Characterizing Mechanical Property Variability in Ti6Al4V produced by Laser Powder Bed Fusion Additive Manufacturing

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May 20th, 2025

sampe Conference & Exhibition

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Laser Powder Bed Fusion (LPBF)

- Advantages
  - Low Buy-to-Fly ratio
  - Nearly unlimited design complexity
  - Enables generative customization
  - Short lead times

- Concerns
  - Variability in the process, reflected in properties
  - Machine qualification

Objective and Outline -

Overall Objective - characterize the variability in microstructure and mechanical properties of Grade 5 Ti6Al4V produced by LPBF to improve metal/component reliability and advance applications across aerospace.

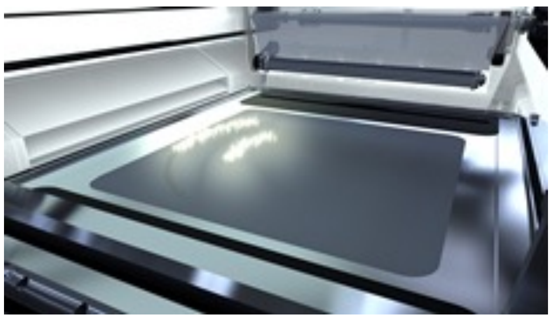
Approach – perform a Round Robin investigation led by the University of Washington and involving multiple other partners in the aerospace industry.

Phase I: Static Properties (completed)

Phase II: Stress-life (finite life) Fatigue Properties

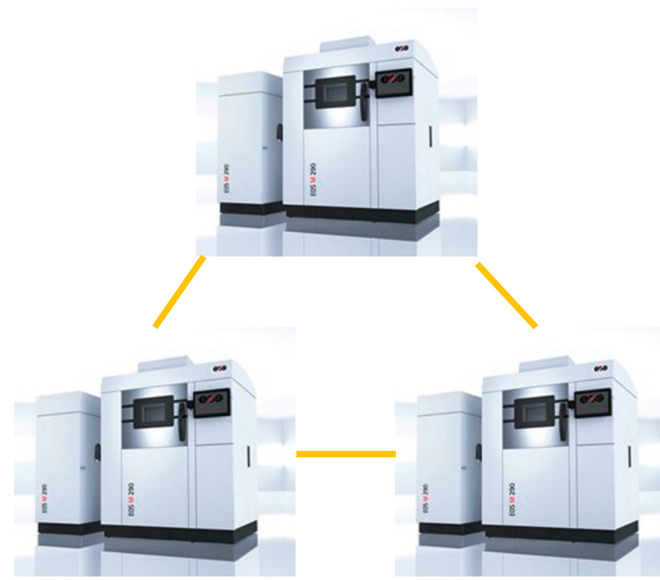
Phase III: Damage Tolerance

Categories of Process Variability in LPBF



I. Intra-Build
(Within single build volume)

II. Inter-Build
(Over multiple builds with same machine)



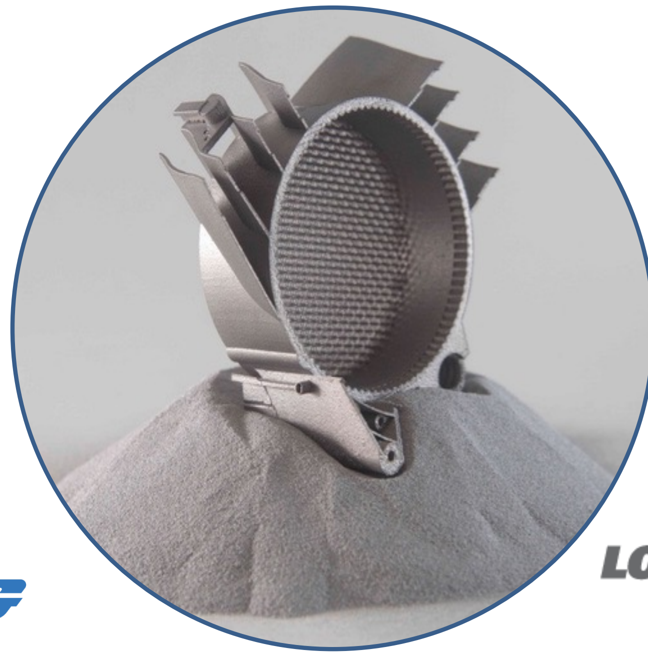
III. Inter-Machine
(Across identical machines)

Round Robin Partners

W

'TORAY'
Toray Precision Co.,Ltd.

BOEING



eos

3D LOGICS

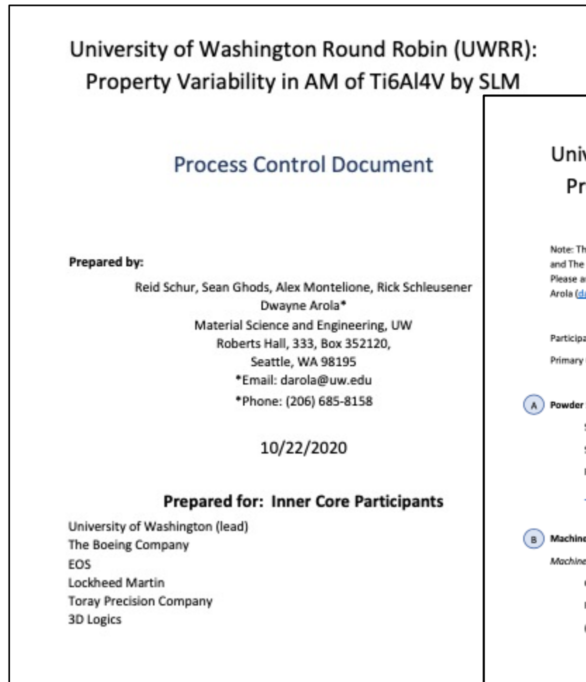
LOCKHEED MARTIN

oerlikon

Overview of Program and Printing

- **All partners operating an EOS M290**
- Single lot of powder for all partners (EOS Grade 5 Ti6Al4V)
- Single Process Control Document (PCD) for all partners
- All partners use same process parameters (default for Ti6Al4V)
- All partners follow same build design

Process Control Document


University of Washington Round Robin (UWRR):
Property Variability in AM of Ti6Al4V by SLM

Process Control Document

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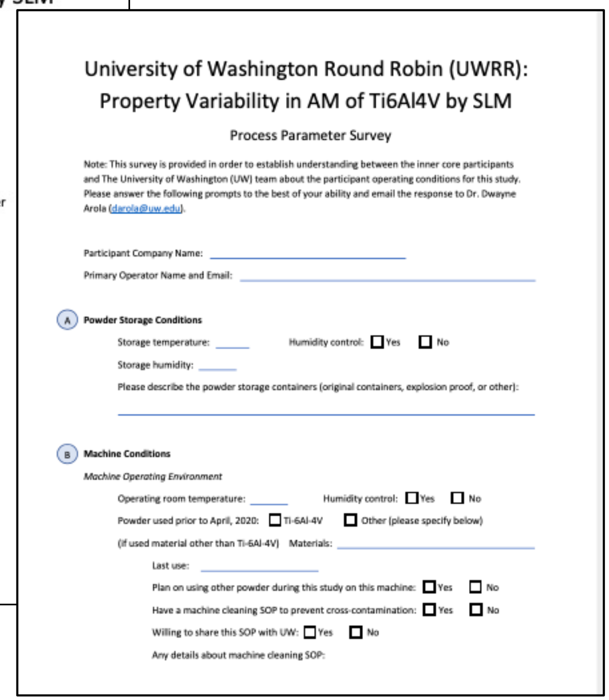
10/22/2020

Prepared for: Inner Core Participants

University of Washington (lead)
The Boeing Company
EOS
Lockheed Martin
Toray Precision Company
3D Logics

Partner Questionnaire (Powder + Machine)


University of Washington Round Robin (UWRR):
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Process Parameter Survey

Note: This survey is provided in order to establish understanding between the inner core participants and The University of Washington (UW) team about the participant operating conditions for this study. Please answer the following prompts to the best of your ability and email the response to Dr. Dwayne Arola (darola@uw.edu).

Participant Company Name: ____

Primary Operator Name and Email: ____

A **Powder Storage Conditions**

Storage temperature: ____ Humidity control: ☐ Yes ☐ No

Storage humidity: ____

Please describe the powder storage containers (original containers, explosion proof, or other):

B **Machine Conditions**

Machine Operating Environment

Operating room temperature: ____ Humidity control: ☐ Yes ☐ No

Powder used prior to April, 2020: ☐ Ti-6Al-4V ☐ Other (please specify below)

(if used material other than Ti-6Al-4V) Materials: ____

Last use: ____

Plan on using other powder during this study on this machine: ☐ Yes ☐ No

Have a machine cleaning SOP to prevent cross-contamination: ☐ Yes ☐ No

Willing to share this SOP with UW: ☐ Yes ☐ No

Any details about machine cleaning SOP:

Metal Post-Processing and Characterization

Post Processing Facilities

Heat Treatment

Nabertherm LH 120/12 w/ P470 controller and gassing box (Argon treatment)

Machining

Omax 2652 Abrasive Waterjet

HAAS CNC Mill (TM-1P)

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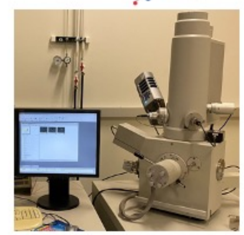
Metal Characterization Facilities

Microscopy

Molecular Analysis Facility

Optical/Stereo Microscopes
Olympus BX 51M | Olympus SZX16



Scanning Electron Microscopes
Philips XL-30 Sirion (+EDS)
TFS Apreo var-press (+EDS + EBSD)

Spectroscopy

X-Ray Fluorescence
Bruker
M4 Tornado

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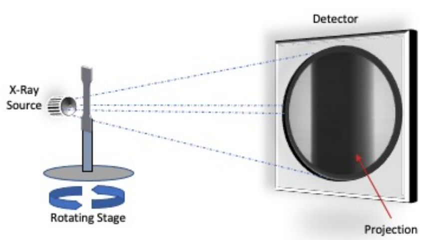
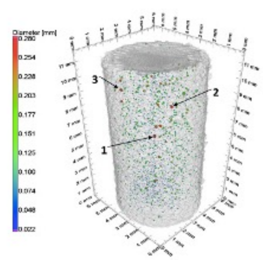
Micro Computed Tomography

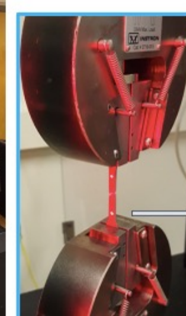
X-Ray Micro Computed Tomography:

- North Star Imaging system, microCT, X5000, Rogers, MN, USA
- 360° x-ray scans and 3D reconstruction

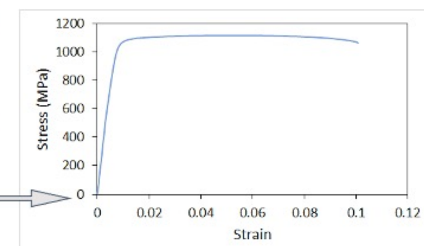




Mechanical Property Characterization (Static and cyclic)



