JAMS
JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

# Characterizing Mechanical Property Variability in Ti6Al4V produced by Laser Powder Bed Fusion (LPBF) Additive Manufacturing

Reid Schur[1], Alex Montelione[1], Rick Schleusener[1]
Mamidala Ramulu[1,2], Dwayne Arola[1,2]

Materials Science and Engineering, Mechanical Engineering, UW, Seattle, WA

*FAA Tech Monitor: Kevin Stonaker / FAA Sponsors: Cindy Ashforth & Michael Gorelik*

sampe North America

*April 18th, 2023*

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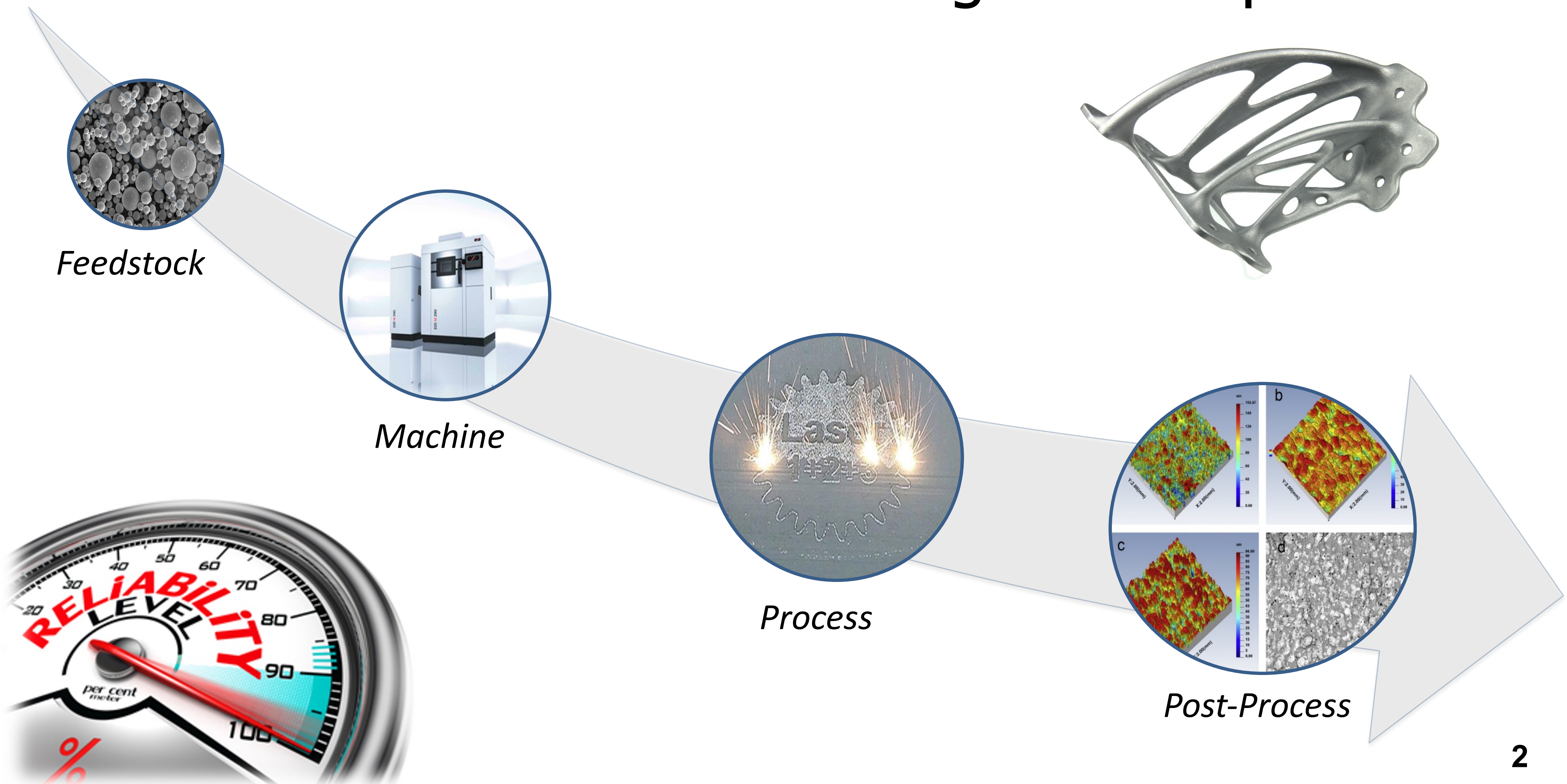
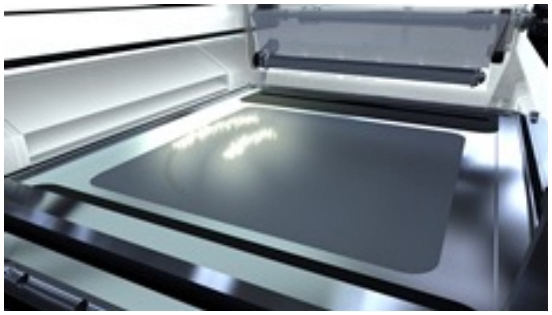
AMTAS
Advanced Materials in Transport Aircraft Structures

# LPBF Additive Manufacturing in Aerospace

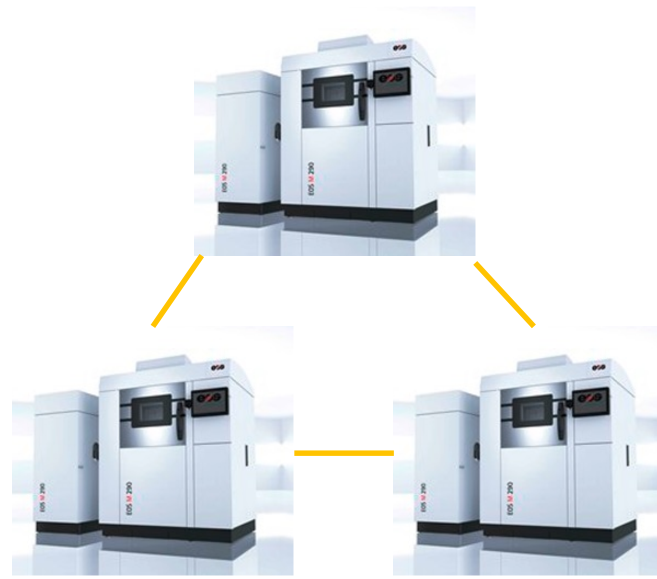


# Categories of Process Variability in LPBF



I. Intra-Build

II. Inter-Build



III. Inter-Machine

# Objective and Aims

**Overall Objective:** Characterize the variability in microstructure and durability of Ti-6Al-4V resulting from LPBF involving multiple identical make/model machines under fixed primary- and post-process conditions.

**Aim 1:** Characterize the intra-build variability

**Aim 2:** Characterize the inter-build variability

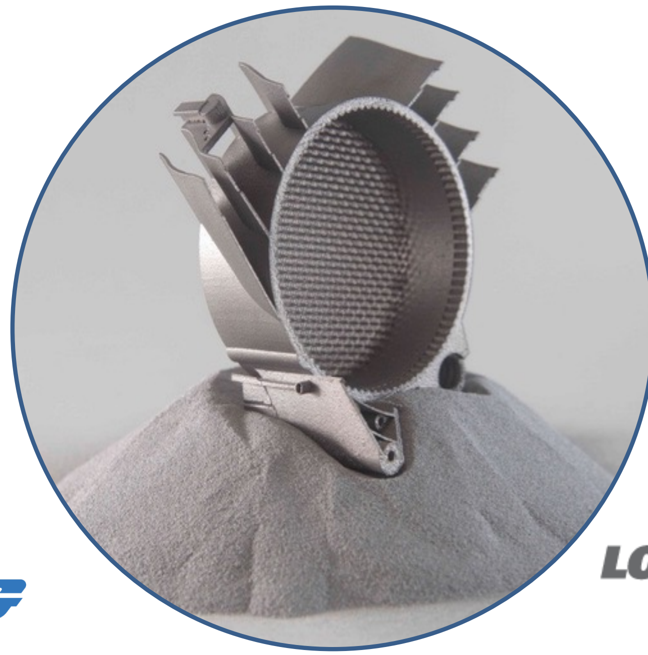
**Aim 3:** Characterize the inter-machine variability

# Round Robin Partners

W

'TORAY'
Toray Precision Co.,Ltd.

BOEING



eos

3D LOGICS

LOCKHEED MARTIN

oerlikon

# Overview of Program and Approach

- **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 (Ti6Al4V)
- All partners follow same build design

<u>Process Control Document</u>

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

Process Control Document

**Prepared by:**

Reid Schur, Sean Ghods, Alex Montelione, Rick Schleusener
Dwayne Arola*
Material Science and Engineering, UW
Roberts Hall, 333, Box 352120,
Seattle, WA 98195
*Email: darola@uw.edu
*Phone: (206) 685-8158

10/22/2020

**Prepared for: Inner Core Participants**

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

<u>Partner Questionaire (Powder + Machine)</u>

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

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**

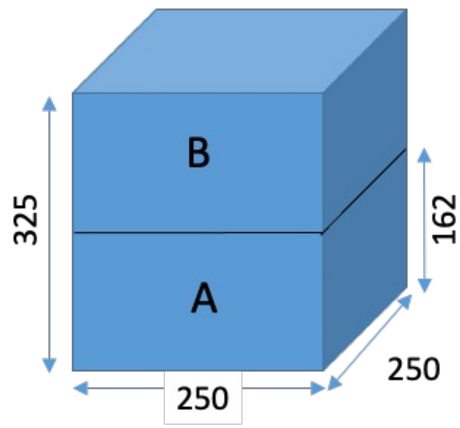
Storage temperature: ____ Humidity control: ☐ Yes ☐ No
Storage humidity: ____
Please describe the powder storage containers (original containers, explosion proof, or other):

(B) **Machine Conditions**

*Machine Operating Environment*

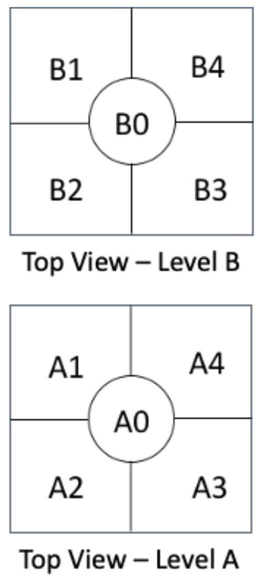
Operating room temperature: ____ Humidity control: ☐ Yes ☐ No
Powder used prior to April, 2020: ☐ Ti-6Al-4V ☐ Other (please specify below)
(if used material other than Ti-6Al-4V) Materials: ______
Last use: ______
Plan on using other powder during this study on this machine: ☐ Yes ☐ No
Have a machine cleaning SOP to prevent cross-contamination: ☐ Yes ☐ No
Willing to share this SOP with UW: ☐ Yes ☐ No
Any details about machine cleaning SOP:

