Factors Affecting Qualification / Certification:

The Effect of Machine Variabilities on Mechanical Properties of LB-PBF Ti-6Al-4V Gr. 5

National Center for Additive Manufacturing Excellence (NCAME)

AUBURN UNIVERSITY

JAMS Technical Review
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Federal Aviation Administration

JAMS Joint Centers of Excellence for Advanced Materials

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

Introduction

- **Project Title:** Factors Affecting Qualification/Certification - The Effect of Machine Variabilities on Mechanical Properties of Additive Manufactured Materials
- **Principal Investigator:** Nima Shamsaei

  (See next slide for complete list of participants.)
- **FAA Technical Monitor:** Kevin Stonaker
- **Source of matching contribution:** Faculty time and use of equipment

Project team

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NCAME Project Team
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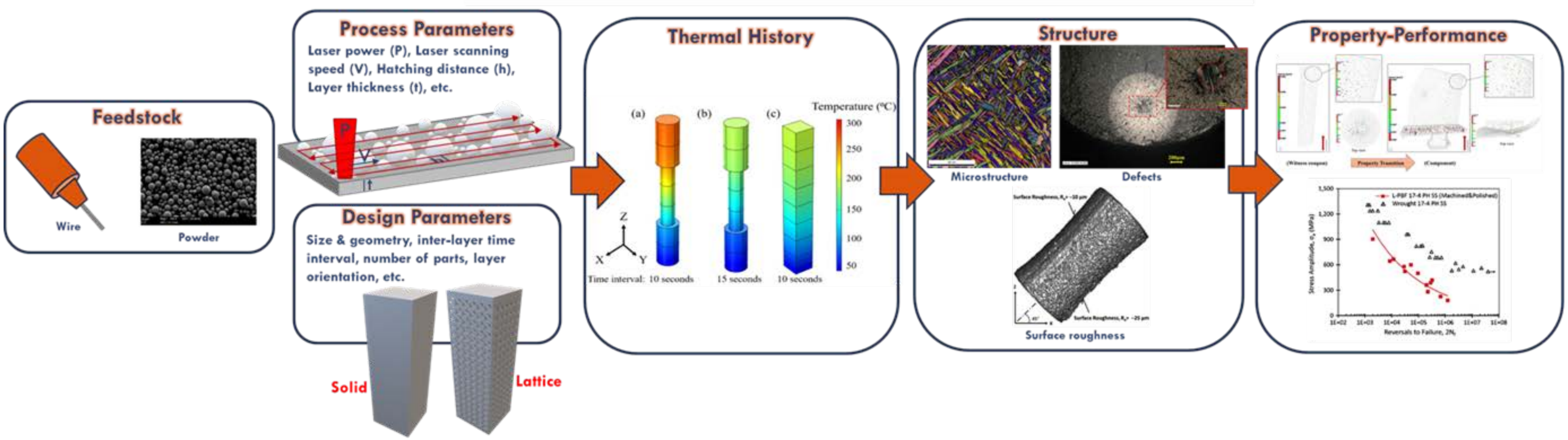
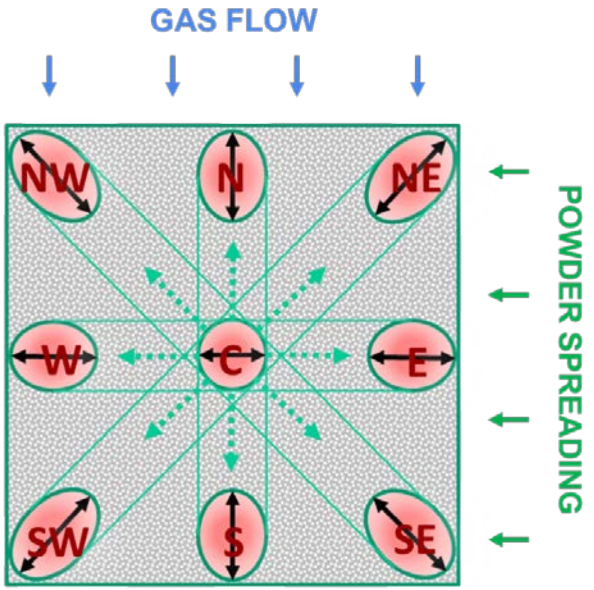
Background

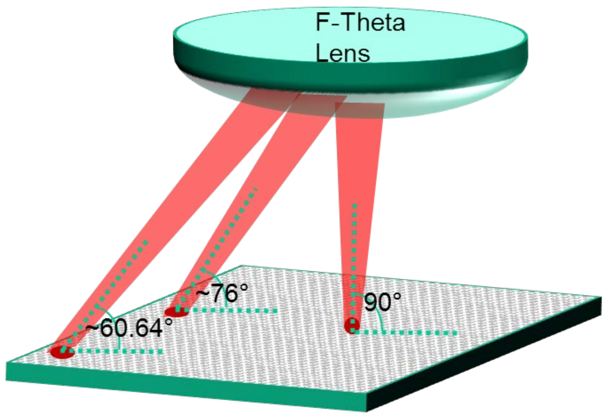
- Effect of key process variables (KPVs) drift within the tolerances on defect content and part performance is **not very well understood**
  - Identified on several Roadmaps
  - **Challenge** arises from the dependency of micro-/defect-structure and mechanical properties to multiple synergistic factors, including **powder quality**, **laser-material interaction**, **inherent heat-transfer effects**, **geometrical factors**, **process parameters**, etc.



Challenge

- For a fixed set of process parameters, factors such as **powder specification**, **location**, **geometry**, and **time interval** can also affect the fabricated parts' structure and properties
- The effect of **power re-use** and **location dependency** will be investigated first so that their influence can be excluded from the KPVs drift study
- Geometry and time interval will be kept constant





Objective & approach

Objective: To understand the effect of KPVs drift within tolerance bands on defect characteristics and mechanical properties of LB-PBF Ti-6Al-4V Gr. 5

Approach: Four steps are taken,

I. Quantify the powder re-use effects to exclude their influences from the KPVs drift study. Geometry and time interval will be kept constant

II. Identify the combined effect of KPVs (laser power, laser spot size, and hatching distance) drift and location on the defect-structure

III. Evaluate the impact of KPVs drift on tensile, fatigue, and high strain rate fracture behaviors using specimens fabricated with worst KPVs/location combinations