Universal Testing System:
Instron Model 5585H; Norwood, MA



ASTM E8 based procedures

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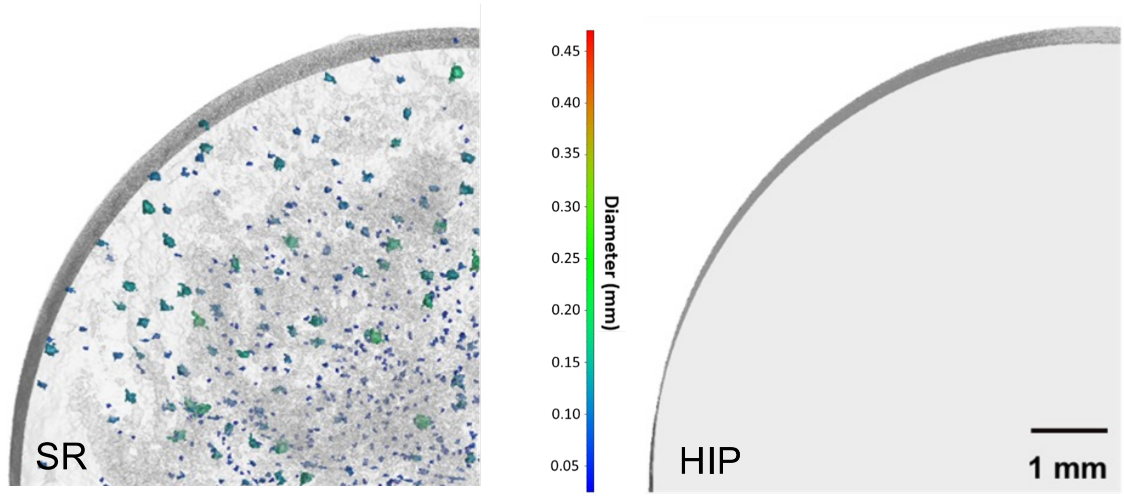
Phase I and II: Post Processing

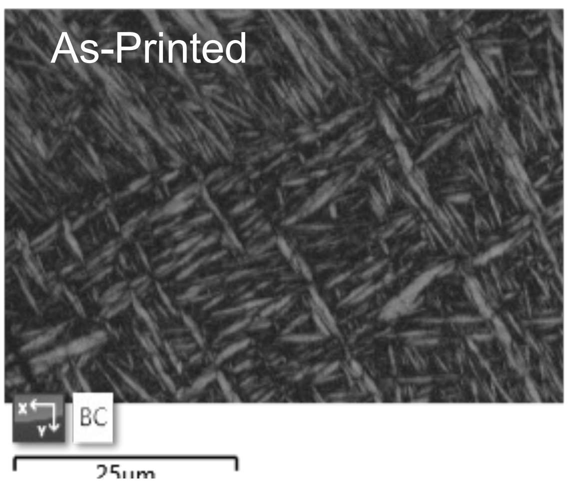
i. Stress relief heat treatment (SR)

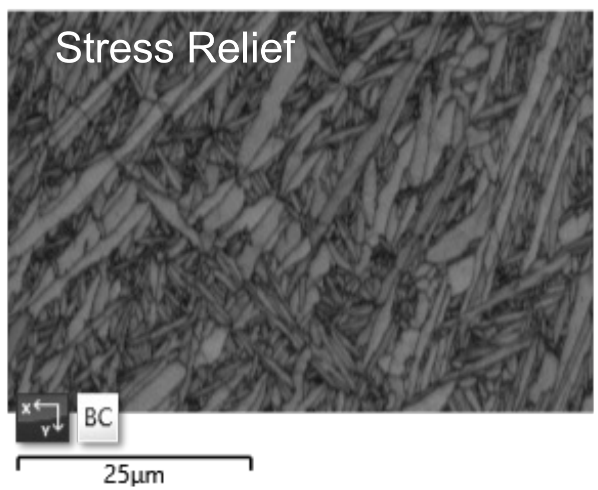
- 745°C for 2 hours in argon

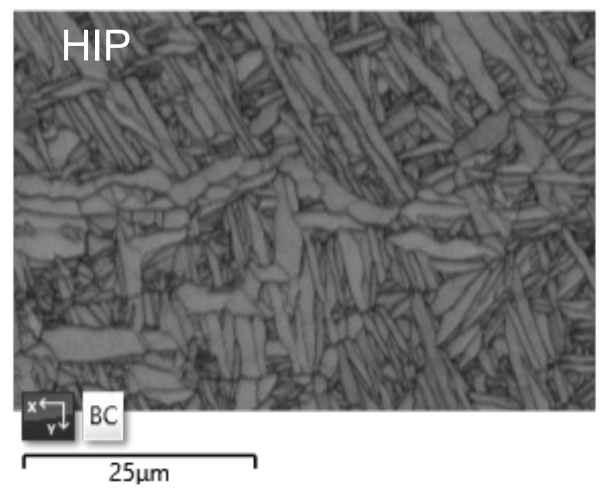
ii. Hot Isostatic Pressing (HIP)

- 815°C for 165 min @ 190 MPa (AMS 7028)

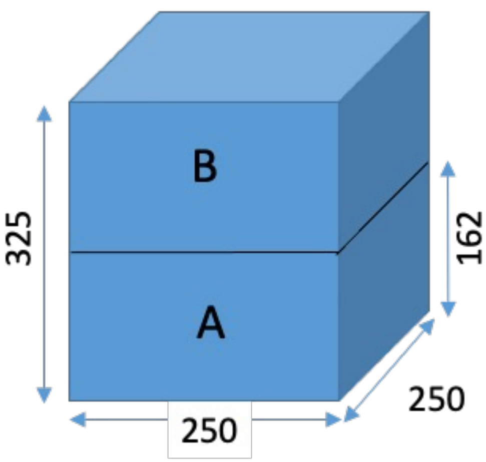






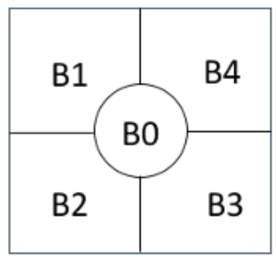


Discretization of Build Volume

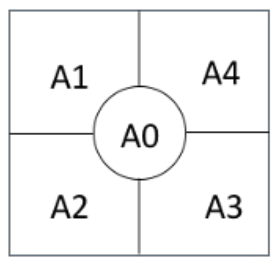


Oblique View

Two Levels (A, B)



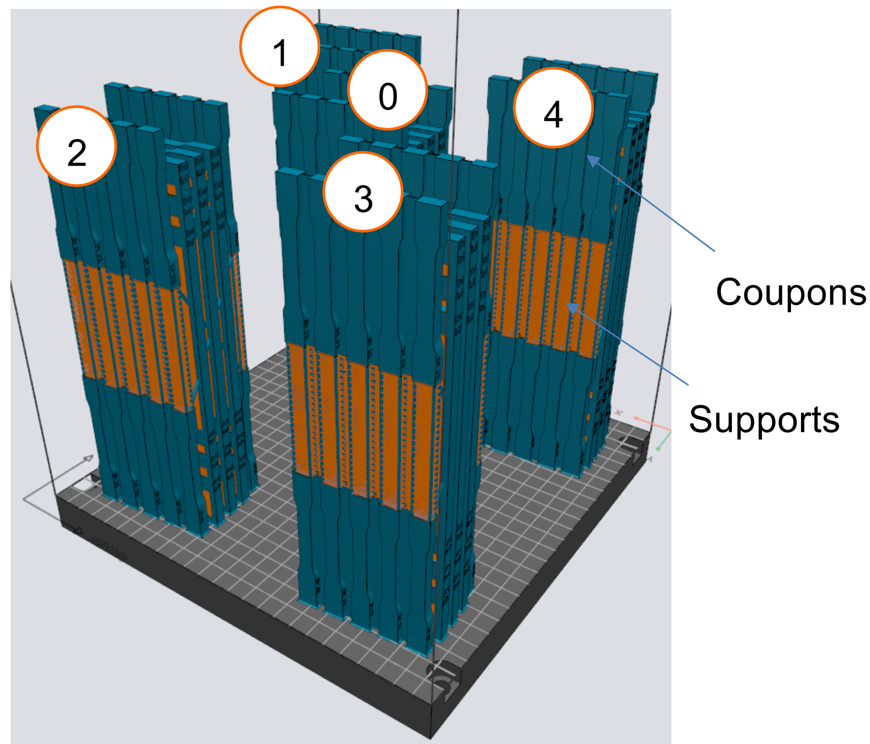
Top View – Level B



Top View – Level A

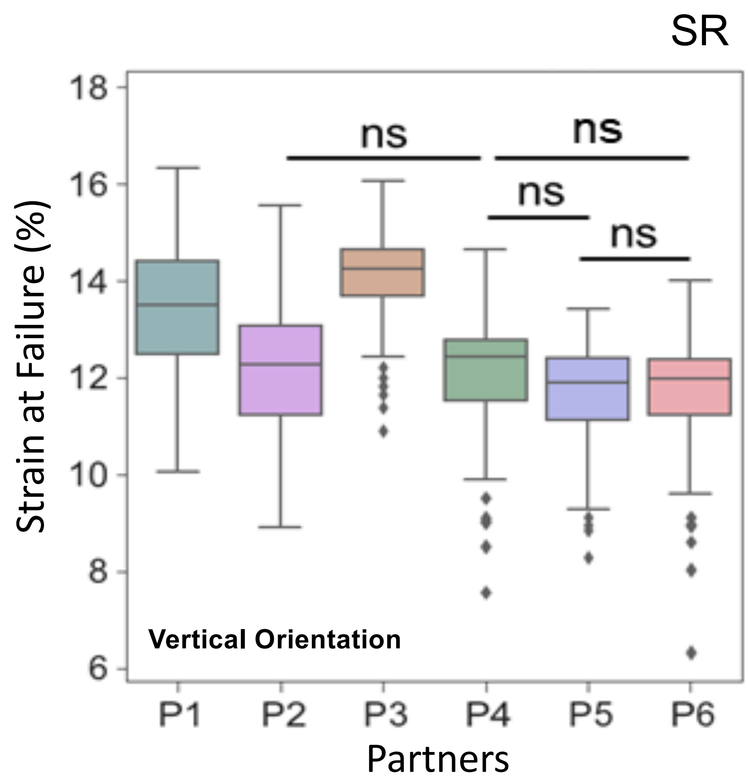
Five Zones per level
(0, 1, 2, 3, 4, 5)