# Build Design and Discretization



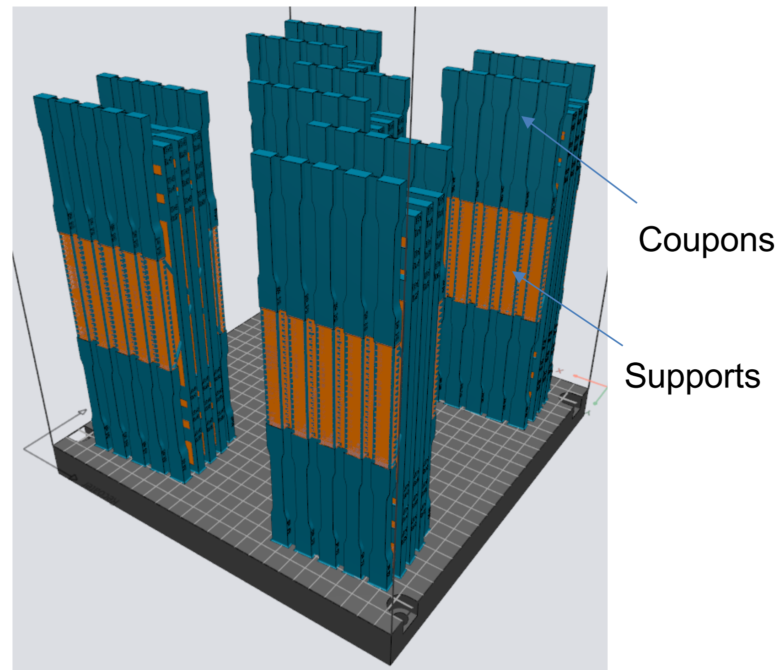

Oblique View

Two Levels (A, B)



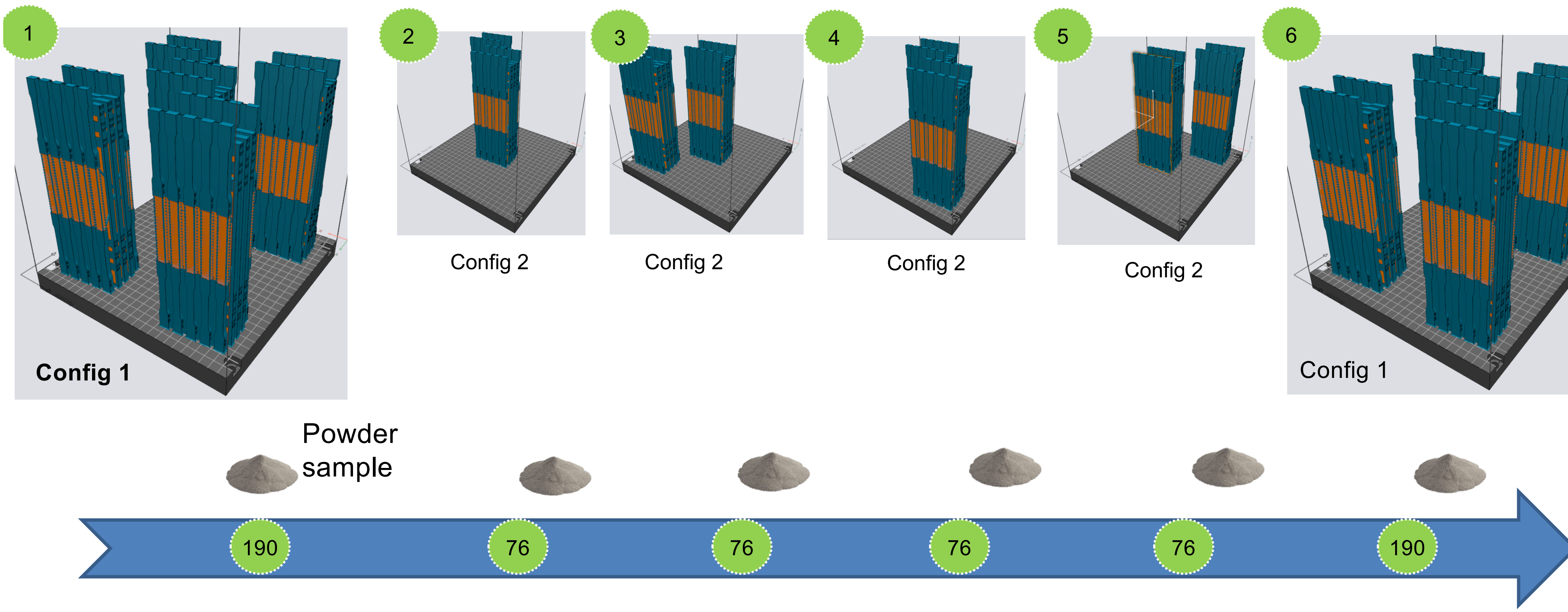

Five Zones per level
(0, 1, 2, 3, 4, 5)

Build Envelope Discretization




Build Design (5 zones, 2 levels)

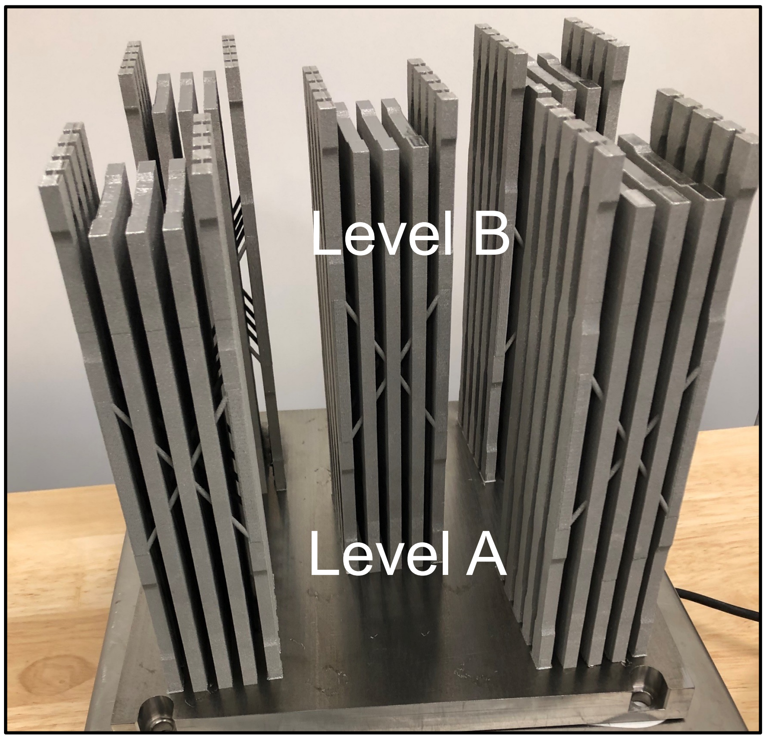
# Round Robin Build Sequence

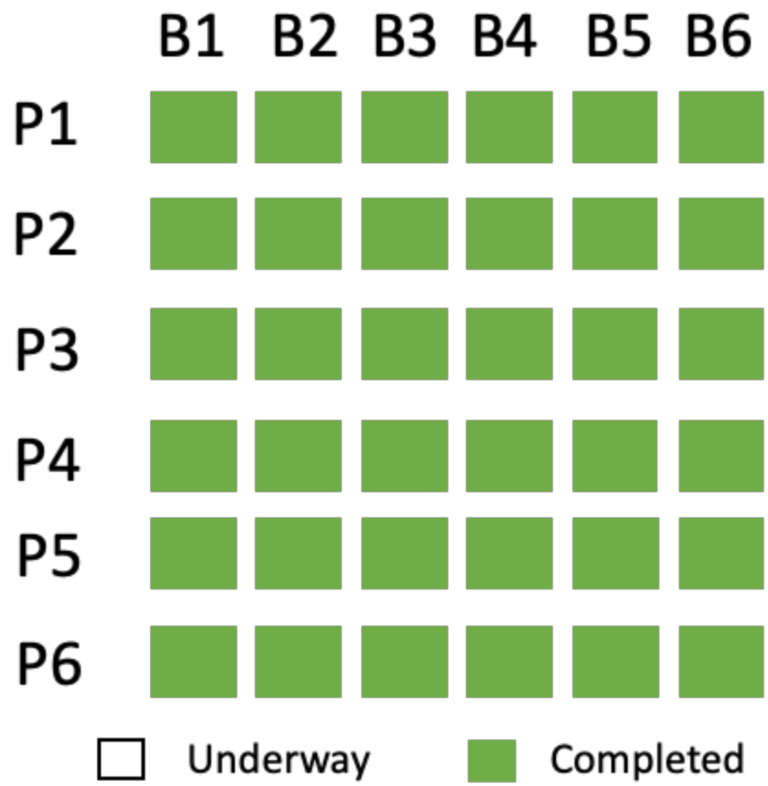



Total specimens per partner = 684

Total Specimens = 684 per partner x 6 partners = <u>4104</u>

# Progress of Partners and Program: Phase I



## 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)

745˚C for 2 hours with furnace cool

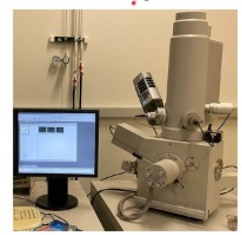
6

## 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**

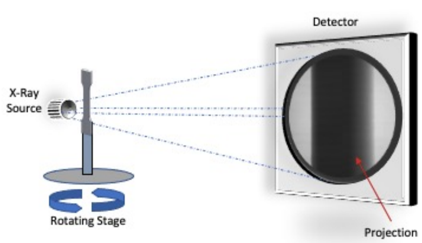
X-Ray Fluorescence
Bruker
M4 Tornado

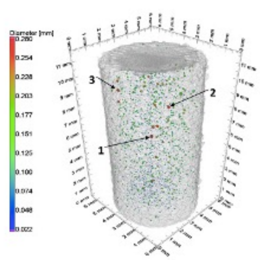
7

## Micro Computed Tomography

**X-Ray Micro Computed Tomography**:

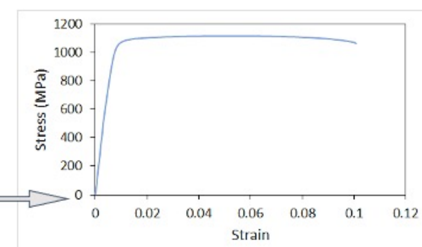
- North Star Imaging system, microCT, X5000, Rogers, MN, USA
- 360° x-ray scans and 3D reconstruction


