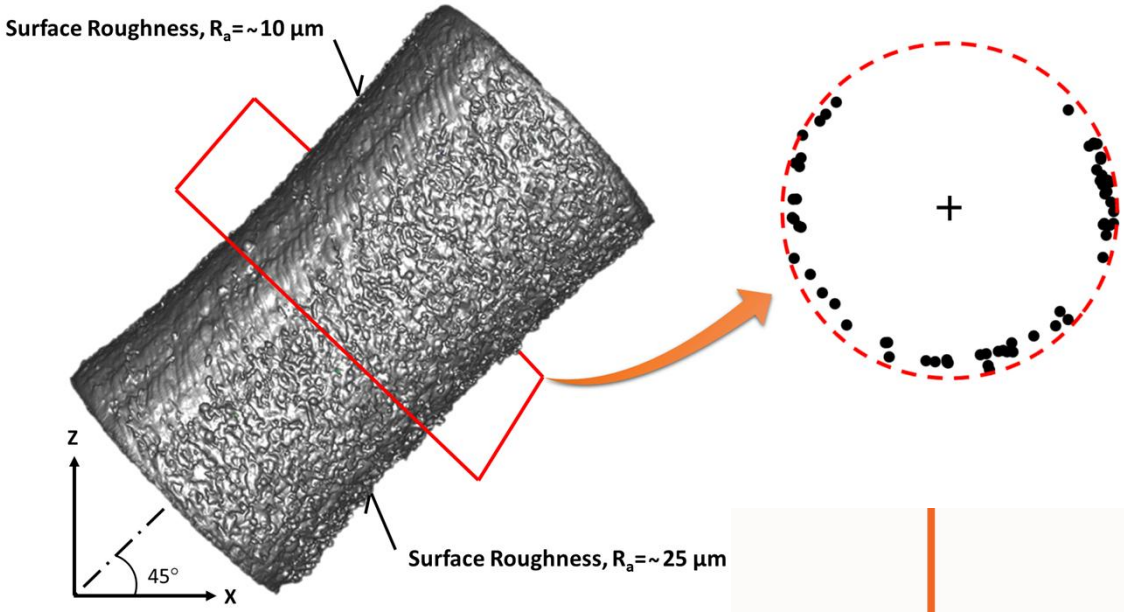


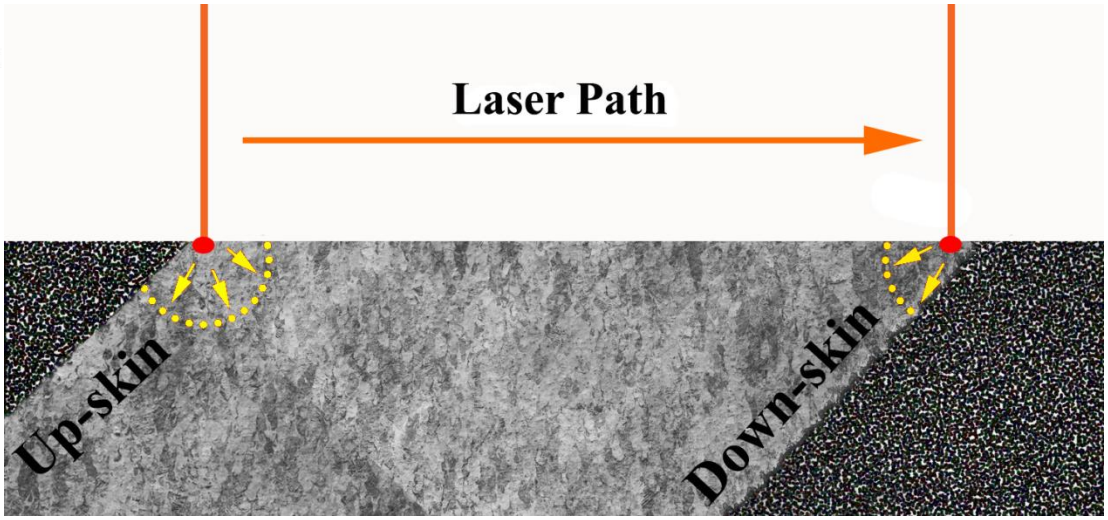

Depth of machining

A Yadollahi and N Shamsaei, "Additive Manufacturing of Fatigue Resistant Materials: Challenges and Opportunities," International Journal of Fatigue, Vol. 98, pp. 14-31, 2017.