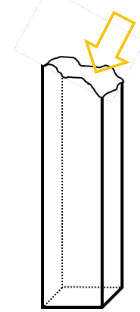
Build Envelope Discretization

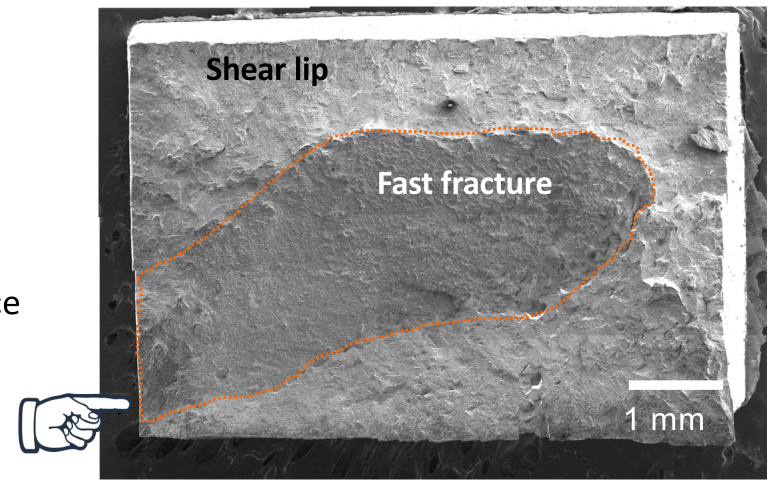


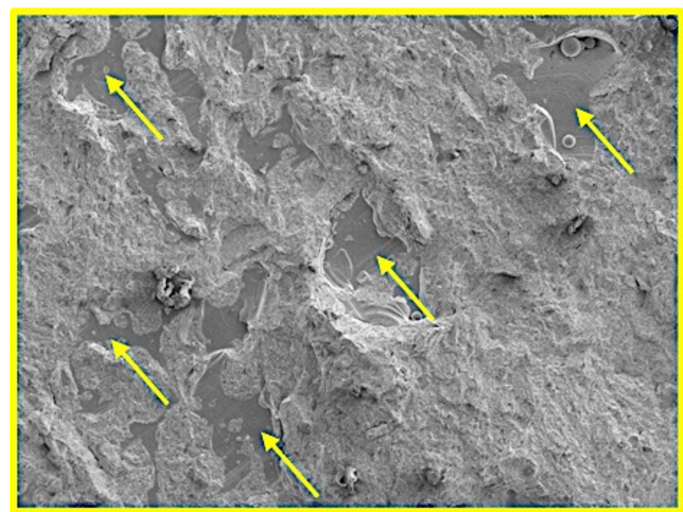
Phase I: Build Design
(5 zones, 2 levels)

Phase I: Tensile Properties









- Significant inter-machine variation in mean response (strain to failure) and outliers

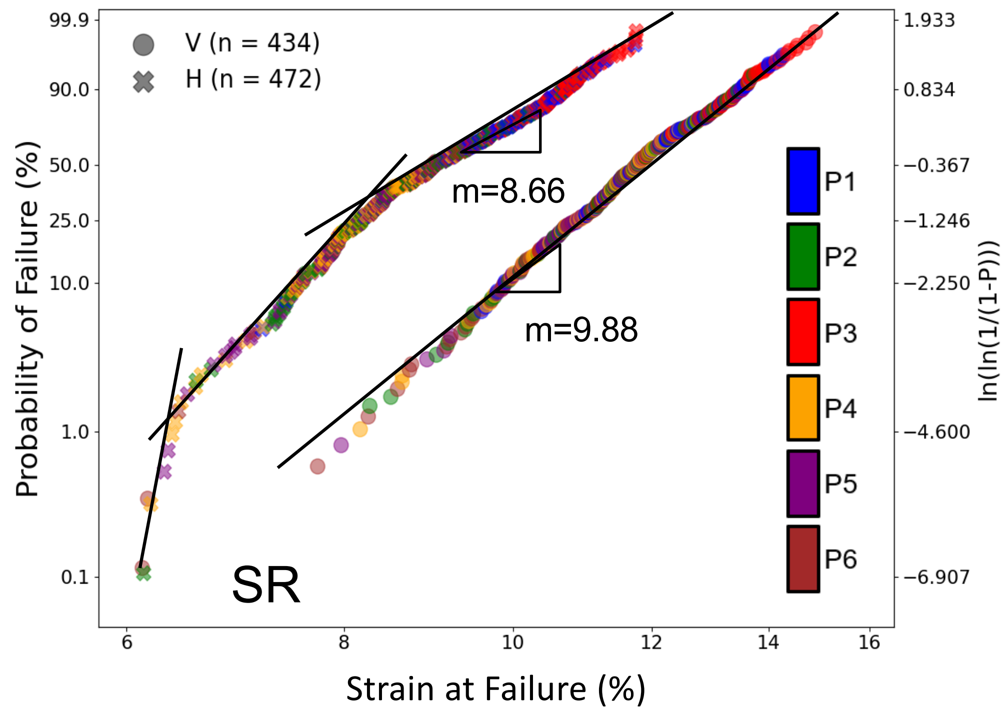
Variability in Strain to Failure

- Weibull distributions for strain at failure are mostly linear
  - Most defect-sensitive measurement

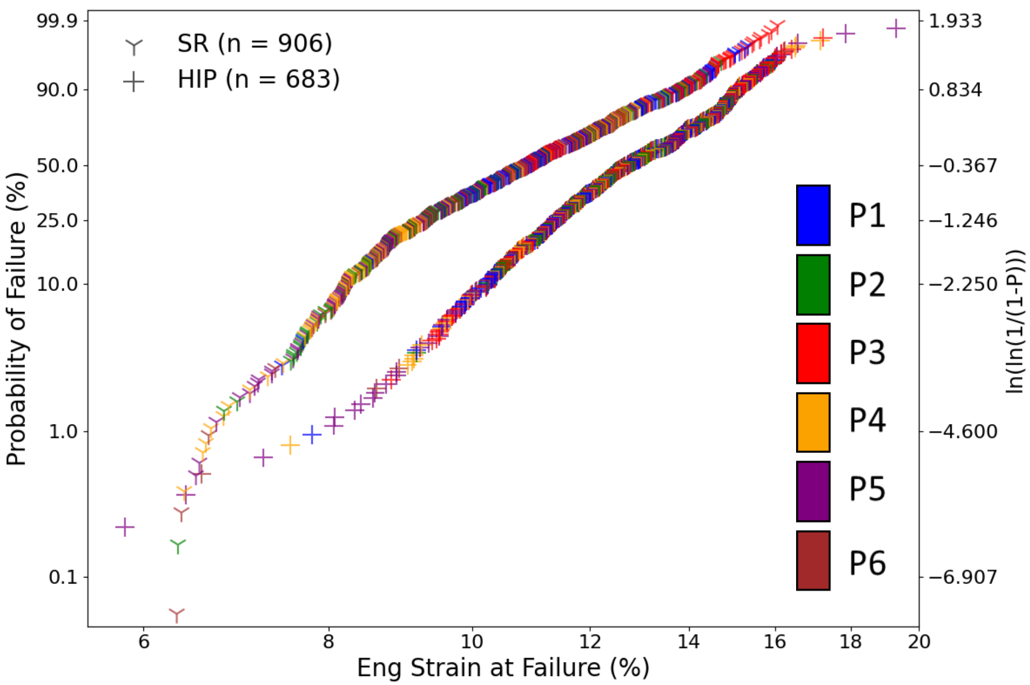
$$P_f = 1 - \exp\left(-\left(\frac{e}{e_\theta}\right)^m\right)$$

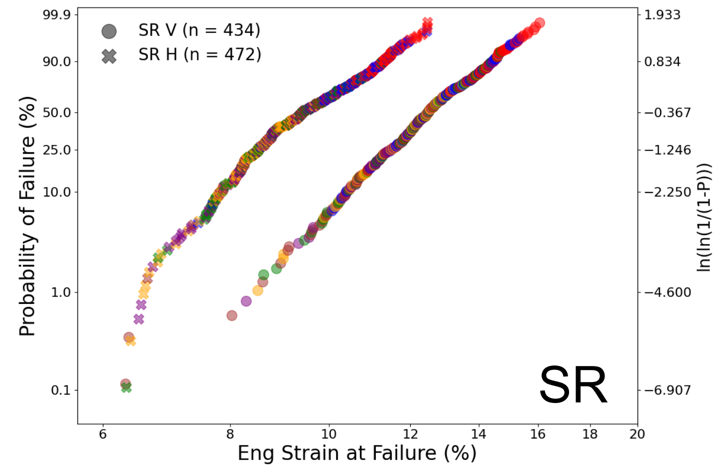
- Vertical orientation exhibits both larger m and single slope
  - single defect family

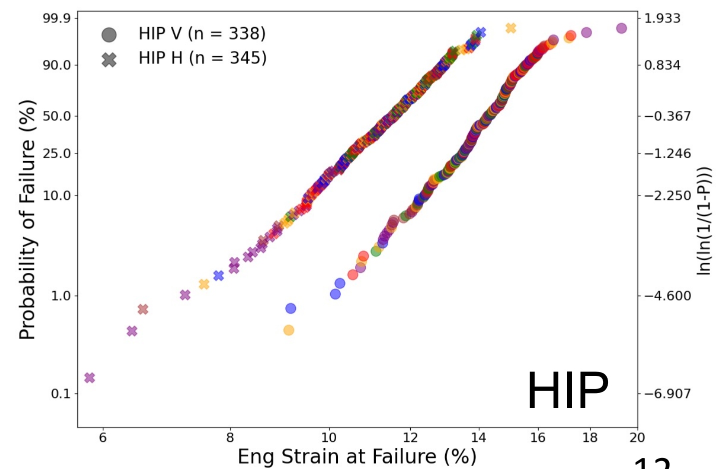
- Horizontal orientation exhibits multi-modal distribution
  - multiple families of contributing defects?



Importance of Orientation & Heat Treatment



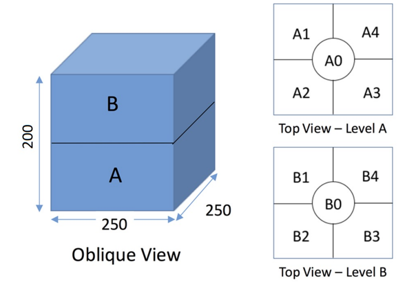




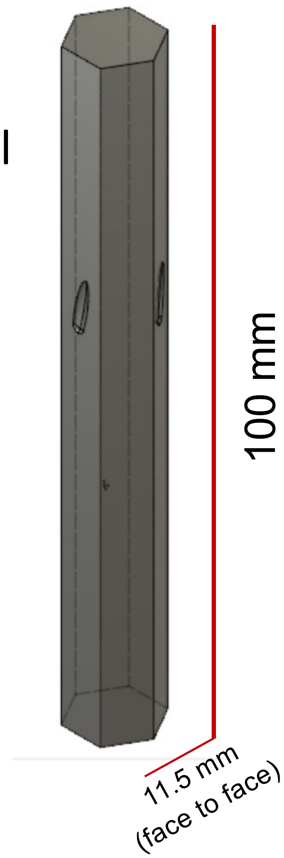
- HIP increased strain at failure and linearized horizontal dataset
- HIP did not remove anisotropy in strain at failure