## Mechanical Property Characterization (Static and cyclic)

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




ASTM E8 based procedures

# Methods - Characterization of Metal and Powder

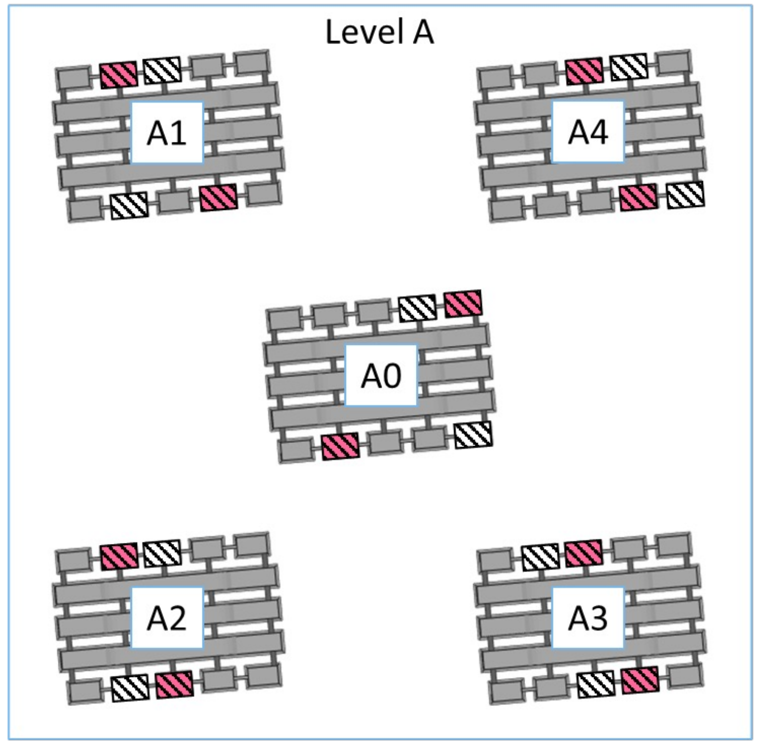
| | Characterization Technique | Properties of Interest |
|---|---|---|
| Metal | **Tensile Testing** → | **Mechanical behavior (ductility, strength, toughness, etc.)** |
| | **Micro Computed Tomography (μCT)** → | **Porosity** (~8μm voxels) |
| | Scanning Electron Microscopy (SEM) → | Microstructure |
| Powder | Light Scattering Powder Analysis (LSPA) → | Particle size distribution |
| | SEM → | Particle morphology |
| | Hall Flow Meter → | Powder flowability |
| | Inert Gas Fusion (IGF) and XRD → | Powder contaminants (oxygen, nitrogen, hydrogen, and carbon) |

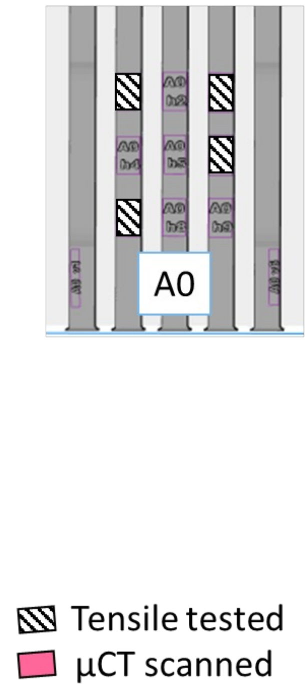
# Methods - Coupon Selection for Analysis

- Subset of total number of coupons used for testing to decrease testing time

- Coupons were pseudo-randomly selected from each zone. Selected coupons were kept identical across the participants.

- Reserved coupons enables other investigations to take place



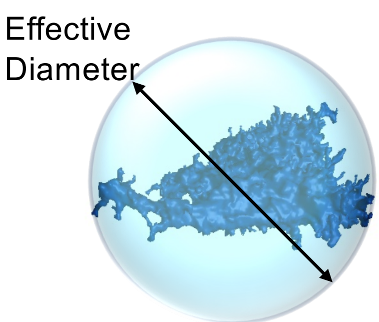




***1652 coupons tensile tested***
***354 vertical coupons µCT scanned***

# Methods - microCT Analysis of Porosity

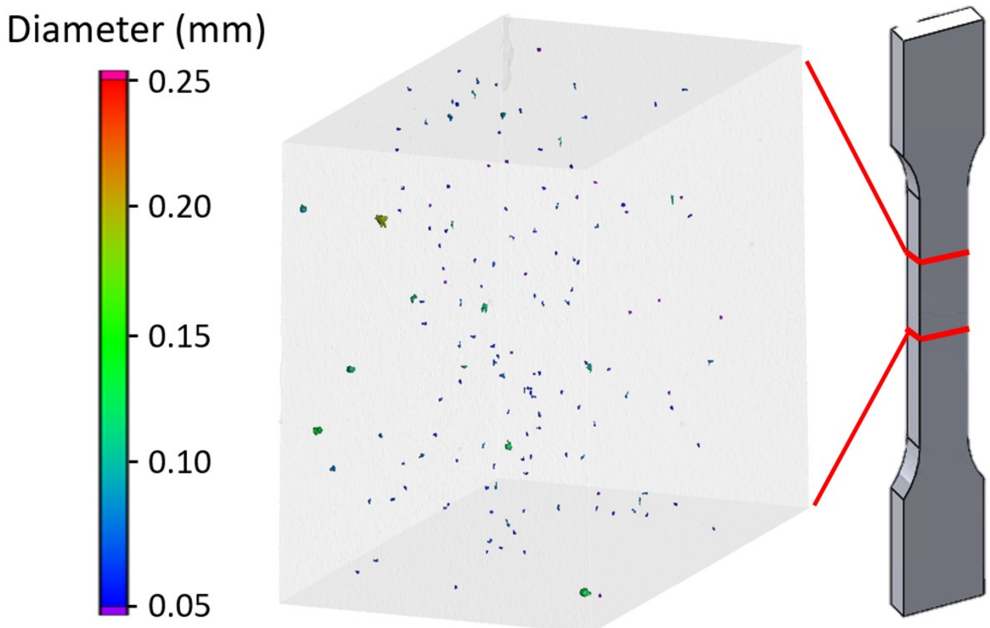
1) Effective Diameter
2) Sphericity
3) Large Pores Per Coupon

$D_{eff} \geq 0.125$ mm



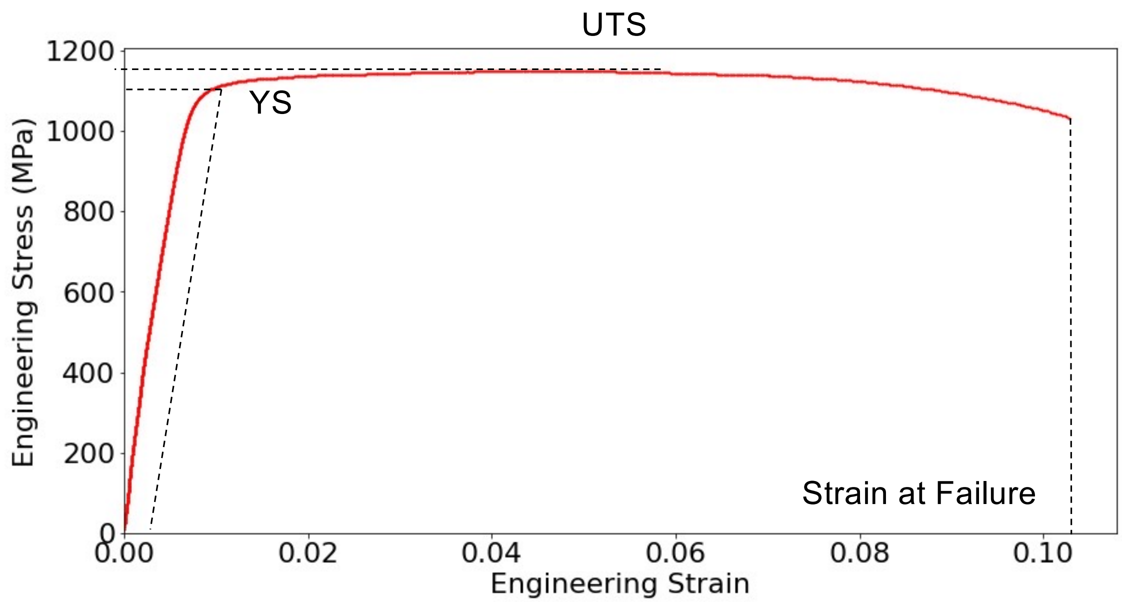

$$\frac{SA_{sphere}}{SA_{pore}} = \text{Sphericity}$$

$<< 1$



# Characterizing the Tensile Properties


ASTM E8, Subsize Coupons
Clip-on extensometer



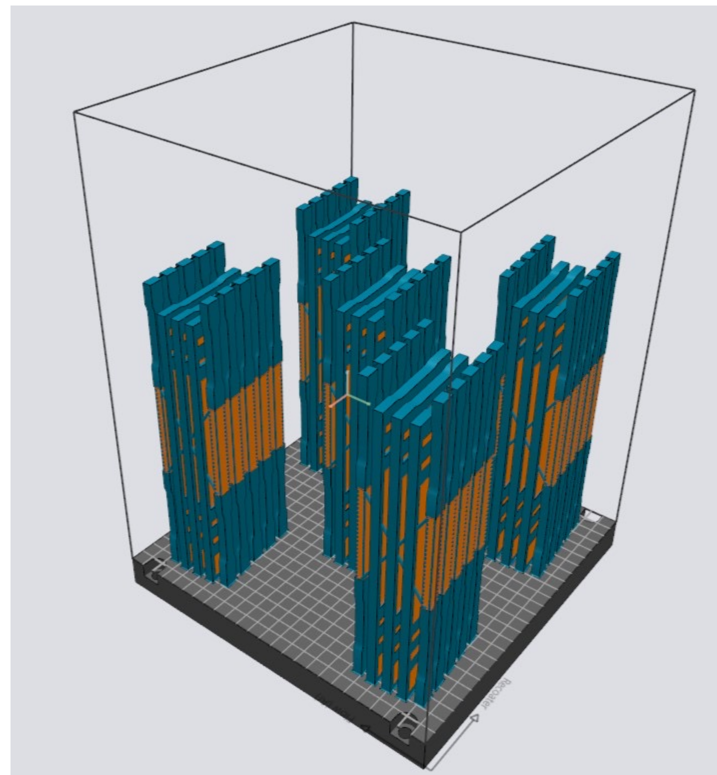

YS = Yield Strength (at 0.002 offset)

