Fatigue Performance And EIDS Distributions of Wrought And Powder-Bed Additively-Manufactured Ti-6Al-4V

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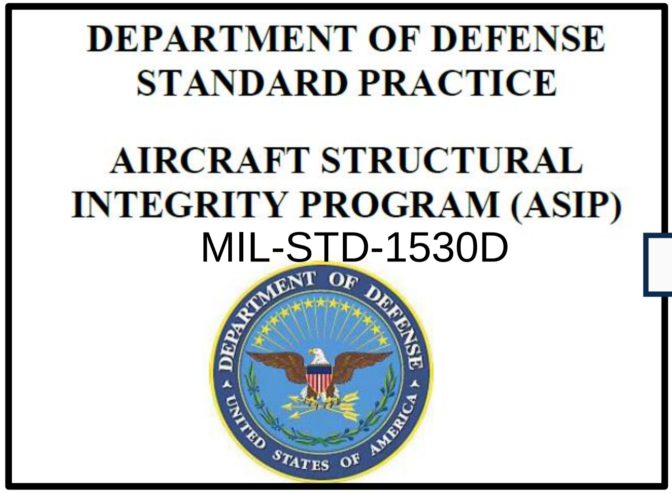
Project motivation and foundational USAF documents

Predictability of structural performance required of AM

Certification of AM materials for DADT

Measurement and interpretation of EIDS values


DEPARTMENT OF DEFENSE
STANDARD PRACTICE

AIRCRAFT STRUCTURAL INTEGRITY PROGRAM (ASIP)
MIL-STD-1530D


Structures Bulletin
AFLCMC/EZ
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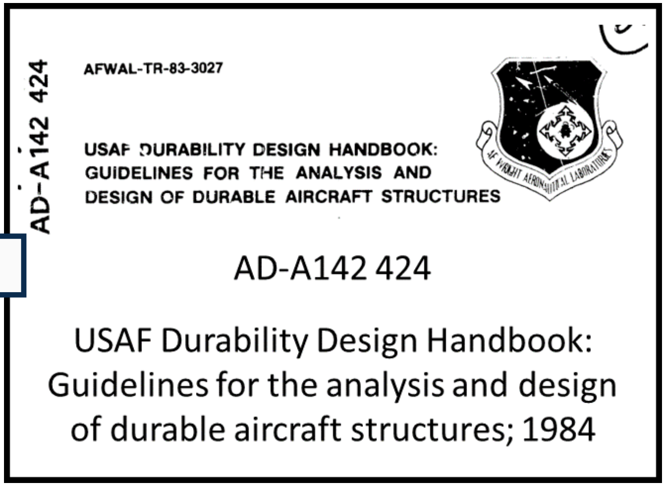
EZ-SB-19-01

Durability and Damage Tolerance Certification for Additive Manufacturing of Aircraft Structural Metallic Parts


AD-A142 424

AFWAL-TR-83-3027

USAF DURABILITY DESIGN HANDBOOK: GUIDELINES FOR THE ANALYSIS AND DESIGN OF DURABLE AIRCRAFT STRUCTURES

AD-A142 424

USAF Durability Design Handbook: Guidelines for the analysis and design of durable aircraft structures; 1984

Key questions:

Do AM parts have EIDS values that are problematic (> DADT limits, > conventional)
How does EIDS vary with orientation, surface, etc.
Can defects associated with EIDS be identified, measured?