# Challenge: Surface Roughness



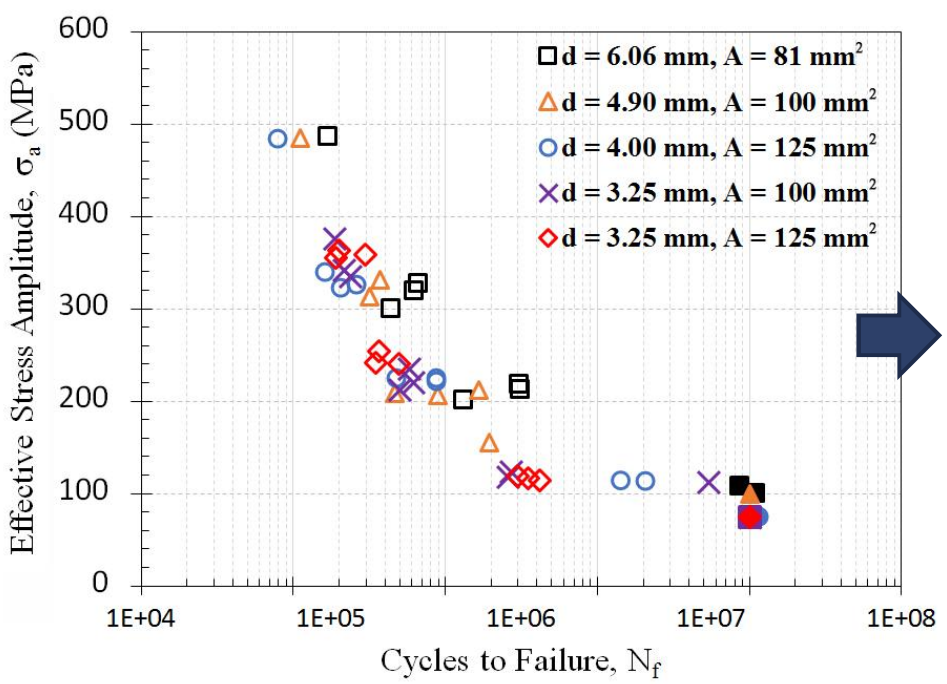


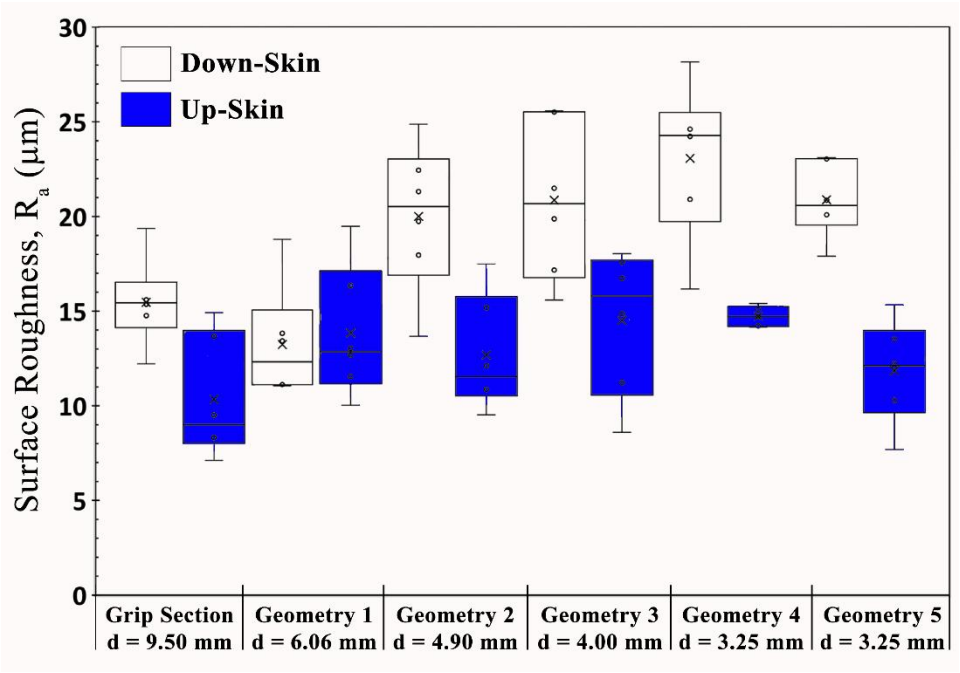




Geometry/shape matters

# Challenge: Surface Roughness





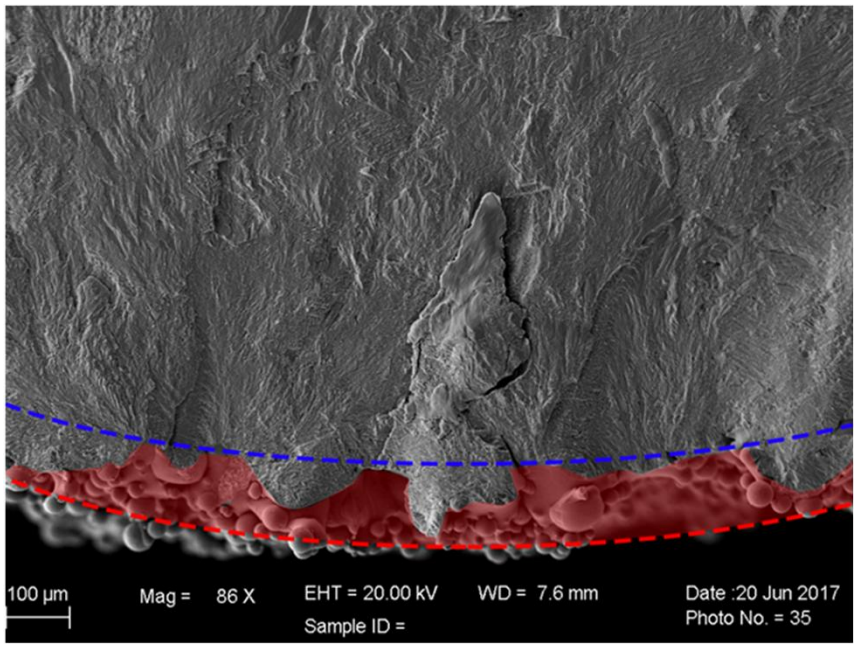

- Specimens were fabricated at 45° angle (diagonal)
- Small diameters (d £ 4.90 mm) showed similar down-skin surface roughness
- Largest diameter resulted in lower roughness which lead to improved fatigue resistance

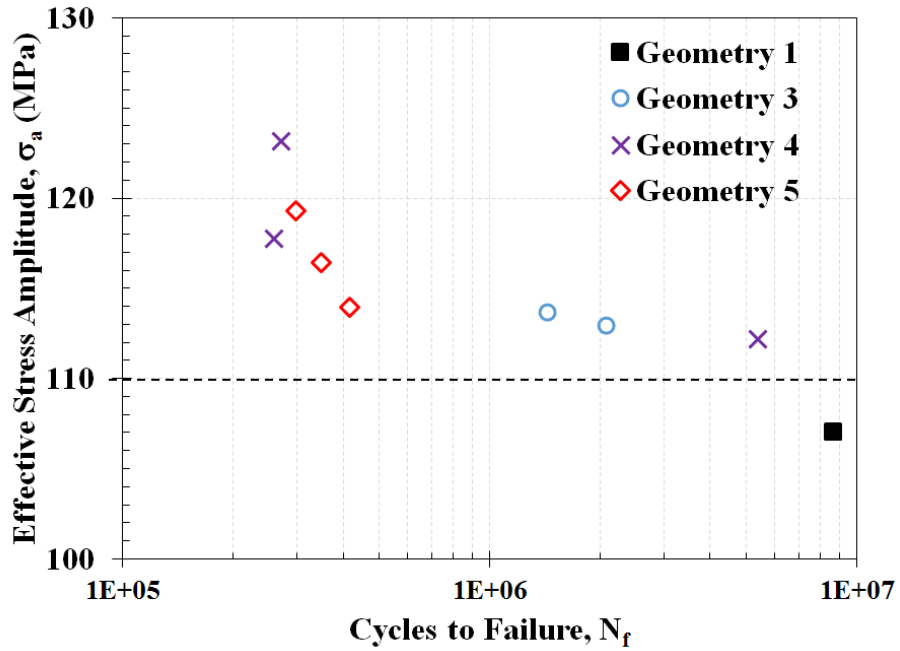
J Pegues, M Roach, R S Williamson, & N Shamsaei, "Surface Roughness Effects on the Fatigue Strength of Additively Manufactured Ti-6Al-4V," International Journal of Fatigue, Accepted 2018.