UTS = Ultimate Tensile Strength

% el = strain at failure

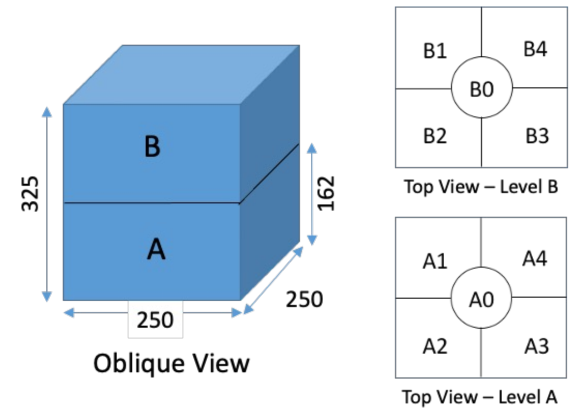
# Intra-Build Analysis: Porosity and Properties

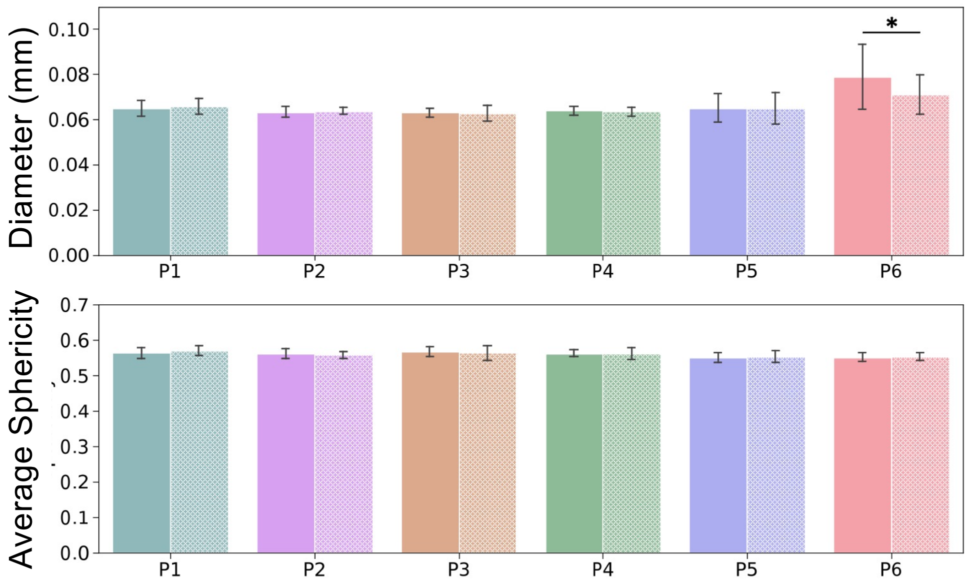
1) Build Height (A vs B)
2) Zones (0 to 4)
3) X and Y position

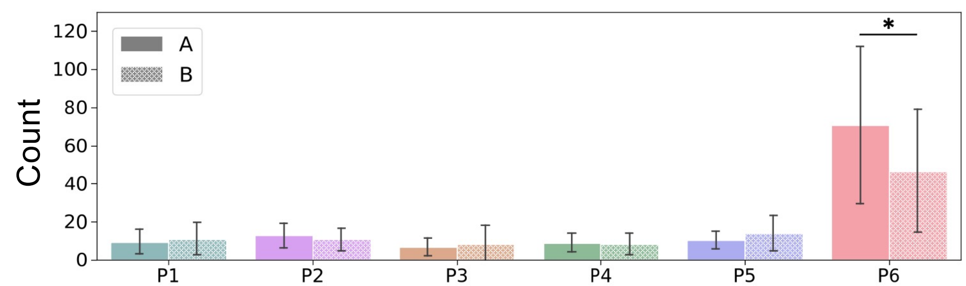


The intra-build analysis presented today includes only the <u>vertical coupons</u>

# Intra-Build: Build Height (Porosity)

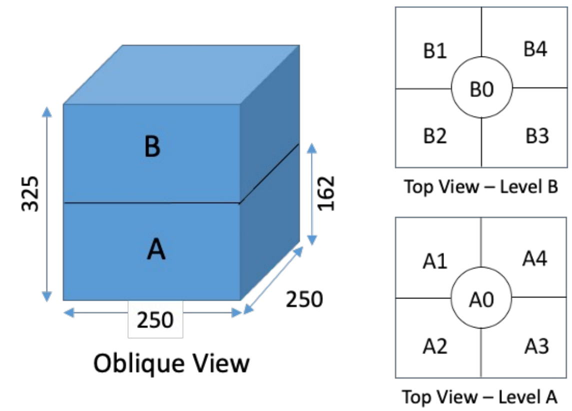


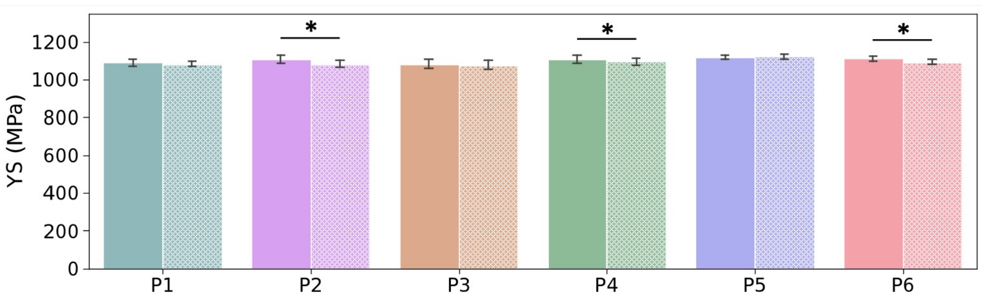



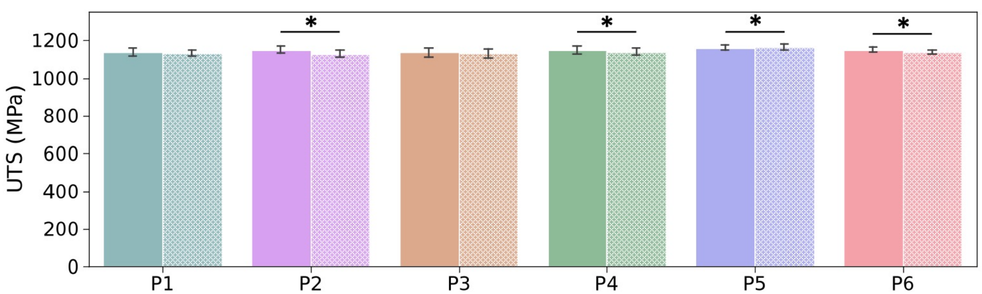



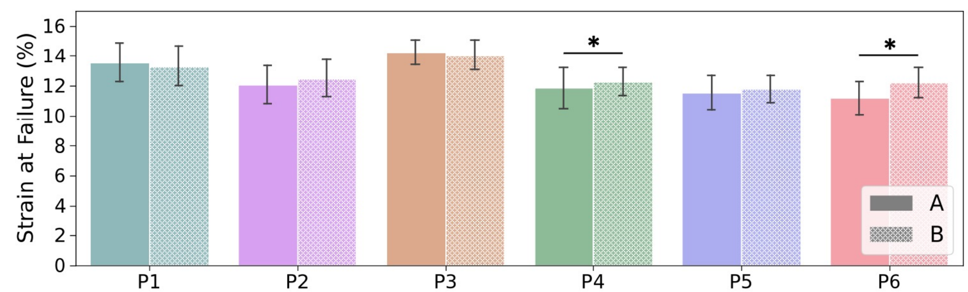

➢ Analysis of Variance (ANOVA) shows only P6 has statistical difference between A and B levels for the average diameter and count of large pores (d ≥ 0.125 mm)

