HENRY O. FUCHS STUDENT AWARD

Fatigue Behavior of Additively Manufactured Materials: Challenges & Opportunities

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November 2nd, 2022

Outline

- Background
- Additive Manufacturing (AM) Snapshot
- Challenges with Fatigue of AM Materials
- Opportunities to improve Fatigue of AM Materials
- Summary
- Achievements

Background

Lead Additive Manufacturing Specialist
(2022-Current)

-Process Engineer
-Material and Machine Qualification

Ph.D. in Mechanical Engineering
(2017-2022)

Establishing the Process-Structure-Property of Additively Manufactured Materials

M.Sc. in Materials Science and Engineering
(2013-2016)

Developing Low-Density Steels and Investigating Their Thermo-Mechanical Behavior

B.Sc. in Materials Science and Engineering
(2009-2013)

Thermo-Mechanical Processing of TWIP Steels

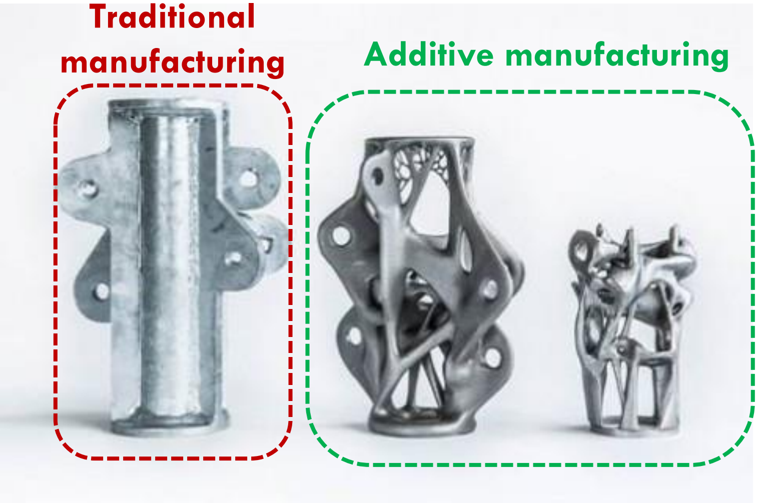
Additive Manufacturing (AM) Snapshot

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

- Fabricate complex geometries
  - Convert assemblies to integrated parts
  - Customize parts for specific applications
- Repair expensive parts
- Fabricate parts on demand

Metals additive manufacturing

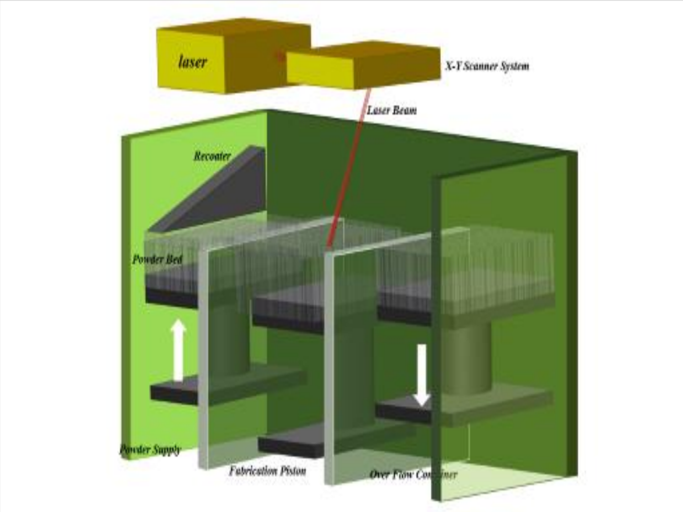
- Powder and/or wire feedstock
- Laser or electron beam energy source



http://www.arup.com/

Laser-Powder Bed Fusion (L-PBF)

https://3dprint.com/52354/3d-



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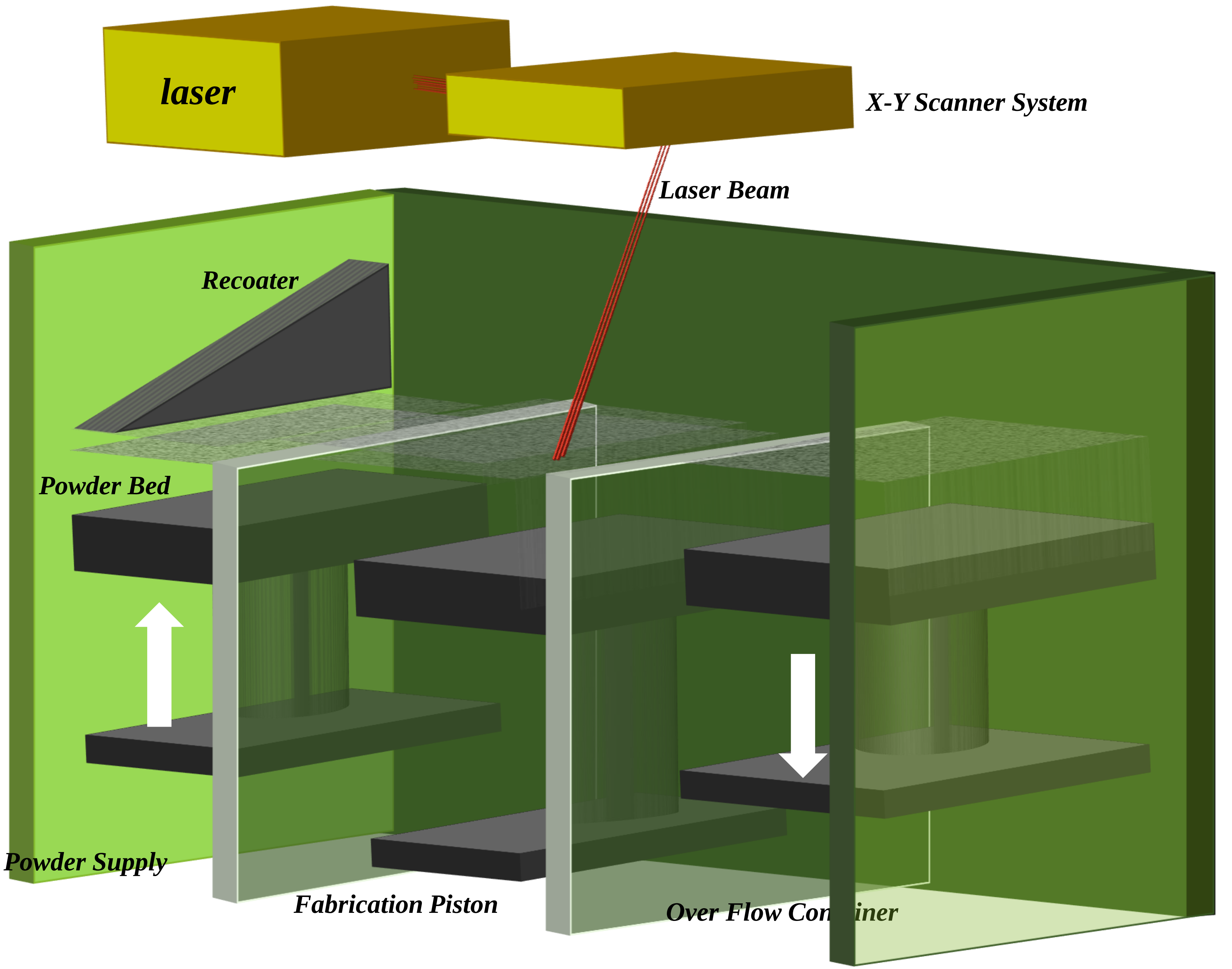
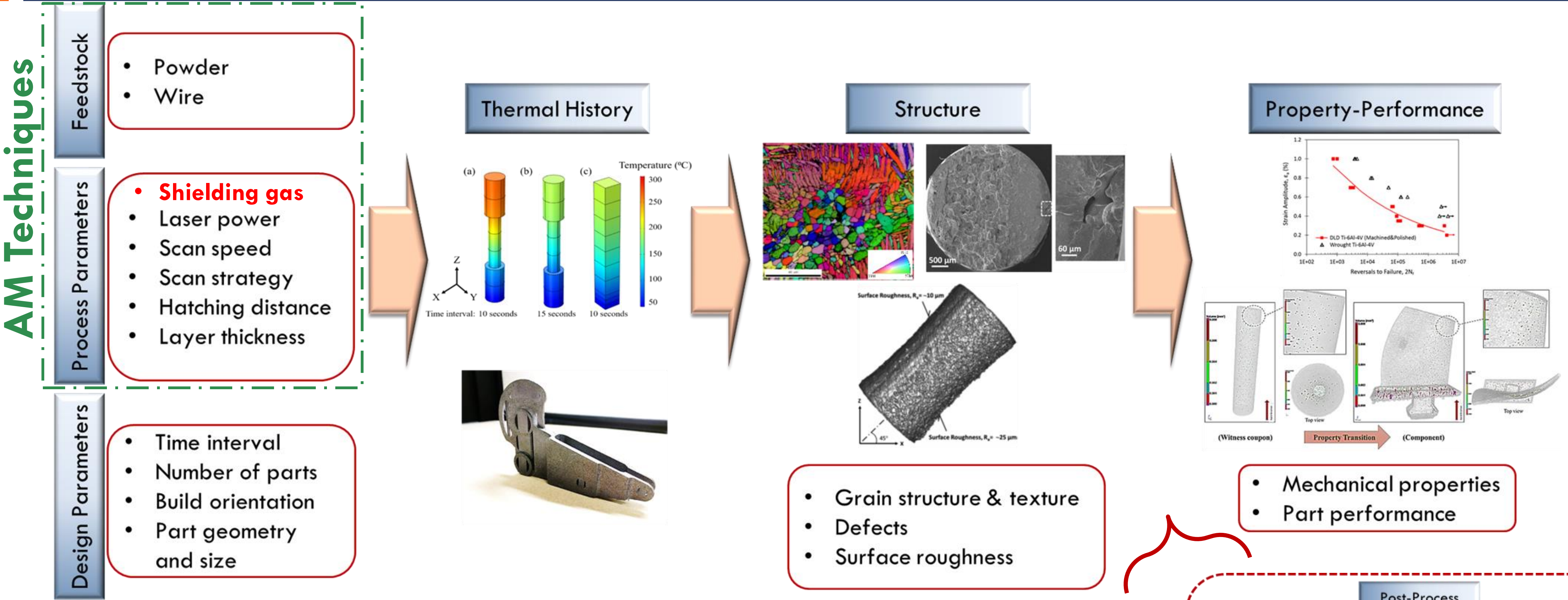
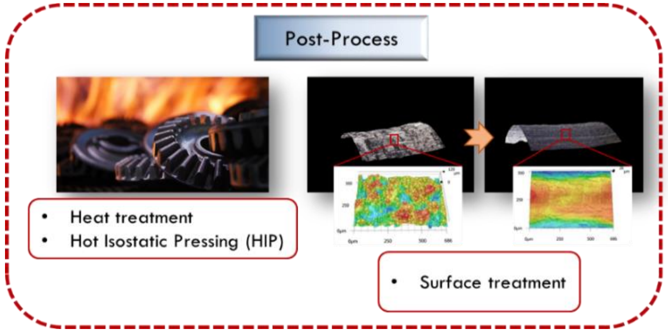
printing-benefits-dental-lab/


laser
X-Y Scanner System
Laser Beam
Recoater
Powder Bed
Powder Supply
Fabrication Piston
Over Flow Con iner

Process-Structure-Property-Performance (PSPP) Relationships





- Process affects the thermal history
- Thermal history influences the structure
- Process or post-process optimizations are required to enhance the properties

