National Center for Additive Manufacturing Excellence

Factors Affecting Qualification/Certification - Effect of Drifts in Key Process Variables within Tolerance on Mechanical Properties of Additively Manufactured Ti-6Al-4V Parts

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Projects sponsored by: Federal Aviation Administration (FAA)

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Introduction

- **Project Title:** Factors Affecting Qualification/Certification - Effect of Drifts in Key Process Variables within Tolerance on Mechanical Properties of Additively Manufactured Ti-6Al-4V Parts
- **Principal Investigator:** Nima Shamsaei

  (See next slide for complete list of participants)

- **FAA Technical Monitor:** Kevin Stonaker
- **Source of matching contribution:** Faculty time and graduate research assistant tuition

Federal Aviation Administration

JAMS

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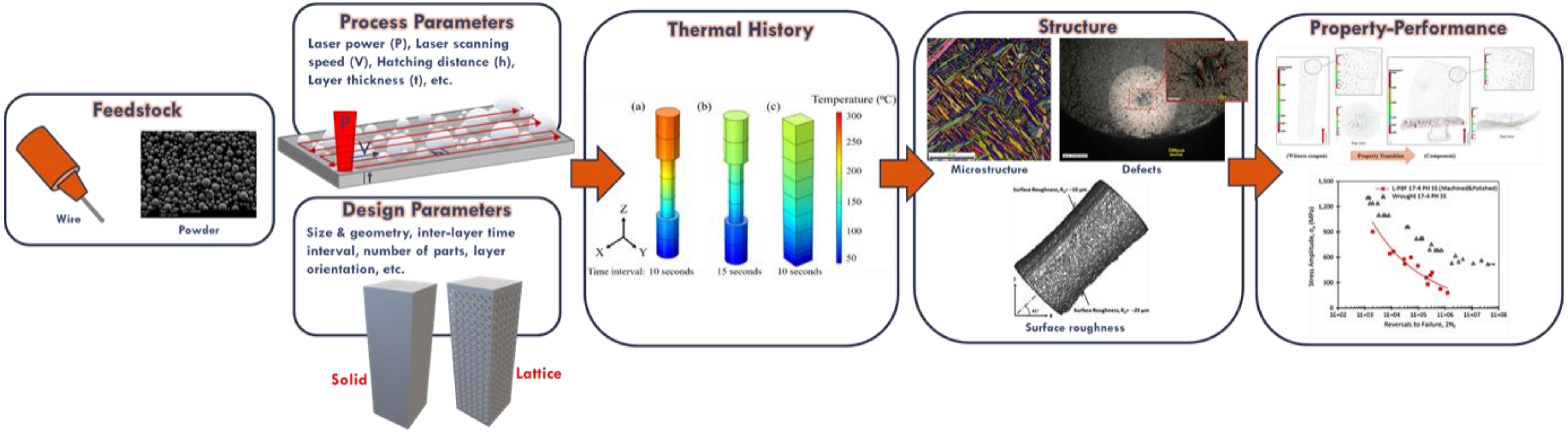
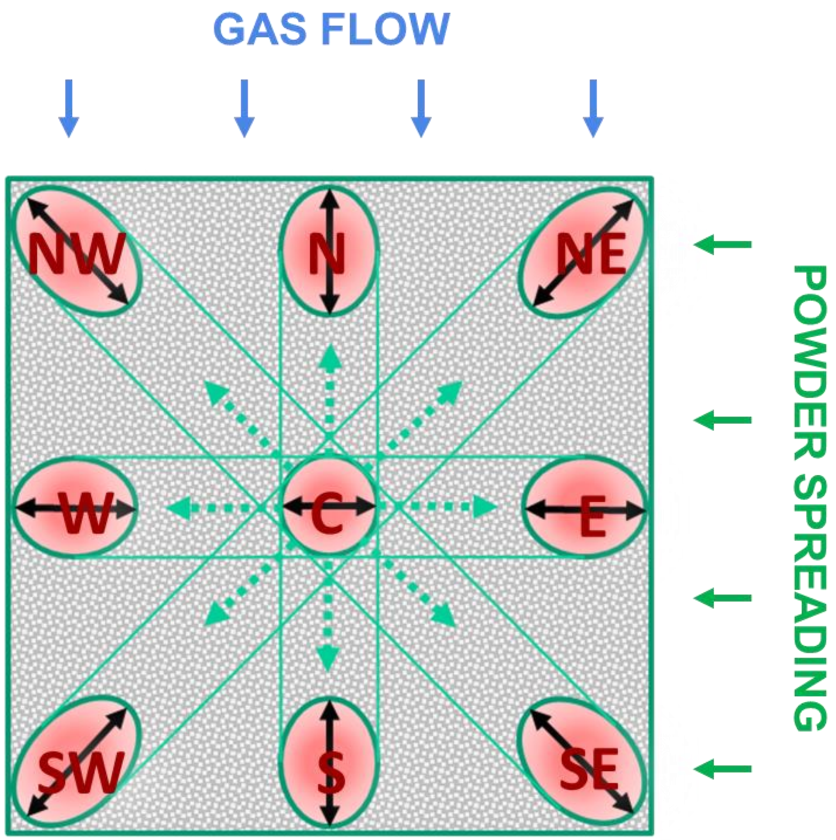
Background



- 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 including America Makes/ANSI AMSC and ASTM R&D
  - Challenge arises from the dependency of micro-/defect-structure and mechanical properties on 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 **powder re-use** and **location dependency** will be investigated first so that their influence, if any, can be excluded from the KPVs drift study
- <u>Geometry and time interval will be kept constant</u>



Objective & Approach

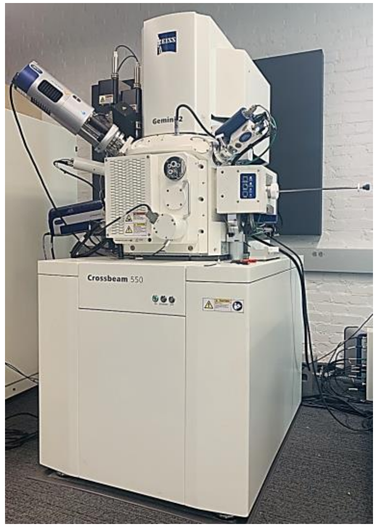
- **Objective**: To understand the effect of KPVs drift within tolerance bands on defect characteristics and mechanical properties of L-PBF Ti-6Al-4V Gr. 5
- **Approach**: Three steps are taken,
  I. Identify the effect of filter clogging and location on the defect-structure, tensile and fatigue behaviors
  II. Identify the combined effect of KPVs (laser power and hatch 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

Fabrication and Testing Equipment

EOS M290 L-PBF Machine

X-ray Computed Tomography (XCT) Machine

MTS Fatigue Testing Machines



Scanning Electron Microscope

- AP&C Ti-6Al-4V Grade 5 powder (15-53 µm) was used as feedstock
- During fabrication, time homogenization, and skywriting features were enabled in the infill region
- All specimens were stress-relieved at 704 °C for 1 hour followed by furnace cooling