# Challenge: Surface Area/Roughness



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



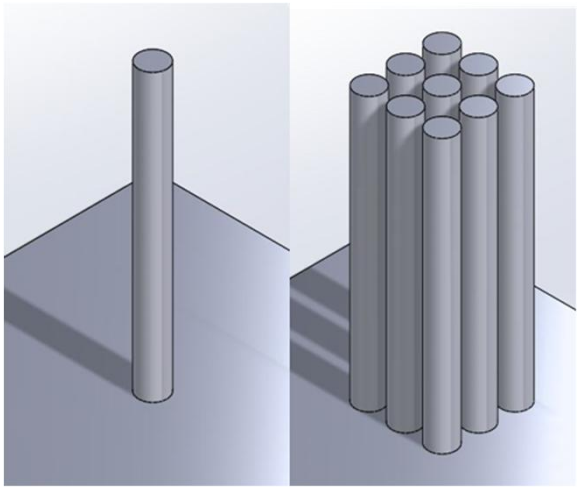



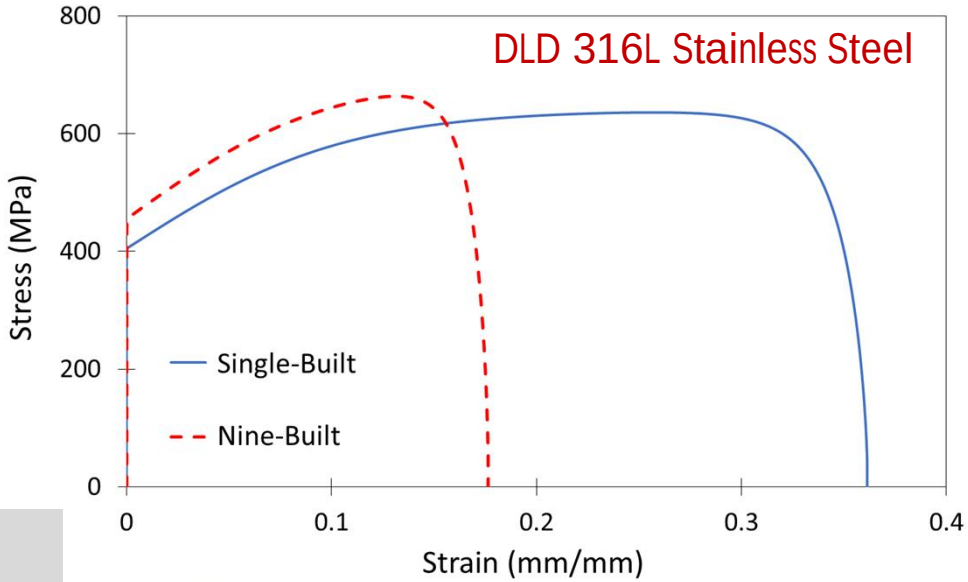

- As gage diameter decreases the differences in nominal gage diameter & effective diameter increases
- Applied stress amplitudes were greater for smaller diameter specimens resulting in the large scatter observed for high cycle fatigue data

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, Accepted 2018.

# Challenge: Time Interval, Size & Geometry








*For a given set of process parameters, parts fabricated together have different properties*

*Need for establishing property-performance relationships (need for standards)*

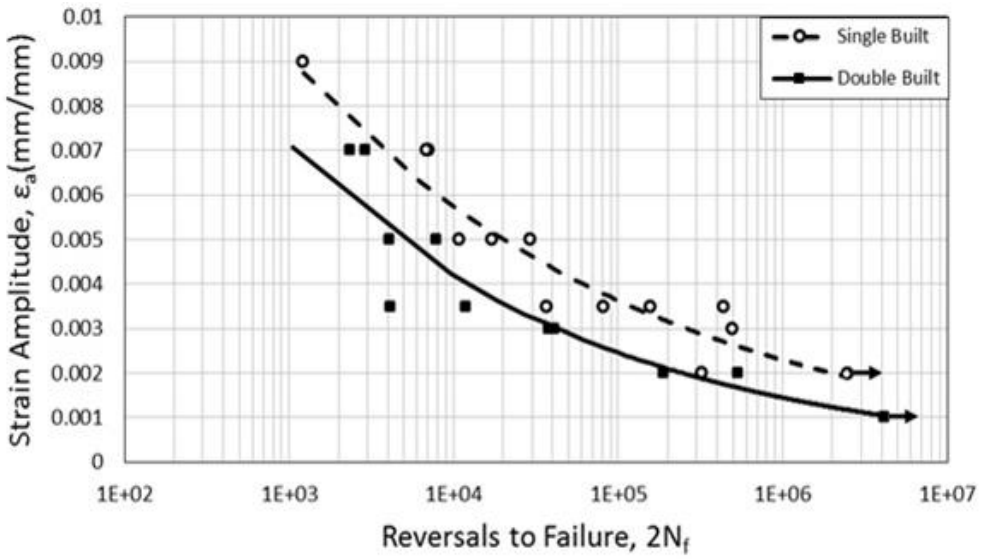
*Structure-property relationships need to be established as well*

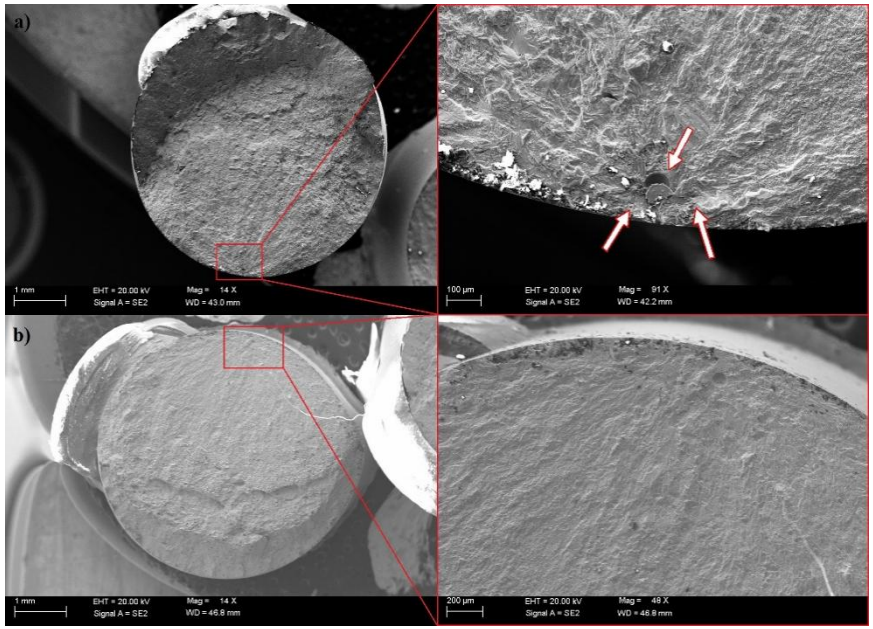

A Yadollahi, N Shamsaei, SM Thompson, D Seely, "Effects of time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel," Materials Science and Engineering A, Vol. 644, pp. 171-183, 2015.