IV. Leverage machine learning and simulations wherever applicable

Deliverables

- Quantitative knowledge on the effect of powder reuse on mechanical performance of LB-PBF Ti-6Al-4V Gr. 5
- Quantitative knowledge on the effect of KPVs drift on defect characteristics and mechanical performance of LB-PBF Ti-6Al-4V Gr. 5
- Establishing the best practices for determining the uncertainty caused by KPVs drift on mechanical properties of LB-PBF materials (broader impact)

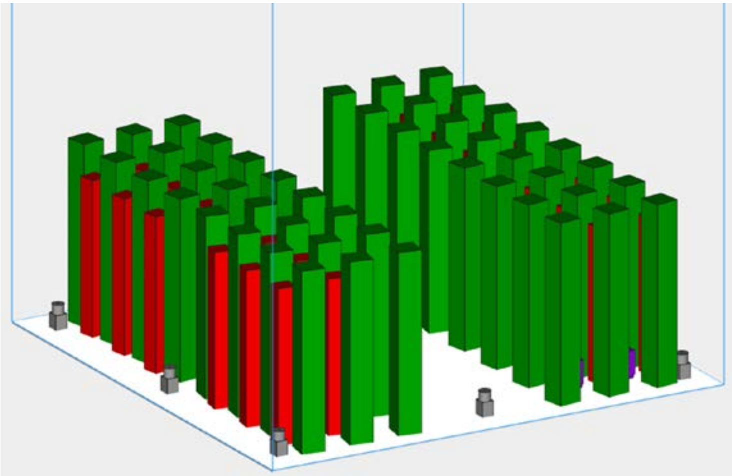
Project tasks

- **TASK 1: Literature Review**
  - Collect information from literature, equipment OEM, FAA AM team, and steering committee
- **TASK 2: Design of Experiments**
  - Design and refine the experiments for LB-PBF Ti-6Al-4V Gr. 5 based on findings from the literature review
- **TASK 3: Powder Re-Use Effects at Different Locations**
  - Understand the effect of powder re-use on the structural integrity (i.e., tensile, fatigue, and high strain rate fracture) of LB-PBF Ti-6Al-4V Gr. 5
- **TASK 4: Identification of the Worst Combination of Location and KPVs**
  - Discover the synergistic effects of location and process parameter combinations on the defect population
- **TASK 5: Variation in Mechanical Properties due to KPVs drift**
  - Generate and compare the mechanical properties resulting from the worst combination of KPVs drift and location
- **TASK 6: Final Report**

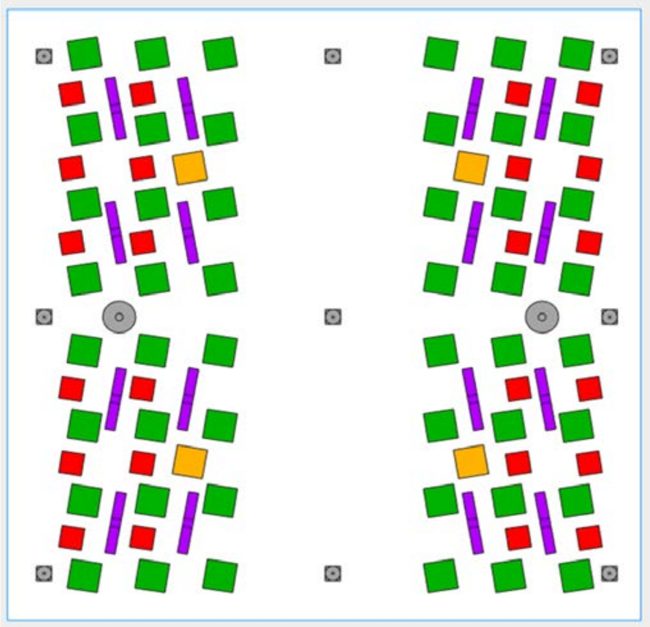
DoE to understand the effect of powder re-use

Powder re-use effect

- Prints start with un-used powder and continues until powder is used several times
  - 48 fatigue specimens (ASTM E466) (12 in each quadrant)
  - 24 tensile specimens (ASTM E8) (6 in each quadrant)
  - 16 high-strain test specimens (4 in each quadrant)
  - 2 powder holders (at both ends) - Note that the powder in E and W may be sampled based on ASTM B215 instead of using the powder holders
  - 4 microscopy specimens (1 in each quadrant)
  - 9 XCT witness coupons