Challenges: Heat Treatment

Laser powder bed fusion (L-PBF) 17-4 PH SS

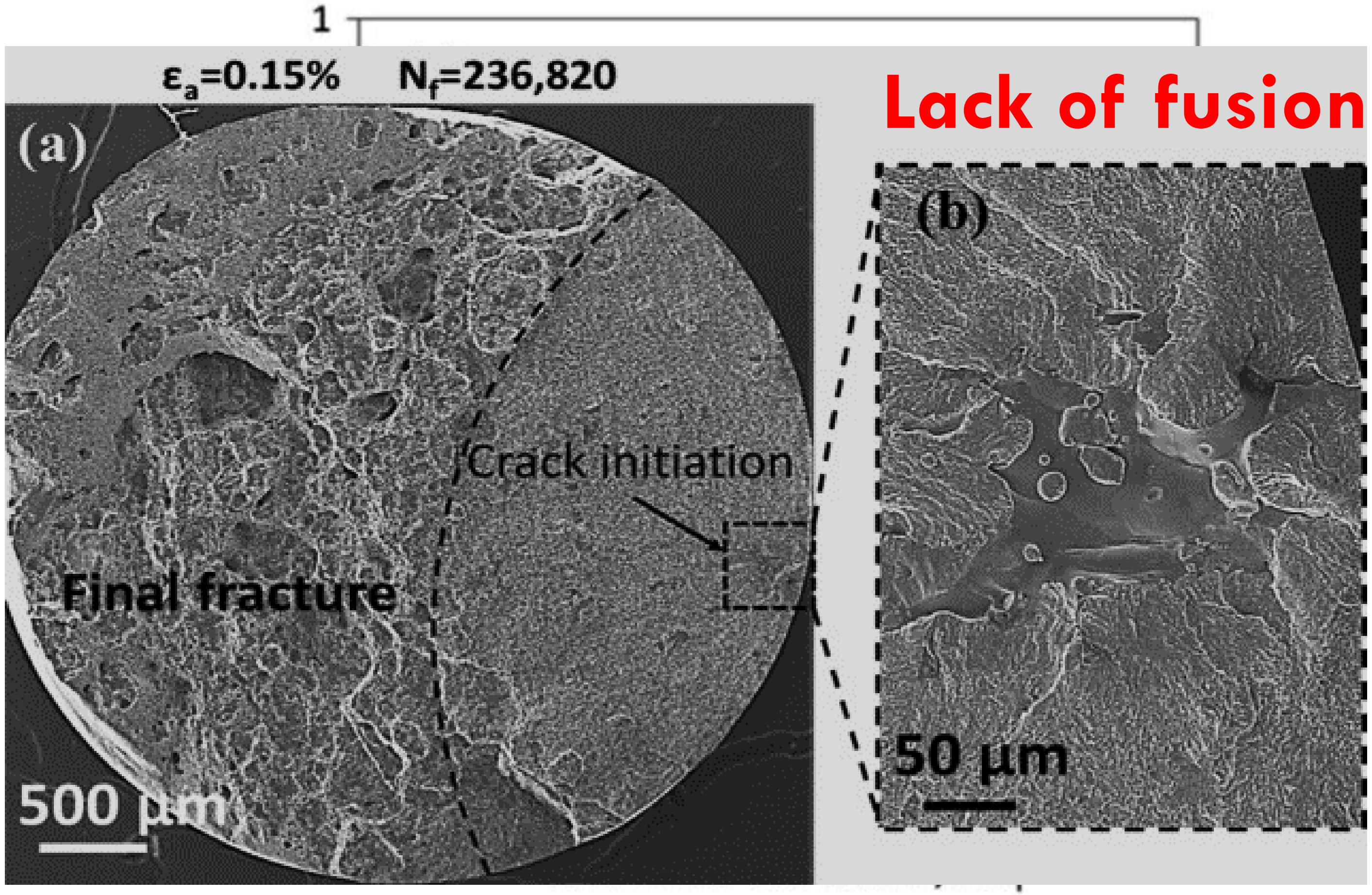
Vertical specimens

Machined specimens

Heat treatment: **CA-H900**

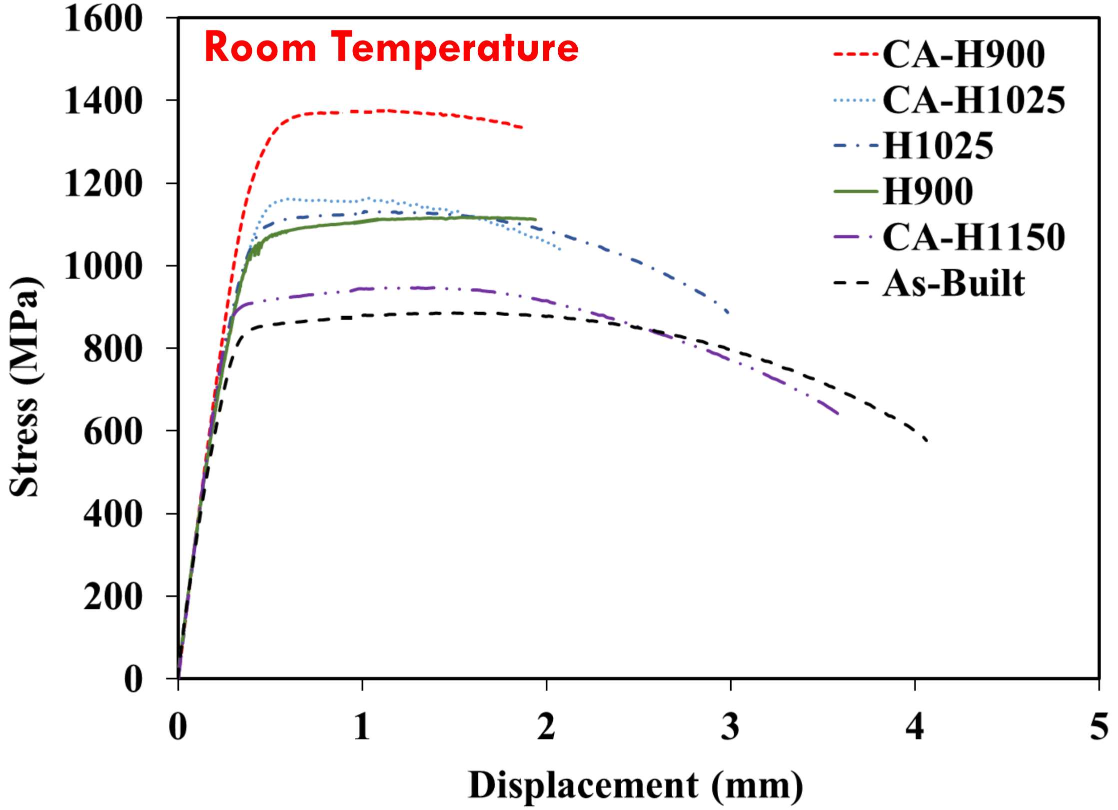
Worse fatigue behavior in **high cycle regime**

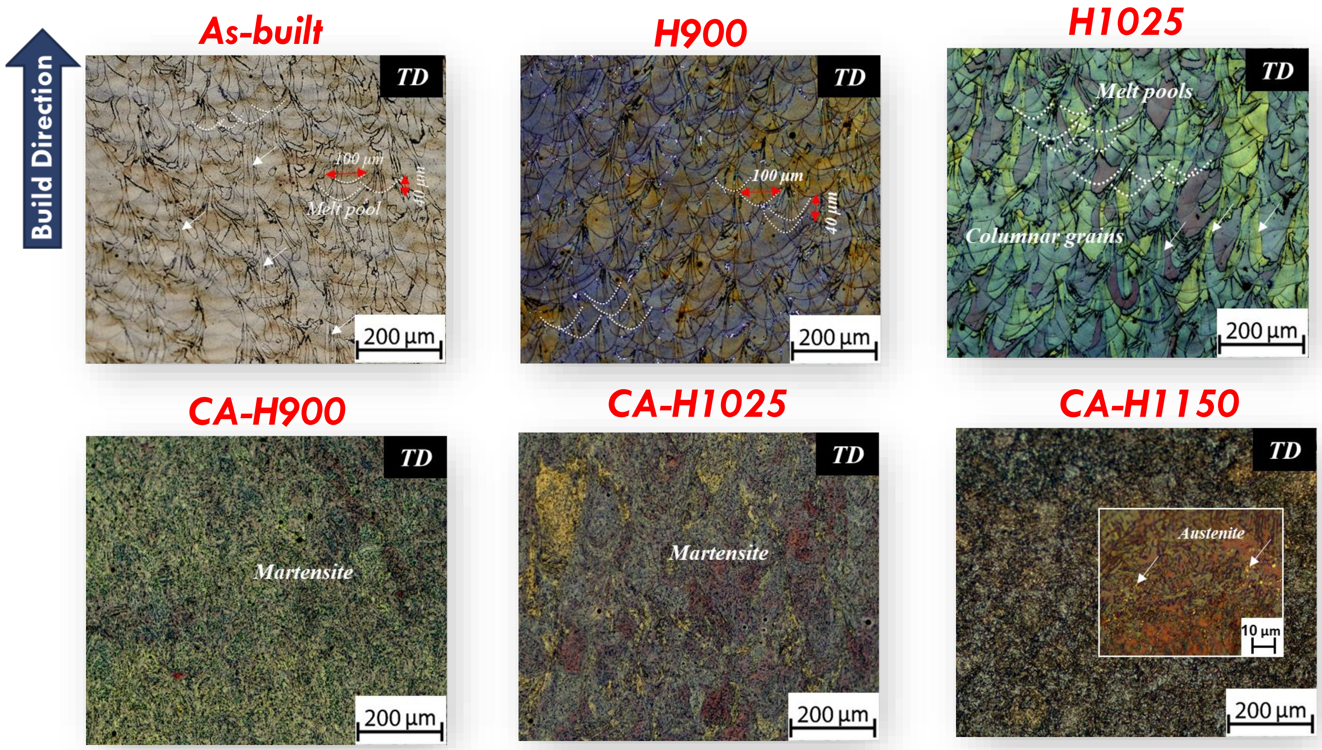
- The ***common heat treatment*** procedure for the wrought material ***may not be the most appropriate*** heat treatment for the L-PBF counterparts



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

Microstructure & Tensile Behavior: Ar-Shielded L-PBF 17-4 PH SS



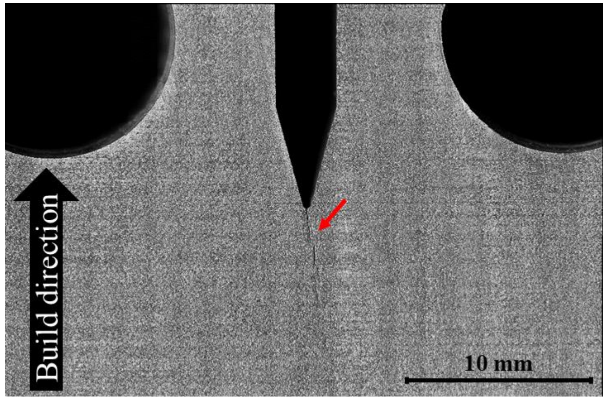


Nezhadfar, P. D., Burford, E., Anderson-Wedge, K., Zhang, B., Shao, S., Daniewicz, S. R., & Shamsaei, N. (2019). Fatigue crack growth behavior of additively manufactured 17-4 PH stainless steel: Effects of build orientation and microstructure. International Journal of Fatigue, 123, 168-179.