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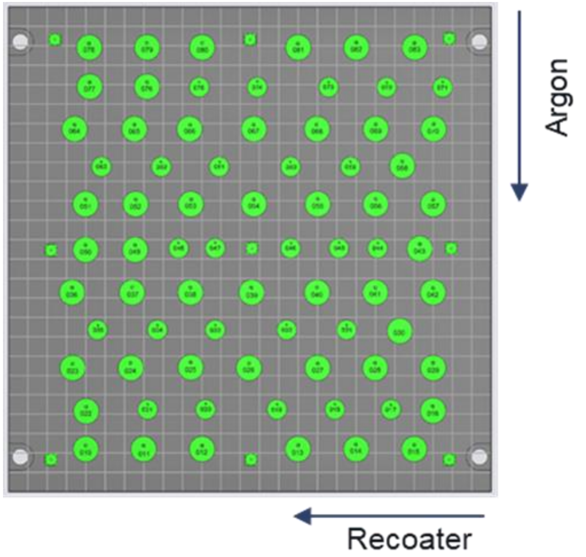
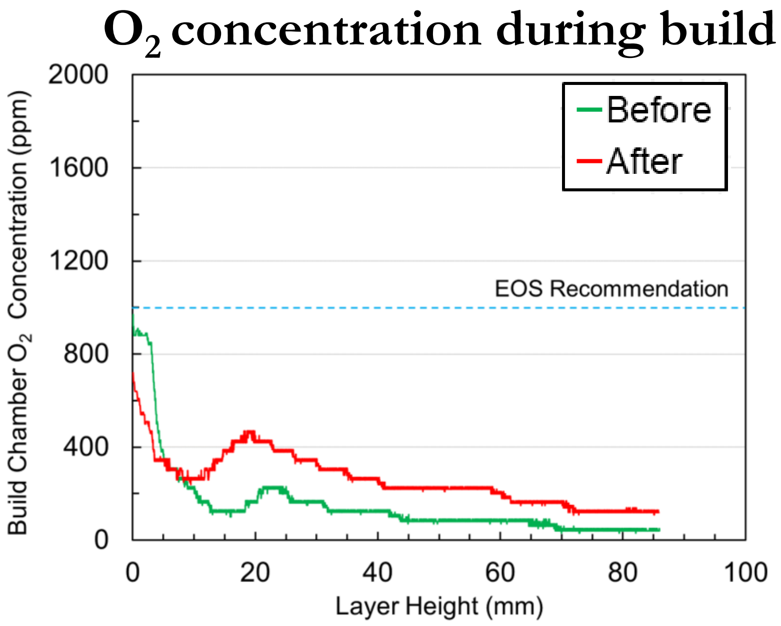
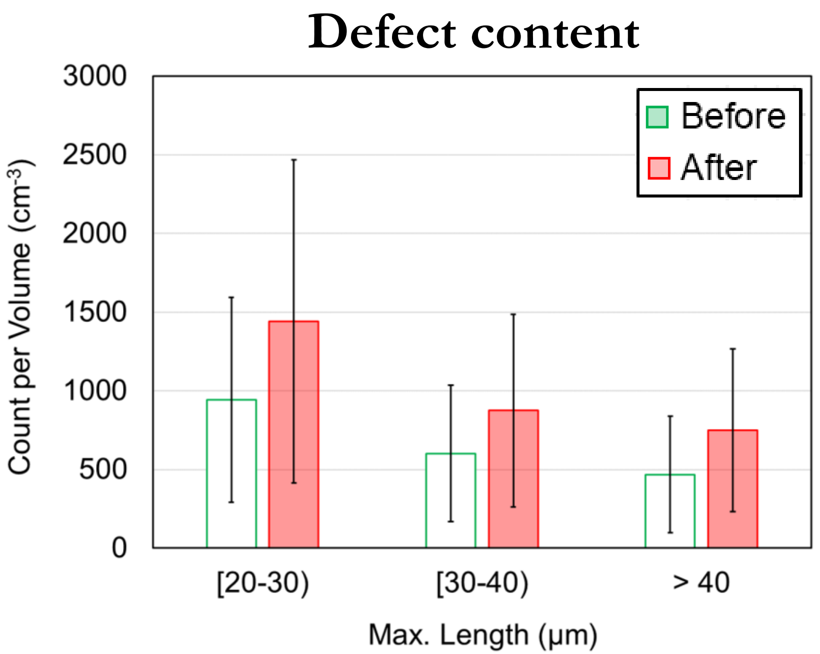
Design of Experiment for Filter Clogging Study