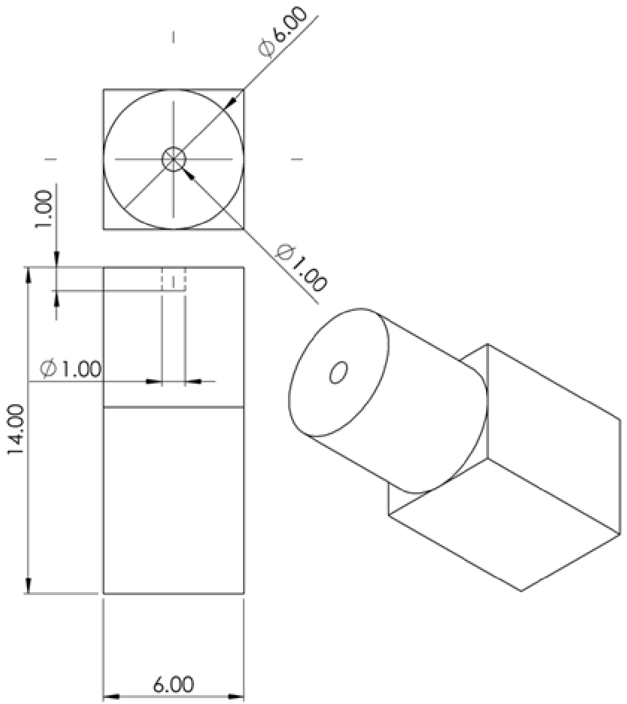


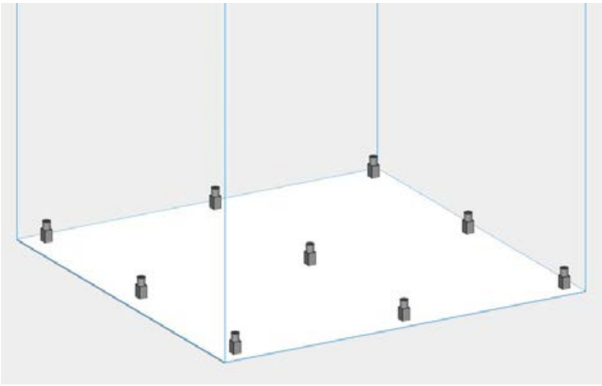
Occupied build plate density= 12%

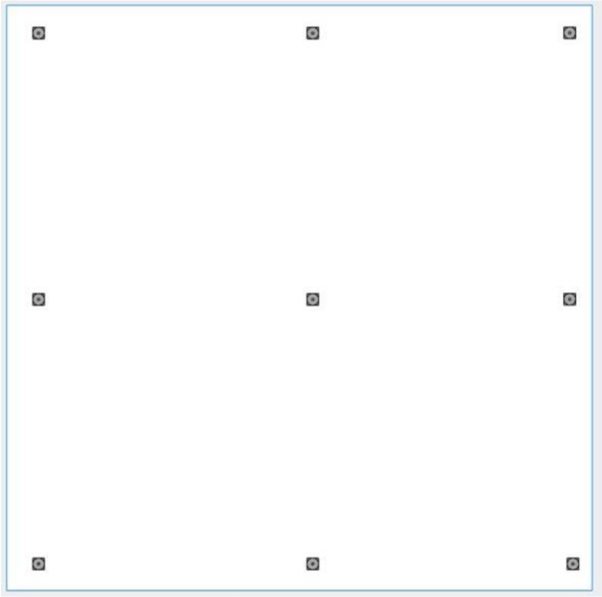


Build quality XCT coupons

- XCT porosity witness coupons are always included in all prints throughout the study







DoE to identify the worst combination of KPVs/location

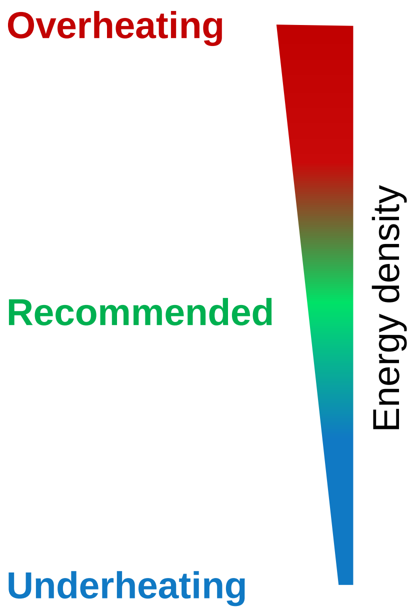
Identify worst KPVs combinations

- Suggested KPVs and their possible deviations from nominal values:
  - **Laser power: ±4%**
  - Scan speed: ±0.015% (accuracy decreases for scan speeds > 3000 mm/s)
  - Layer thickness: ±0.1 µm
  - **Hatching distance: ±2.4%**
  - **Laser spot size (focal dimeter): 80 µm ± 5 µm** (highly depends on material and laser powder, not monitored)
- Scan speed and layer thickness are excluded from this study due to their small drifts
- Only laser power (P), laser spot size (d) and hatching distance (h) will be included for further analyses
- P, d and h will be either individually or simultaneously altered to increase or decrease the energy density (E) from the baseline

Identify worst KPVs combinations

- Only overheating and underheating KPV combinations will be investigated as they can intensify the defect population

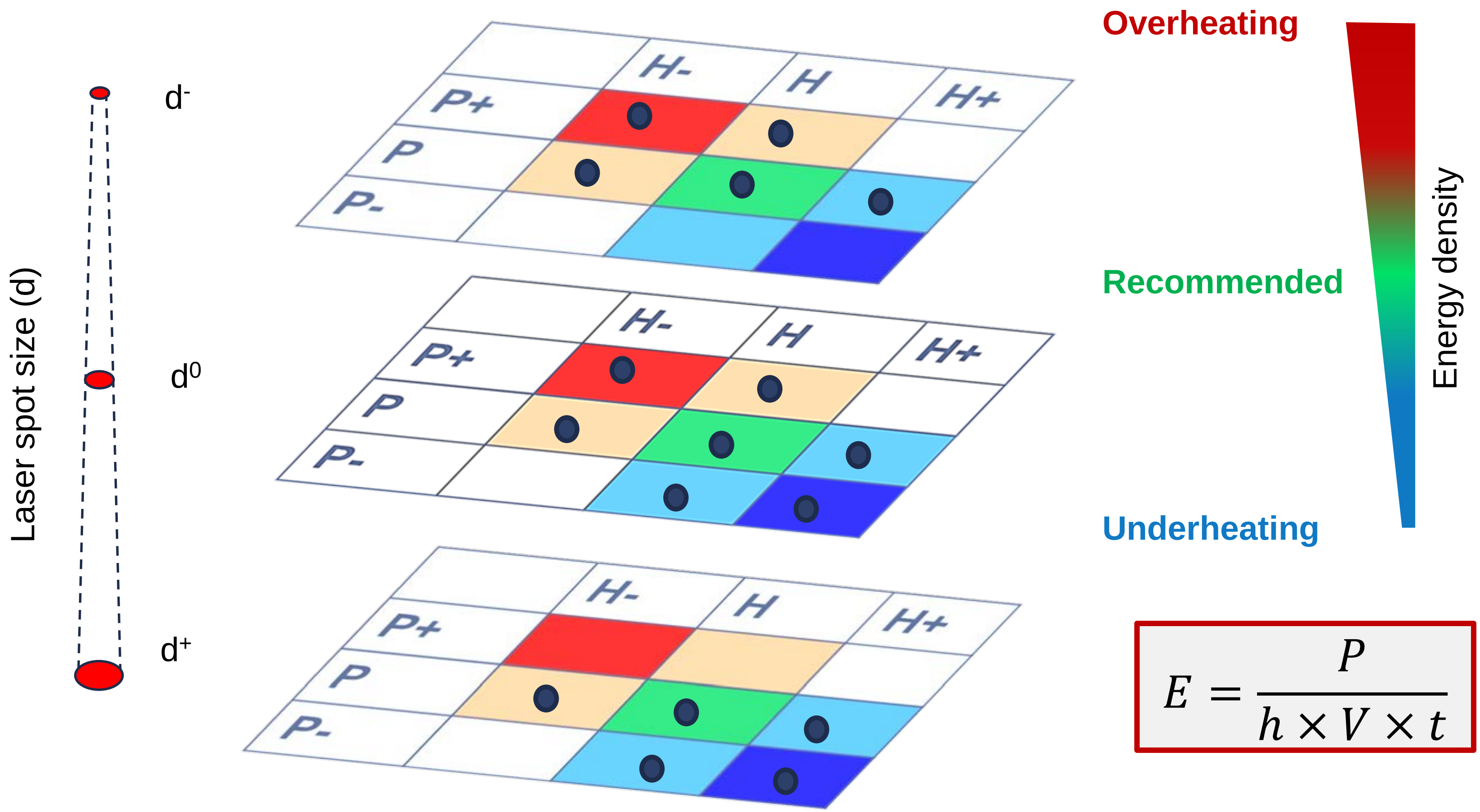
Factorial Design Parameters		Hatch spacing (h)		
Laser power (P)	Laser spot size (d)	h^+	h°	h^-
P^+	d^+	$P^+ d^+ h^+$	$P^+ d^+ h^\circ$	$P^+ d^+ h^-$
	d°	$P^+ d^\circ h^+$	$P^+ d^\circ h^\circ$	$P^+ d^\circ h^-$
	d^-	$P^+ d^- h^+$	$P^+ d^- h^\circ$	$P^+ d^- h^-$
P°	d^+	$P^\circ d^+ h^+$	$P^\circ d^+ h^\circ$	$P^\circ d^+ h^-$
	d°	$P^\circ d^\circ h^+$	$P^\circ d^\circ h^\circ$	$P^\circ d^\circ h^-$
	d^-	$P^\circ d^- h^+$	$P^\circ d^- h^\circ$	$P^\circ d^- h^-$
P^-	d^+	$P^- d^+ h^+$	$P^- d^+ h^\circ$	$P^- d^+ h^-$
	d°	$P^- d^\circ h^+$	$P^- d^\circ h^\circ$	$P^- d^\circ h^-$
	d^-	$P^- d^- h^+$	$P^- d^- h^\circ$	$P^- d^- h^-$