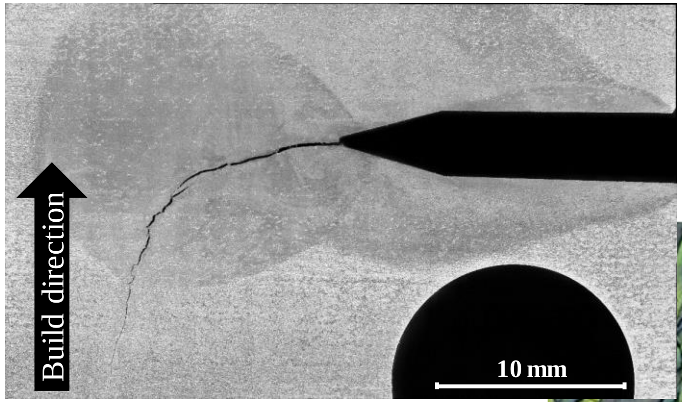
- Heat treatment increases the strength due to the precipitation hardening mechanism
- CA step, as well as the duration of aging heat treatment, can affect the strength and ductility

FCG Behavior: Direct Aging Issue

H1025 (direct aging): 552 ˚C/4 hrs

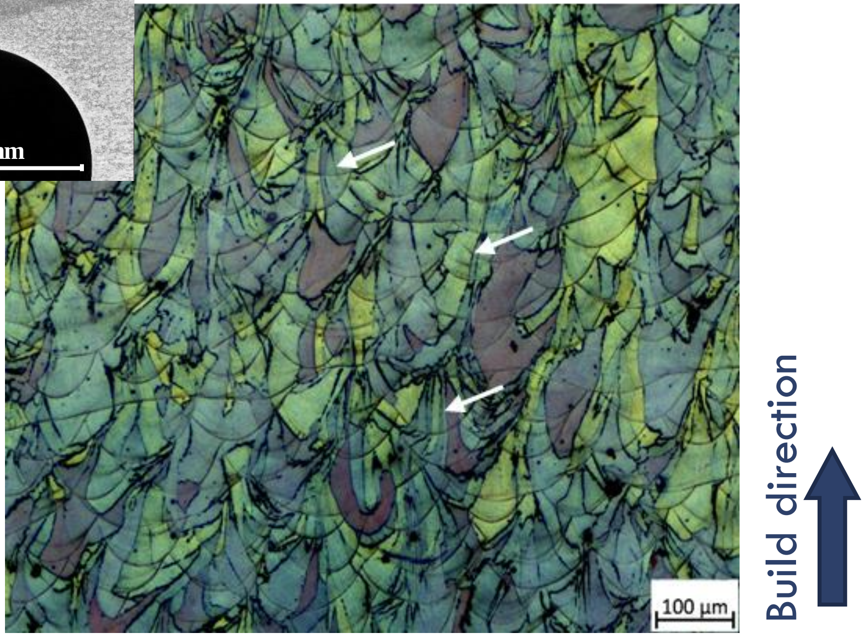


Vertical



Horizontal

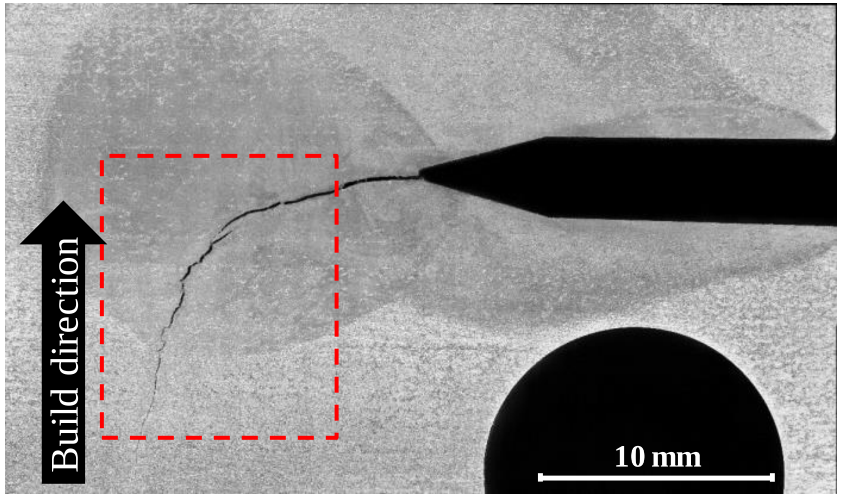
No FCG data were recorded



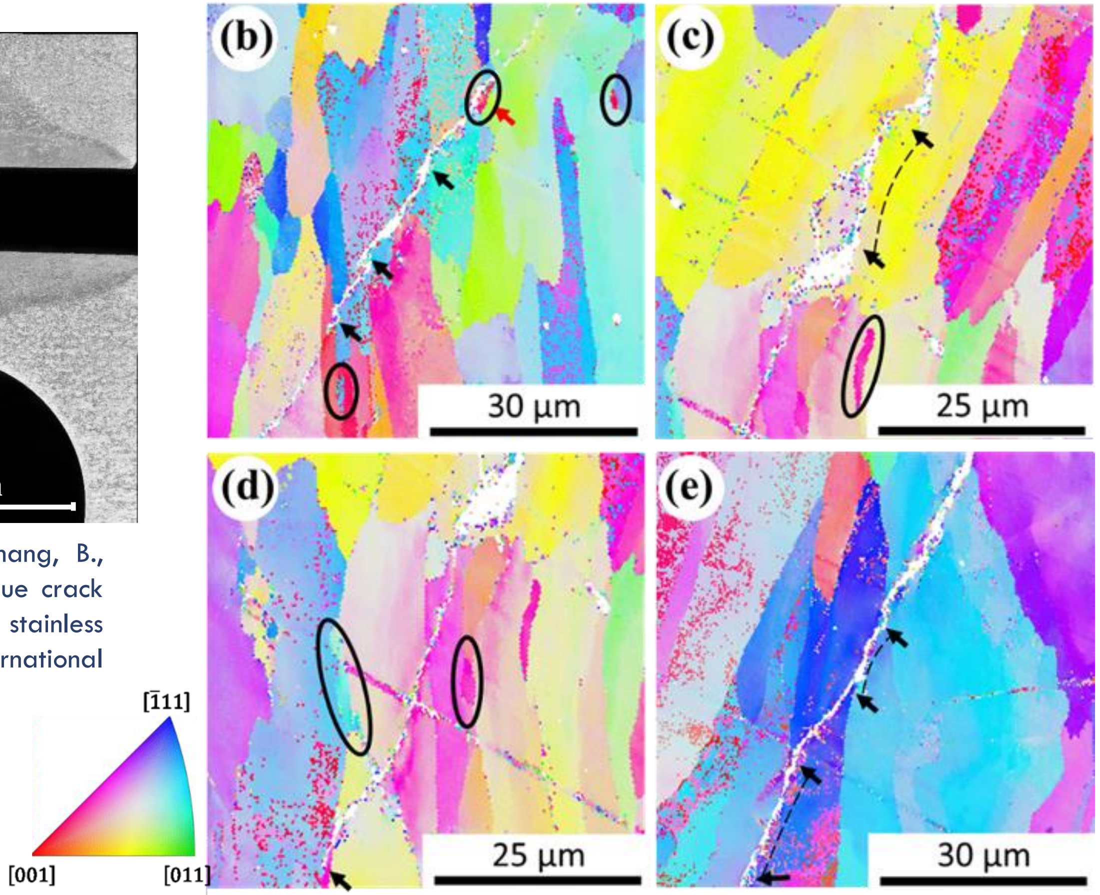
- Vertical specimens: Crack occurred after heat treatment
- Horizontal specimens: Crack deflected from mode I to mode II along with the columnar grains

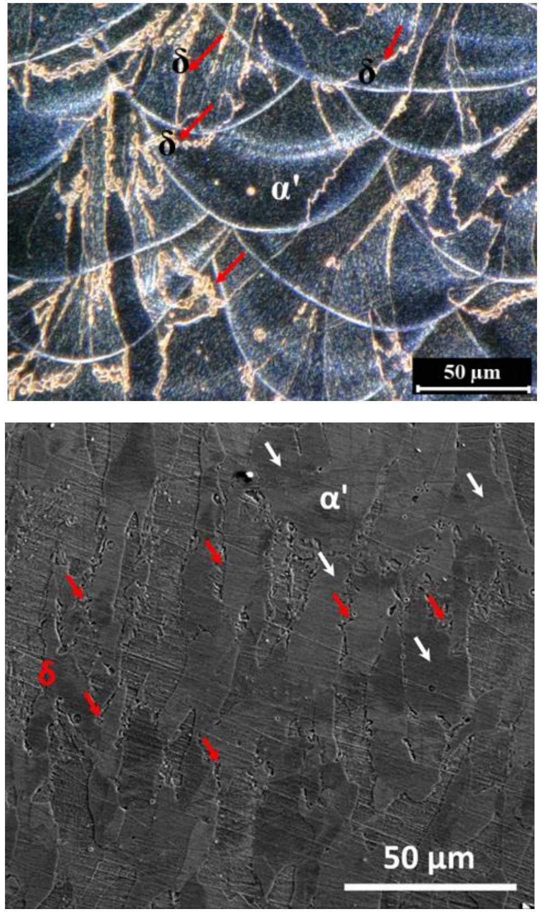
Nezhadfar, P. D., Burford, E., Anderson-Wedge, K., Zhang, B., Shao, S., Daniewicz, S. R., & Shamsaei, N. (2019). Fatigue crack growth behavior of additively manufactured 17-4 PH stainless steel: Effects of build orientation and microstructure. International Journal of Fatigue, 123, 168-179.

FCG Behavior: Direct Aging Issue



Nezhadfar, P. D., Burford, E., Anderson-Wedge, K., Zhang, B., Shao, S., Daniewicz, S. R., & Shamsaei, N. (2019). Fatigue crack growth behavior of additively manufactured 17-4 PH stainless steel: Effects of build orientation and microstructure. International Journal of Fatigue, 123, 168-179.

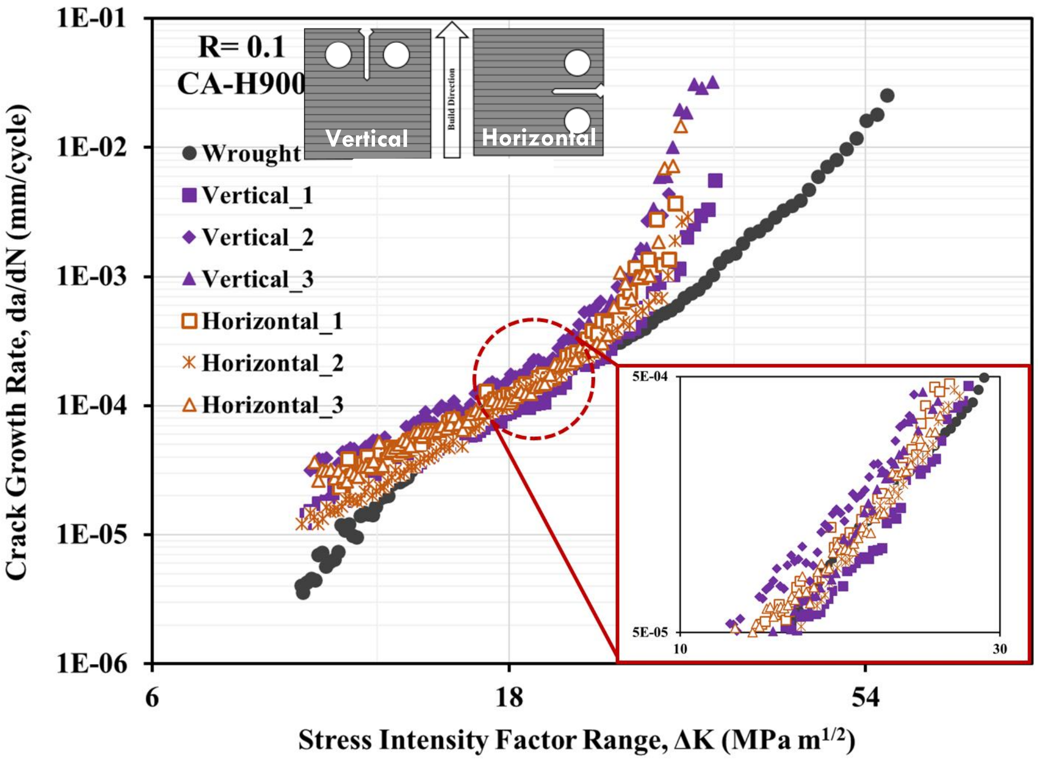


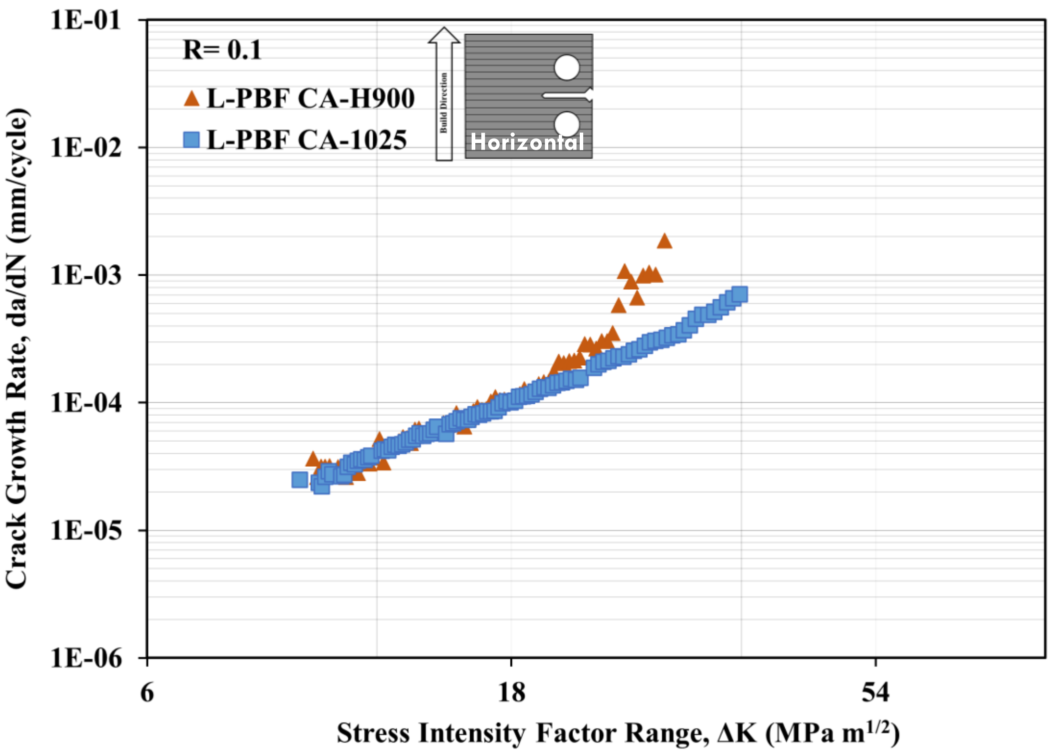


brittle δ-ferrite on the grain boundaries

- Transgranular and intergranular crack propagation
- Intergranular due to the presence of brittle δ-ferrite on the grain boundaries
- Direct aging may not be an option for the L-PBF 17-4 PH SS