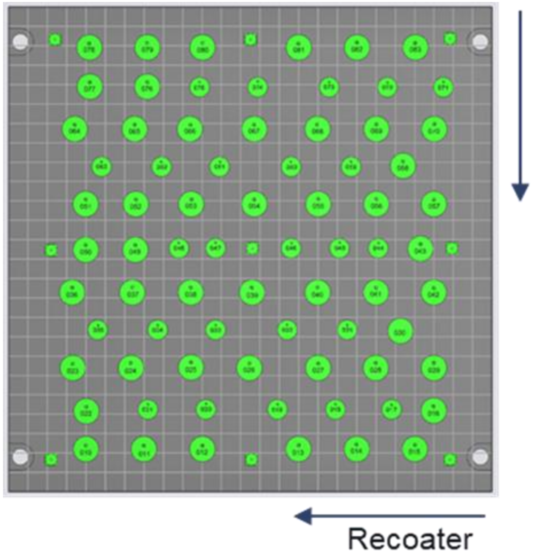


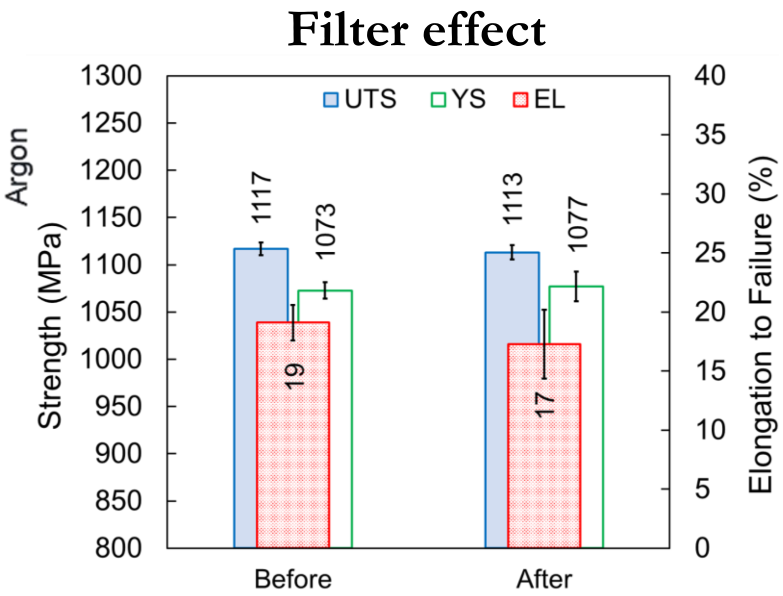


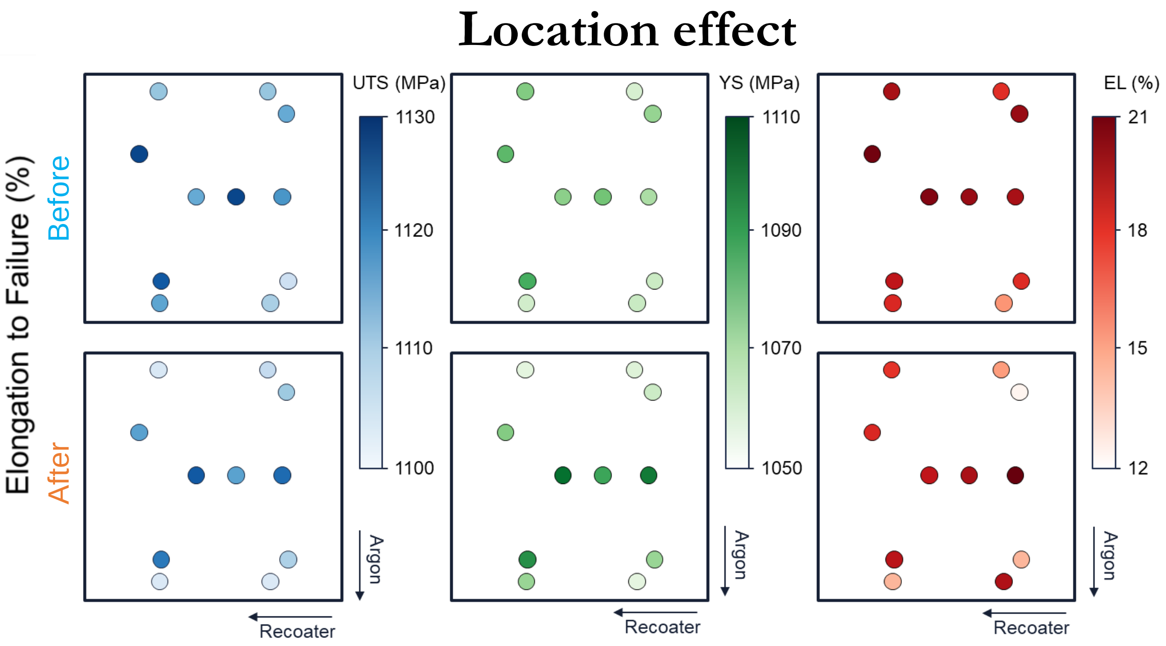


- Two identical prints were conducted using EOS recommended process parameters, one when the cartridge filters had 100 hours left on them, and the second one after filters were newly changed
- For the first print, 1-time reused powder was used, whereas for the second print 2-time reused powder was used
- Similar oxygen content inside the build chamber during fabrication and defect content were noted

Effects of Filter Clogging on Tensile Properties



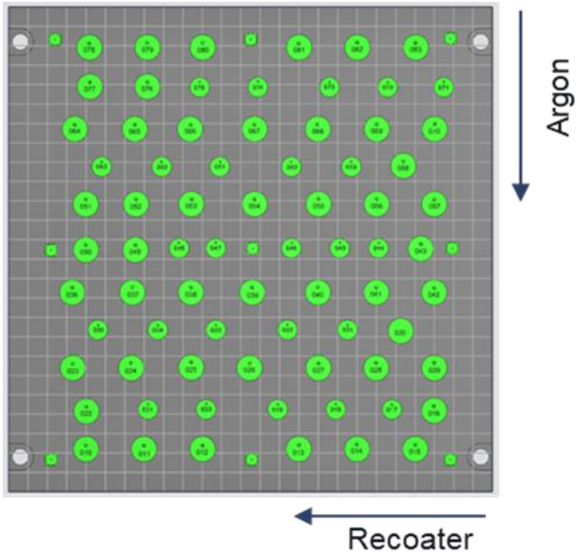




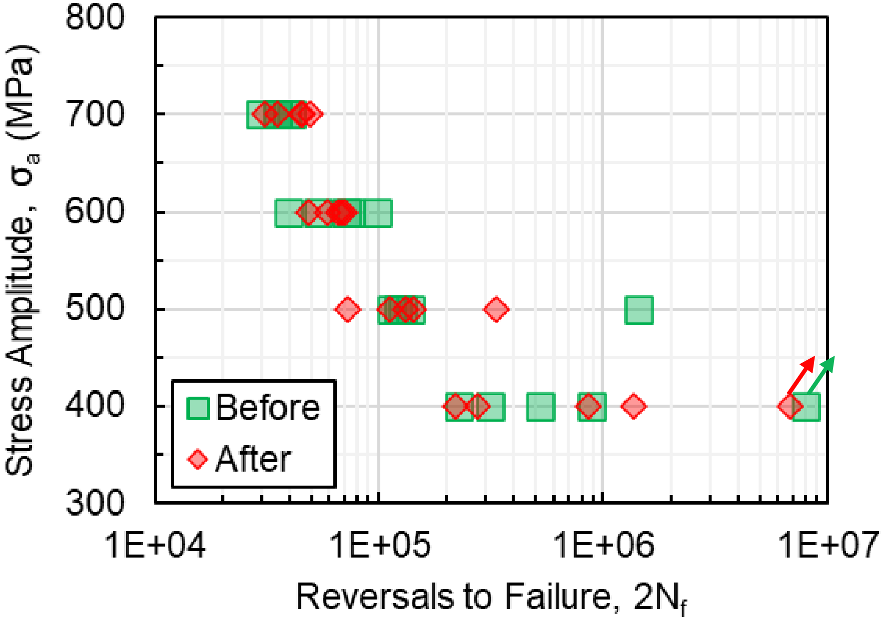
Note: 11 specimens per condition were tested from different locations of the build plate for this study

- No effect of filter clogging on tensile properties was observed
- Specimens positioned near the build plate's center generally displayed slightly better tensile properties compared to those placed closer to the edge, both before and after the filter change

Effects of Filter Clogging on Fatigue Performance

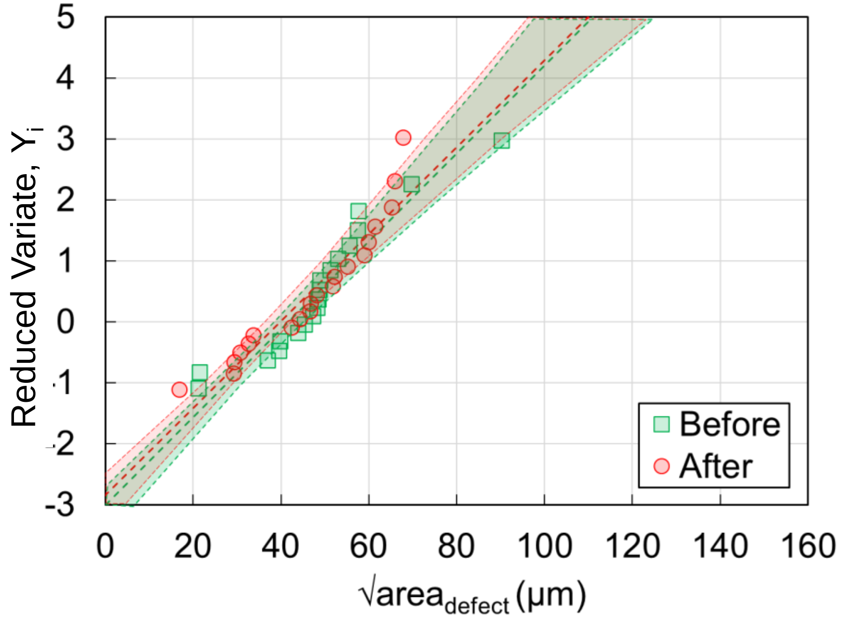


Stress-life behavior



Note: Tilted arrows indicate specimens failed from grips
5 specimens per stress level were tested

Critical defect size distribution



- No significant difference in fatigue lives was observed before and after the filter change