Objectives – this work

- Provide to the USAF preliminary EIDS data developed for PBF AM Ti-6Al-4V

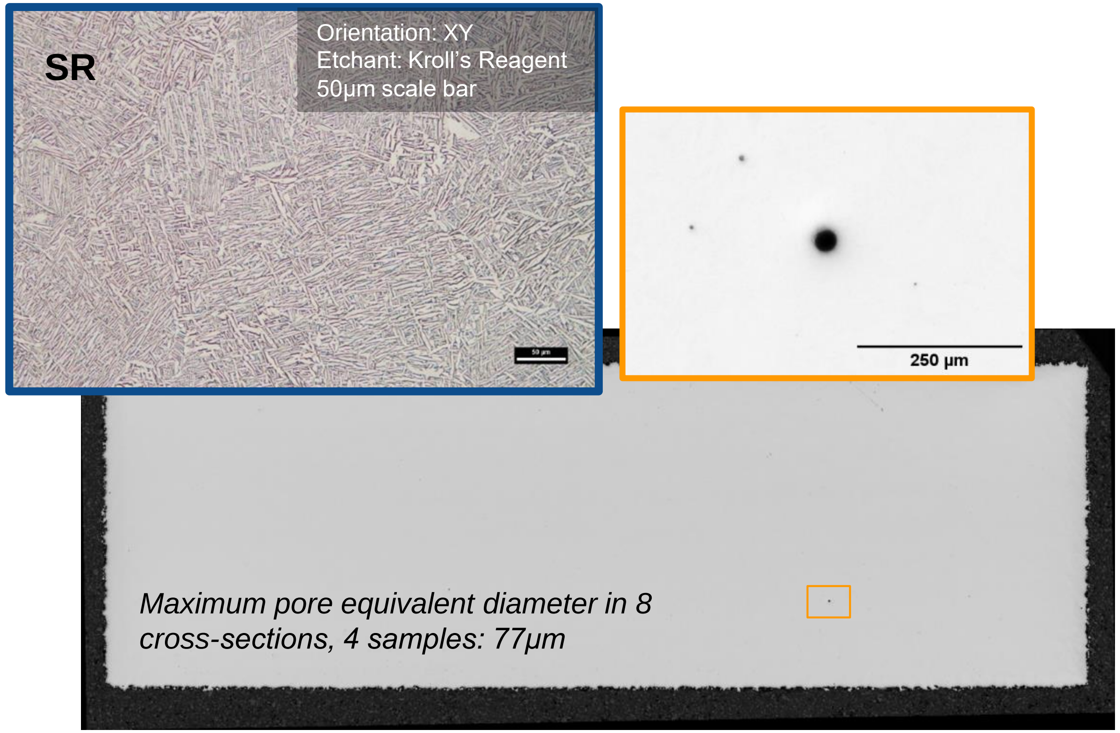
- Explore variation in EIDS distributions with:
  - Fabrication modality
  - Surface condition
  - Orientation

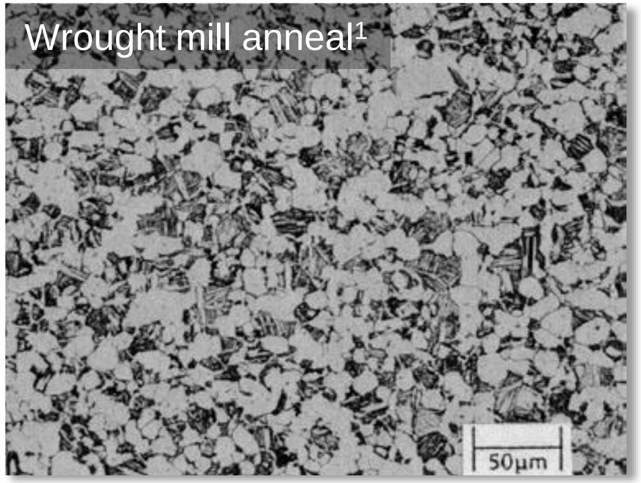
- Identify gaps in analysis methodology: foundation for further development of analytical approach

MATERIAL AND AM PROCESS

Material and Processing

- Powder-bed additive manufacturing
  - Laser – EOS M290 → Stress relief (SR): 913 ± 14°C for 3 hr, rapid Ar cooling
  - Electron-beam – Arcam Q10+ → HIP (proprietary conditions)
- Wrought
  - Forged plate → Solution heat treat 932±14 °C / 1h + mill-anneal 704±14 °C / 2h