# Intra-Build: Build Height (Tensile Properties)



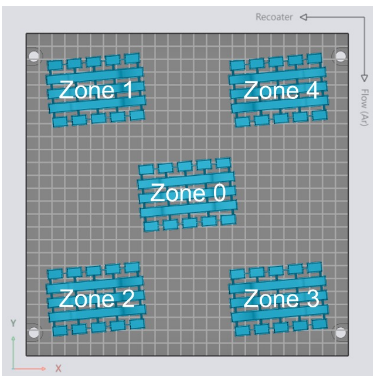



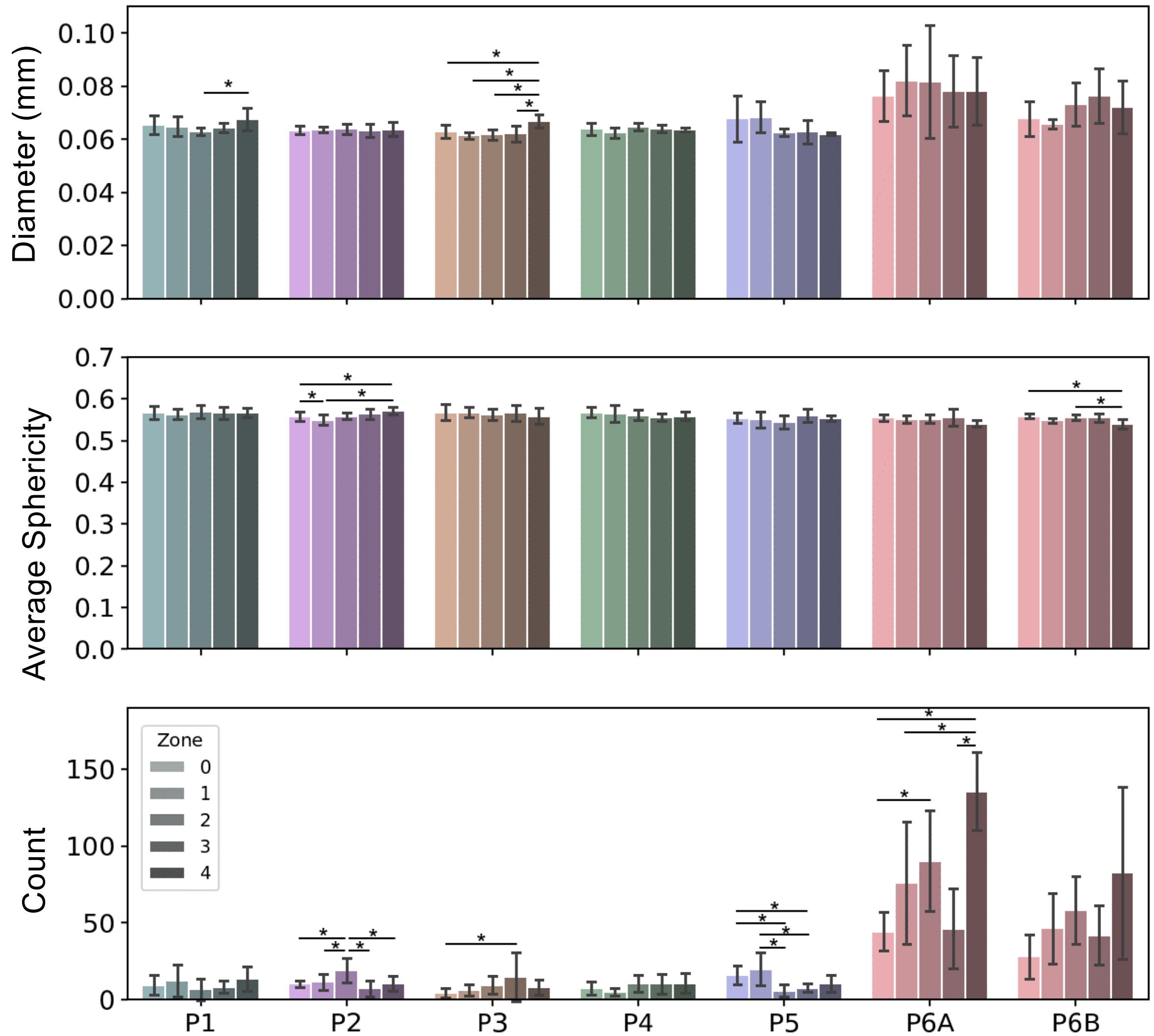

- Significant differences identified
- Magnitude of difference in strength is negligible (~10 MPa)
- Larger difference between A and B levels for strain at failure (up to 1% strain)

# Intra-Build: Zones

## Pore Characteristics

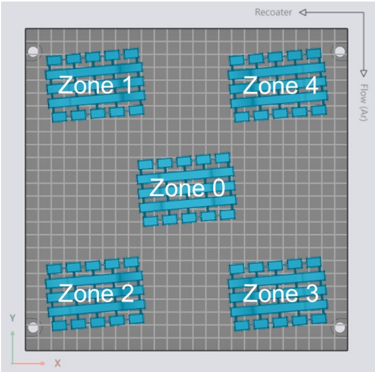



- ➢ Analysis of P6 metal separated for height levels
- ➢ Some significant differences. Inconsistent zones between machines

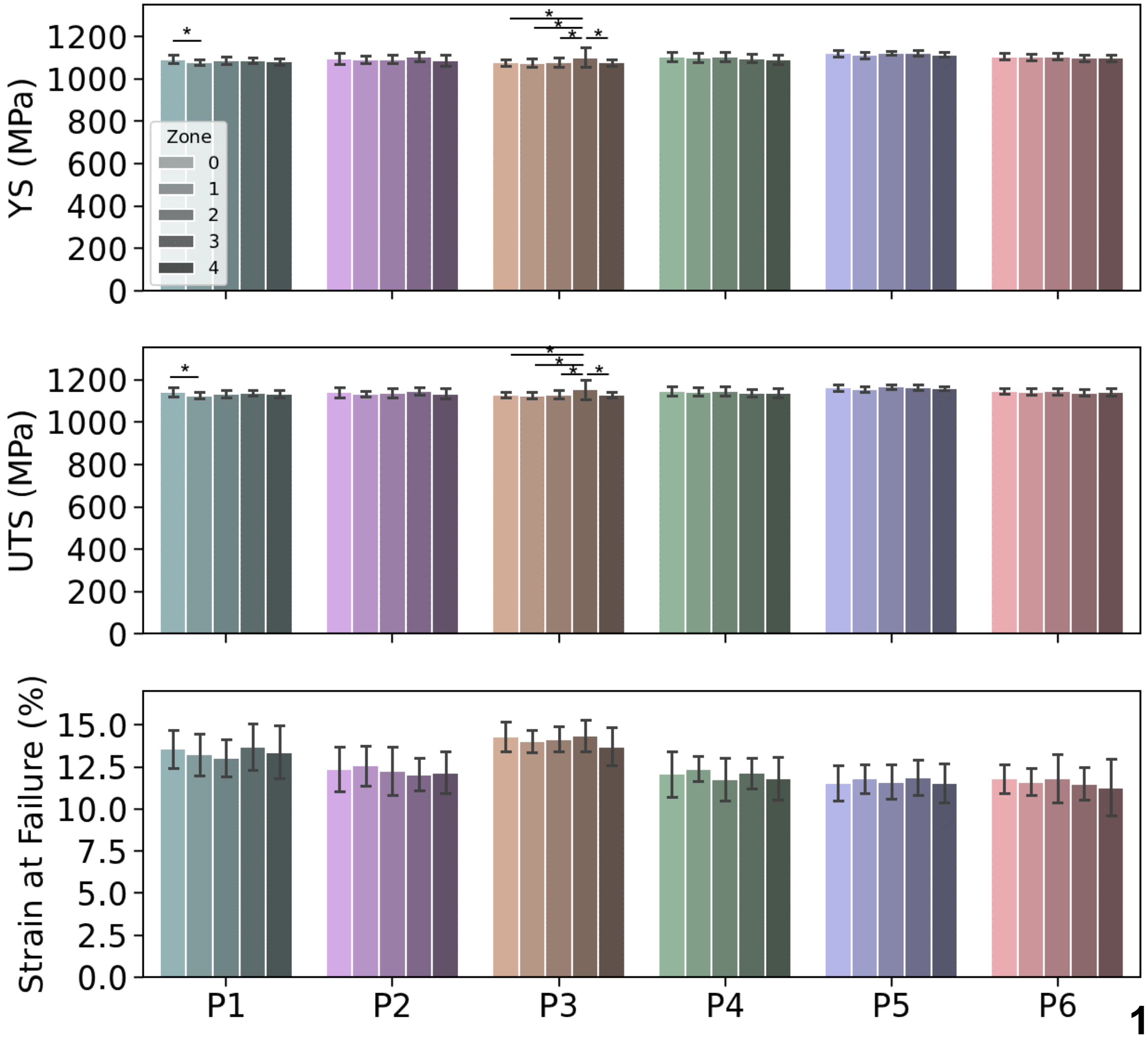


# Intra-Build: Zones

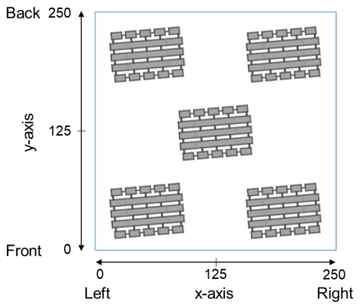
## Tensile Properties



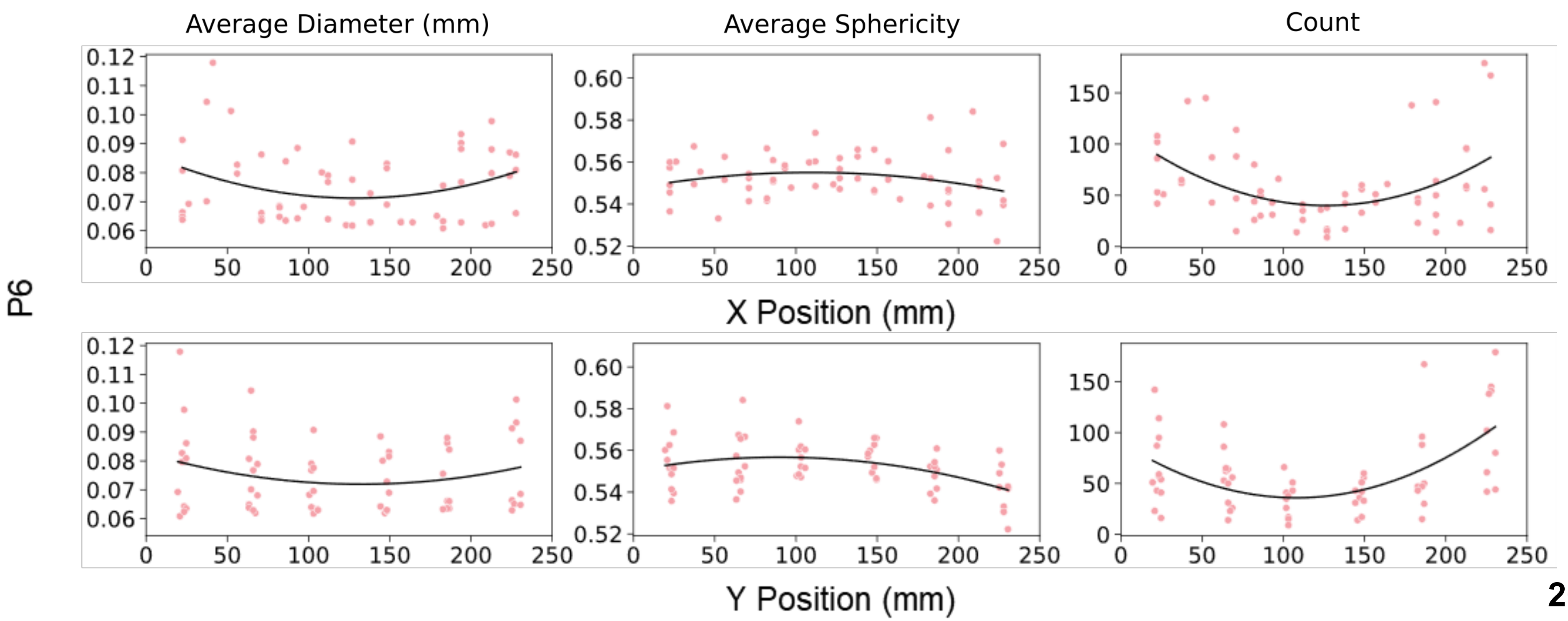

- Few significant differences between zones
- Significant differences always include Zone 0, independent of machine.