$$E = \frac{P}{h \times V \times t}$$

Identify worst KPVs combinations

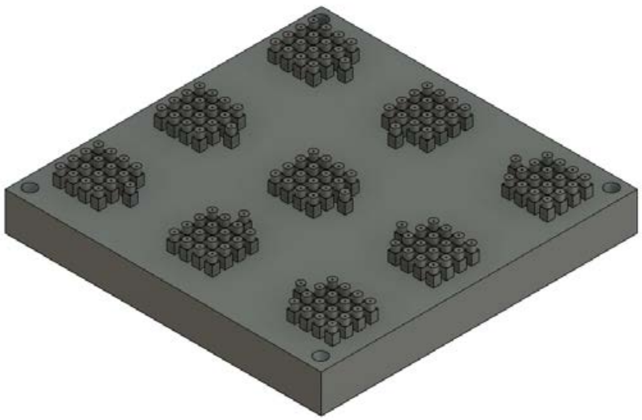
- Only overheating and underheating KPV combinations will be investigated as they can intensify the defect population

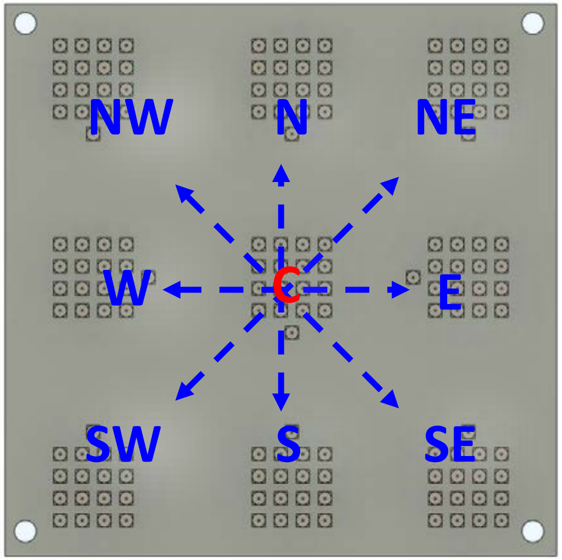


$$E = \frac{P}{h \times V \times t}$$

Identify worst KPVs/location combinations

- To account for location dependency, XCT coupons will be fabricated in 9 locations (N, S, W, E, NW, NE, SW, SE, and C)
- For this print, 17 (KPVs combinations) × 9 (locations) coupons will be fabricated/scanned to determine worst combinations of KPVs/location
- Time homogenization and skywriting will be activated during fabrication





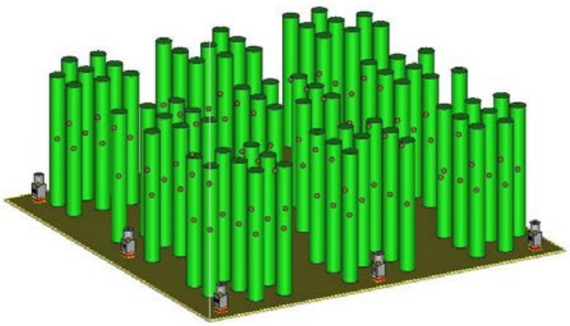
Occupied build plate density = 9%

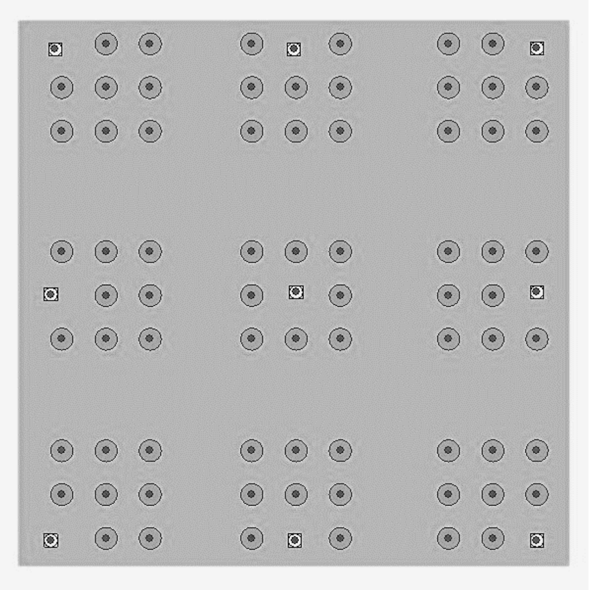
DoE to determine impact of KPVs drift on mechanical performance

Effect of KPVs drift on properties

- All specimens will be **fabricated based on the worst combination of KPVs/location**
- XCT coupons will be fabricated via recommended KPVs to monitor the effect of powder re-use (whenever possible)
- The tensile specimens will be machined to solely focus on the defects and microstructure of the parts
- The fabrication will be repeated at least multiple times for the tensile specimens to have 8 specimens per condition
  - 136 tensile specimens (17 sets of 8 specimens)
  - 6 specimens will be tested for each condition and 2 kept as backup
  - 9 XCT coupons per built plate