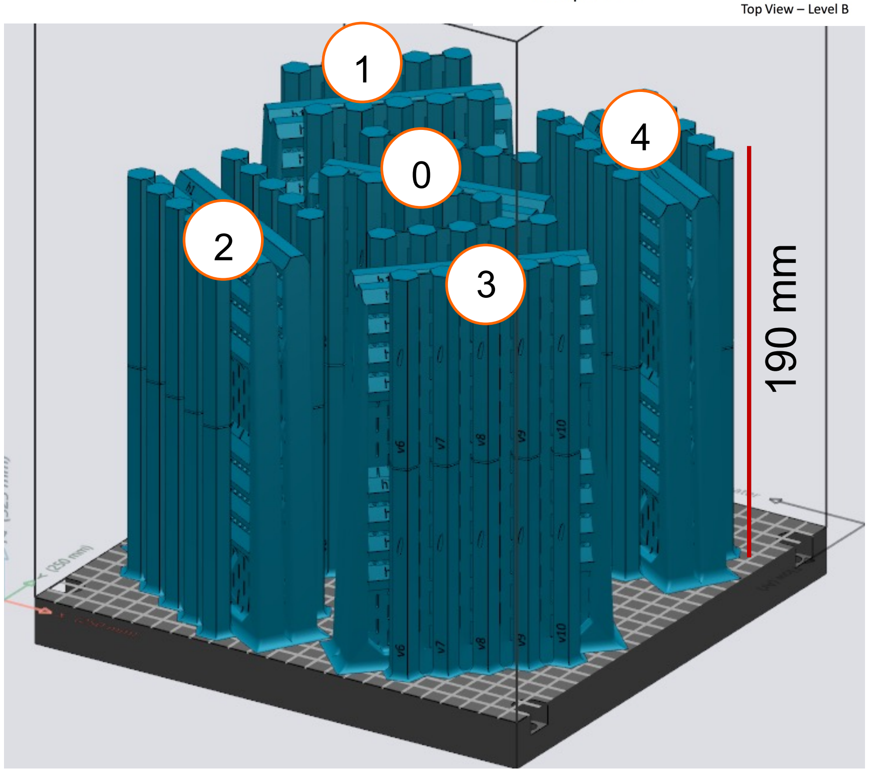
Phase II: Finite Life Fatigue

Phase II: Build Design Details

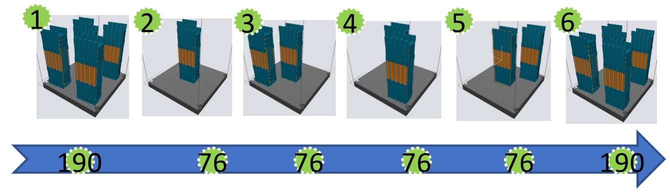


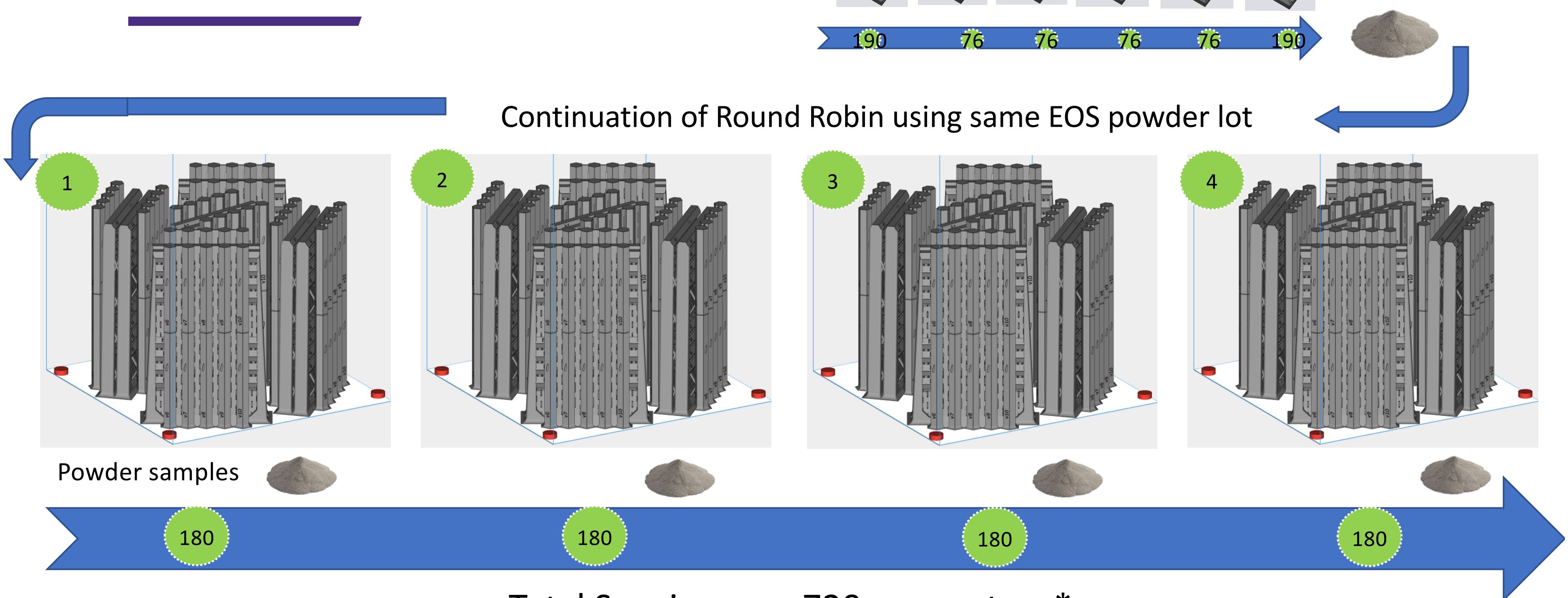
- Two levels and five primary zones on each level
- Each zone comprised of hexagonal coupon blanks with **vertical** and **horizontal** orientations
- Machined into final fatigue coupons with longitudinal grind according to ASTME466
- Mitigating effect of near surface porosity
- Fiducial marks for 3D registration of layers and defects





Phase II: Build sequence





Total Specimens = 720 per partner*

Post-processing of metal involves:

i) Heat treatment

ii) Net shape machining to ASTM E466

*If partner performs four builds

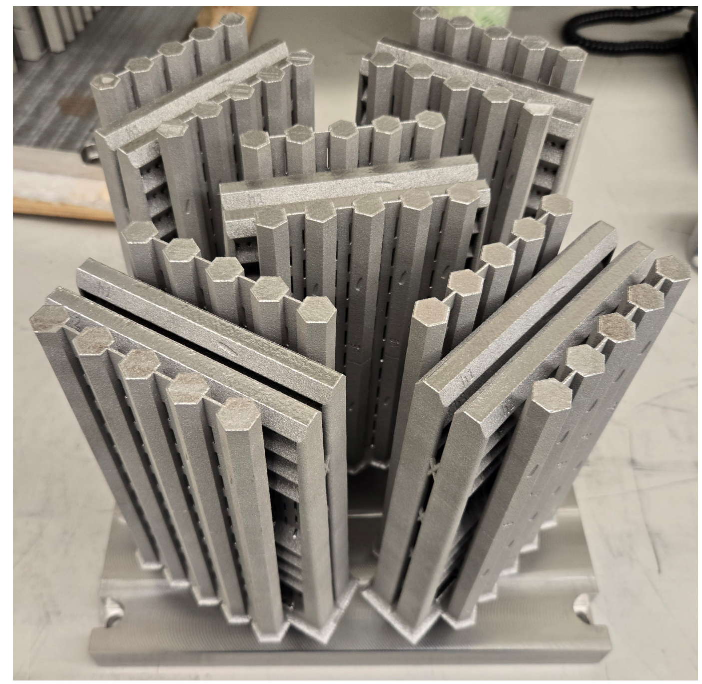
Phase II: Printing Progress

■ Complete

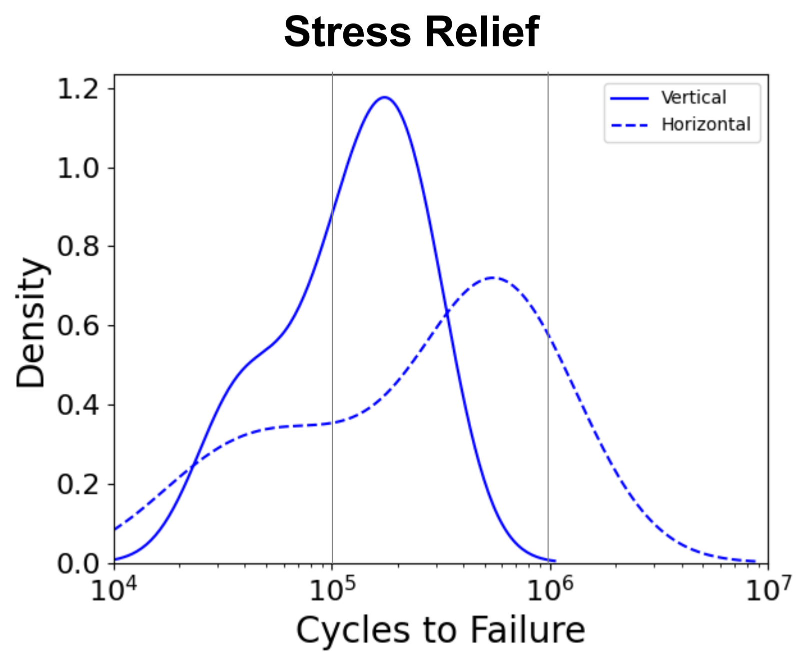
□ Planned

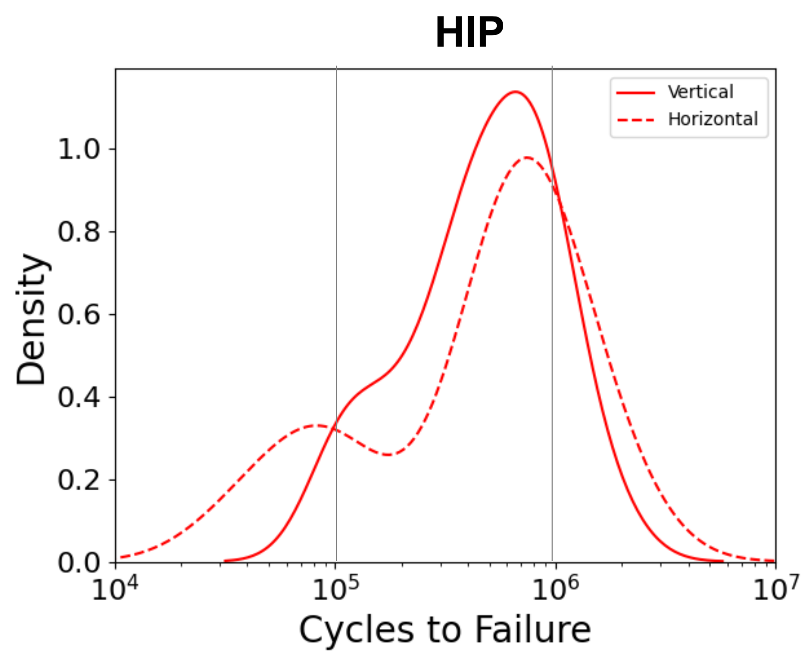
Builds

Partner	B1	B2	B3	B4	
P1	■	■	■	■	w EOSTATE in-situ data
P2	■	■	■	■	w/EOSTATE in-situ data
P3	■	■	■	■	w/EOSTATE in-situ data
P4	□				w/EOSTATE in-situ data
P5	□				w/o EOSTATE
P6	To be determined …..				