# Challenge: Time Interval, Size & Geometry



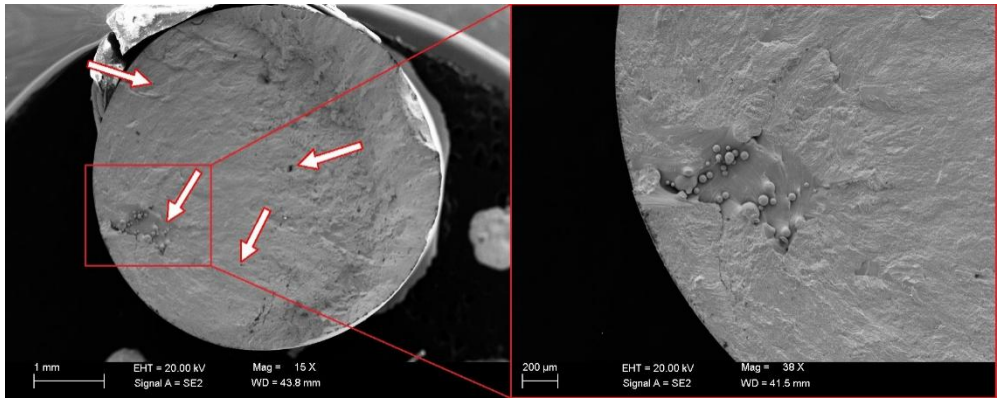
Machined DLD Ti-6Al-4V




Single Built

Double Built




*Need for establishing property-performance relationships (need for standards)*

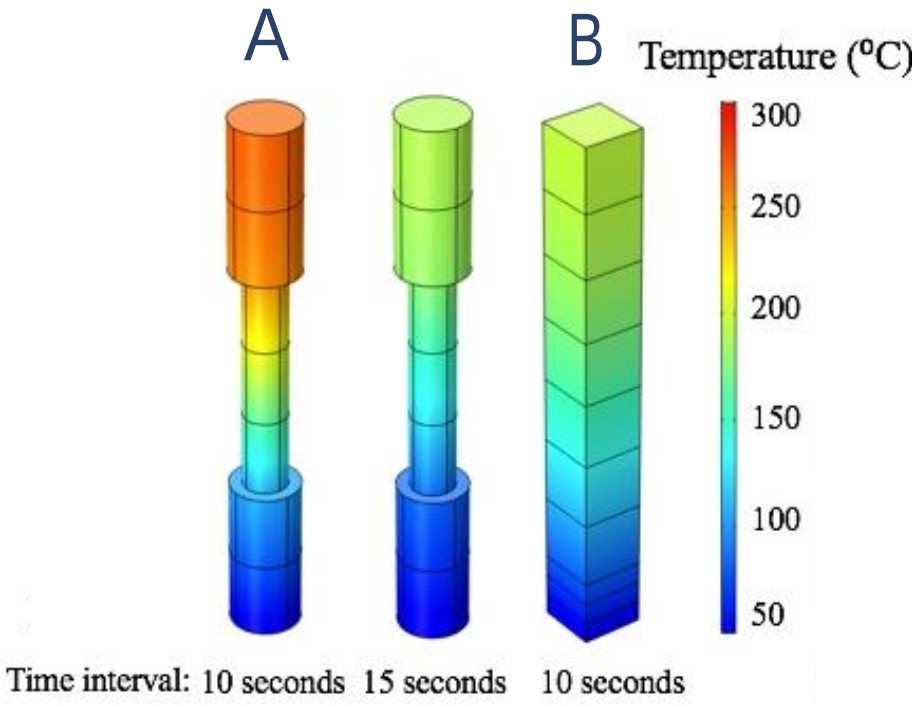
B Torries, N Shamsaei, "Fatigue Behavior and Modeling for Additively Manufactured Ti-6Al-4V Including the Inter-Layer Time Interval Effects," JOM, Vol. 69, pp. 2698-2705, 2017.

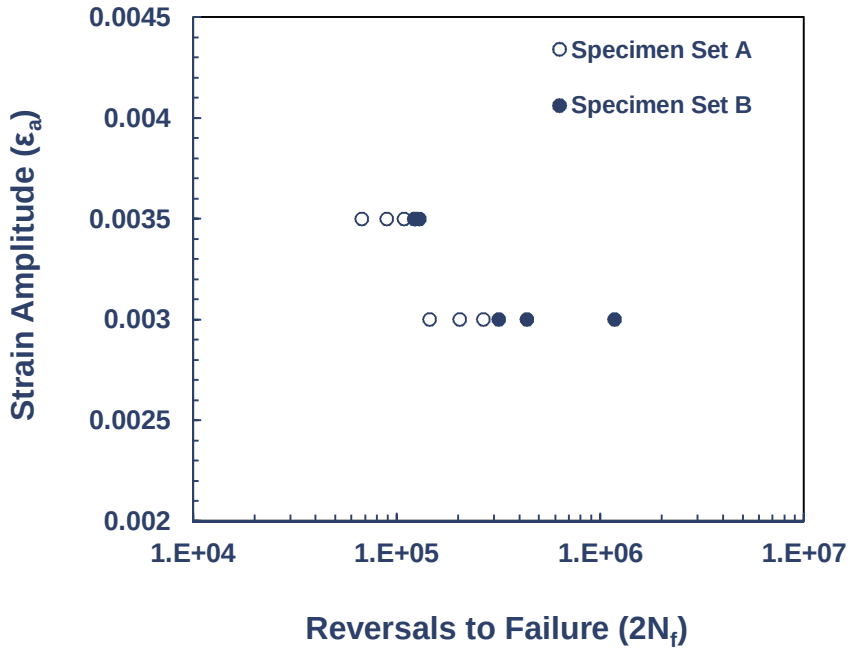
# Challenge: Time Interval, Size & Geometry



- Temperature response, and thus cooling rate, is dependent on part size and shape for the same process parameters
- Parameters found optimal for specimens do not provide similar thermal histories for various size/shape components