FCG Behavior: Appropriate Heat Treatment

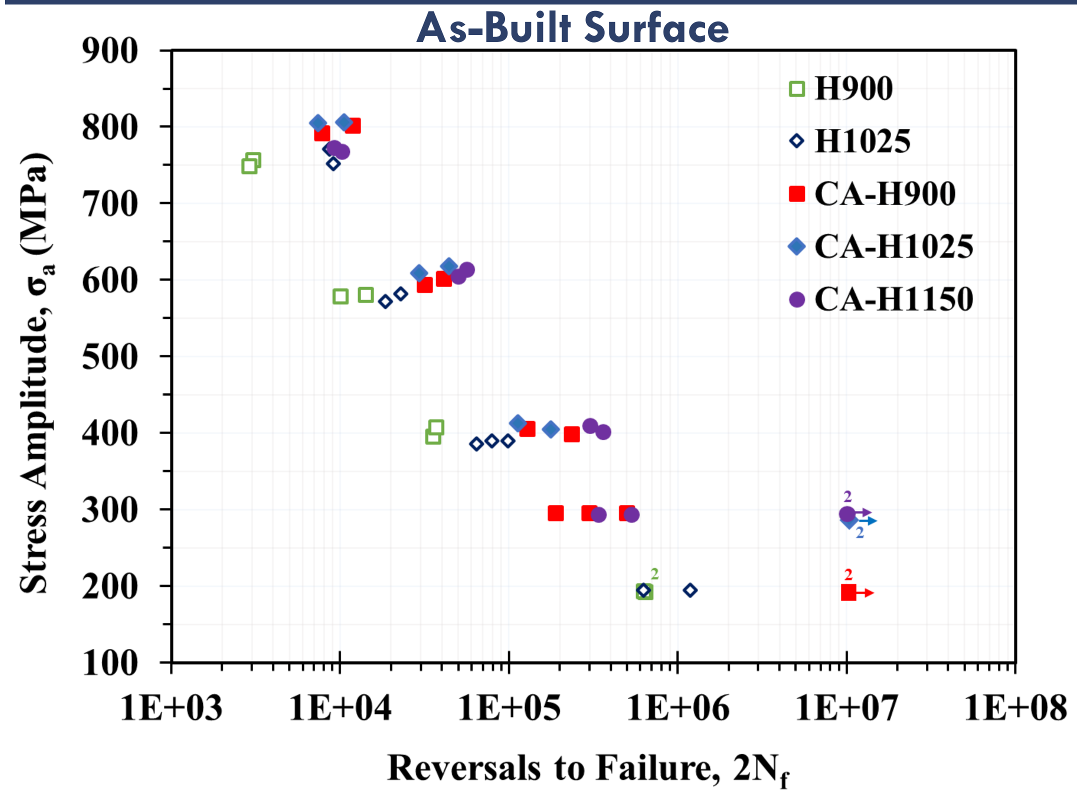


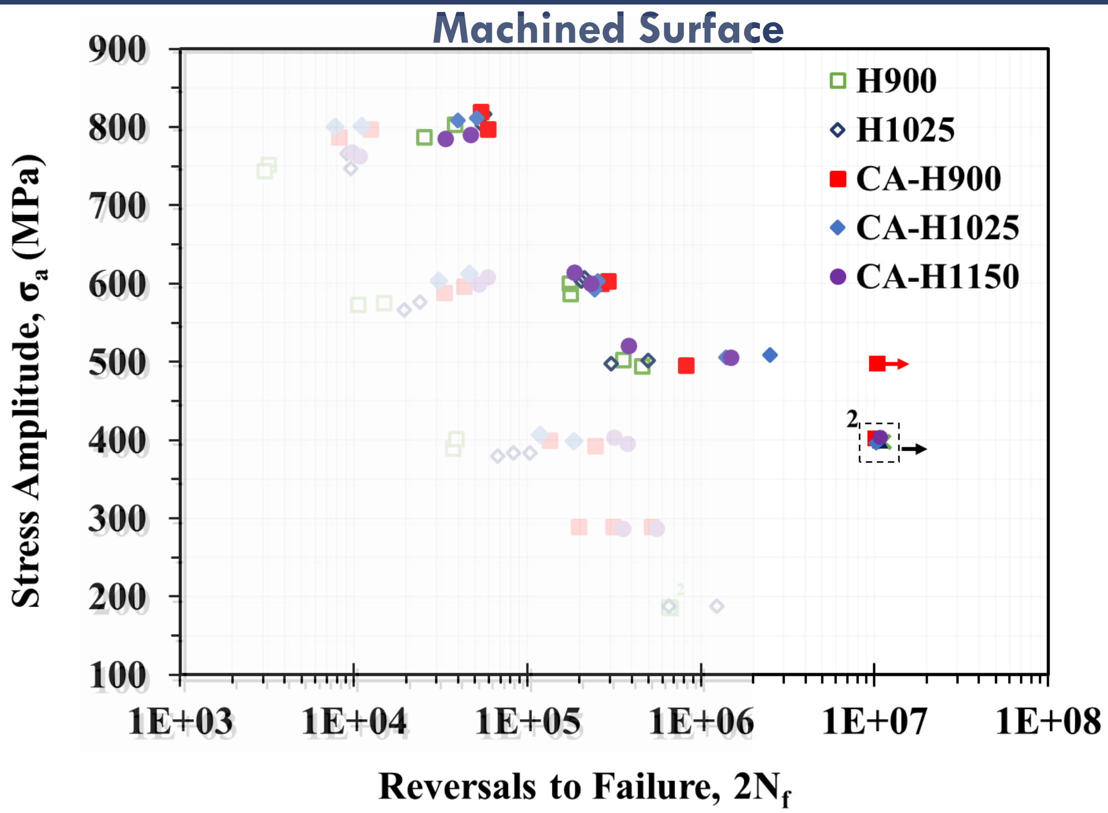


- L-PBF and wrought material in CA-H900 condition have similar fatigue crack growth rates in the Paris regime
- No anisotropy is noticed for L-PBF specimens with different notch direction
- CA-H1025 heat-treated L-PBF specimens result in a lower FCG rate than the CA-H900 counterparts in the unstable crack growth region (region III)

Nezhadfar, P. D., Burford, E., Anderson-Wedge, K., Zhang, B., Shao, S., Daniewicz, S. R., & Shamsaei, N. (2019). Fatigue crack growth behavior of additively manufactured 17-4 PH stainless steel: Effects of build orientation and microstructure. International Journal of Fatigue, 123, 168-179.

Challenges: Surface Roughness & Heat Treatment

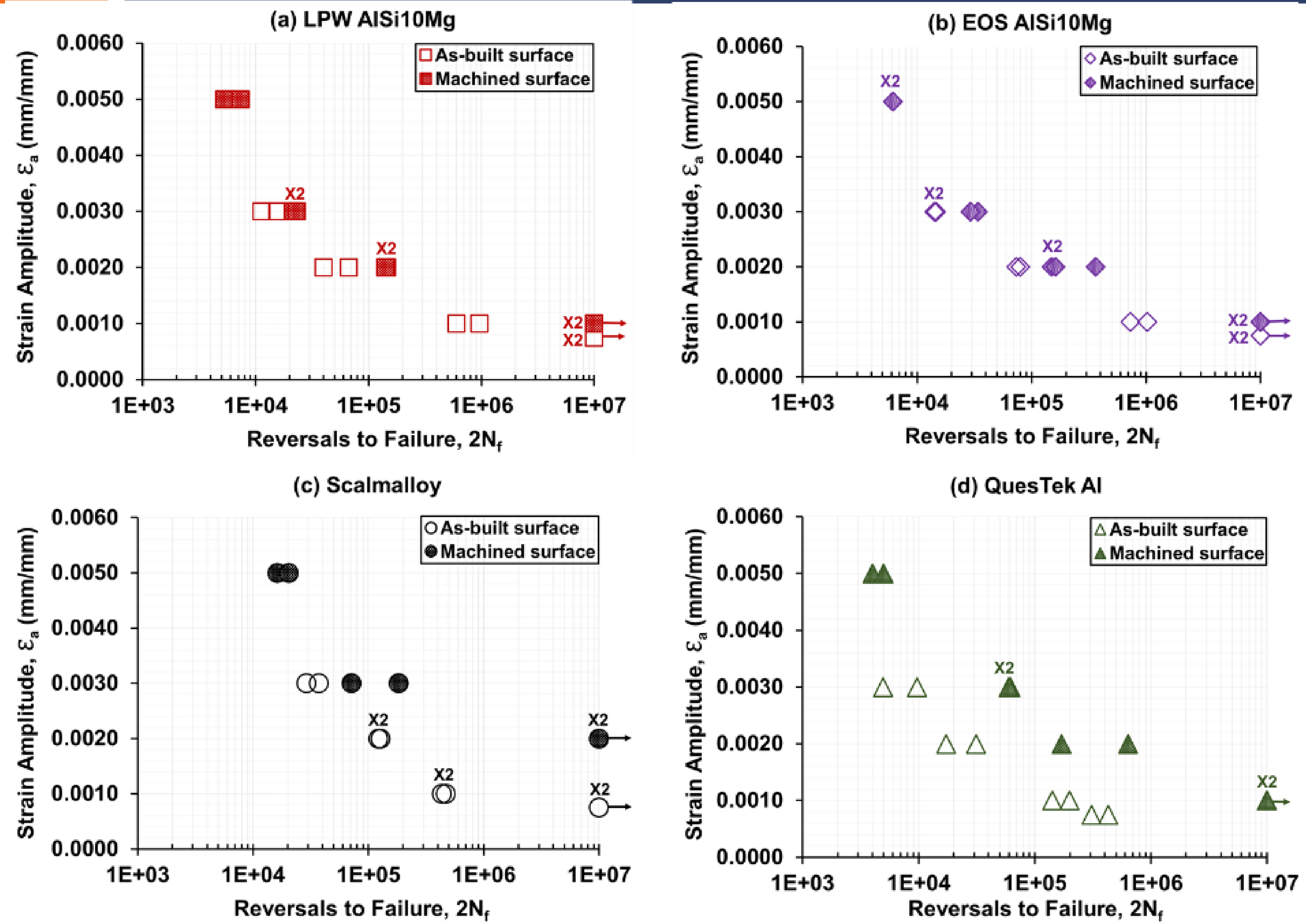




- CA improves the fatigue resistance of the material in all fatigue regimes
- CA-H1025 is applicable even with different surface conditions, resulting in less scatter in fatigue results
- According to the **high tensile strength** and **less scatter** in fatigue results → **CA-H1025**
- If **high ductility** is required, **CA-H1150** is also applicable

Nezhadfar, P. D., Burford, E., Anderson-Wedge, K., Zhang, B., Shao, S., Daniewicz, S. R., & Shamsaei, N. (2019). Fatigue crack growth behavior of additively manufactured 17-4 PH stainless steel: Effects of build orientation and microstructure. International Journal of Fatigue, 123, 168-179.