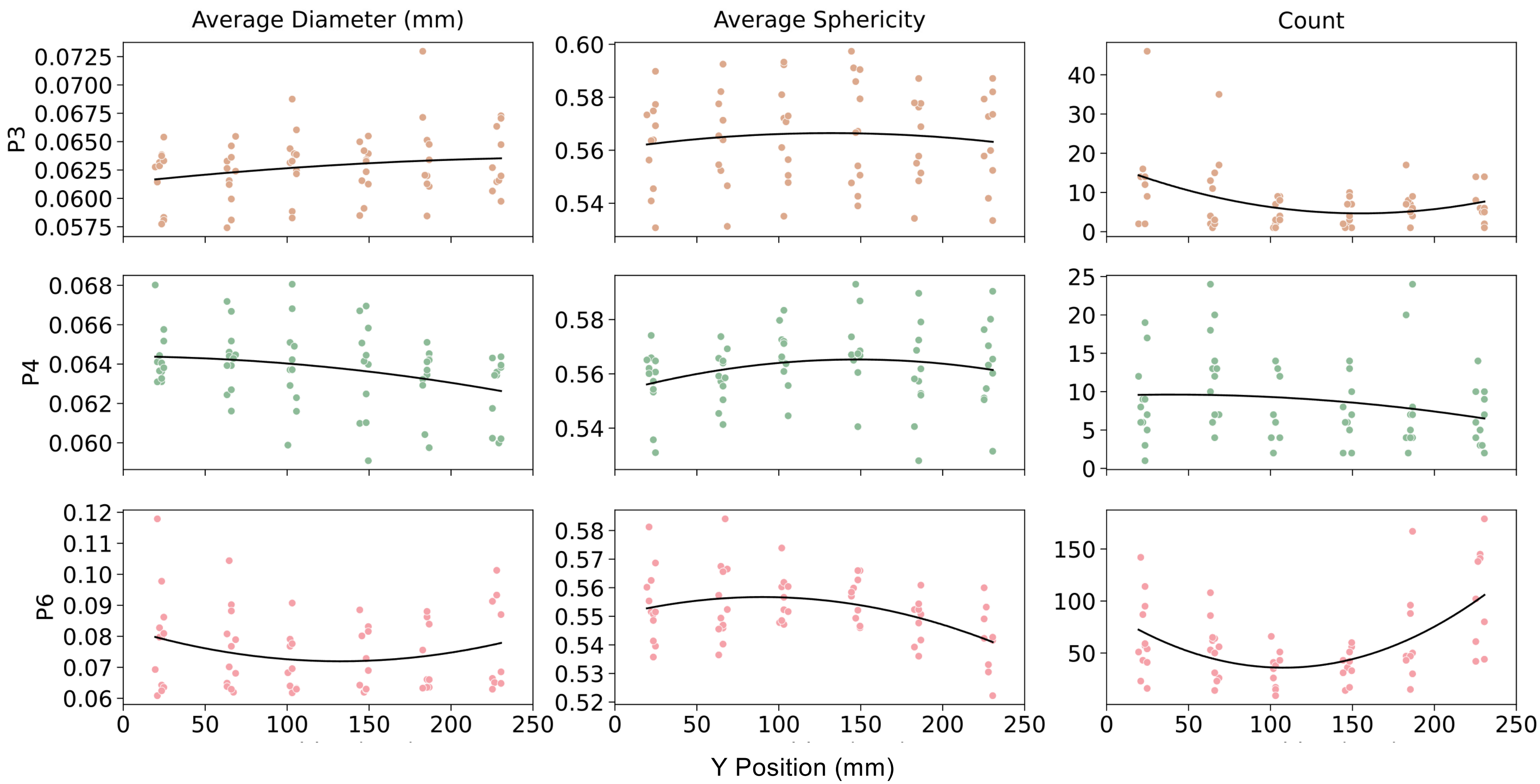
# Intra-Build: Exact Position (Porosity)




- Process physics can result in spatial distributions.
- Pore distribution of P6 is approximately radially symmetric



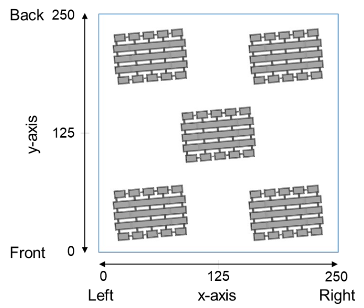
# Intra-Build: Unique Porosity Distributions

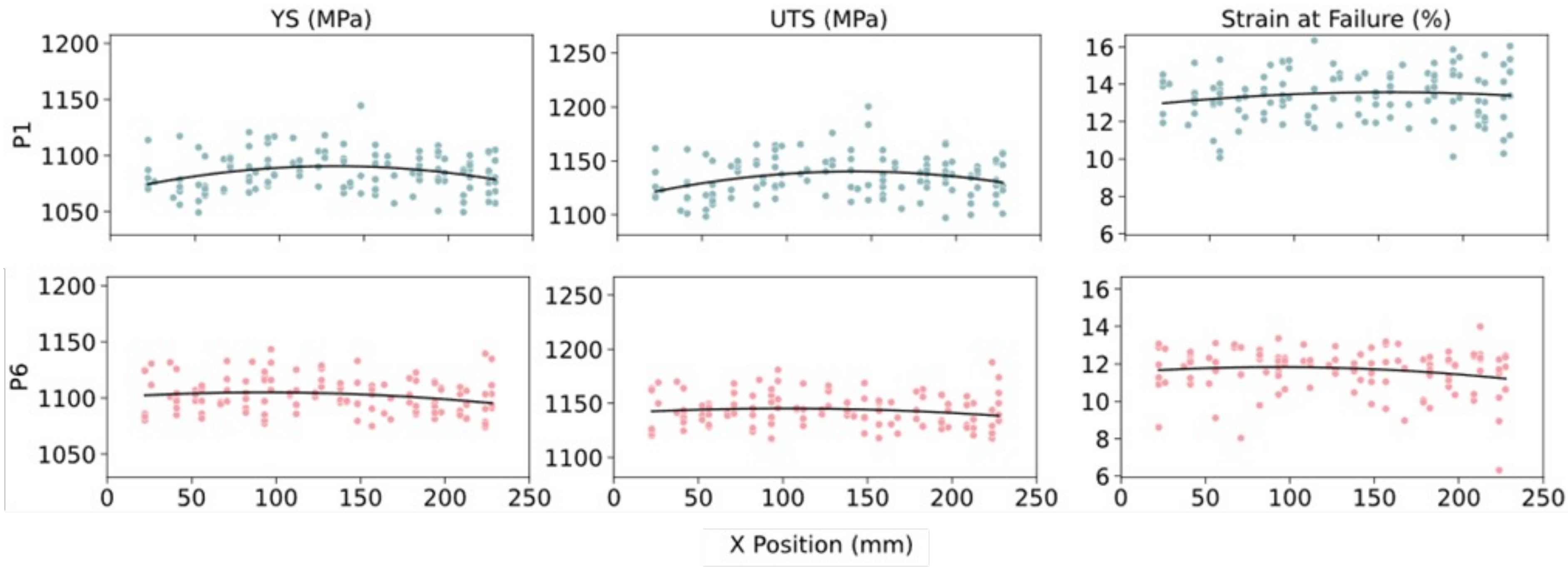



➢3 machines have trends along y-axis of varying strength

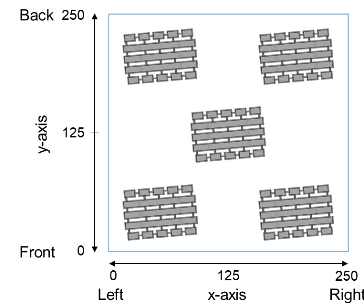
# Intra-Build: Tensile Properties

- P1 and P6 are the only machines with an x-axis dependency

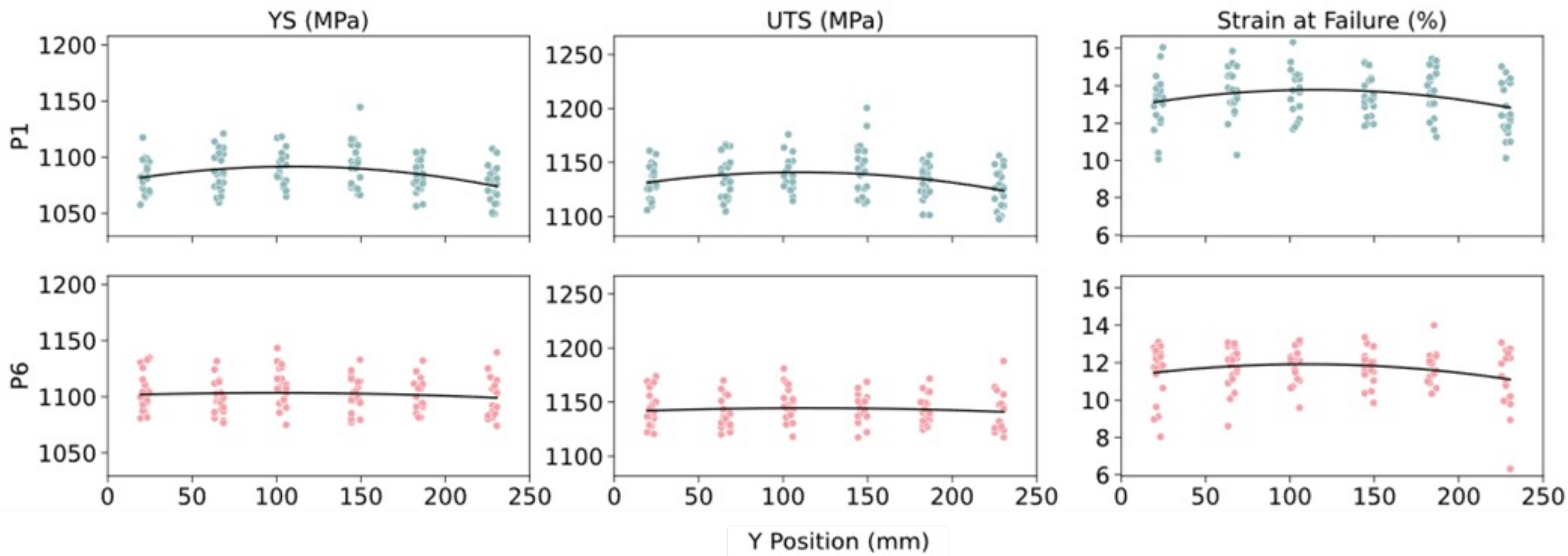


# Intra-Build: Tensile Properties

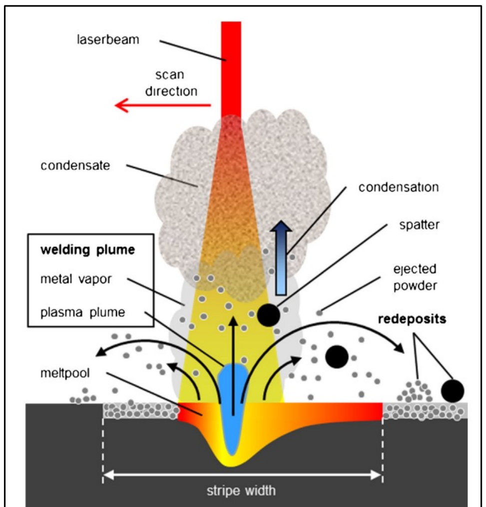



- P1 and P6 have strongest y-axis dependency
- Gas flow and radial laser incidence angle may explain these trends