Specimen → Component



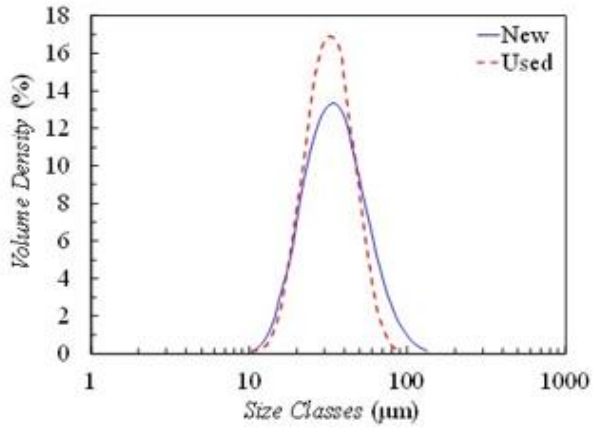



# Challenge: Powder Quality

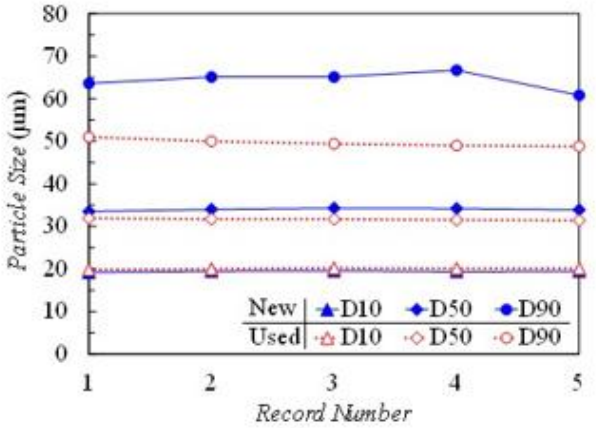


- Used powder is reconditioned by sieving and reintroducing into new powder.
- The quality of powder and the number of times it has been recycled may also effect the fatigue behavior.
- Particle size distribution narrows after powder reconditioning affecting flowability of powder.

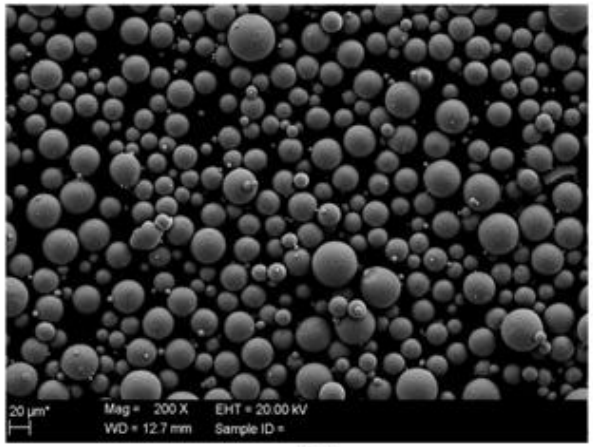
L-PBF Ti-6Al-4V



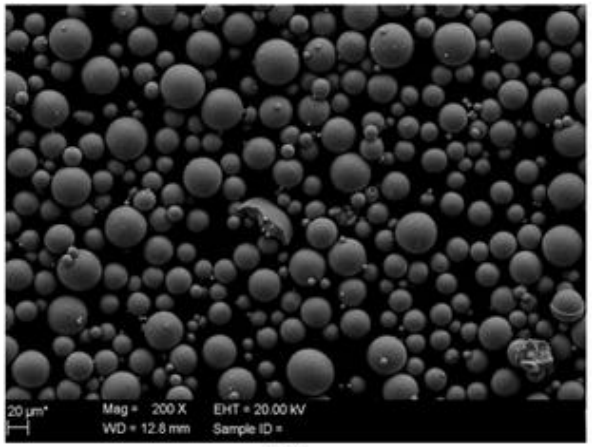

(a)




(b)



(c)

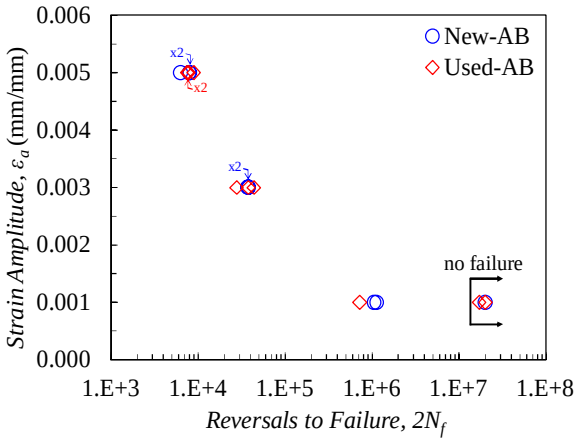


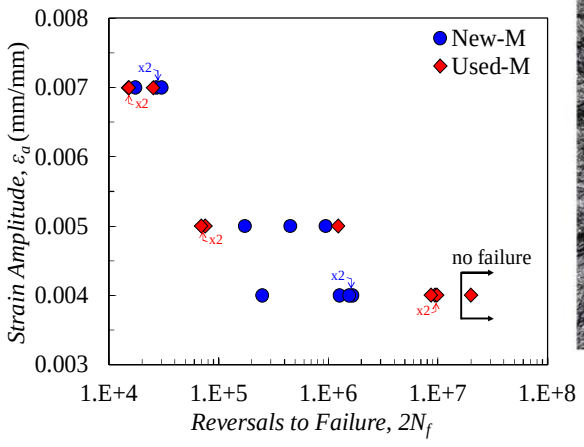
(d)