Fatigue Behavior of Al Alloys: Surface Roughness

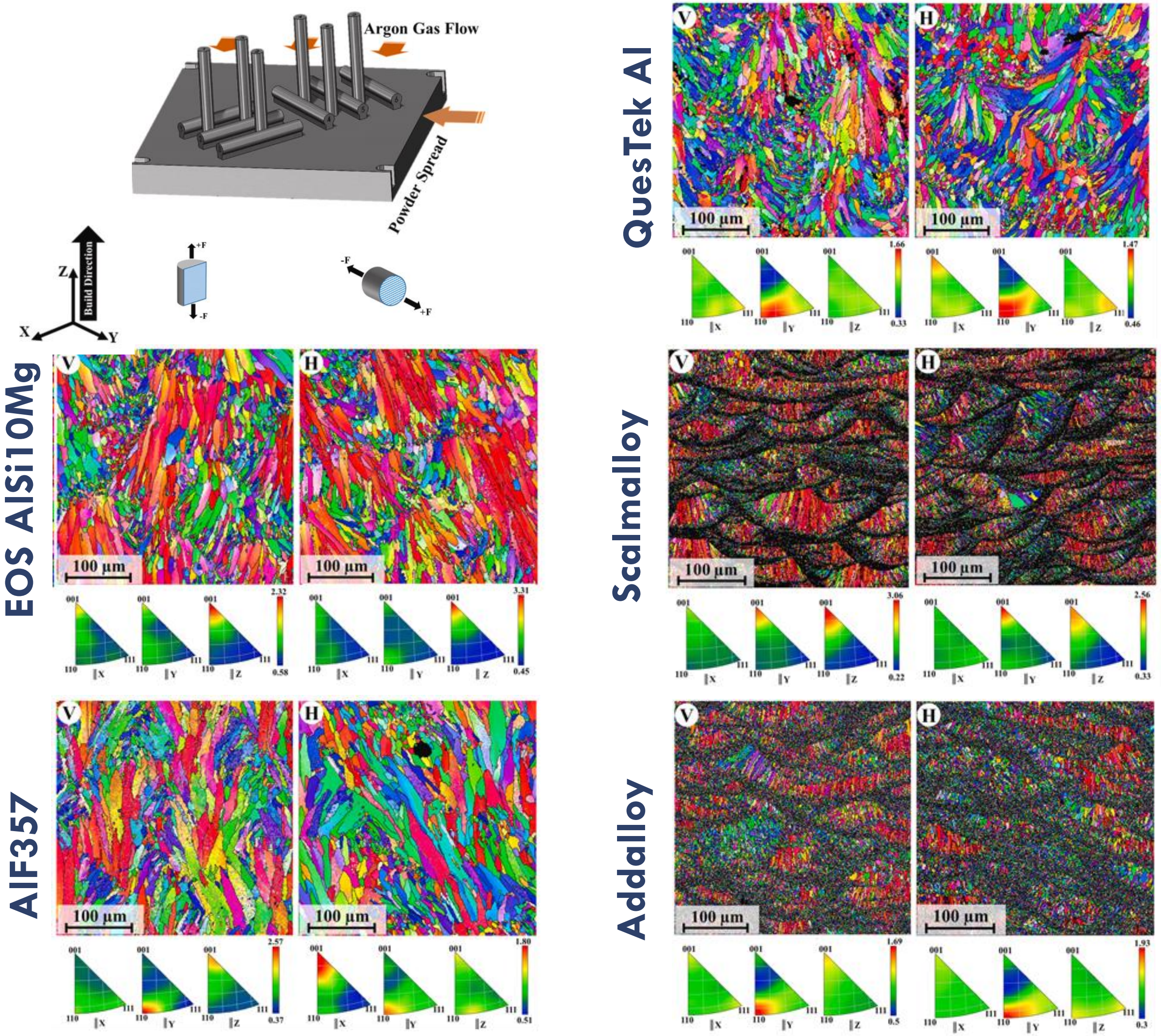


- Machining improved the fatigue performance of L-PBF Al specimens
- Fatigue performance increased significantly after machining for specimens with non-optimized surface process parameters (Scalmalloy and QuesTek Al)

Muhammad, Muztahid, P. D. Nezhadfar, Spencer Thompson, Ankit Saharan, Nam Phan, and Nima Shamsaei. "A comparative investigation on the microstructure and mechanical properties of additively manufactured aluminum alloys." International Journal of Fatigue 146 (2021): 106165.

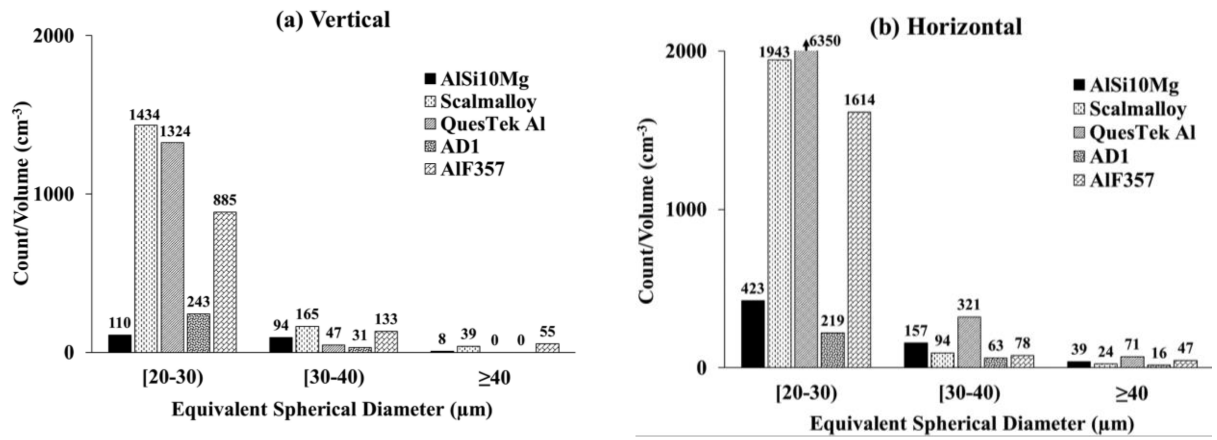
Challenges: Build Orientation

- The grain structure (i.e., size and morphology of grains) was not much affected by the build orientation
- The preferred crystallographic orientation of grains **with respect to the loading direction** was different between the vertical and horizontal specimens
- The grains were mainly < 011 >- and < 111 >-oriented (i.e., the easy cross slip for FCC structure) in horizontal specimens and mostly <001>-oriented in vertical specimens

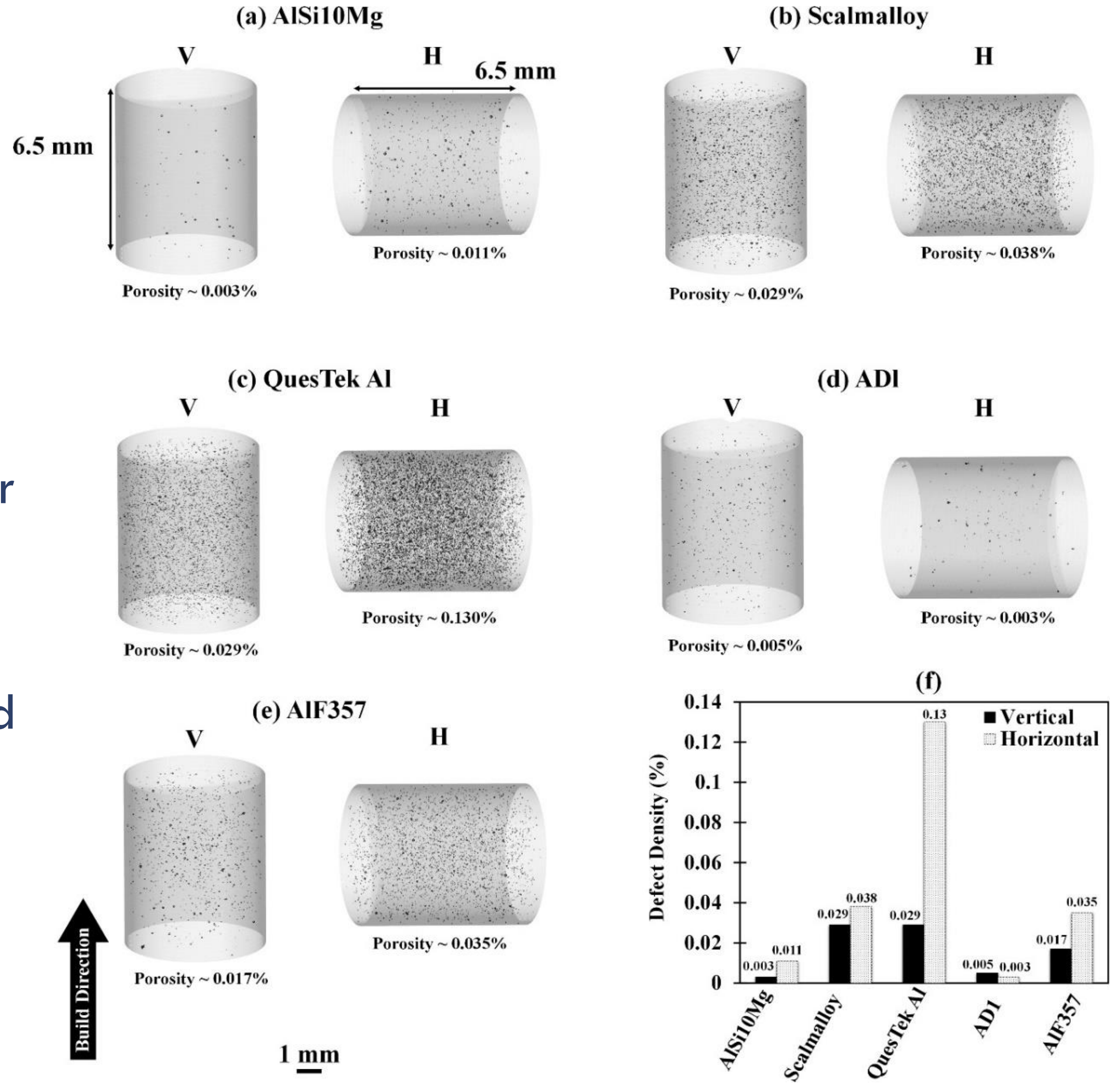


Nezhadfar, P. D., Spencer Thompson, Ankit Saharan, Nam Phan, and Nima Shamsaei. "Structural integrity of additively manufactured aluminum alloys: Effects of build orientation on microstructure, porosity, and fatigue behavior." Additive Manufacturing 47 (2021): 102292.

Challenges: Build Orientation



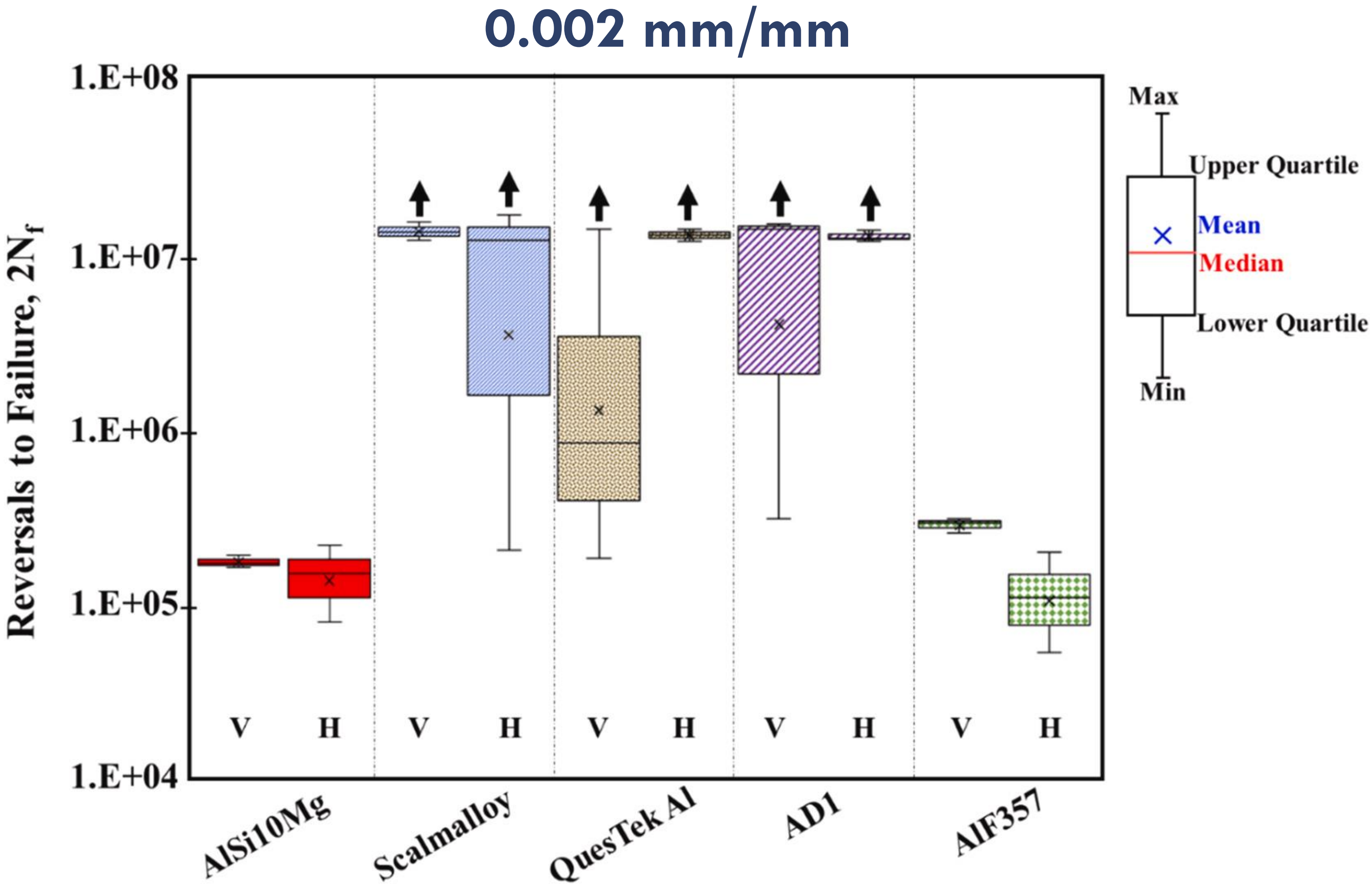
- A higher level of volumetric defects was observed for the horizontal L-PBF Al specimens than the vertical counterparts → variation in thermal history
- Lower variation in defect density level of vertical and horizontal L-PBF Addalloy and Scalmalloy specimens due to the lower thermal conductivity (~%30) than other alloys