Objective & Approach

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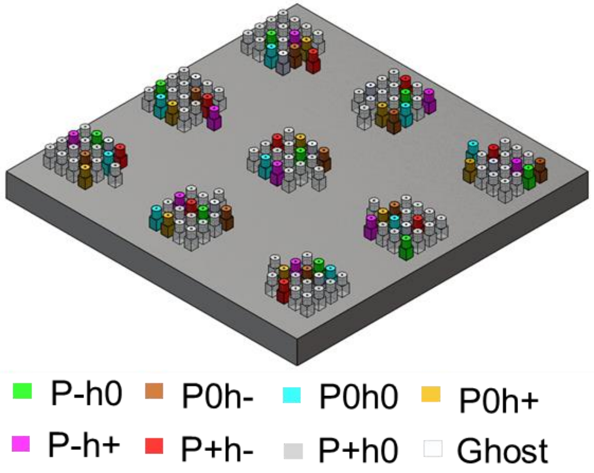
  I. Identify the effect of filter clogging and location on the defect-structure, tensile and fatigue behaviors
  II. Identify the combined effect of KPVs (laser power and hatch distance) drift and location on the defect-structure
  III. Evaluate the impact of KPVs drift on tensile, fatigue, and high strain rate fracture behaviors using specimens fabricated with worst KPVs/location combinations

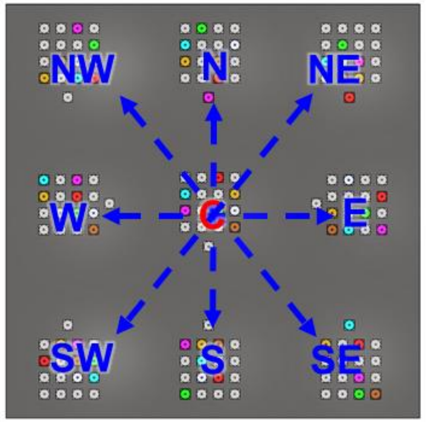
Design of Experiment for KPV Drift

Factorial Design Parameters

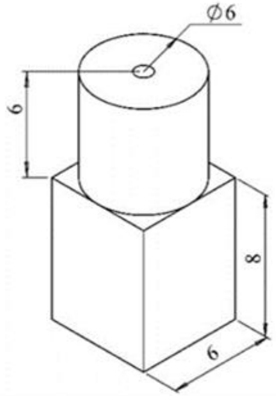
	Hatch distance (h)		
Laser power (P)	h+	h0	h-
P+	P+h+	P+h0	P+h-
P0	P0h+	P0h0	P0h-
P-	P-h+	P-h0	P-h-

Note: The combinations in gray were not considered for this study





Occupied build plate density = 6%



Unit: mm

- KPVs and their possible deviations in EOS M290 from the nominal values are laser power by ± 4% and hatch distance by ± 2.4%
- Energy density levels higher than the recommended value (shown by **green** text) were considered as "overheating" (shown by **red** text), while the lower ones were considered as "underheating" (shown by **blue** text)
- 9 locations including N, S, W, E, NW, NE, SW, SE, and C were considered to capture the location dependency
- XCT was used to obtain the relative density and defect distribution within the coupons

Combined Effects of Location and KPV Drift

P+h0	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9984		99.9993		99.9996		99.9984		99.9992
Max length (µm)	98		56		45		139		83
Avg. length (µm)	27		25		23		30		26
90 th percentile length	44		39		34		53		42
# > 40 µm /volume (cm^{-3})	252		121		33		321		175

P0h-	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9940		99.9992		99.9996		99.9996		99.9993
Max length (µm)	134		94		48		51		58
Avg. length (µm)	27		29		21		24		26
90 th percentile length	42		48		30		37		39
# > 40 µm/volume (cm^{-3})	709		144		11		44		89

P+h-	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9984		99.9994		99.9998		99.9995		99.9990
Max length (µm)	56		75		48		66		55
Avg. length (µm)	24		23		25		24		27
90 th percentile length	34		39		37		40		39
# > 40 µm /volume (cm^{-3})	153		121		22		88		100

P-h+	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9911		99.9938		99.9991		99.9933		99.9955
Max length (µm)	113		207		60		119		108
Avg. length (µm)	30		31		25		30		29
90 th percentile length	50		54		37		48		46
# > 40 /volume (cm^{-3})	1749		1205		88		1424		789

P0h+	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9968		99.997		99.9997		99.9898		99.9967
Max length (µm)	95		120		45		139		131
Avg. length (µm)	30		29		23		31		29
90 th percentile length	50		49		33		52		47
# > 40 µm/volume (cm^{-3})	587		543		22		1772		543

P-h0	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9980		99.9979		99.9996		99.9966		99.9922
Max length (µm)	78		88		52		93		103
Avg. length (µm)	28		27		25		28		30
90th percentile length	42		43		38		46		46
# > 40 µm /volume (cm^{-3})	428		410		22		658		1595

P0h0	NE	N	NW	E	C	W	SE	S	SW
Density (%)	99.9982		99.9991		99.9997		99.9988		99.9979
Max length (µm)	93		59		41		86		95
Avg. length (µm)	27		24		25		26		27
90 th percentile length	44		35		36		44		43
# > 40 µm/volume (cm^{-3})	245		111		33		222		291