Fatigue Life Distributions: SR vs HIP





- Increase in fatigue life as a result of HIP treatment

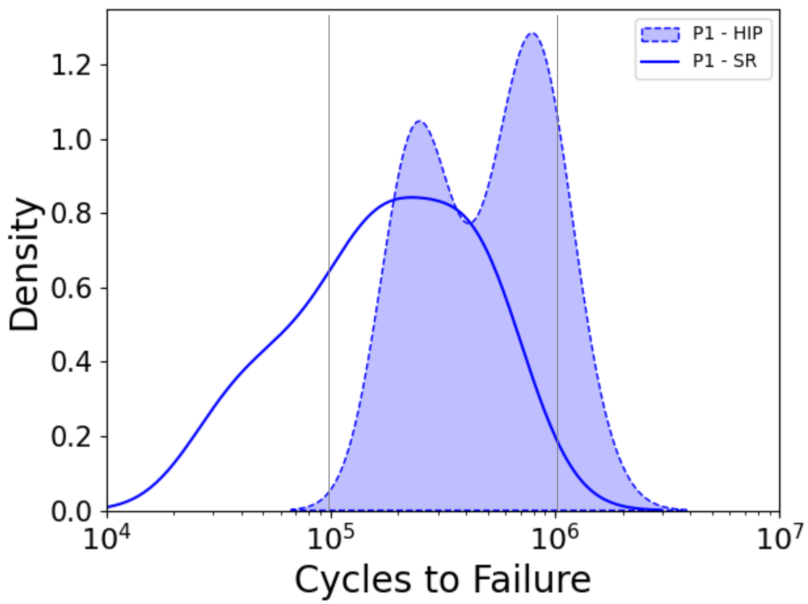
  $SR_{avg} = 2.33 \times 10^5$ cycles; $HIP_{avg} = 5.93 \times 10^5$ cycles

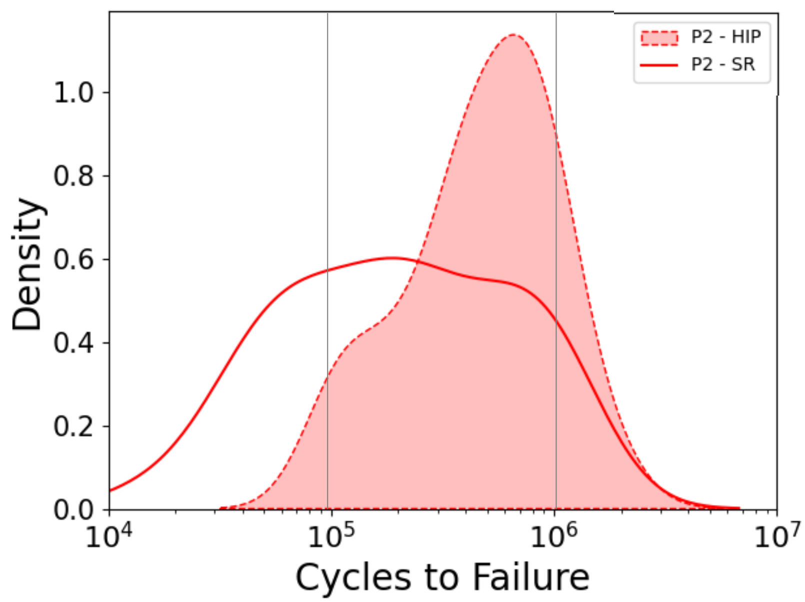
- HIP substantially reduces anisotropy between horizontal and vertical orientations

* All data shown tested at 850 MPa max stress

* Partner #1

Fatigue Life Distributions: SR vs HIP (Vertical)





Partner 1:

- SR_{avg} = 2.46 × 10^5 cycles
- HIP_{avg}= 5.83 × 10^5 cycles

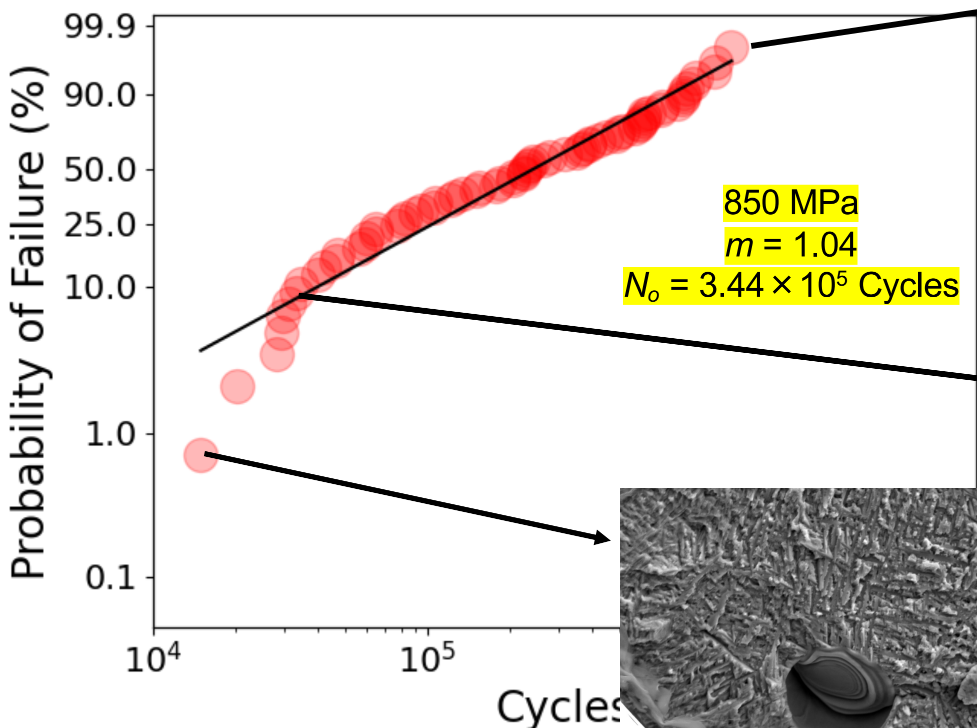
Partner 2:

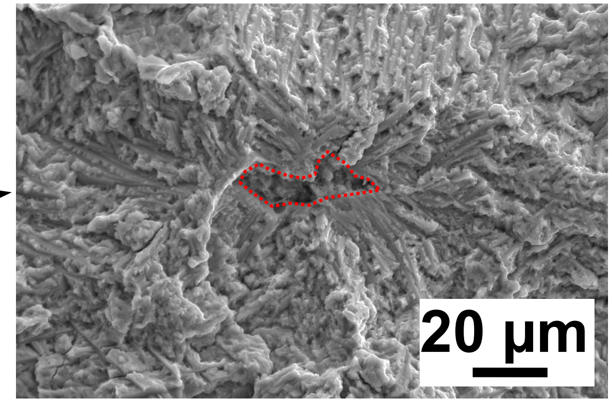
- SR_{avg} = 3.47 × 10^5 cycles
- HIP_{avg}= 6.30 × 10^5 cycles

- Reduction in intra-build and inter-machine variability after HIP treatment!

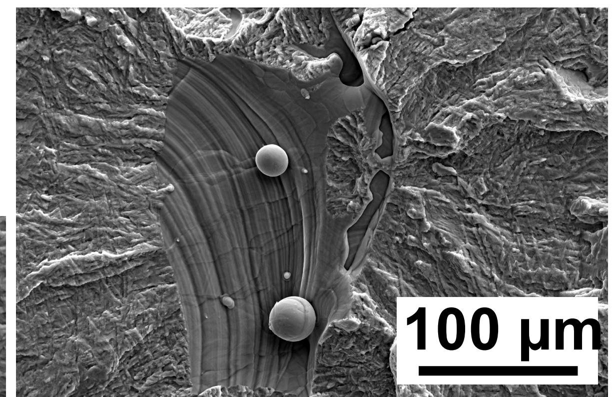
* All data shown tested at 850 MPa max stress

Root Cause: SR Condition

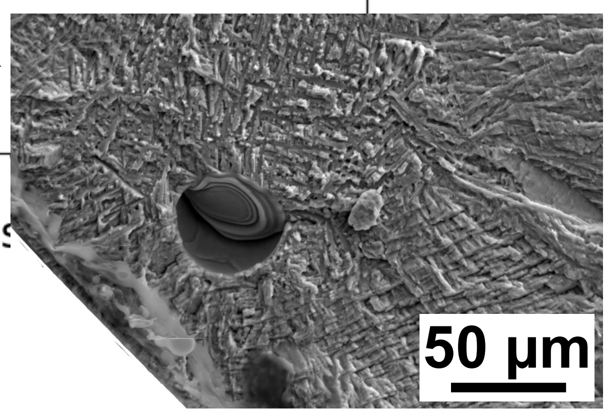




Internal carbon FOD



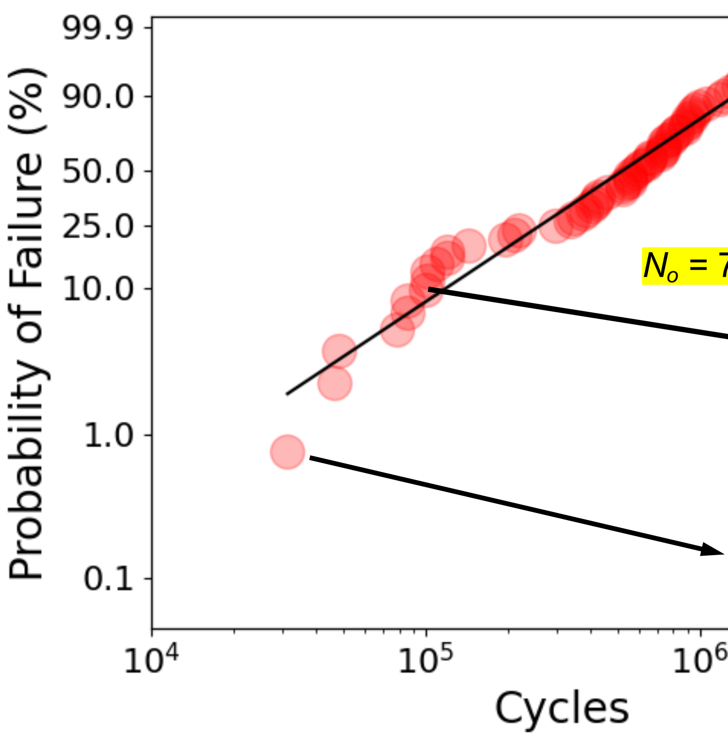
Internal LOF defect

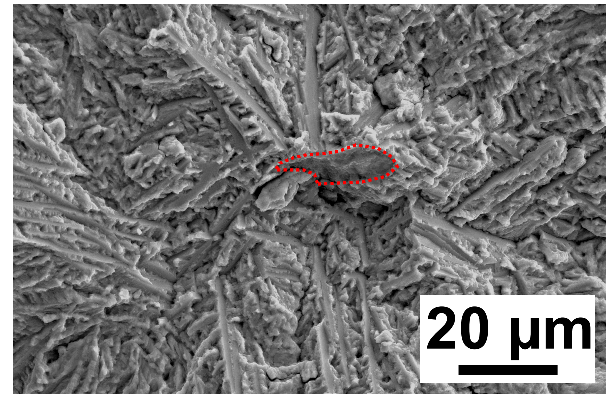


Near-surface LOF defect

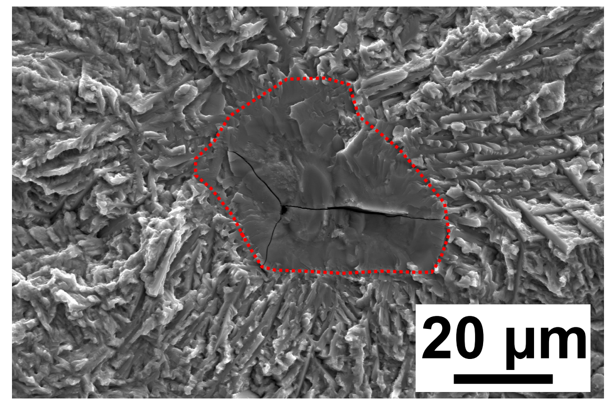
$$P_f = 1 - \exp\left(-\left(\frac{N}{N_o}\right)^m\right)$$