Tensile





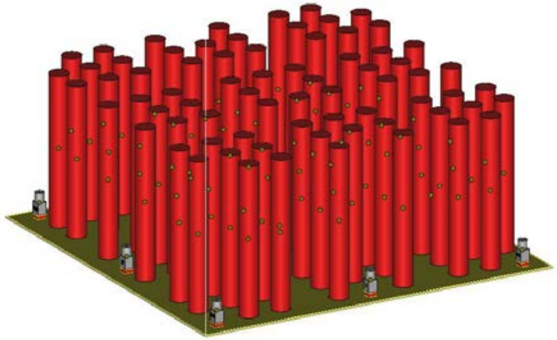
Occupied build plate density = 10%

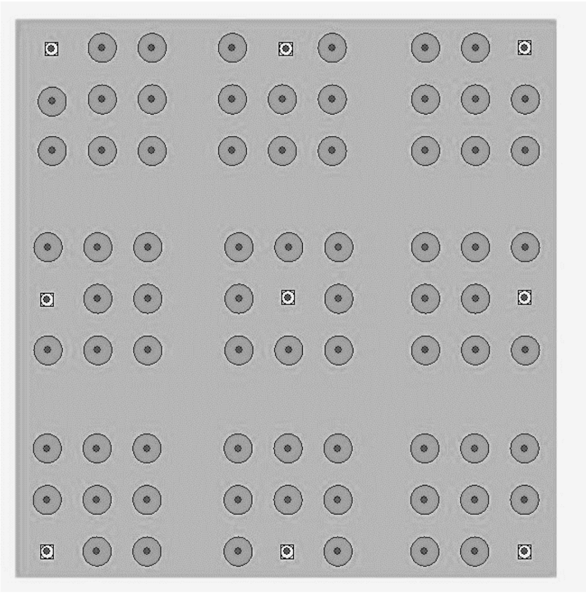
* The number of specimens may be adjusted to minimize the occupied build plate density to avoid excessive spatter, and powder layer disturbance due to recoater-part interaction

Effect of KPVs drift on properties

- All specimens will be **fabricated based on the worst combination of KPVs/location**
- XCT coupons will be fabricated via recommended KPVs to monitor the effect of powder re-use (whenever possible)
- Specimens will be machined to only investigate the effects of volumetric defects
- The fabrication will be repeated as needed to have 16 specimens per condition
  - 255 fatigue specimens (17 sets of 15 specimens)
  - 12 specimens will be tested for each condition and 3 kept as backup
  - 9 XCT coupons per build plate

Fatigue





Occupied build plate density = 16%

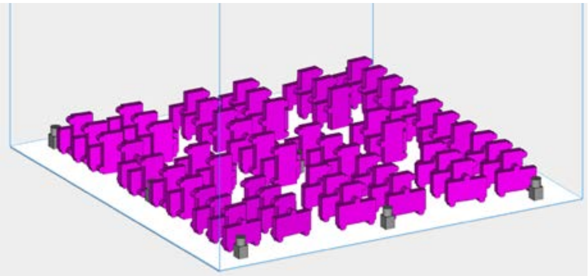
* The number of specimens may be adjusted to minimize the occupied build plate density to avoid excessive spatter, and powder layer disturbance due to recoater-part interaction

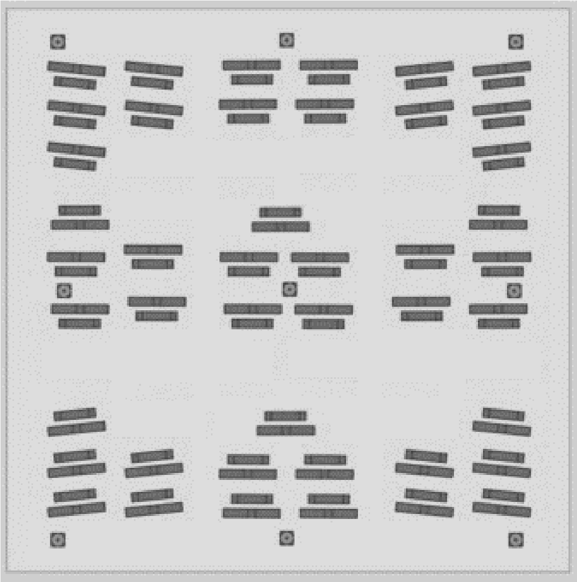
Effect of KPVs drift on properties

- All specimens will be **fabricated based on the worst combination of KPVs/location**
- High strain rate impact specimens are intended to be used in the as-built surface condition
- The fabrication will be repeated at least multiple times for the high strain rate impact specimens to have 5 specimens per condition
  - 85 vertical specimens (17 sets of 5 specimens)
  - 85 horizontal specimens (17 sets of 5 specimens)
  - 3 specimens will be tested for each condition and 2 kept as back up
  - 9 XCT coupons per build plate

* The number of specimens may be adjusted to minimize the occupied build plate density to avoid excessive spatter, and powder layer disturbance due to recoater-part interaction