Note: Defects smaller than 15 µm (equivalent to 3 voxels) were not considered

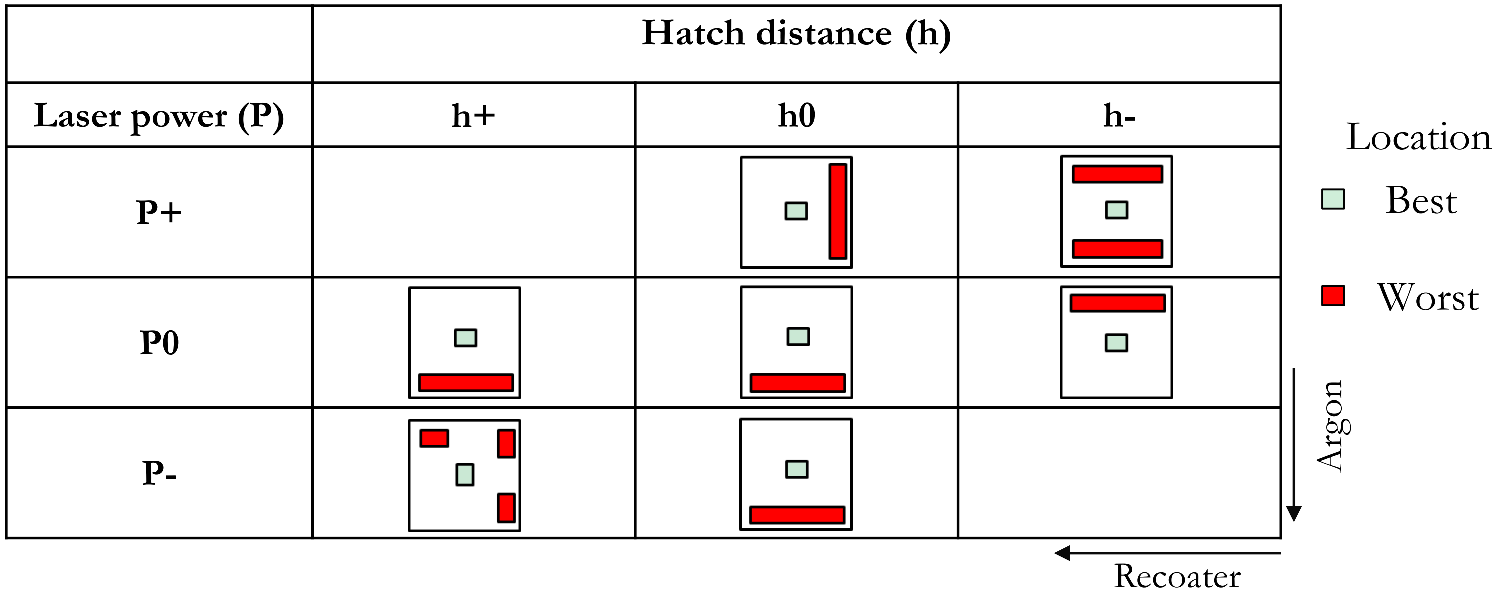
Green → Better
Red → Worse

Combined Effects of Location and KPV Drift

	Hatch distance (h)		
Laser power (P)	**h+**	**h0**	**h-**
P+	P+h+	P+h0	P+h-
P0	P0h+	P0h0	P0h-
P-	P-h+	P-h0	P-h-

Note: The combinations in gray were not considered for this study

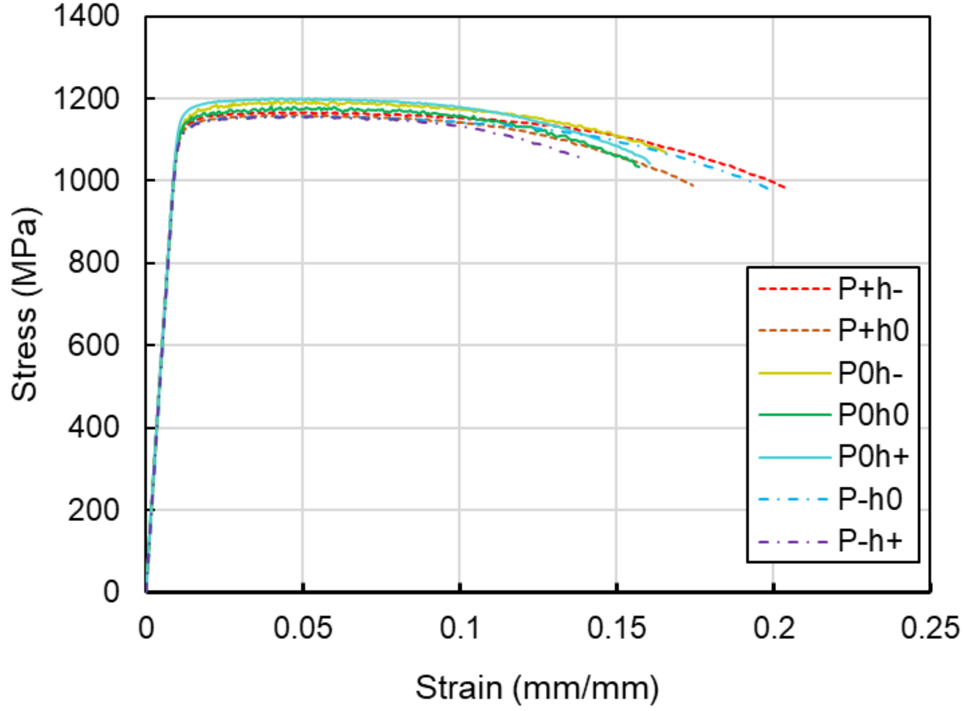
Summary of location effect



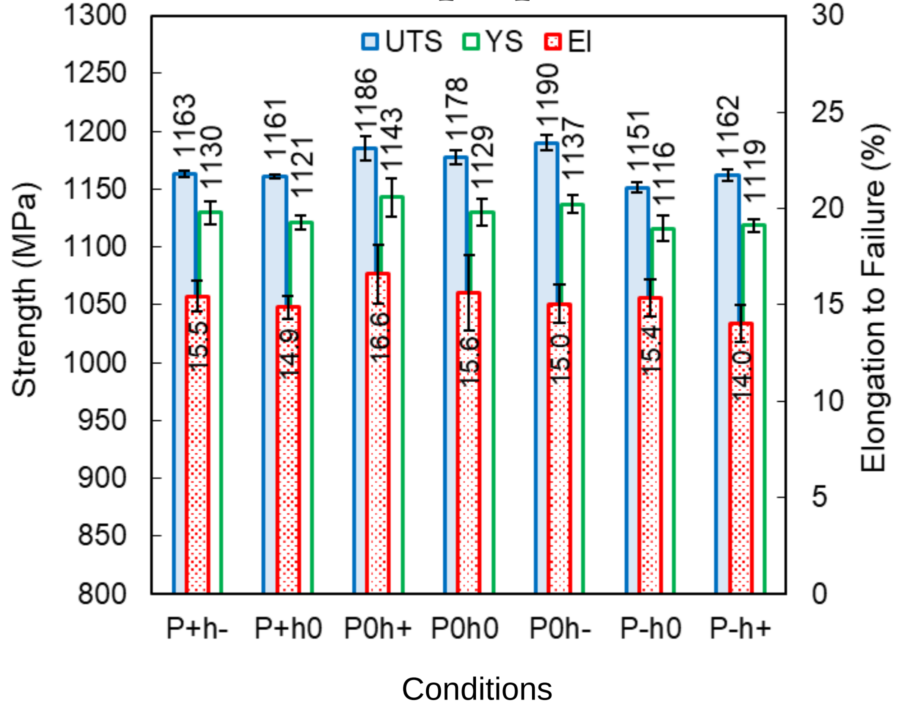
- 10 builds were fabricated, 7 for fatigue/tensile, and 3 for high strain rate specimens
  - 105 fatigue (7 x 15), 42 tensile (7 x 6), and 42 high strain rate (7 x 6) specimens were fabricated
- Specimens were fabricated in their respective best and worst locations based on the XCT coupons results