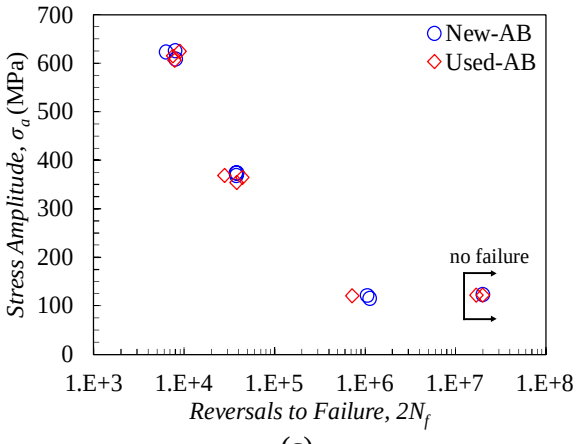
# Challenge: Powder Quality

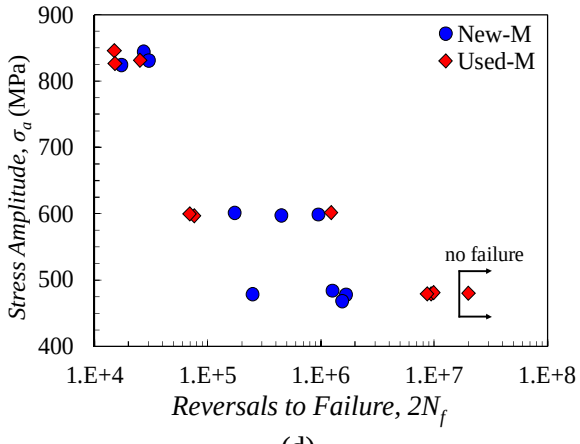


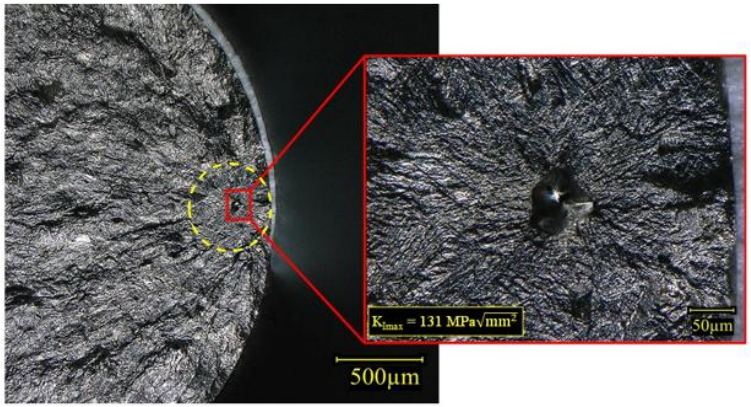
L-PBF Ti-6Al-4V



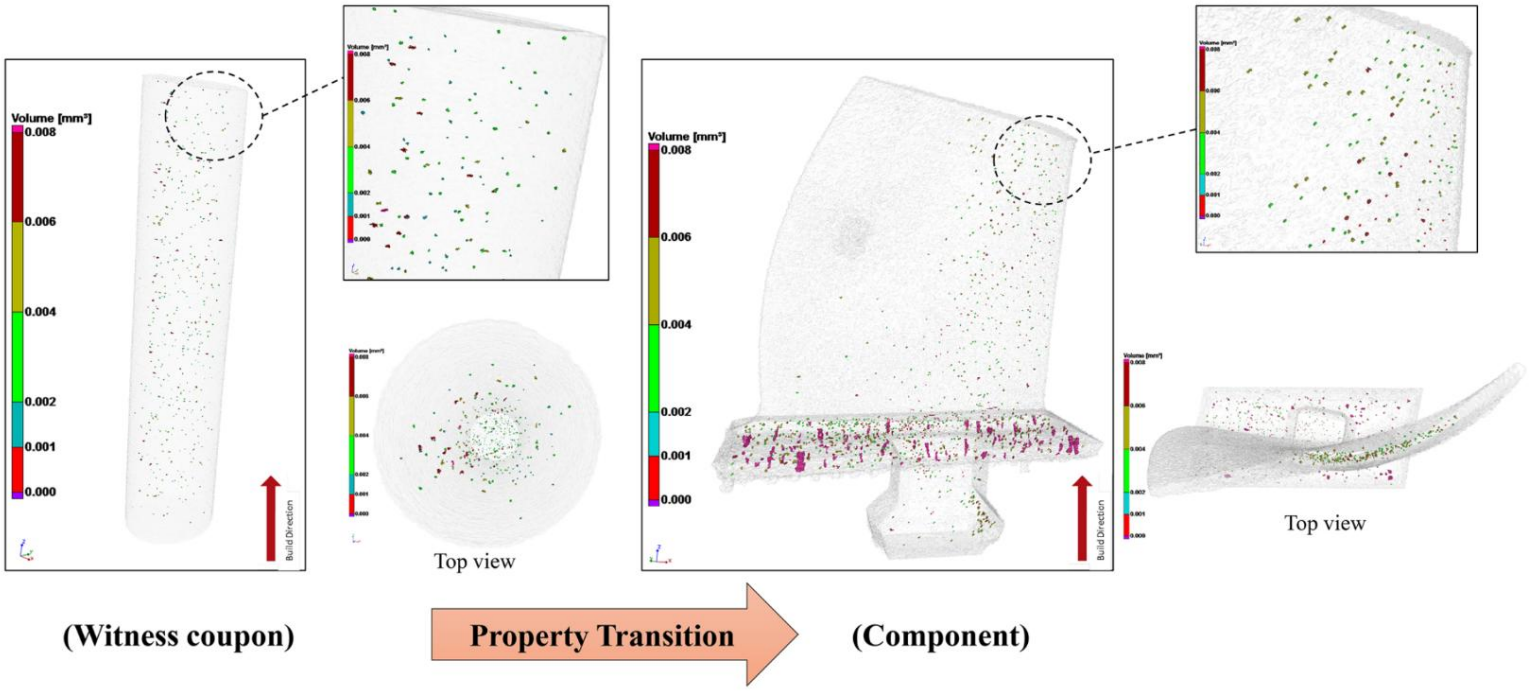




- Specimens fabricated with used powder had better fatigue resistance in the long life regime!
- Better flowability correlated with smaller defects and improved fatigue resistance in the HCF.

# Challenges






*Need for establishing specimen property-part performance relationships (need for developing appropriate standards for AM) to address:*

- Porosity
- Geometry / size
- Time intervals
- Build orientation
- Surface roughness
- Depth of machining
- Heat treatments
- Powder, and more

M Seifi, M Gorelik, J Waller, N Hrabe, N Shamsaei, S Daniewicz, JJ Lewandowski, "Progress Towards Metal Additive Manufacturing Standardization to Support Qualification and Certification," JOM, Vol. 69, pp. 439–455, 2017.