Nezhadfar, P. D., Spencer Thompson, Ankit Saharan, Nam Phan, and Nima Shamsaei. "Structural integrity of additively manufactured aluminum alloys: Effects of build orientation on microstructure, porosity, and fatigue behavior." Additive Manufacturing 47 (2021): 102292.

Anisotropy in Fatigue Behavior: Build Orientation

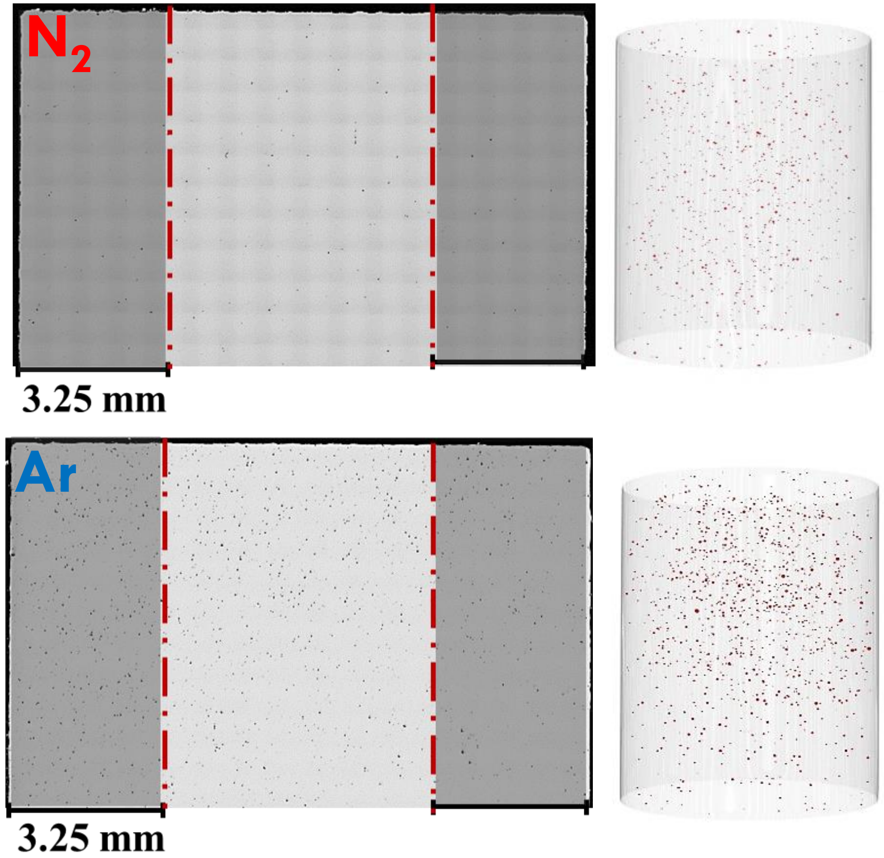
- There was no significant build orientation dependency at the higher strain amplitude of 0.003 mm/mm
- The AlF357 and QuesTek Al specimens showed anisotropy in fatigue behavior at 0.002 mm/mm strain amplitude
- Fatigue anisotropy in AlF357 and QuesTek Al are related to the **type of defects** in vertical (pores) and horizontal (LoF) specimens

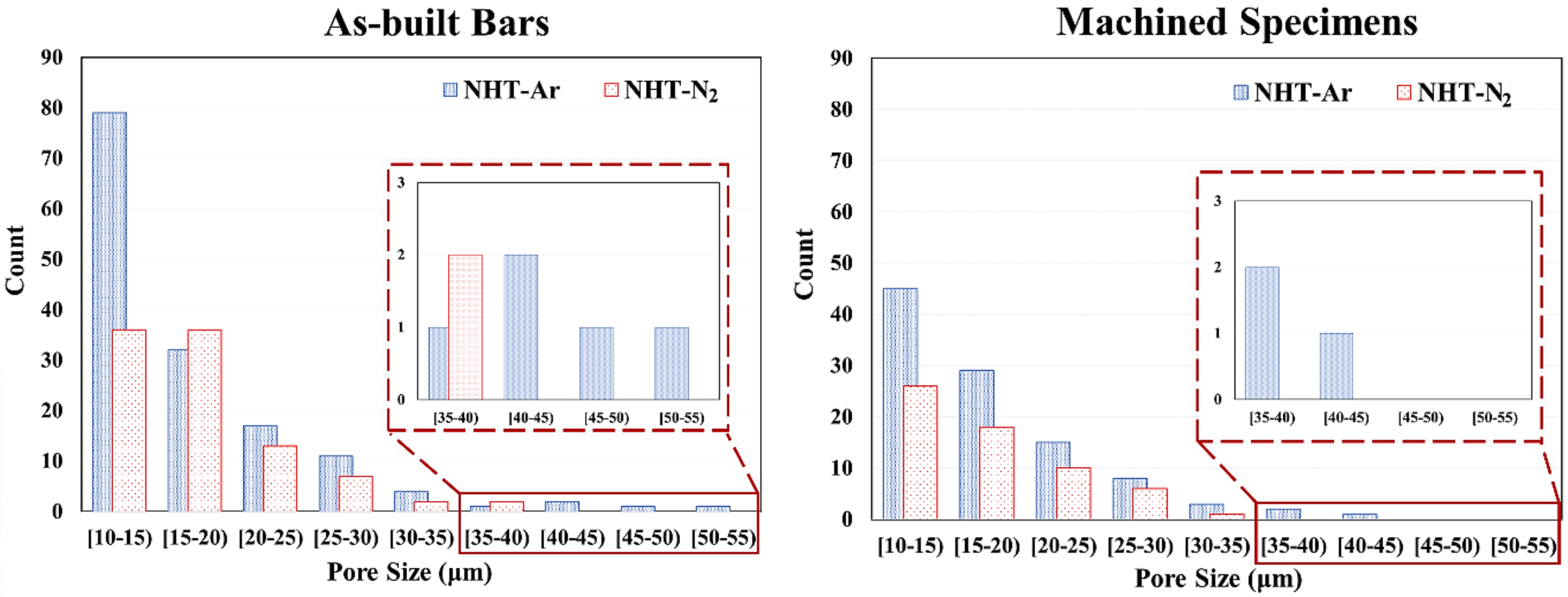


Nezhadfar, P. D., Spencer Thompson, Ankit Saharan, Nam Phan, and Nima Shamsaei. "Structural integrity of additively manufactured aluminum alloys: Effects of build orientation on microstructure, porosity, and fatigue behavior." Additive Manufacturing 47 (2021): 102292.

Opportunities: Process Parameters – Shielding Gas Type

L-PBF 17-4 PH SS

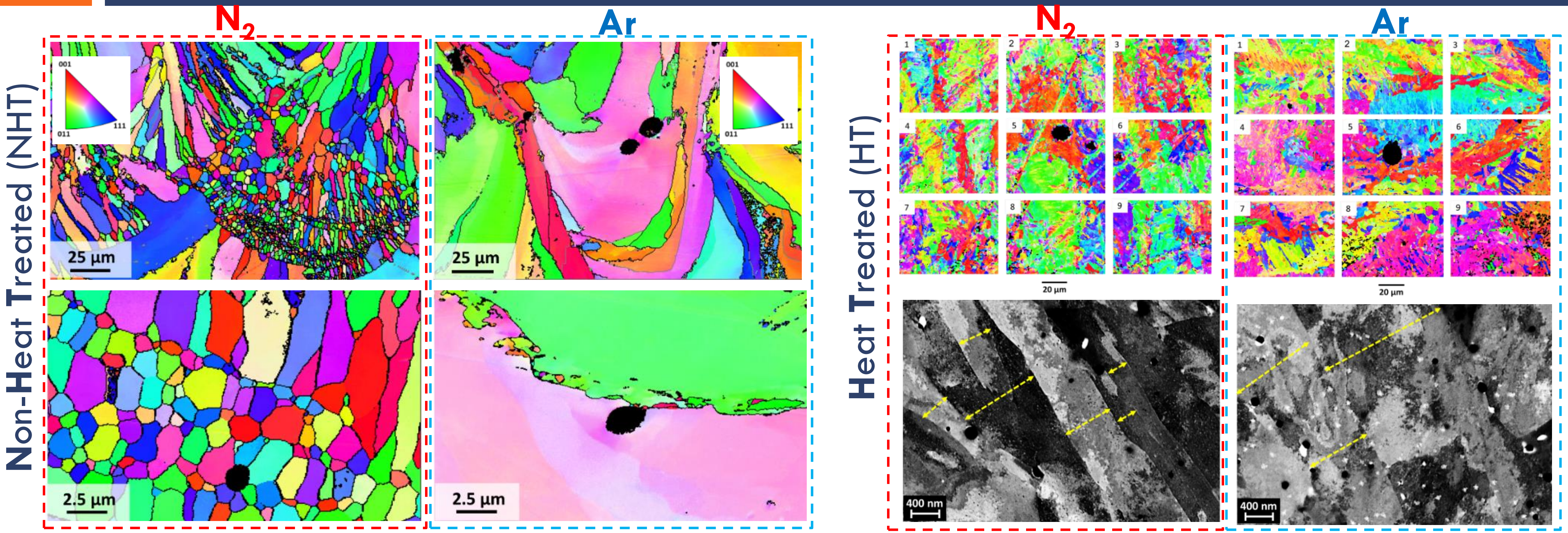




Nezhadfar, P.D., Anderson-Wedge, K., Daniewicz, S. R., Phan, N., Shao, S., Shamsaei, N., Improved high cycle fatigue performance of additively manufactured 17-4 PH stainless steel via in-process refining micro-/defect-structure, Additive Manufacturing, 2020

- Smaller and fewer pores observed in N_2-shielded specimens
- Due to the lower cooling/solidification rate in N_2-shielded specimens as well as deeper melt pools, entrapped gases have the chance to escape