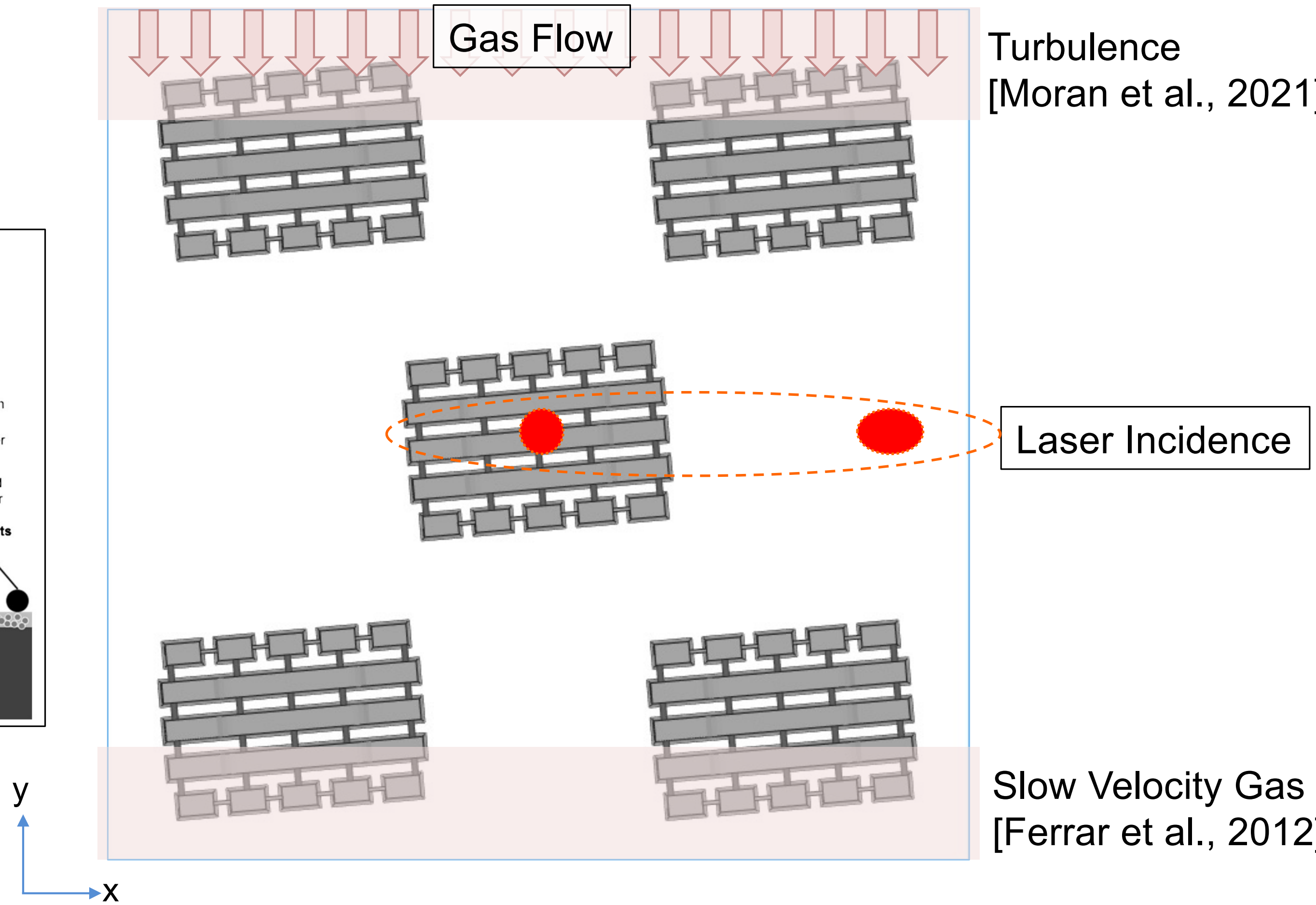


# Intra-Build: Contribution of Shielding Gas

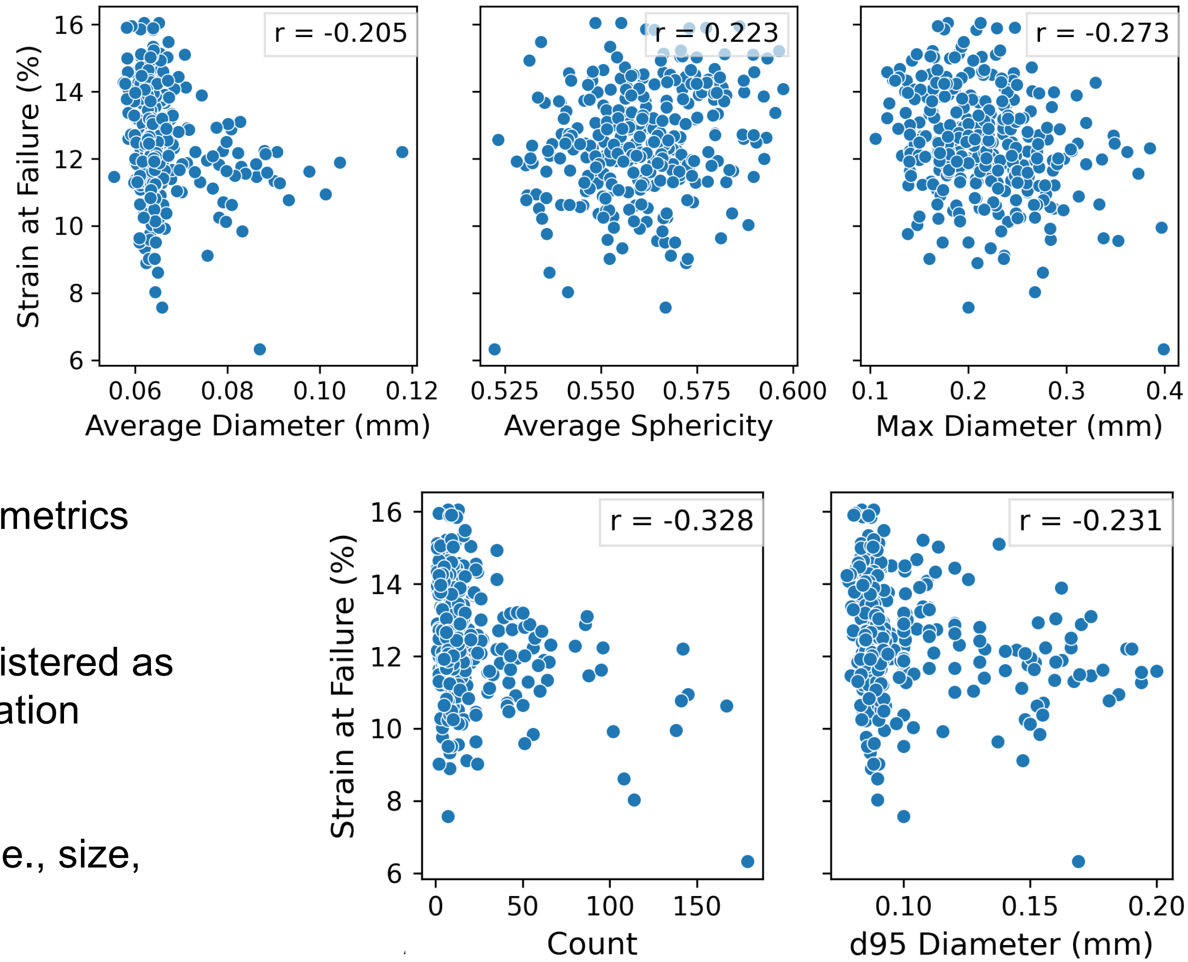
## Root Cause




[Ladewig et al., 2016]

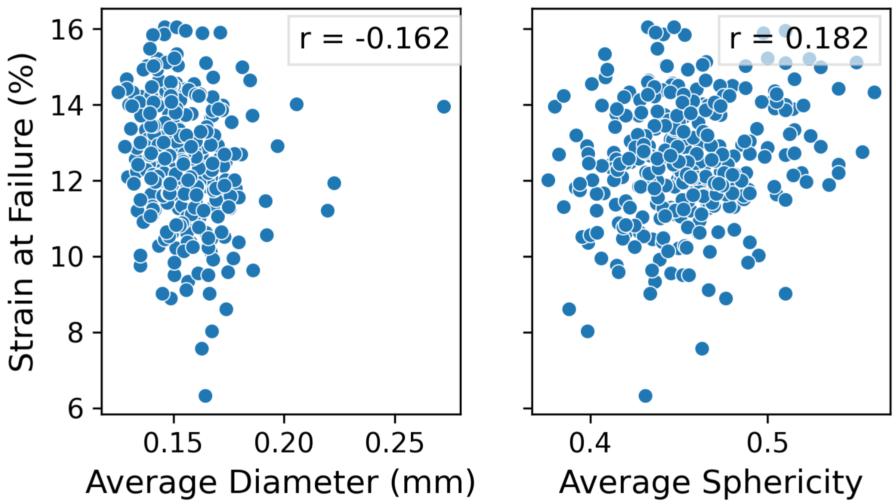


# Porosity and Strain at Failure Correlations

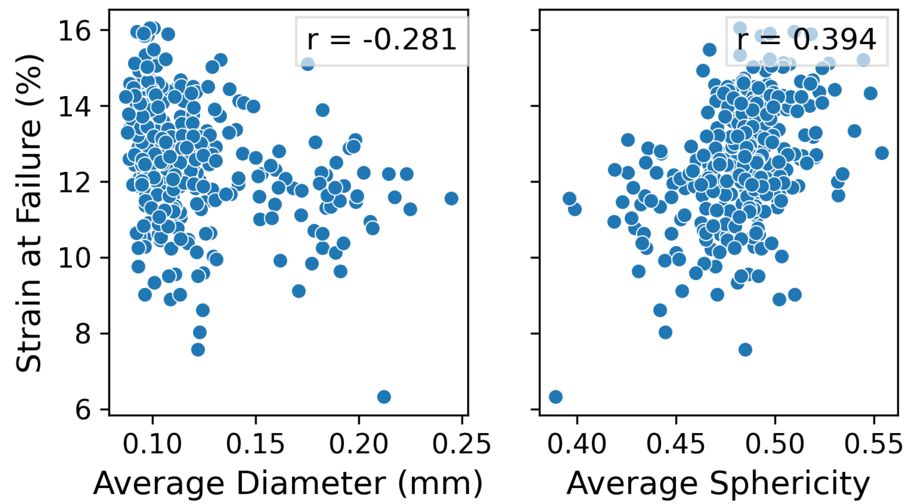



- ➢ No correlation between porosity metrics and strain at failure
- ➢ Pores on the surface are not registered as pores by μCT which limits correlation
- ➢ Do not capture multiple pore characteristics simultaneously (i.e., size, shape, location, clustering)