Effects of KPV on Tensile Properties

Stress-strain behavior



Tensile properties

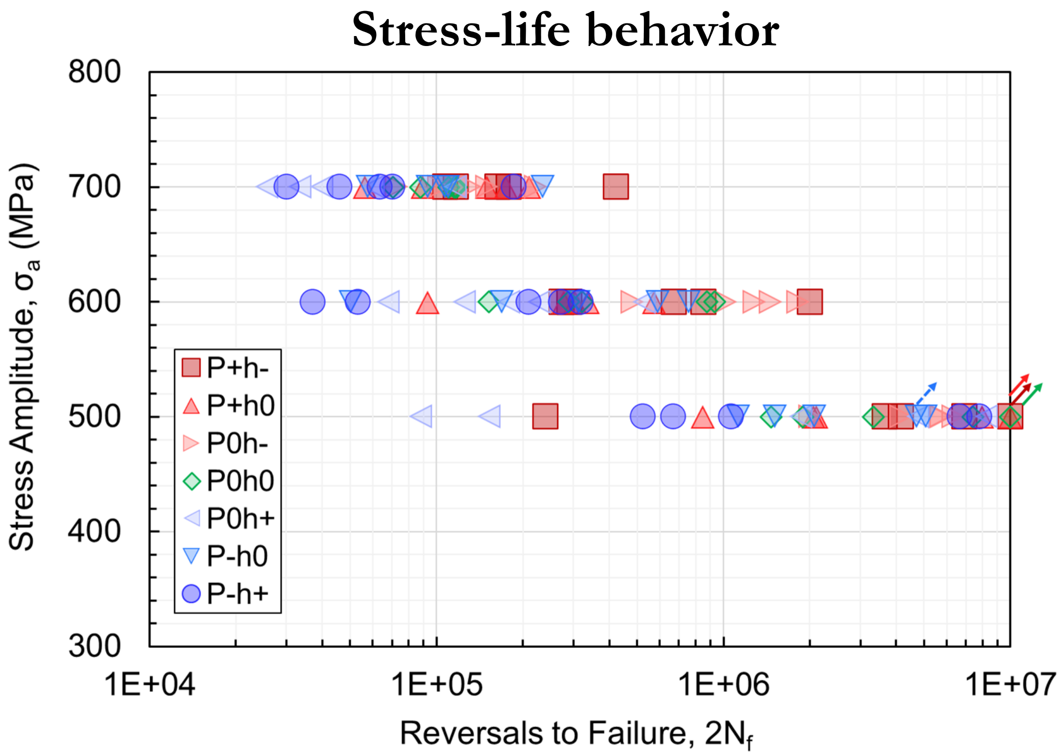


- Within the KPV tolerances, no significant difference on tensile properties was observed

Note: 6 specimens per condition were tested

	Hatch distance (h)		
Laser power (P)	h+	h0	h-
P+	P+h+	P+h0	P+h-
P0	P0h+	P0h0	P0h-
P-	P-h+	P-h0	P-h-

Effects of KPV on Fatigue Behavior

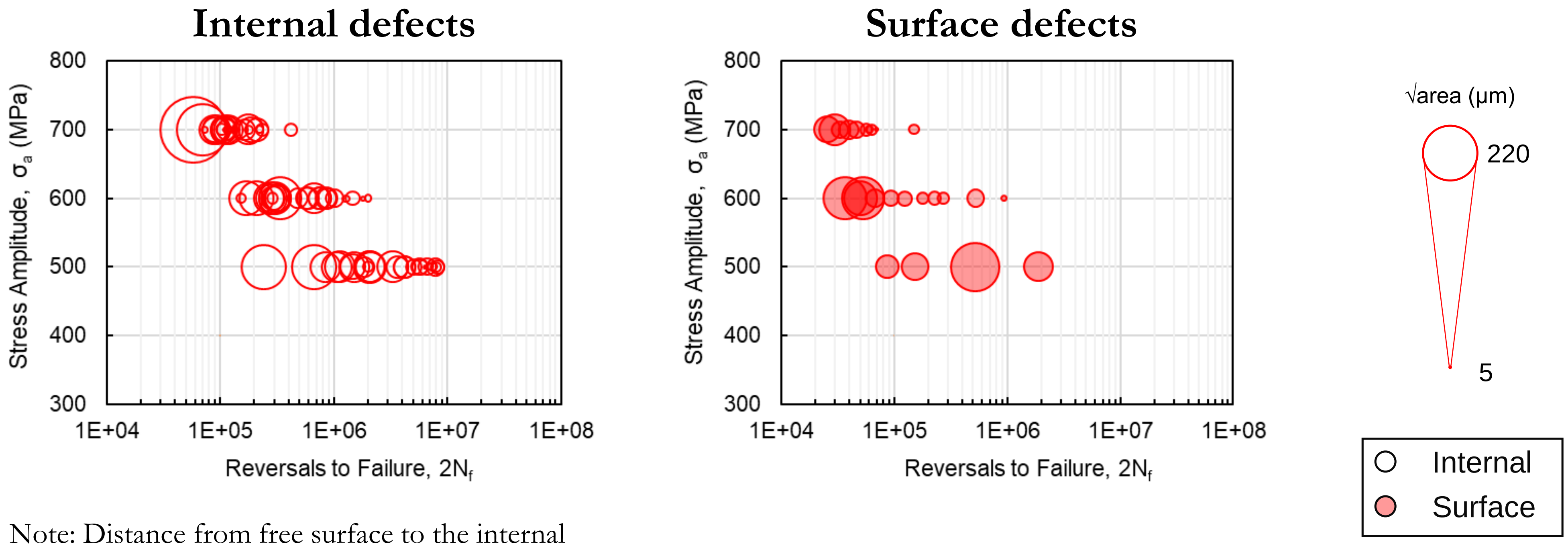


	Hatch distance (h)		
Laser power (P)	h+	h0	h-
P+	P+h+	P+h0	P+h-
P0	P0h+	P0h0	P0h-
P-	P-h+	P-h0	P-h-

- No clear trends in fatigue lives were observed within the KPV tolerances

Note: 5 specimens per stress level per condition were tested

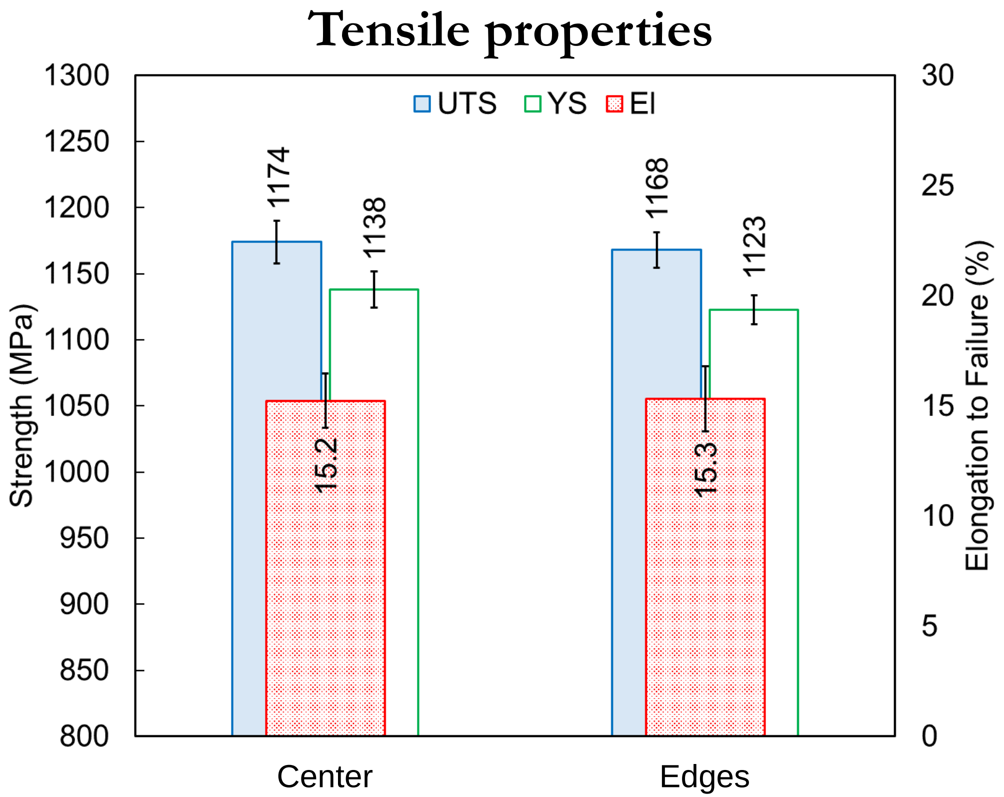
Effects of KPV on Defects and Fatigue Behavior