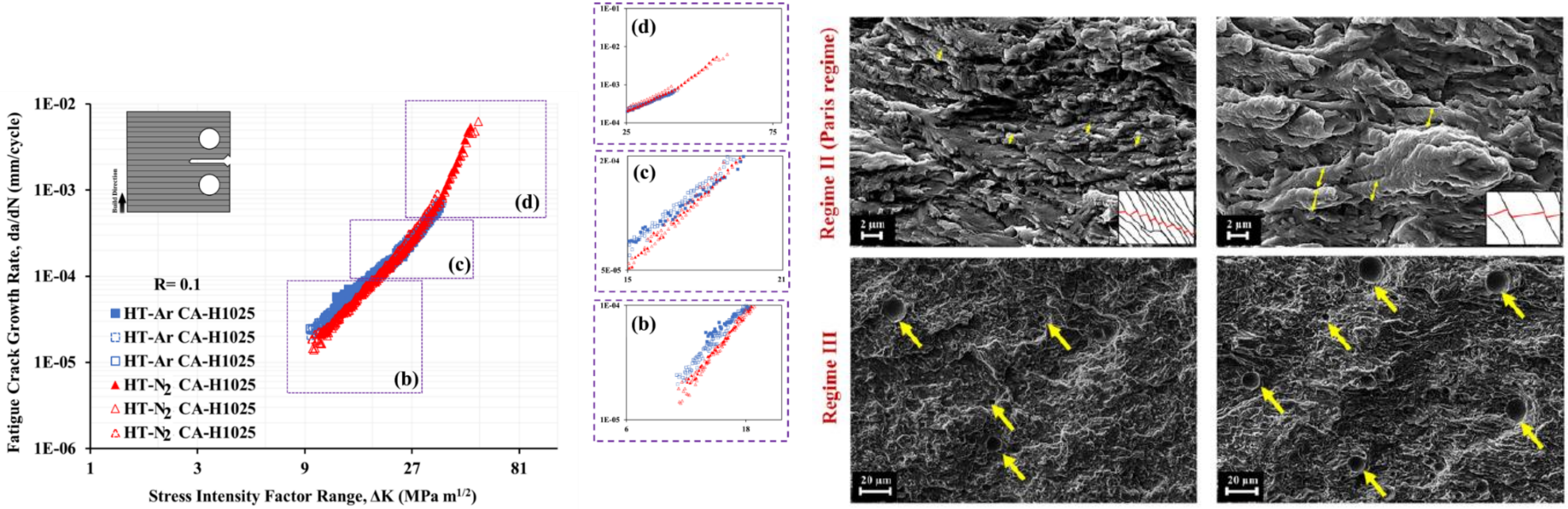
Opportunities: Process Parameters – Shielding Gas Type



- N_2-shielded specimens have finer microstructure than Ar ones in both NHT and HT conditions
- Fine equiaxed grains, mostly around pores in NHT N_2-shielded specimens
- N can diffuse to the material and refine the microstructure
- HT-N_2 specimens possess finer lath martensite (560 nm) as compared to HT-Ar (1400 nm)

Nezhadfar, P.D., Anderson-Wedge, K., Daniewicz, S. R., Phan, N., Shao, S., Shamsaei, N., Improved high cycle fatigue performance of additively manufactured 17-4 PH stainless steel via in-process refining micro-/defect-structure, Additive Manufacturing, 2020

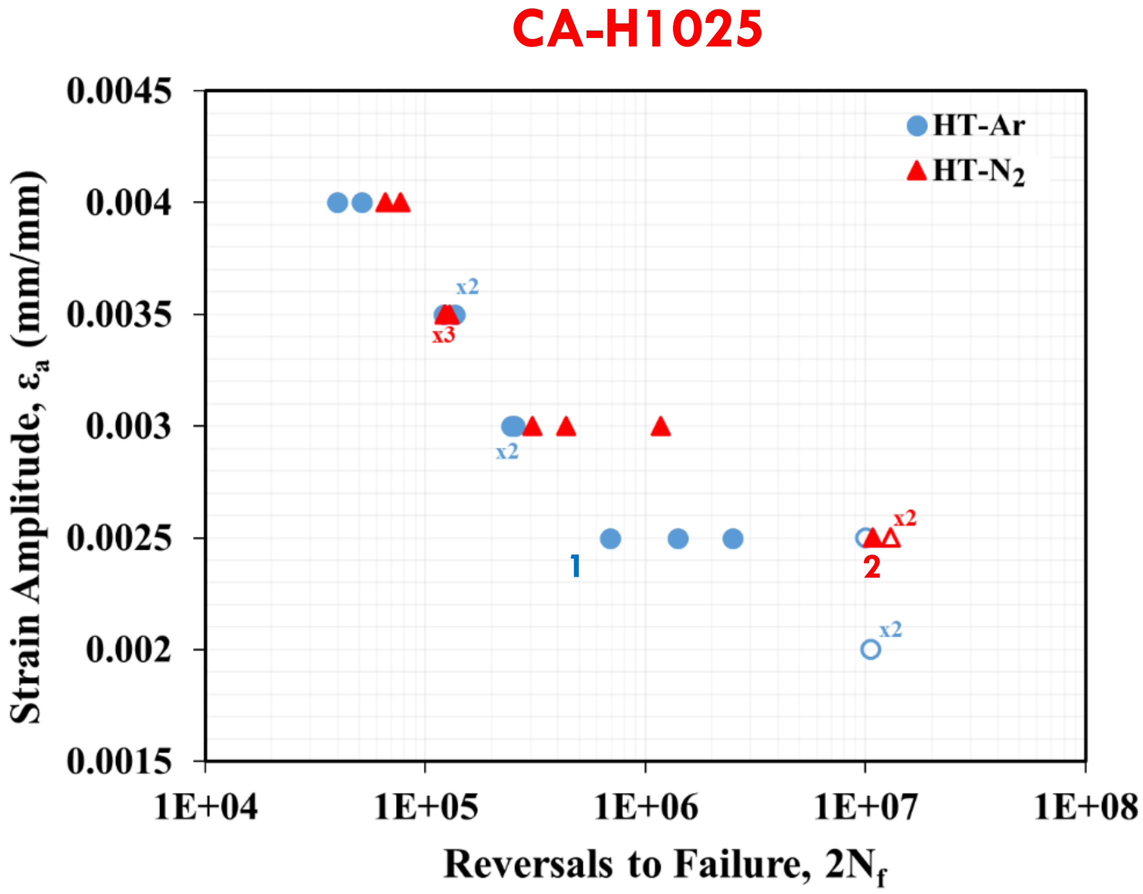
Opportunities: Process Parameters – Shielding Gas Type

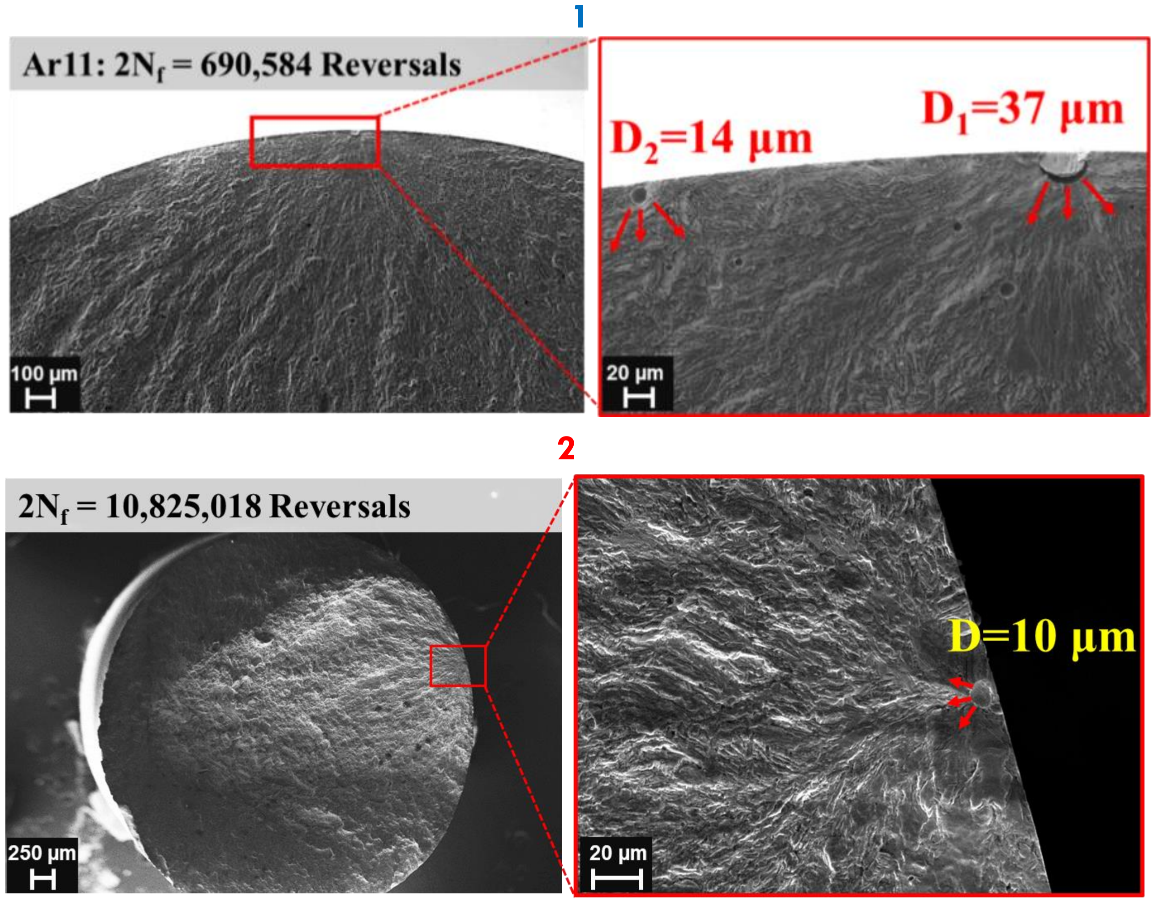


- Although some differences are noticed at the beginning, the FCG curves collapse on each other toward the unstable crack growth region
- Higher fatigue crack initiation resistance is expected for the N_2-shielded specimens due to the finer microstructure as well as fewer and smaller defects

Nezhadfar, P.D., Anderson-Wedge, K., Daniewicz, S. R., Phan, N., Shao, S., Shamsaei, N., Improved high cycle fatigue performance of additively manufactured 17-4 PH stainless steel via in-process refining micro-/defect-structure, Additive Manufacturing, 2020