High strain rate fracture



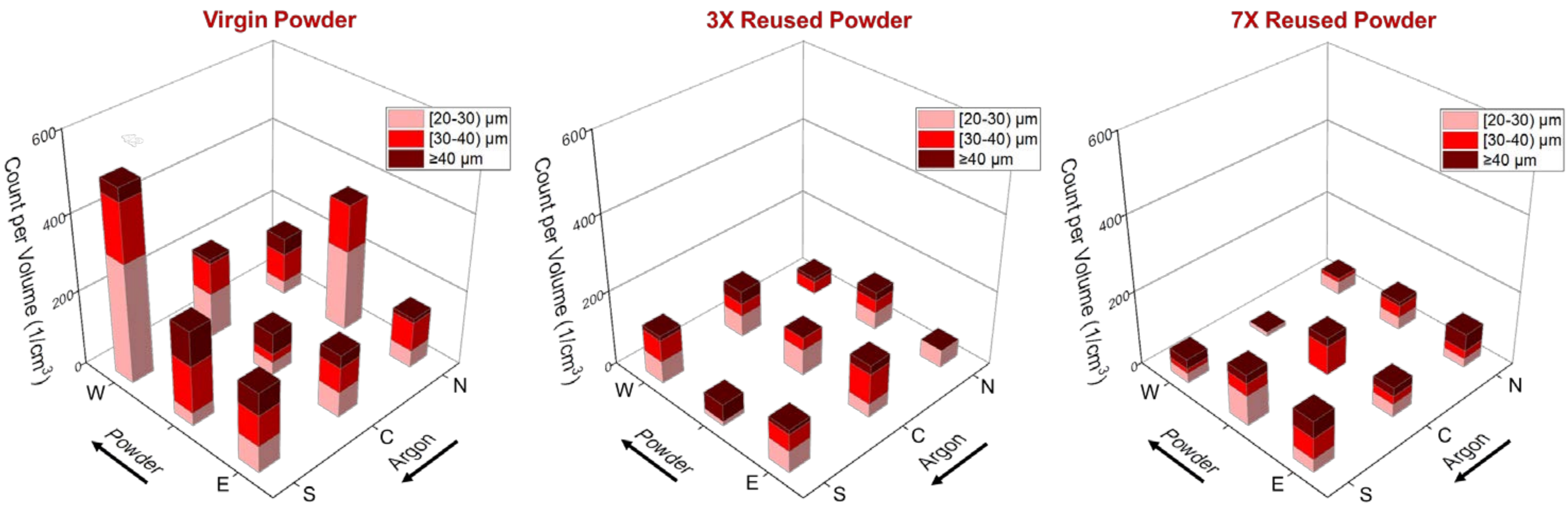


Occupied build plate density = 11%

Preliminary results

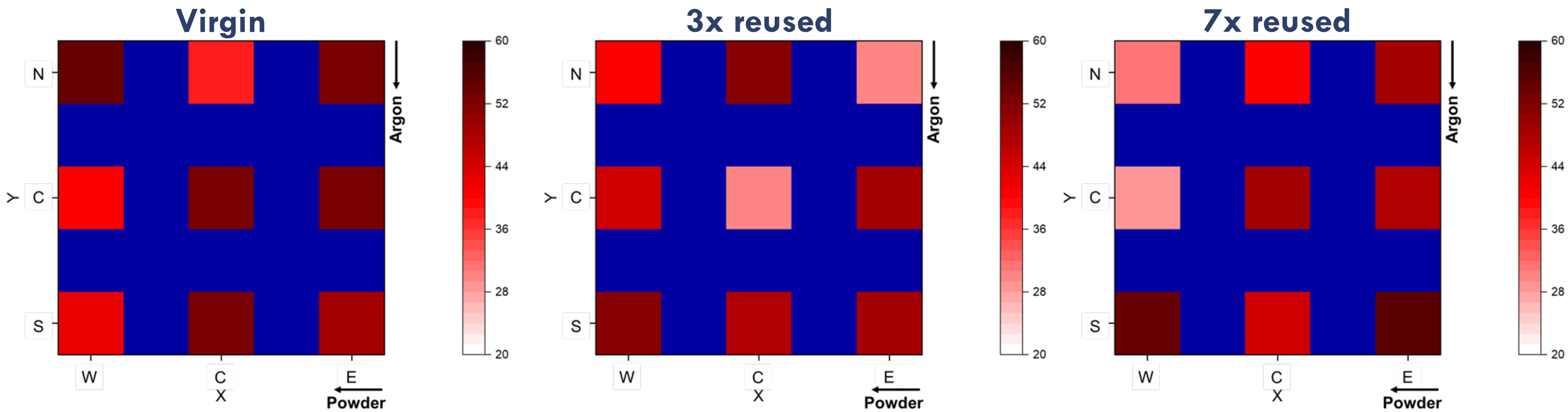
Powder re-use effect: defect characteristics

- South locations tend to produce more defects
- Defect population tend to decrease in re-used powder