Root Cause Defects: HIP

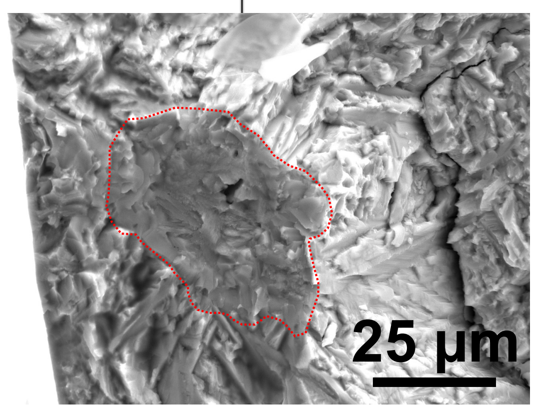




Internal carbon FOD



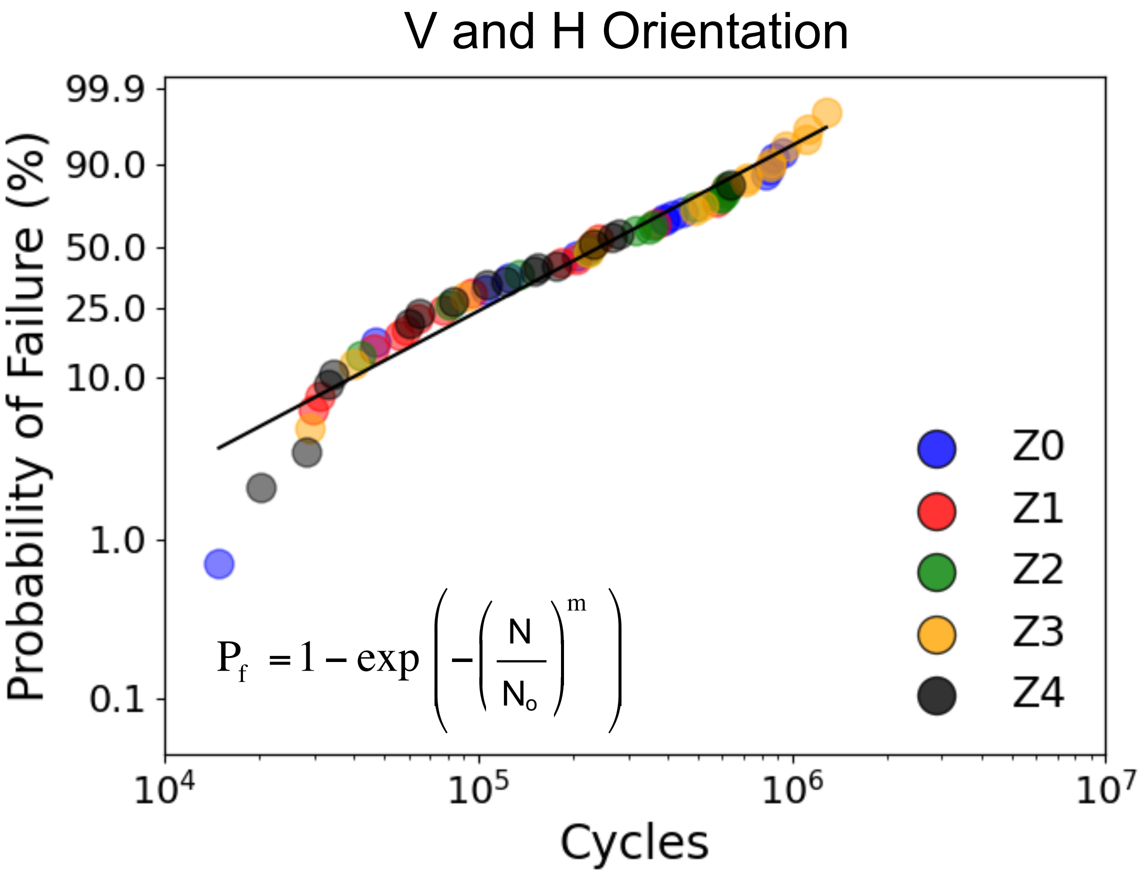
Internal brittle microstructural feature

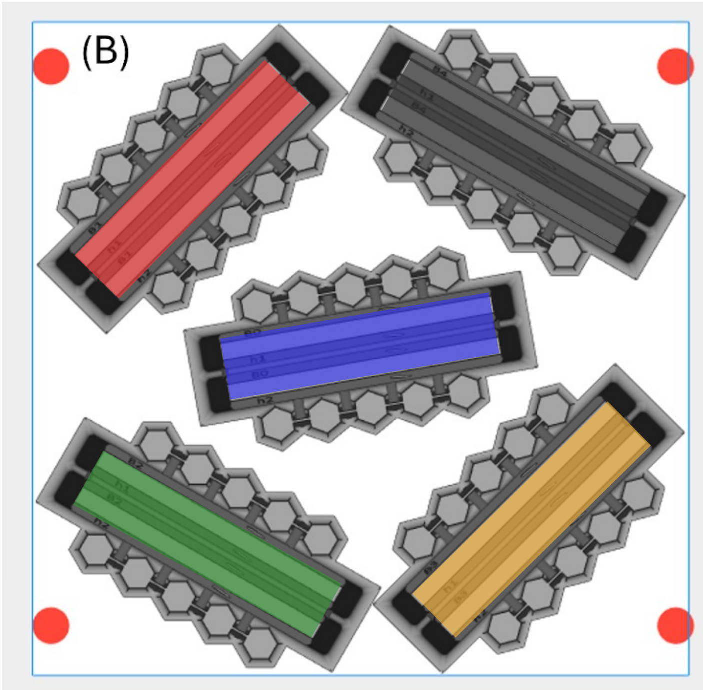


Near-surface brittle microstructural feature

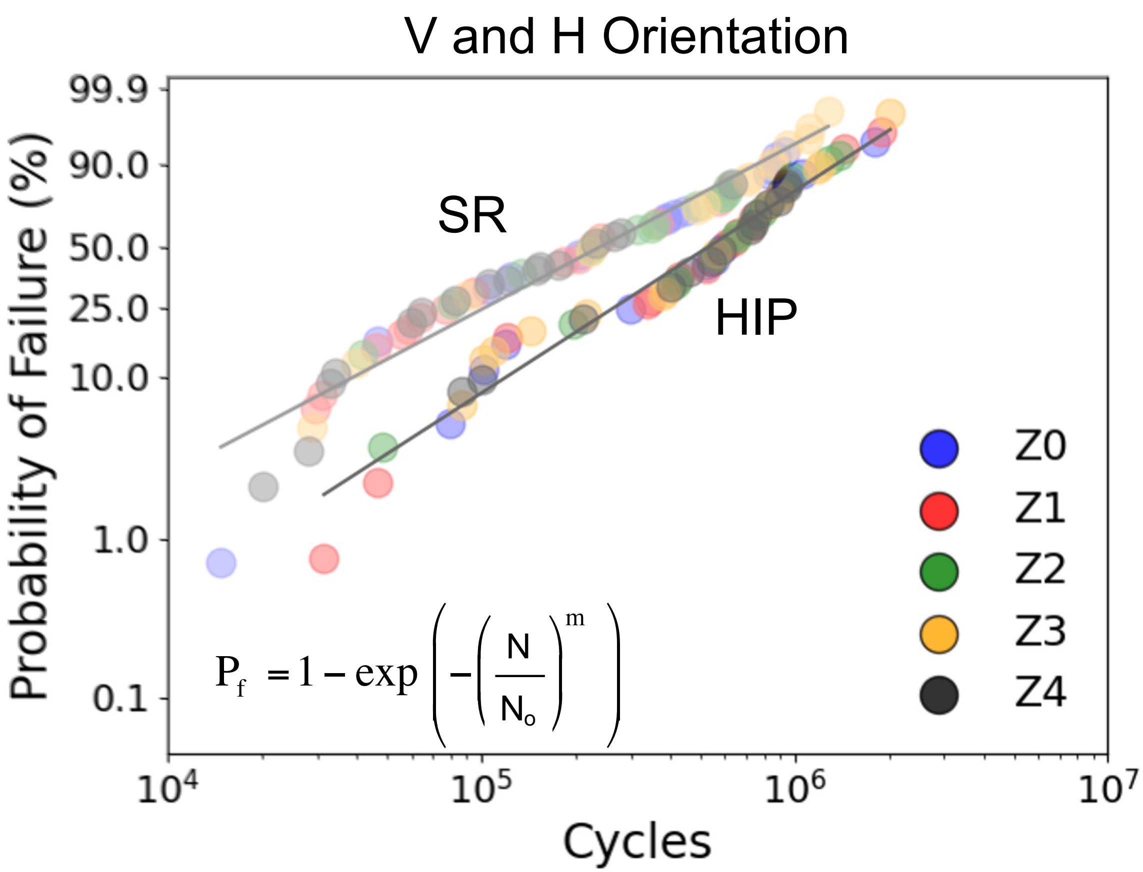
$$P_f = 1 - \exp\left(-\left(\frac{N}{N_o}\right)^m\right)$$

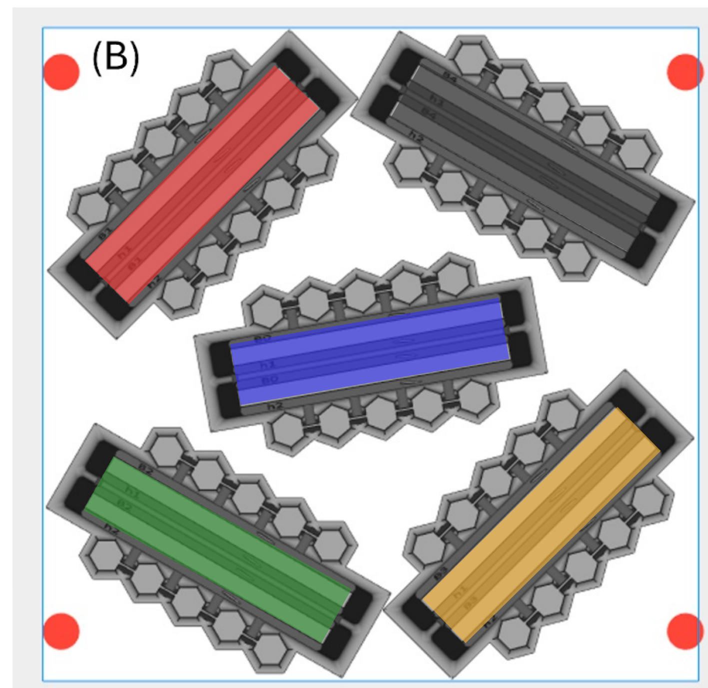
Spatial Variations in Life: **SR Condition**