Opportunities: Process Parameters – Shielding Gas Type

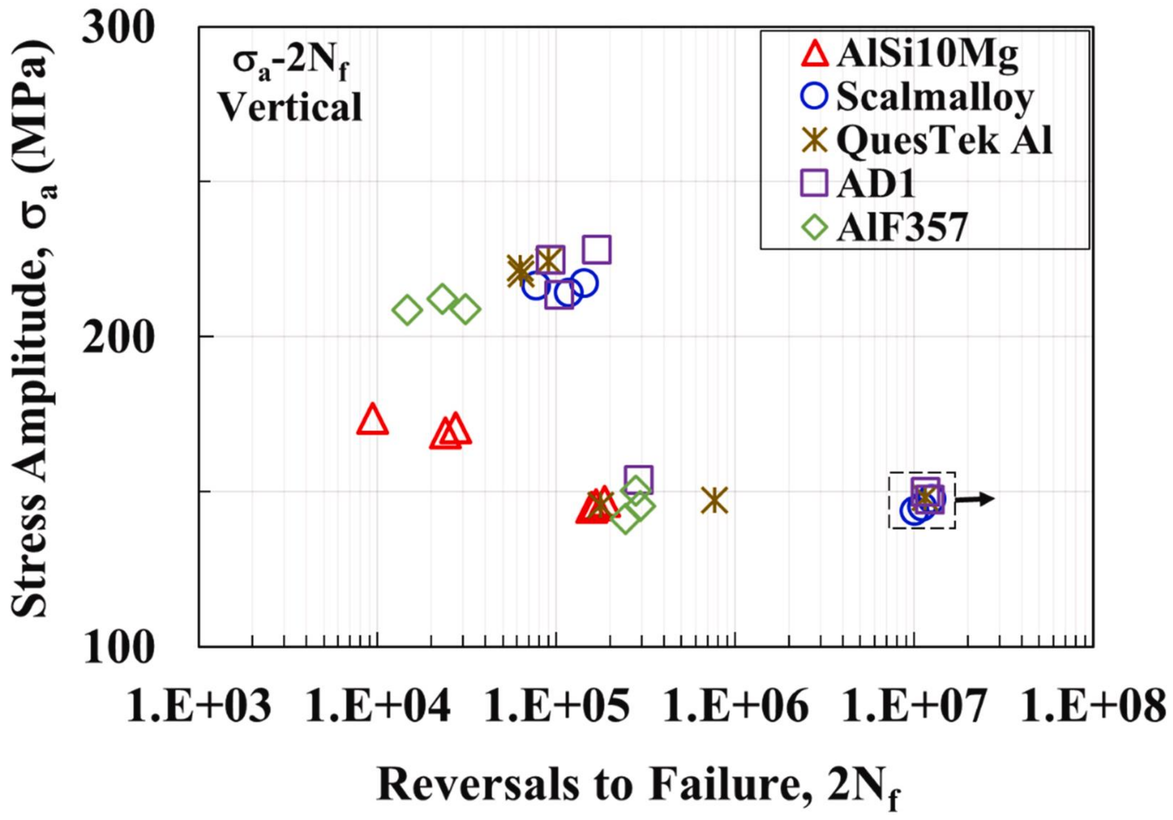


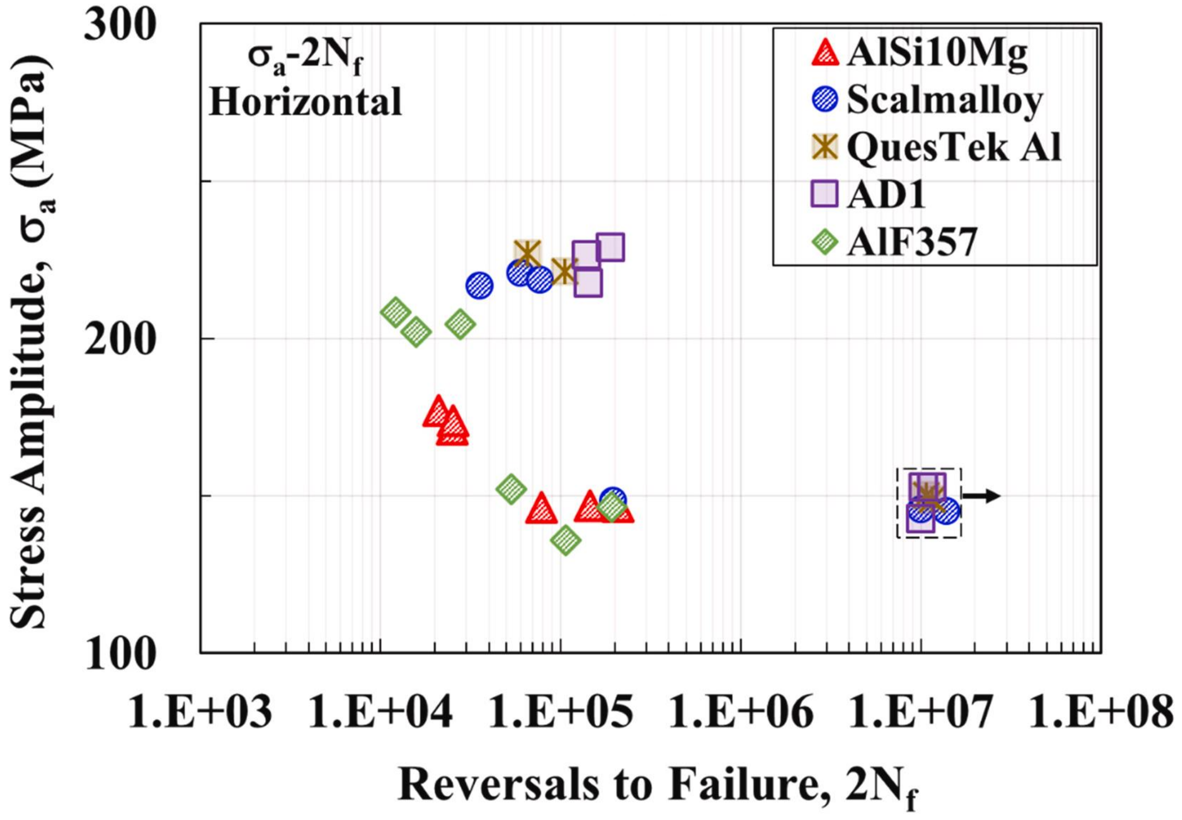


- HT-N_2 specimens have slightly better fatigue performance in LCF, and exhibit considerable improvement in HCF regime compared to HT-Ar ones

Nezhadfar, P.D., Anderson-Wedge, K., Daniewicz, S. R., Phan, N., Shao, S., Shamsaei, N., Improved high cycle fatigue performance of additively manufactured 17-4 PH stainless steel via in-process refining micro-/defect-structure, Additive Manufacturing, 2020

Opportunities: Alloy Development





- Stress response: Addalloy ≈ Scalmalloy ≈ QuesTek Al > AlF357 > AlSi10Mg
- Fatigue life: Addalloy ≈ Scalmalloy ≈ QuesTek Al > AlF357 ≈ AlSi10Mg

Nezhadfar, P. D., Spencer Thompson, Ankit Saharan, Nam Phan, and Nima Shamsaei. "Structural integrity of additively manufactured aluminum alloys: Effects of build orientation on microstructure, porosity, and fatigue behavior." Additive Manufacturing 47 (2021): 102292.

Conclusion

Process-Structure-Property-Performance (PSPP) Relationships

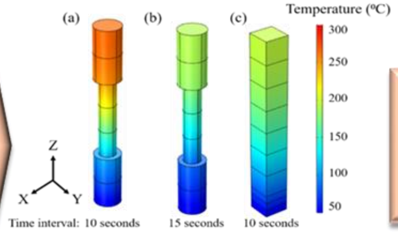
AM Techniques

Feedstock
- Powder
- Wire

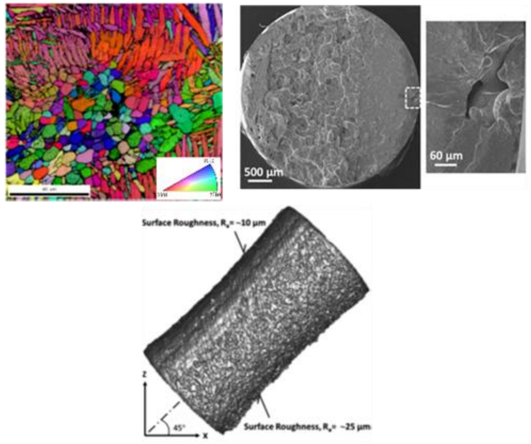
Process Parameters
- Laser power
- Scan speed
- Scan strategy
- Hatching distance
- Layer thickness
- **Shielding gas**

Design Parameters
- Time interval
- Number of parts
- Build orientation
- Part geometry and size

Thermal History

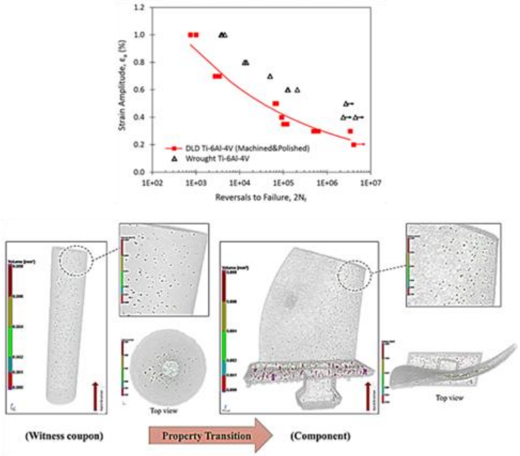


Structure



- Grain structure & texture
- Defects
- Surface roughness

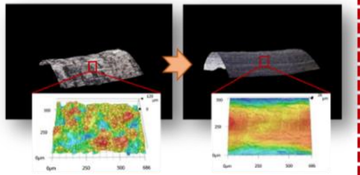
Property-Performance



- Mechanical properties
- Part performance

Post-Process

- Heat treatment
- Hot Isostatic Pressing (HIP)



- Surface treatment

✓ Establishing the PSPP relationships for the AM materials and AM techniques is essential to expedite their adoption to the industries

Achievements

- **Awards and Honors**
  - 1st place in ASTM Center of Excellence (CoE) presentation student competition
  - Outstanding Doctoral Student Award from Auburn University
  - Dube Tribology Scholarship Award
  - Peer-Review award from MSEA, IJF, and Additive Manufacturing journals for having outstanding contribution
- **Research Projects**
  - Investigated the process-structure-property performance of additively manufactured precipitation hardened (PH) stainless steels (i.e., 17-4 PH and 15-5 PH) via L-PBF and LP-DED, collaborated with **NASA.**
  - Investigated the tribology behavior of the additively manufactured 17-4 PH stainless steel.
  - Established the process-structure-property performance of metal binder jetting (MBJ) 17-4 PH stainless steel, collaborated with **CETIM.**
  - Investigated the fatigue life assessment for the L-PBF 17-4 PH SS, collaborated with **Politecnico di Milano, Italy.**
  - Investigated the microstructure and mechanical behavior of additively manufactured contemporary Al alloys, collaborated with **NAVAIR** and **EOS.**
  - Enhanced the fatigue behavior and ductility of additively manufactured 316L stainless steel by preheating the build platform in collaboration with **NAVAIR.**
  - Microstructure characterization of additively manufactured AlSi10Mg for the **ASTM Industrial Consortium.**
  - Investigated the high-temperature fatigue performance of additively manufactured Inconel 718.
- **Services**
  - Served and mentored graduate students on projects
  - Metallography and microscopy lab coordination

Publications

Book Chapter

1. **Nezhadfar, P.D.**, Thompson, S., Saharan, A., Phan, N., Shamsaei, N., Fatigue and failure analysis of an additively manufactured contemporary aluminum alloy, **ISBN: 978-3-030-65395-8, 2020. 2021**

Invited Journal Papers

2. **Nezhadfar, P.D.**, Gradl, P, R., Shao, S., Shamsaei, N., "Microstructure and Deformation Behavior of Additively Manufactured 17-4 Stainless Steel: Influence of Manufacturing Techniques from Laser Powder Bed Fusion (L-PBF) to Laser Powder Directed Energy Deposition (LP-DED)," ***JOM, 2021***

Journal Papers

3. **Nezhadfar, P.D.** Gradl, P, R., Verquin, B., Lefebvre, F., Reynaud, C., Robert, M., Shao, S., Shamsaei, N. Microstructure and mechanical behavior of additively manufactured 17-4 PH stainless steel: a comparison across L-PBF, LP-DED, and MBJ **(Ready to be submitted)**
4. **Nezhadfar, P.D.**, Nandi, I., Welsh, J., Simsiriwong, J., Shamsaei, N., Very high cycle fatigue behavior of additively manufactured 17-4 PH stainless steel: Effect of heat treatment and specimen geometry **(Ready to be submitted)**
5. **Nezhadfar, P.D.**, Welsh, J., Simsiriwong, J., Shao, S., Shamsaei, N., High and very high cycle fatigue behavior of additively manufactured 17-4 PH stainless steel: Effect of shielding gas type **(Ready to be submitted)**
6. **Nezhadfar, P.D.**, Thompson, S., Saharan, A., Phan, N., Shamsaei, N., Structural Integrity of Additively Manufactured Aluminum Alloys: Effects of Build Orientation on Microstructure, Porosity, and Fatigue Behavior, ***Additive Manufacturing, 2021***
7. Muhammad, M., **Nezhadfar, P.D.**, Thompson, S., Saharan, A., Phan, N., Shamsaei, N., A comparative investigation on the microstructure and mechanical properties of additively manufactured aluminum alloys, ***International Journal of Fatigue*, 2021**
8. **Nezhadfar, P.D.**, Phan, N., Shamsaei, N., Enhancing ductility and fatigue strength of additively manufactured metallic materials by preheating the build platform, ***Fatigue & Fracture of Engineering Materials & Structures, 2021***
9. **Nezhadfar, P.D.**, Anderson-Wedge, K., Daniewicz, S. R., Phan, N., Shao, S., Shamsaei, N., Improved high cycle fatigue performance of additively manufactured 17-4 PH stainless steel via in-process refining micro-/defect-structure, ***Additive Manufacturing, 2020***
10. **Nezhadfar, P.D.**, Johnson, AS, Shamsaei, N., Fatigue behavior and microstructural evolution of additively manufactured Inconel 718 under cyclic loading at elevated temperature. ***International Journal of Fatigue*, 2020**
11. Romano, S., **Nezhadfar, P.D.**, Beretta, S., Seifi, M., Shamsaei, N., High cycle fatigue behavior and life prediction for additively manufactured 17-4 PH stainless steel: Effect of sub-surface porosity and surface roughness, ***Theoretical and Applied Fracture Mechanics, 2020***
12. Sanjeev KC, **Nezhadfar, P.D.**, C. Phillips, M. S. Kennedy, Shamsaei, N., R. L. Jackson, Tribological behavior of 17-4 PH stainless steel fabricated by traditional manufacturing and laser-based additive manufacturing methods, ***Wear, 2019***

Publications

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