# Summary

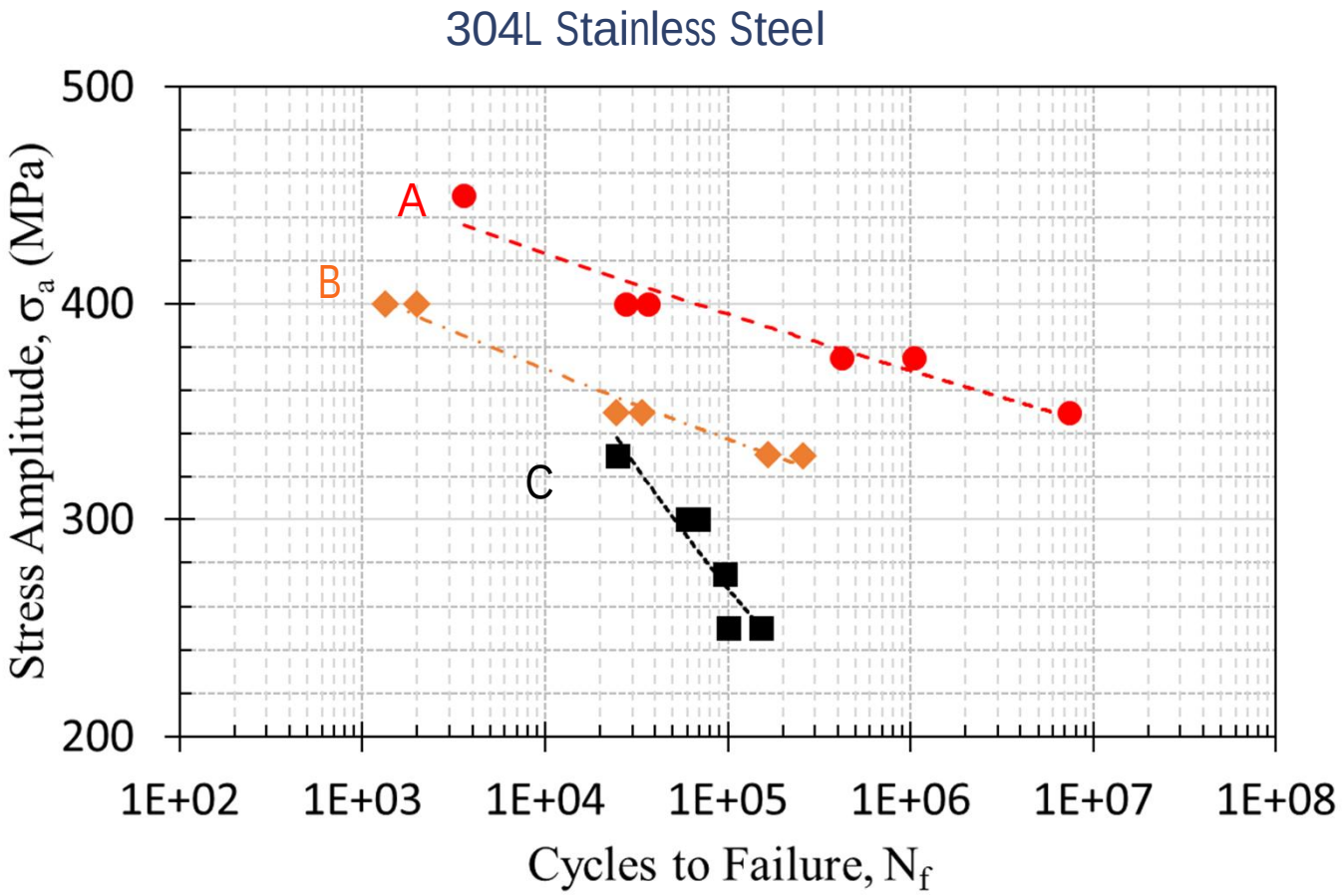


- Additive Manufacturing provides opportunities and risks.
- Fatigue resistance is one of the major challenges against the widespread adoption of AM parts.
- Establishing the powder-process-structure-property-performance relationships of AM materials is vital to minimize their manufacturing-induced defects and improve their reliability.
- Mechanical testing methods, design procedures, etc. need to be standardized.
- Specimen properties may not be applied directly to determine component performance due to different thermal histories. Thus, establishing property-performance relationships is vital.

# Quiz!



Label the fatigue curves as: wrought, AM machined/polished, and AM as-built




A)

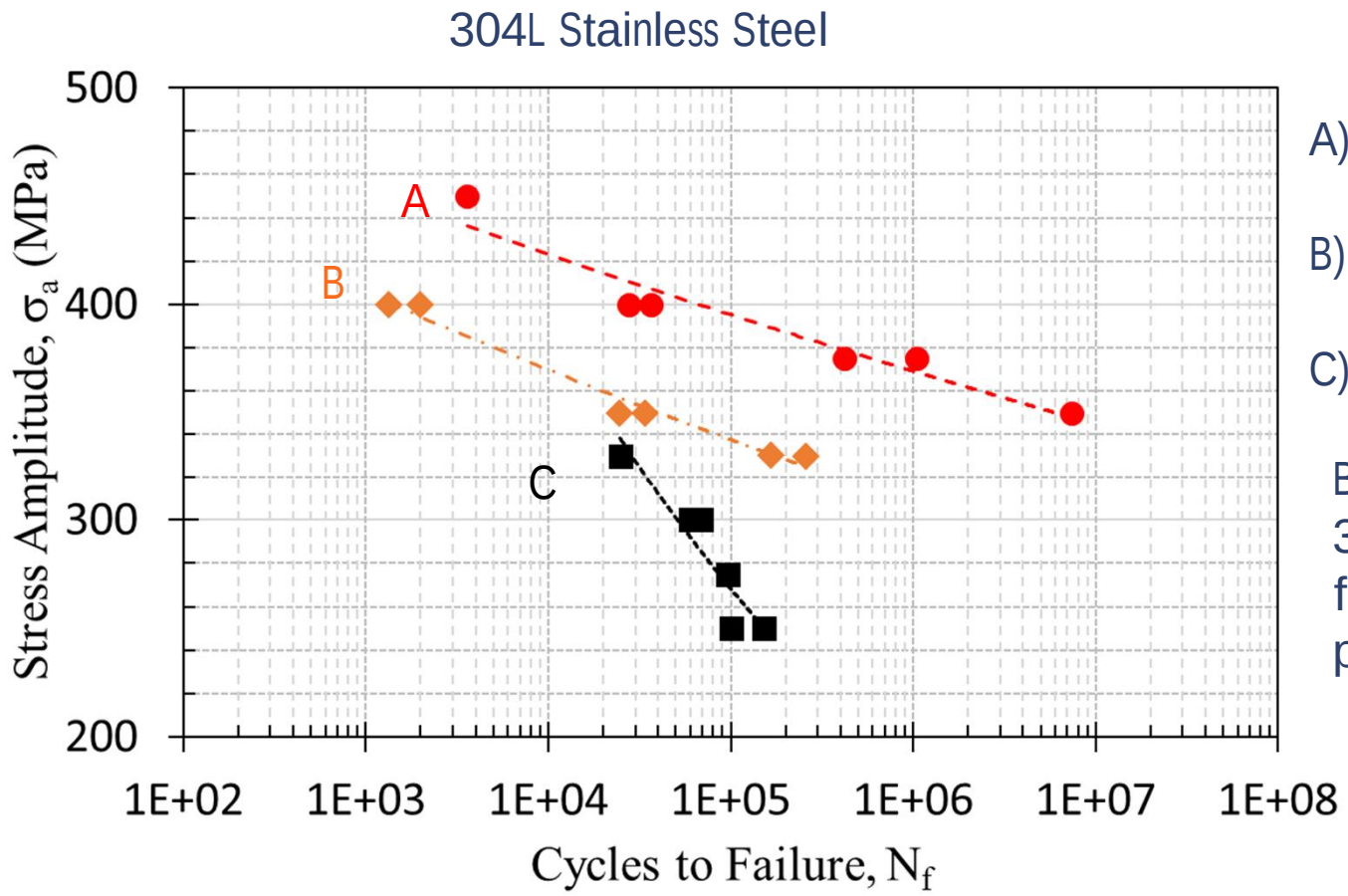
B)