Spatial Variations in Life: **SR vs HIP Condition**

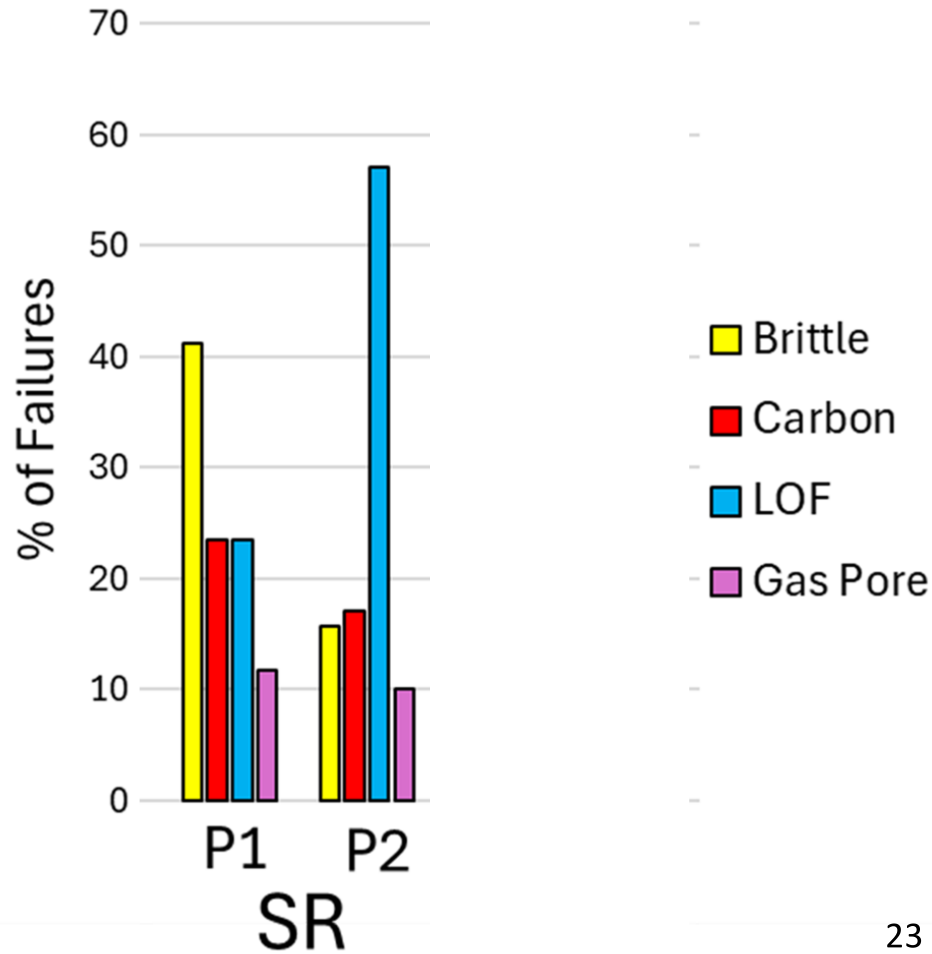




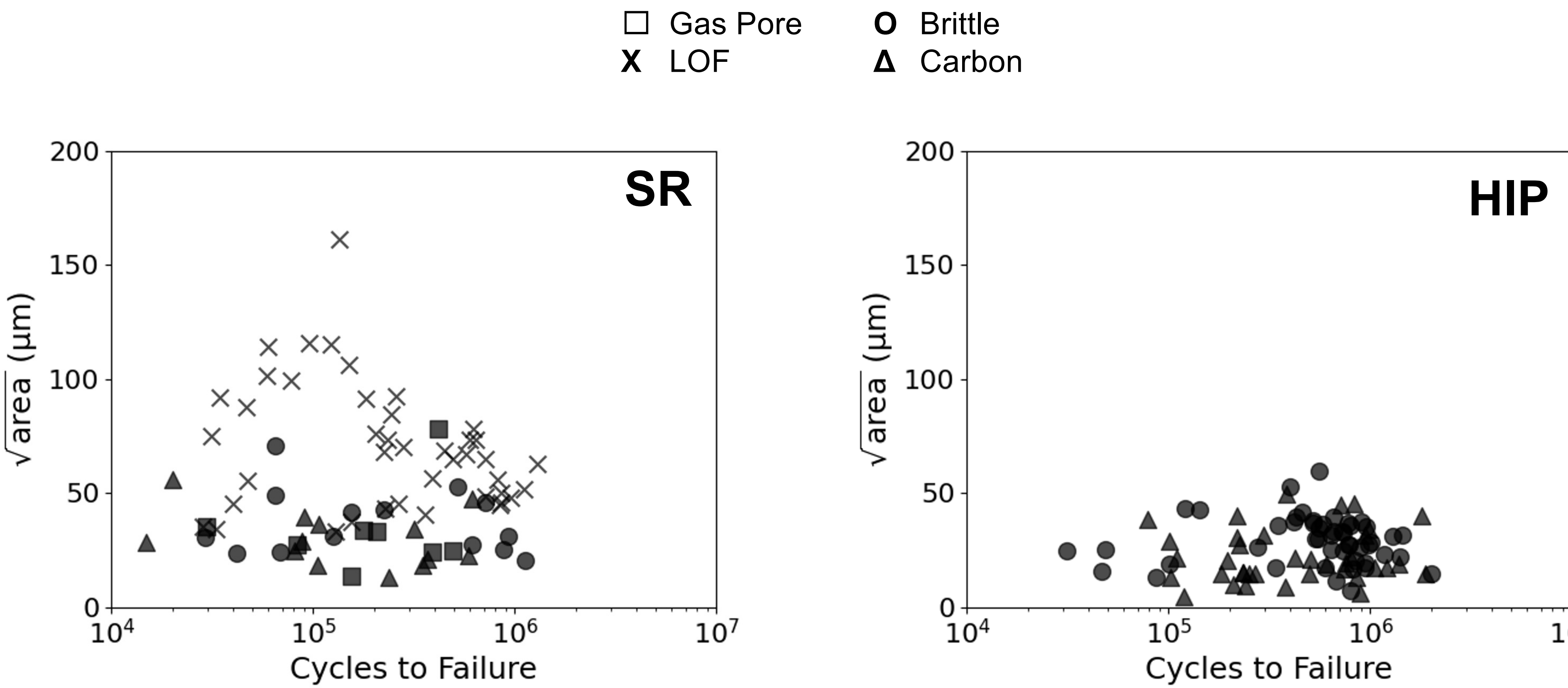
Phase II: Failure Origin Breakdown

- **SR Condition**
  - Failure dominated by voids
  - FOD failures observed
  - Inter-machine differences

- **HIP Condition**
  - Failure by carbon FOD and brittle microstructural features (appear driven by Tungsten FOD)
  - **Zero** porosity-related defects observed on fracture surfaces



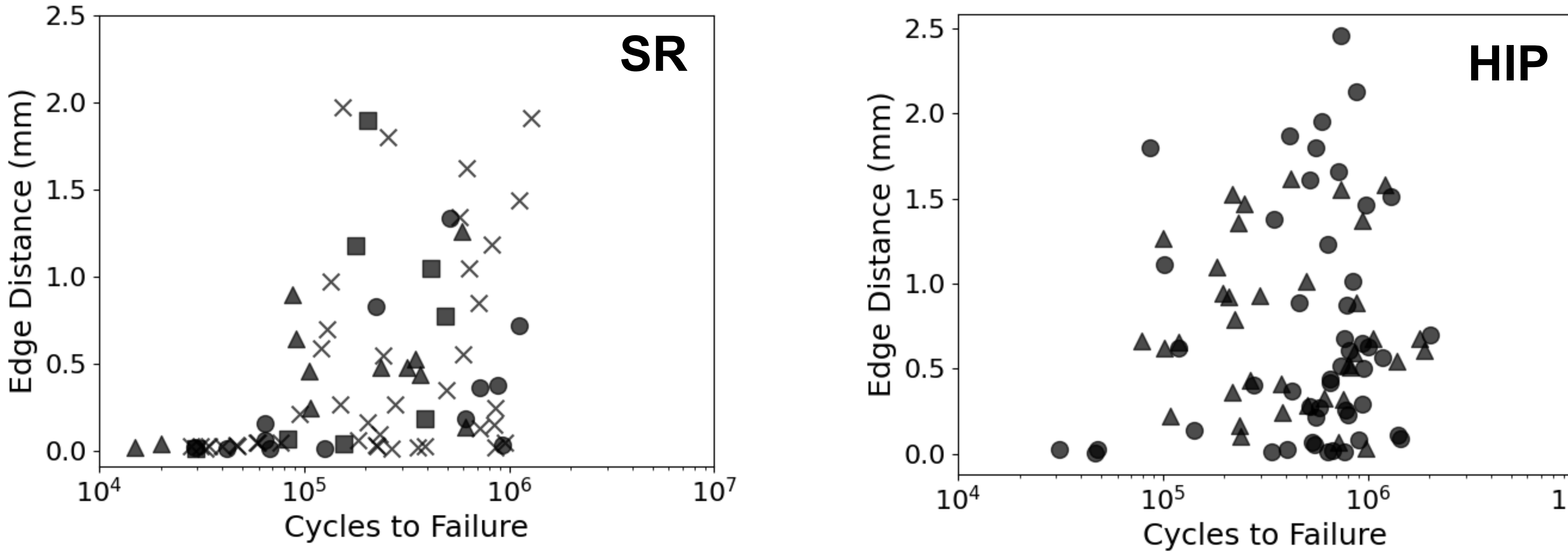
Correlating Defects and Life : **SR and HIP Condition**



- Measures of dimensions are based on root cause defect revealed on fracture surface

Correlating Defects and Life : **SR and HIP Condition**

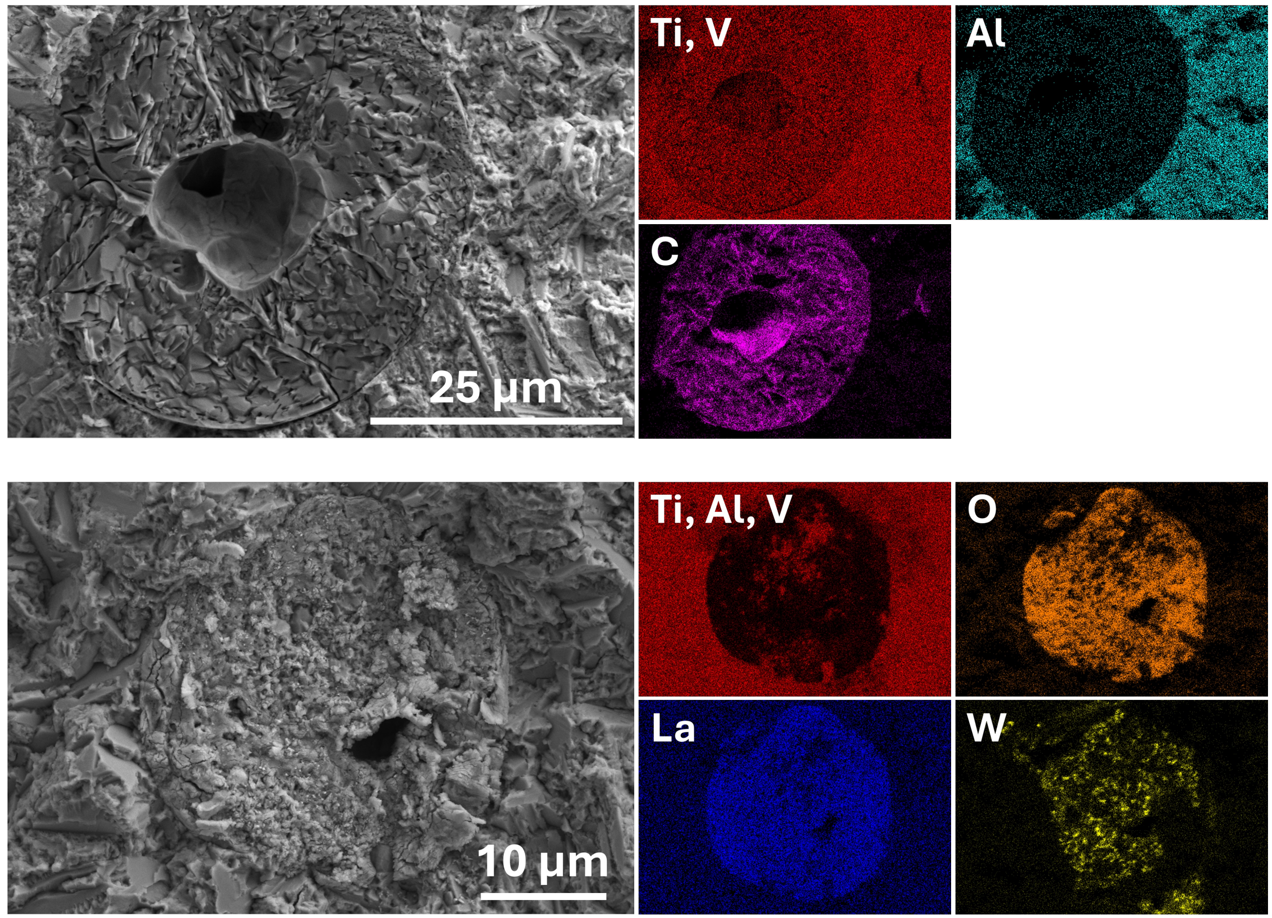
☐ Gas Pore
X LOF
O Brittle
Δ Carbon



- Measures of distance are based on location of root cause defects revealed on fracture surface