Note: Distance from free surface to the internal defects has not been taken into consideration

- Defect size, measured using Murakami's approach, was identified as a major factor influencing fatigue behavior
- Other influencing factors (i.e., defect shape, location) will be evaluated alongside the data from defect criticality project

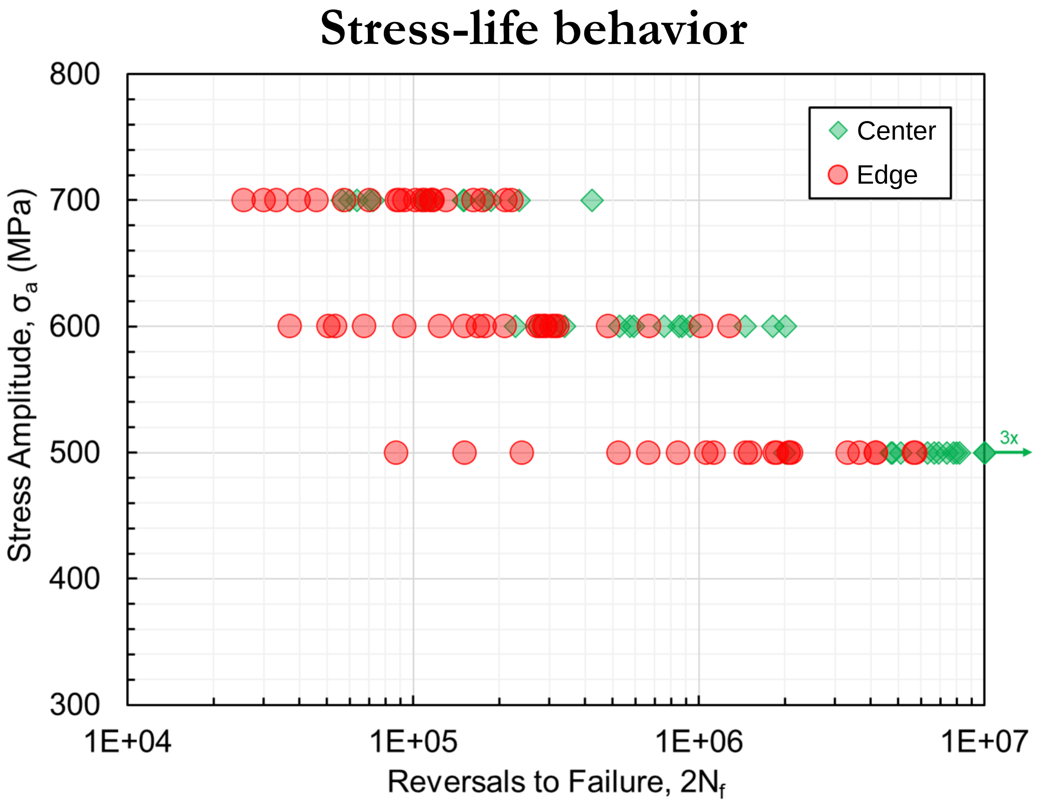
Effects of Location on Tensile Properties

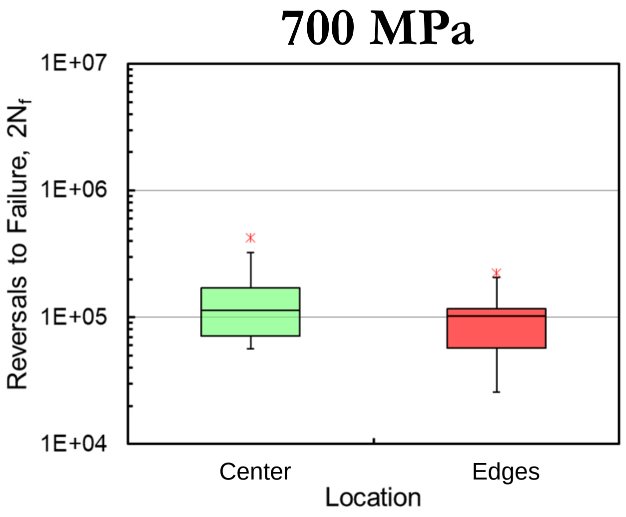


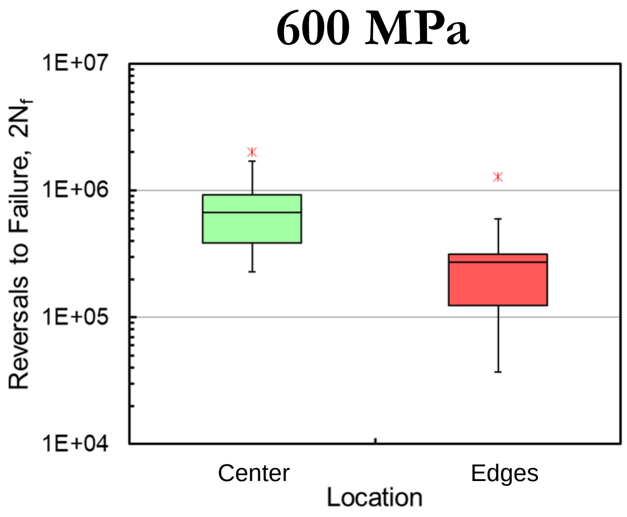
- No significant difference in tensile properties was noticed across different locations

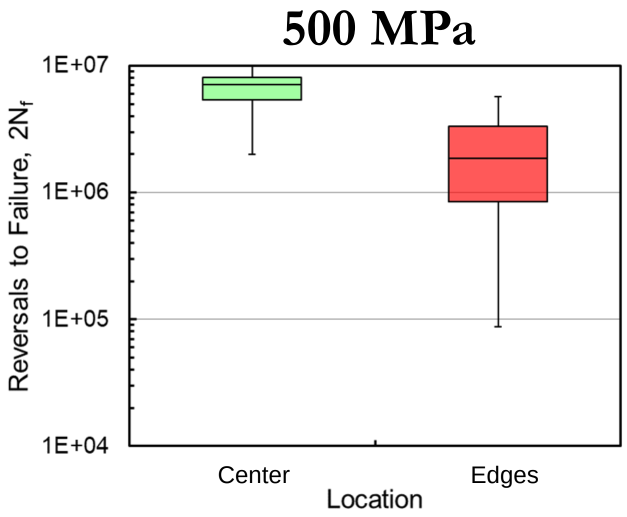
Note: 14 and 28 specimens were tested for center and edges, respectively