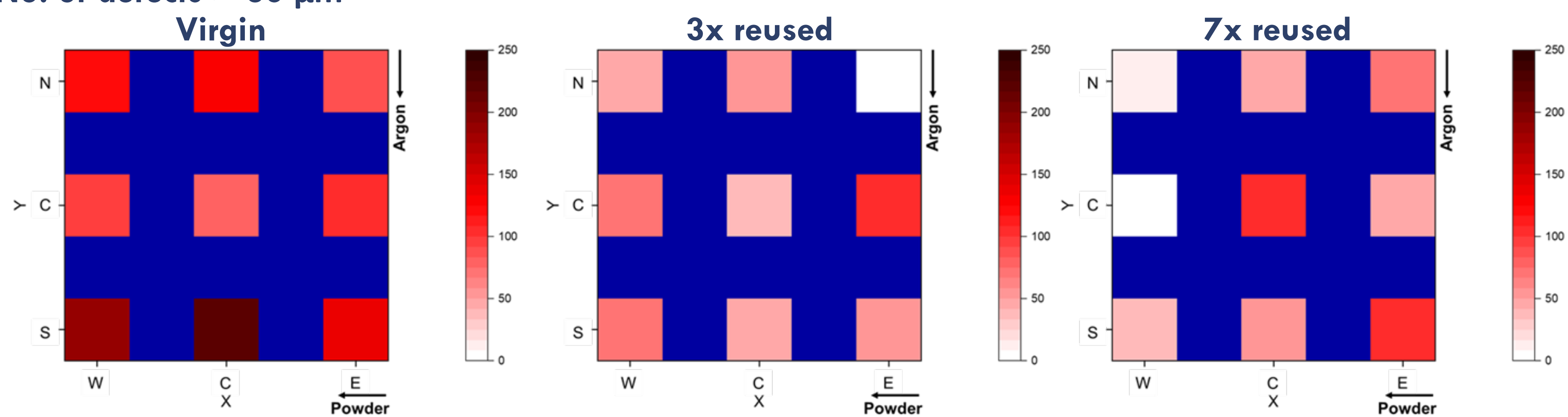


Powder re-use effect: defect characteristics

Maximum defect size

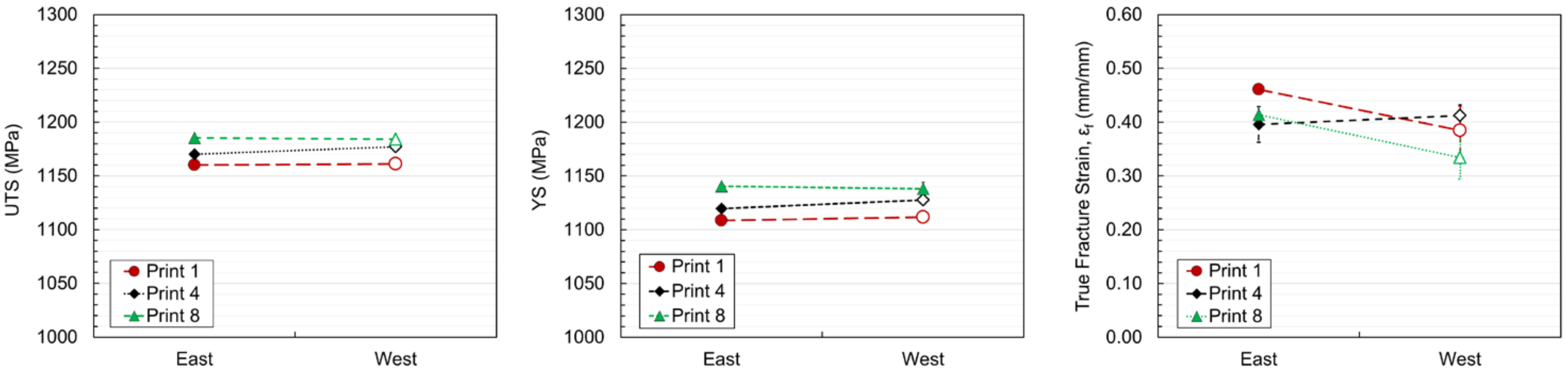


No. of defects > 30 µm

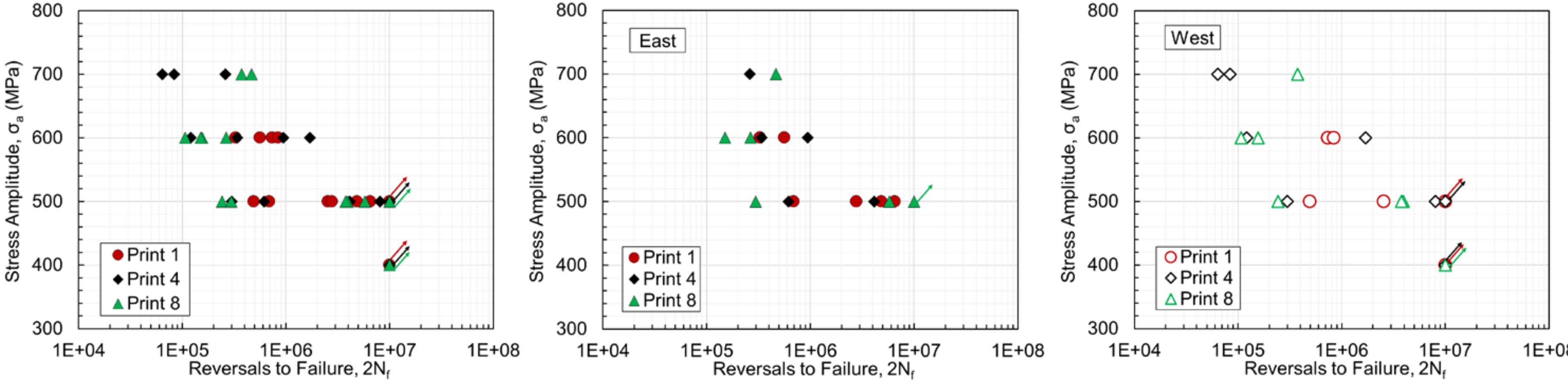


Powder re-use effect: mechanical properties

Tensile properties:

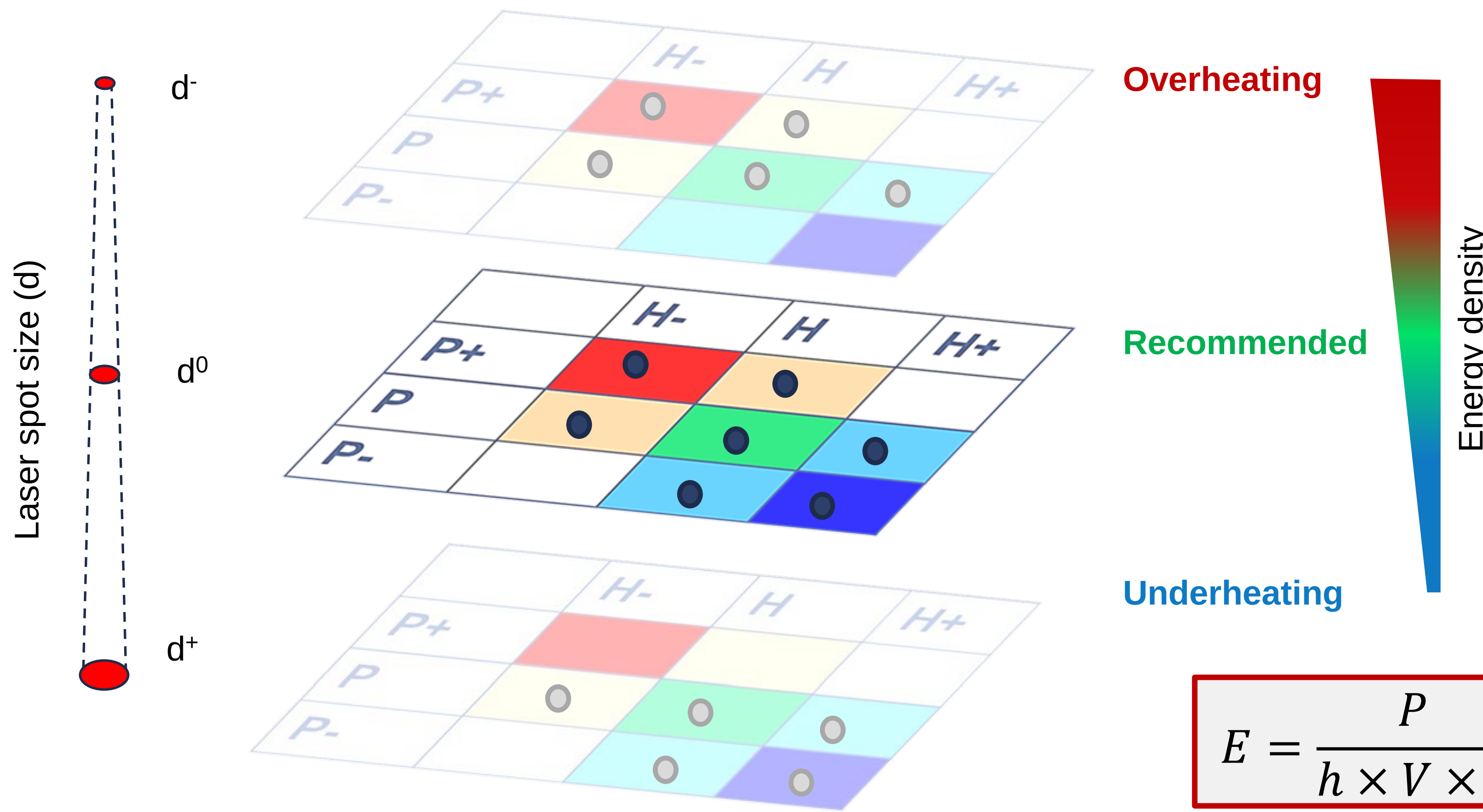


Fatigue properties:



Identify worst KPVs combinations

- So far, only nominal laser spot size was used for fabrication of XCT coupons



$$E = \frac{P}{h \times V \times t}$$

Location dependency and KPVs drift effects

p^+h^0	NE	N	NW	E	C	W	SE	S	SW
Density	100	100	100	100	100	99.9999	99.9996	99.9999	99.9998
Max length	35	22	39	32	36	35	76	47	46
90^{th} percentile length							49		40
> 40 /volume	22	0	0	0	0	0	68	11	11

p^0h^-	NE	N	NW	E	C	W	SE	S	SW
Density	100	100	100	100	100	100	100	100	99.9999
Max length	35	21	0	30	23	32	32	43	59
90^{th} percentile length								38	56
> 40 /volume	0	0	0	0	0	0	0	23	34

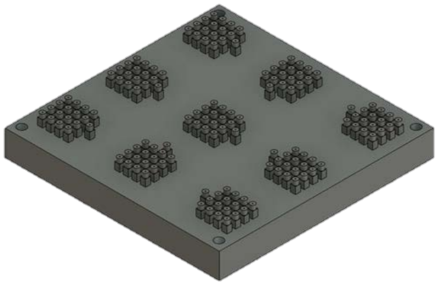
p^+h^-	NE	N	NW	E	C	W	SE	S	SW
Density	99.9999	100	100	100	100	100	99.9998	100	99.9999
Max length	51	40	30	0	27	36	73	26	91
90^{th} percentile length		38				32	67		70
> 40 /volume	11	0	0	0	0	0	23	0	11

p^-h^+	NE	N	NW	E	C	W	SE	S	SW
Density	99.9999	100	99.9999	99.9999	100	100	99.9987	99.9997	99.9987
Max length	45	34	62	42	29	22	91	46	135
90^{th} percentile length	40		45	39	29		49	38	129
> 40 /volume	22	0	22	11	0	0	275	45	180

p^0h^+	NE	N	NW	E	C	W	SE	S	SW
Density	100	100	100	99.9999	100	100	99.9988	100	99.9995
Max length	42	24	50	37	32	32	98	40	48
90^{th} percentile length	35			30			50		38
> 40 /volume	11	0	11	0	0	0	135	0	68

p^-h^0	NE	N	NW	E	C	W	SE	S	SW
Density	99.9997	100	100	99.9999	100	99.9999	99.9996	99.9999	99.9977
Max length	80	67	35	36	31	47	115	57	169
90^{th} percentile length	71			32		42	59	54	70
> 40 /volume	44	11	0	0	0	23	79	23	407

p^0h^0	NE	N	NW	E	C	W	SE	S	SW
Density	99.9999	100	100	100	100	100	100	100	99.9993
Max length	43	27	39	48	34	25	23	34	129
90^{th} percentile length									69
> 40 /volume	22	0	0	11	0	0	0	0	170



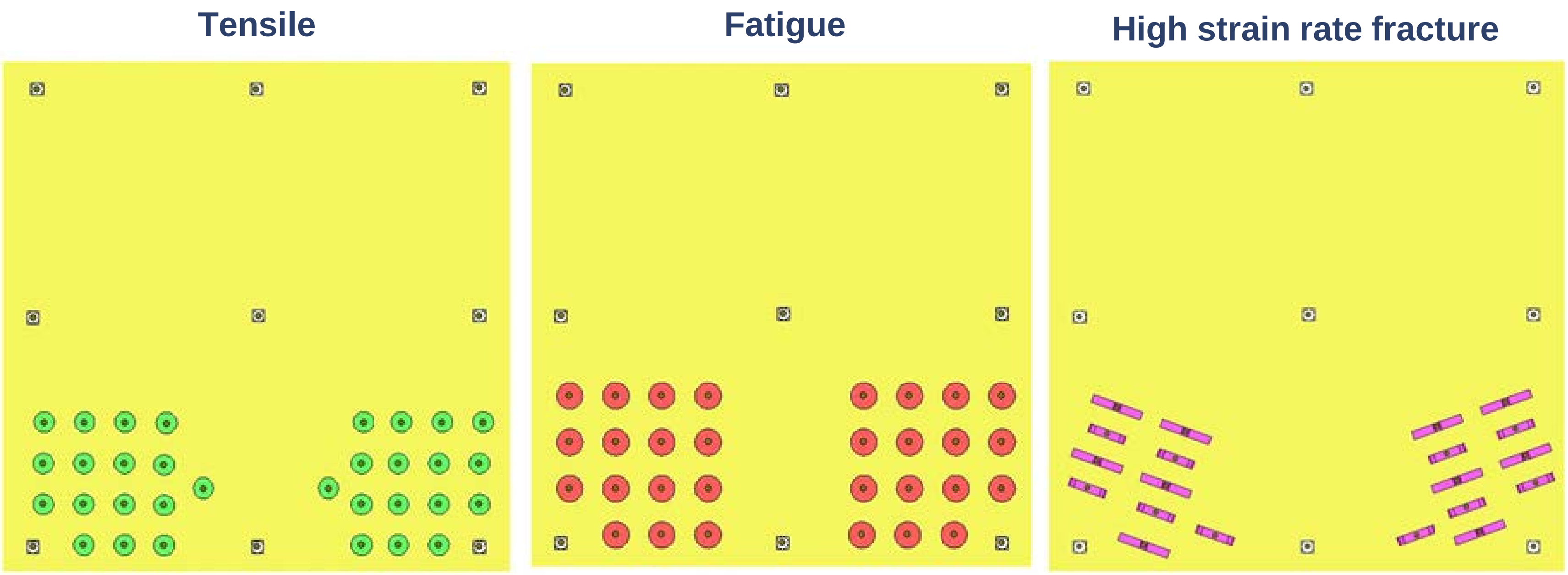
Green → Better
Red → Worse

- SE or SW generally performed worse for most KPVs.

A volume of ~(5 x 5 x 5) mm^3 was considered for all specimens
Gray box indicates overestimation of defect size due to the small number of defects found

Next step

- Fabrication of specimens will be limited to SW and SE locations as they were found to produce the worst defect conditions



- Data on powder re-use is planned to be fully analyzed and become available by the end of 2021