# Porosity and Strain: Large Pores Only




(a) Pores ≥ 0.125mm Diameter




(b) Pores ≥ d90 Diameter

- Improved correlation with d90 diameter, but still weak

# Overall Variability in Mechanical Properties

All Machines

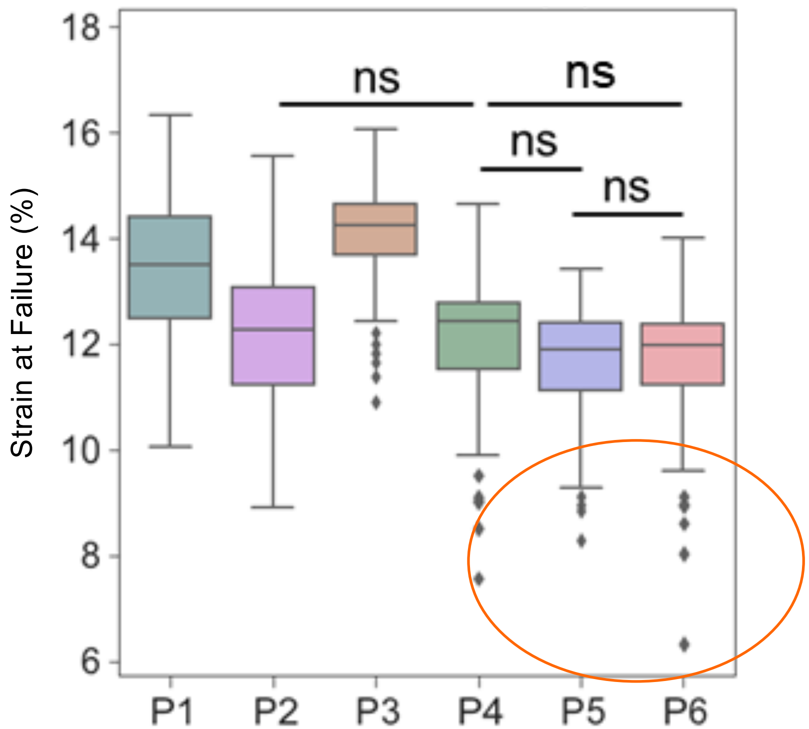
| | CoV of YS (%) | CoV of UTS (%) | CoV of Strain at Failure (%) |
|---|---|---|---|
| Vertical | 2.1 | 1.9 | 11.8 |
| Horizontal | 2.2 | 1.9 | 14 |
| Wrought | 1.8 | 1.8 | 8.3 |

Identically Heat Treated (P2, P4, P5, P6)

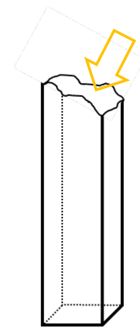
| | CoV of YS (%) | CoV of UTS (%) | CoV of Strain at Failure (%) |
|---|---|---|---|
| Vertical | 1.9 | 1.8 | 10 |
| Horizontal | 1.7 | 1.6 | 12.1 |
| Wrought | 1.8 | 1.8 | 8.3 |

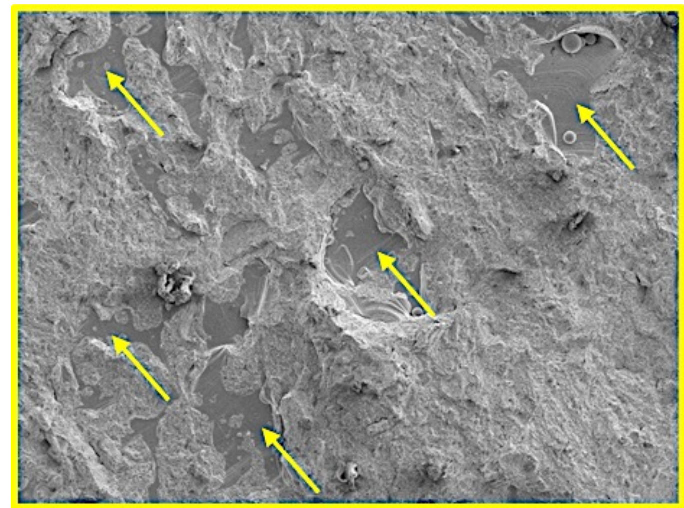
- 33 wrought Ti-6Al-4V coupons cut from the same sheet of metal were tested for comparison
- AM metal has similar variability to wrought form metal

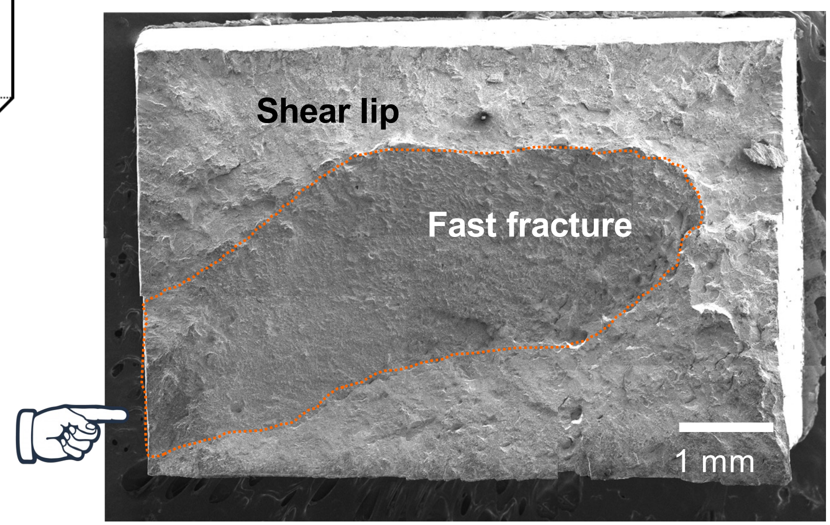
# Inter-Machine: Outliers



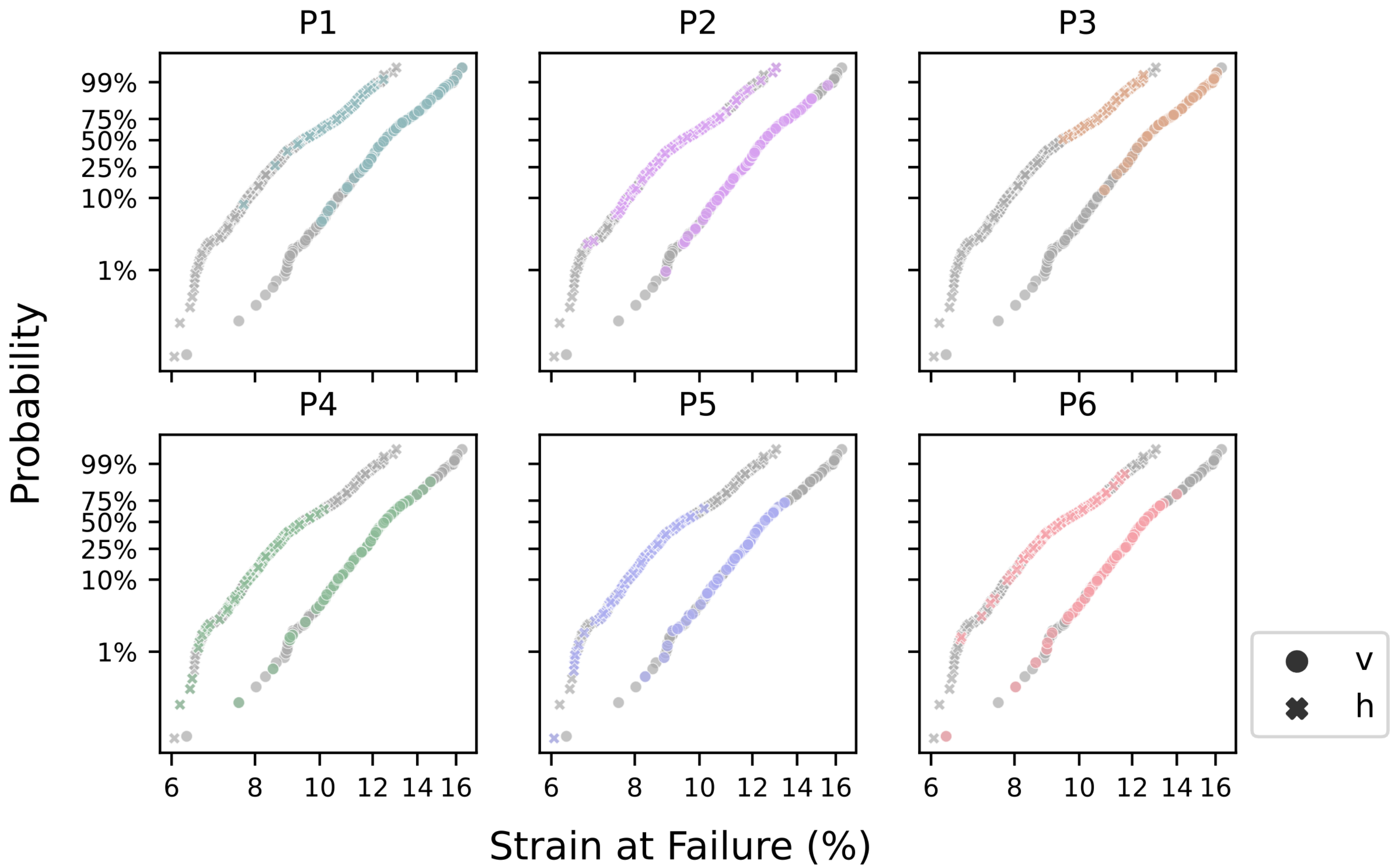

Fracture Surface







# Inter-Machine: Weibull Distributions



# Conclusions

1) Variability exists on the intra-build, inter-build, and inter-machine levels, however the overall magnitude for the static properties is similar to that for wrought titanium

2) Design for additive manufacturing (DFAM) can accommodate the variability exhibited by most machines, however outlier machines do exist, necessitating individualized DFAM

3) Greatest sources of variability appear to originate from issues with machine maintenance or post-processing variability – fine-tuning machine maintenance may allow for broader machine equivalency

# Acknowledgements


A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

JCDREAM

BOEING

LOCKHEED MARTIN

oerlikon

Toray Precision Co., Ltd.

eos

3D LOGICS

*Thank you!*