Phase II: Composition of Foreign Object Debris

- Interesting insight on failure origins from fractography
- Large powder-sized carbon particle
- Large powder-sized LaO particle with dispersed W nanoparticles
- FOD is likely introduced in powder through atomization process – largely observed in HIP specimens



Limitations:

- **It is unclear if the FOD are a result of the feedstock or the machine**
  - Single powder source has complicated the process for diagnosing source of FOD

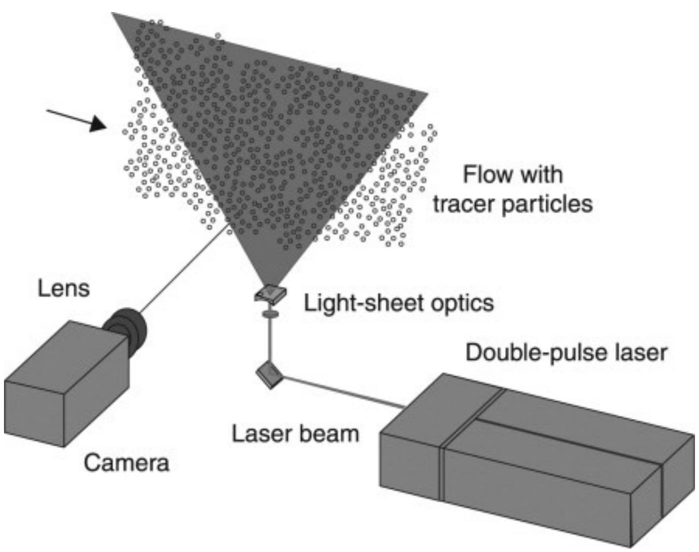
- **Additional aspects of machine condition are not reflected**
  - e.g. glass cover condition, gas filter loading, etc

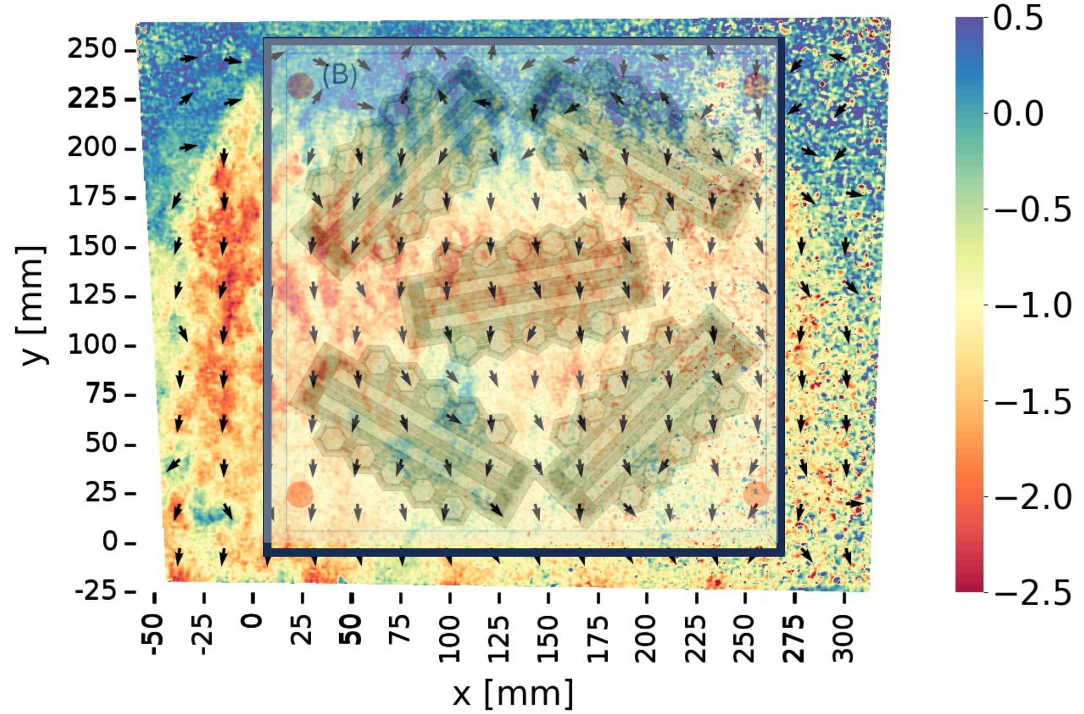
- **Environmental factors are potentially relevant but not considered**

- **Does not reflect influence of post-processing surface treatments**
  - No failures initiated from surface in HIP condition
  - **Zero** porosity-related defects observed on fracture surfaces

Analysis of Spatial Variation in Inert Gas Flow

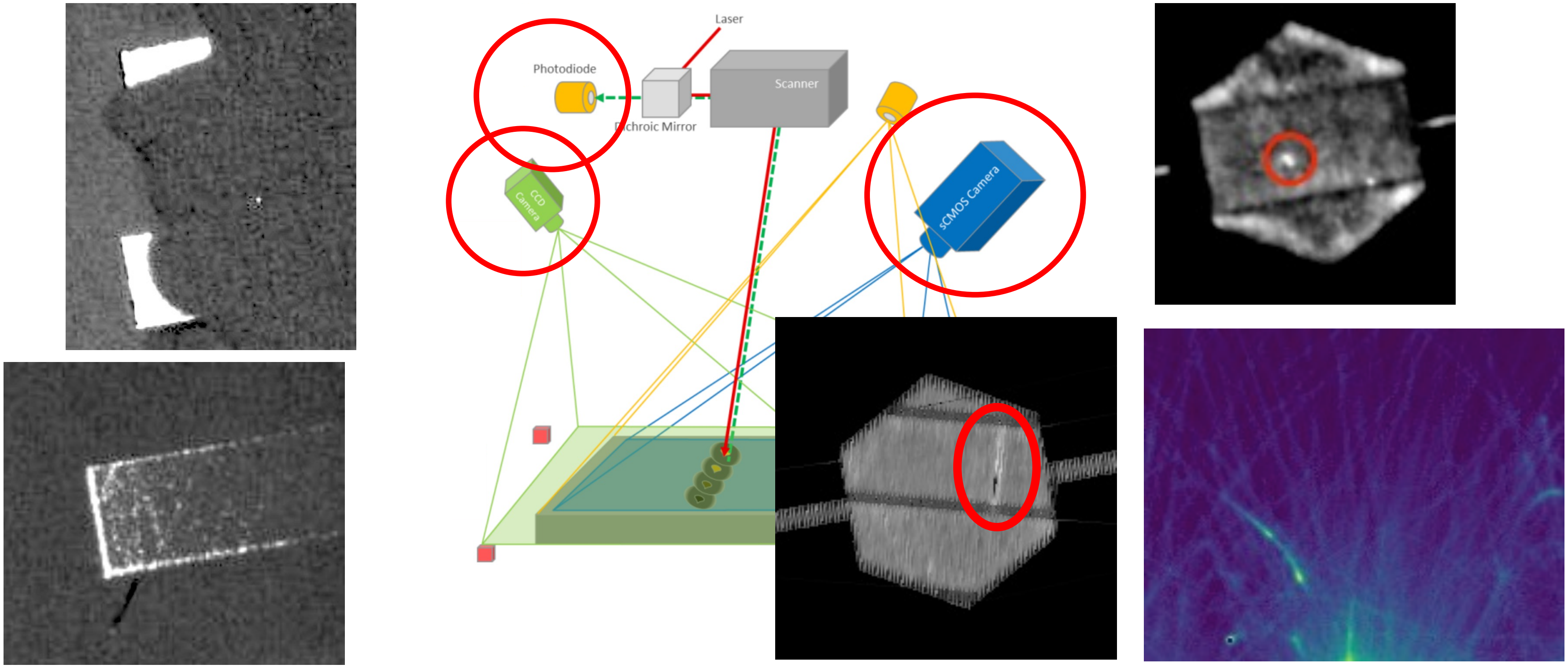
- A mock build chamber (1:1 scale) was constructed with OEM gas ducting for the EOS M290
- Quantifying gas flow using particle image velocimetry (PIV).





[1] Abeyta et al,

In-situ Monitoring Analysis Underway

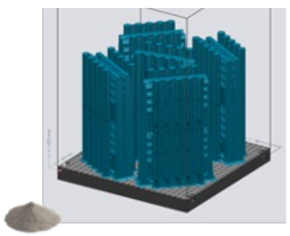


- **OT imaging** – long exposure thermal image, shows hot spots and spatter
- **Powderbed imaging** – visible light image, shows short feeding, and edge warping
- **Meltpool imaging** – co-axial monitoring of laser spot, tracks meltpool temperature
- Processing and evaluation of anomalies performed using Peregrine.

Recruiting Additional Partners to Engage

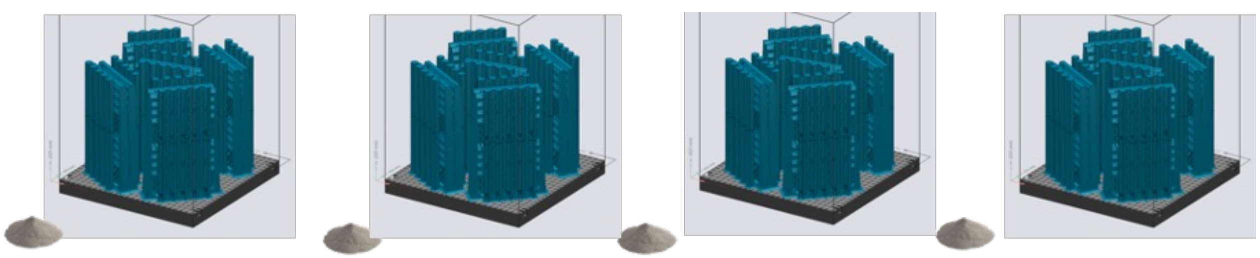
i) Partner performs one build

- enables characterization of: i) intra-build, and ii) inter-machine variability



ii) Partner performs four identical builds

- enables characterization of intra-build, inter-build and inter-machine variability



Summary

- HIP treatment according to AMS 7028 results in significant increase in fatigue life of metal for both horizontal and vertical orientations; largest benefit to vertical orientation

- While anisotropy in the quasi-static properties is retained after HIP, the finite life fatigue responses of the vertical and horizontal orientations are not significantly different.

- Root cause defects in HIP condition are FOD consisting largely of carbon and tungsten contaminants. No failures yet attributed to LOF

- Recruiting additional partners that seek to evaluate their process variability with respect to a robust database

Acknowledgements

Special thanks to Cory Cunningham and Reid Schur of The Boeing Company.


Reused Powder, LPBF
Grade 5, Ti6Al4V
EOS M290_UW RR
After 6 Build cycles
Thank you.....
Courtesy: Chris Liu, UW Capstone
50 µm