Effects of Location on Fatigue Behavior









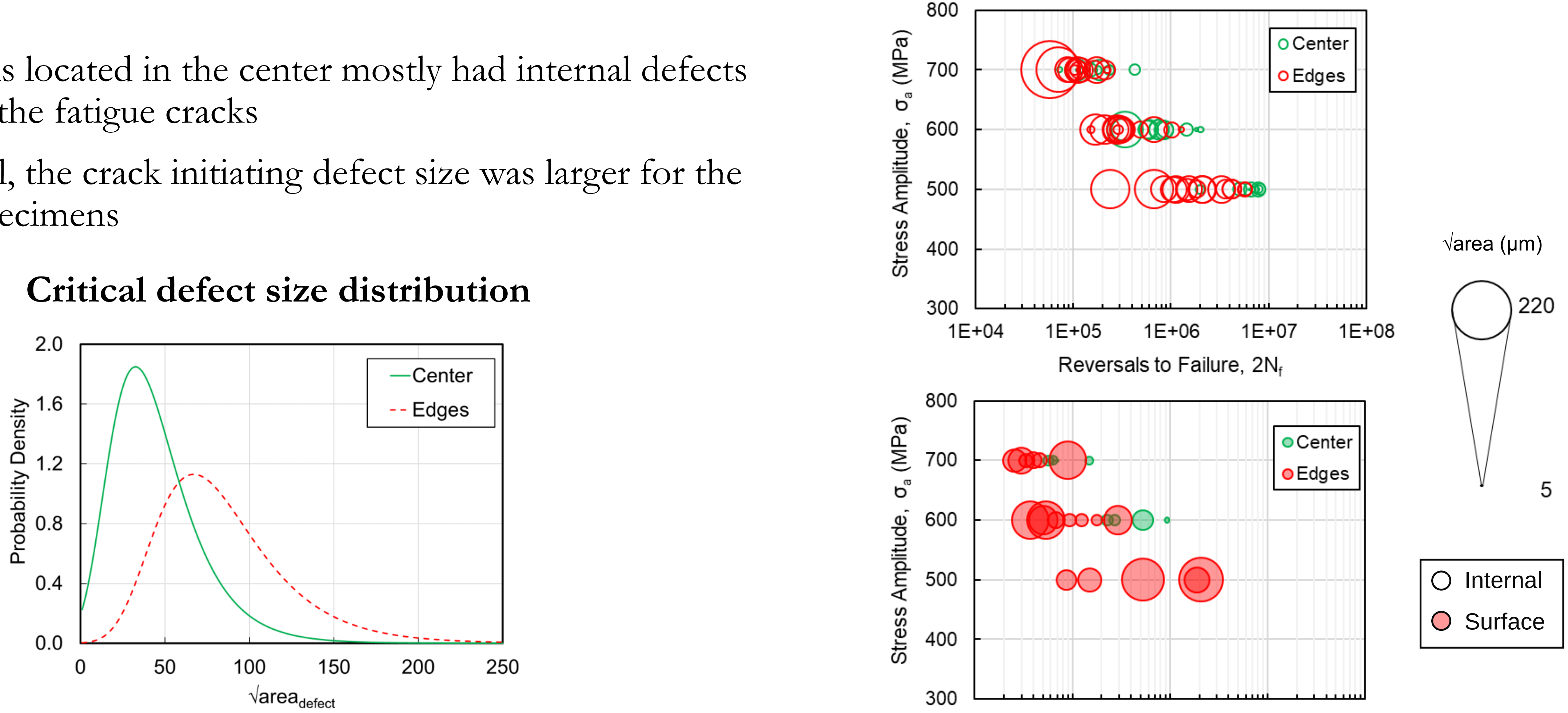
- Effect of specimen location on fatigue behavior was more prominent at 500 MPa

Note: 42 and 63 specimens were tested for center and edge locations, respectively

Effects of Location on Fatigue Behavior

- Specimens located in the center mostly had internal defects initiating the fatigue cracks
- In general, the crack initiating defect size was larger for the corner specimens

Critical defect size distribution



Note: Distance from free surface to the internal defects has not been taken into consideration

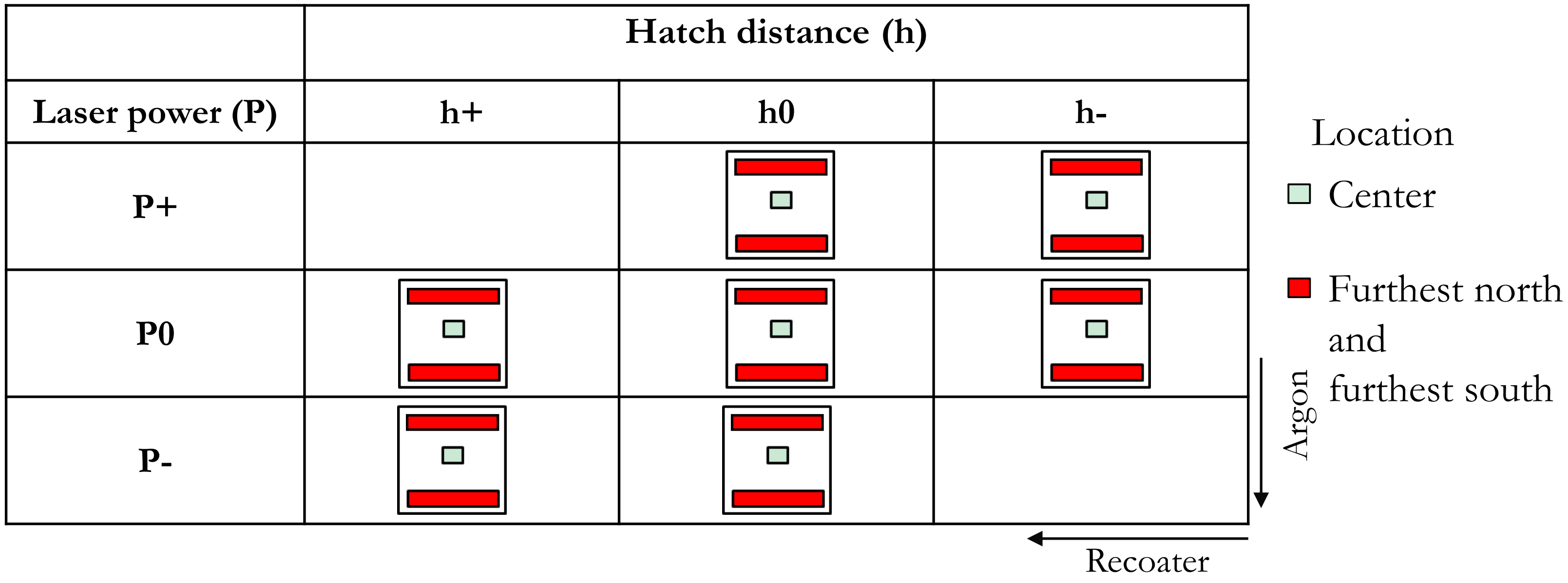
Summary

- Neither tensile nor fatigue behavior was affected by filter clogging, as long as filters are replaced before the end of recommended hours by EOS
- Tensile and fatigue behaviors were not affected by change in KPV within the tolerance
- Location of the specimen on the build plate influenced the fatigue behavior, with this effect being more pronounced at lower stress amplitudes
- In general, larger defects initiated fatigue cracks in specimens fabricated closer to the edge of build plate

Ongoing Work: Design of Experiment for KPV Drift

	Hatch distance (h)		
Laser power (P)	**h+**	**h0**	**h-**
P+	P+h+	P+h0	P+h-
P0	P0h+	P0h0	P0h-
P-	P-h+	P-h0	P-h-

Note: The combinations in gray were not considered for this study



- 4 builds were fabricated with **layer thickness of 60 µm** to be tested for fatigue/tensile specimens
  - 189 fatigue (7 x 27) and 49 tensile (7 x 7) specimens were fabricated
- Specimens were fabricated in the center and corner locations based on the previous results of specimens fabricated with layer thickness of 30 µm
- Specimens are currently being machined

Thank You for Your Attention!

- National Center for Additive Manufacturing Excellence (NCAME)