C)

# Quiz! - Answer



Label the fatigue curves as wrought, AM machined/polished, and AM as-built




A) AM-Machined/Polished

B) Wrought

C) AM as-built

Because of microstructure 304L SS shows better fatigue resistance despite porosity!

# Thank You

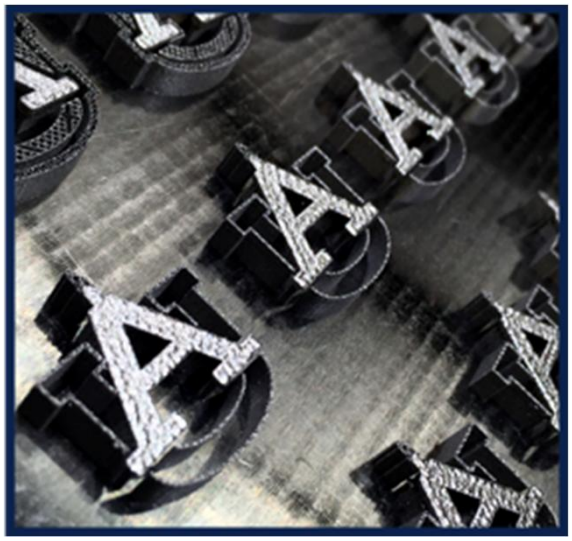



- Funding from National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), Department of Defense, Naval Air Systems Command (NAVAIR), ASTM International, TDA Inc., and AlphaSTAR Inc. is greatly appreciated.


- Thank you all for your attention!


*Contact info:* *Jonathan Pegues*

jwp0040@auburn.edu
www.eng.auburn.edu/ncame

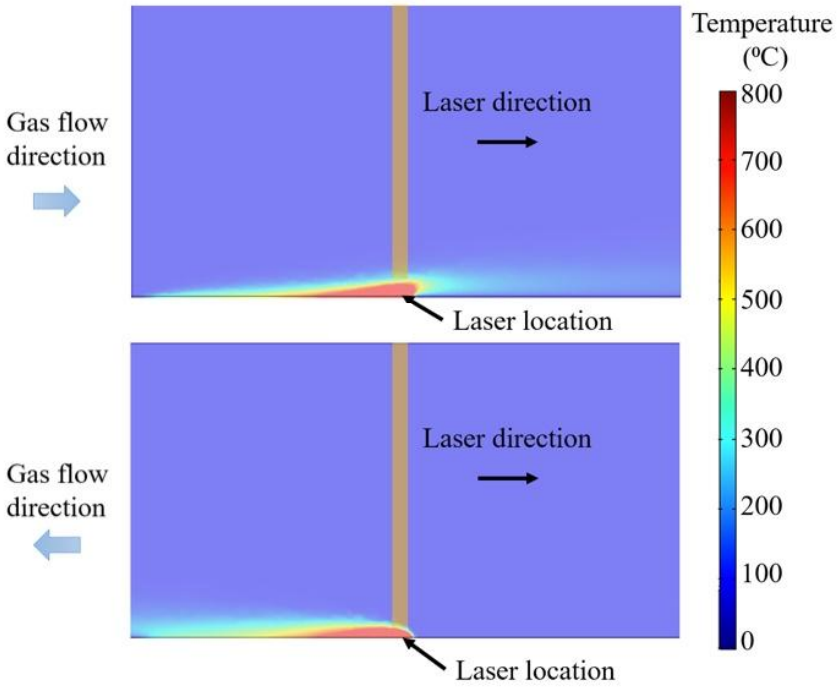



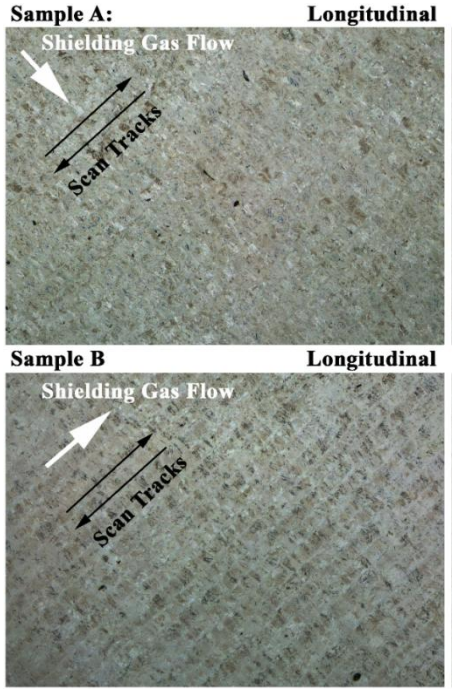

THIS IS TRADITION.
THIS IS SPIRIT.
THIS IS PASSION.
THIS IS AUBURN.

# Challenge: Shielding Gas



- During fabrication, when the shielding gas flows in the same direction as the laser movement, pre-heated gas is pushed in front of the melt pool and decreases the temperature gradient
  - Resulting in variations in residual stress and/or microstructure




M Masoomi, J Pegues, SM Thompson, N Shamsaei, "Effects of shielding gas flow on heat transfer during laser-powder bed fusion of Ti-6Al-4V," Addit. Manuf., 2018.

| Direction | Sample A | Sample B |
|---|---|---|
| Transverse 0° | 84.6 µm | 94.2 µm |