1. JP Gallagher et al, AFRL-ML-WP-TR-2001-4159, 2001

PBF Material: Composition

Specimen Pedigree						Composition measurement							
Sample ID	Sample description	Use Modality	Build	Reuse No.	Form	O	N	C	H	Al	V	Fe	Y
F2924-14	ASTM standard	--	--	--	--	0.20	0.05	0.08	0.015	5.50 - 6.75	3.50 - 4.50	0.30	0.005
MC-21-1112	AP&C Cert (LPBF cut)	EOS	--	--	Powder	0.17	0.01	<0.01	0.002	6.38	4.04	0.20	<0.001
MC-21-1113	AP&C Cert (EBM cut)	Arcam	--	--	Powder	0.12	0.01	0.01	0.01	6.4	3.99	0.20	<0.001
13258-05	Reuse 2 Powder	EOS	B	2	Powder	0.124	0.008	0.014	0.0016	6.33	4.09	0.21	<0.0005
13258-05	Reuse 2 Sail 1	EOS	B	2	Solid	0.136	0.016	0.016	0.0005	6.36	3.99	0.21	<0.0005
14007-01	Reuse 6 Powder	EOS	G	6	Powder	0.128	0.011	0.013	0.0017	6.35	4.08	0.21	<0.0005
14007-01	Reuse 6 Sail 1	EOS	G	6	Solid	0.172	0.028	0.016	0.0005	6.34	3.99	0.21	<0.0005
14038-04	Reuse 10 Powder	EOS	H	10	Powder	0.136	0.014	0.014	0.0023	6.31	4.01	0.21	<0.0005
14038-04	Reuse 10 Hex Bar	EOS	H	10	Solid	0.142	0.021	0.016	0.0005	6.39	3.99	0.20	<0.0005
14911-01	Reuse 17 Powder	EOS	O	17	Powder	0.173	0.011	0.0146	0.0028	6.35	4.09	0.20	<0.0005
14911-01	Reuse 17 Sail	EOS	O	17	Solid	0.177	0.003	0.0202	0.0005	6.36	4.16	0.19	<0.0005

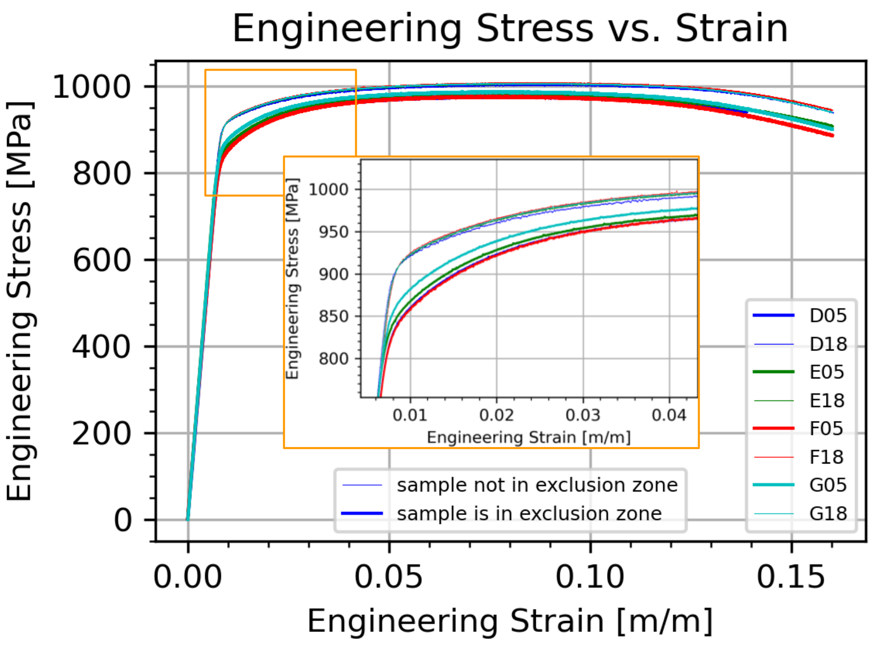
Methods: Oxygen & Nitrogen - Inert gas fusion - ASTM E 1409-13
Carbon - Combustion infrared detection - ASTM E 1941-16
Hydrogen - Inert gas fusion – ASTM E 1447- 16
All others - Direct current plasma emission spectroscopy - ASTM E 2371-13

Compositions meet ASTM F2924-14 specification (powder bed fusion Ti-6Al-4V) for:
- Source powder
- up to 17x reused powder samples
- up to 17x reuse consolidated metal

LPBF Material: Tensile testing

- Powder bed fusion using direct metal laser melting (DMLM) on EOS M290
- Optimized post processing
  - Stress relief (SR): 1675 ± 25°F for 3 hr - 0 min / + 30 min, followed by rapid Ar cooling

EOS M290 ASTM E8-21 Tensile Data							
Effort	Excluded zone for allowables calculation	Powder, Heat treat condition, and build orientation		Yield Strength [MPa] Mean	UTS [MPa] Mean	Elongation [%] Mean	Number of data points
ASTM F2924-14	--	Class A-D, minimum	XY	825	895	10	--
	--		Z	825	895	10	--
Archival	No	AP&C Ti-6Al-4V Stress Relief	XY	945	1020	17	182
	No		Z	931	1014	18	189
Current	No	AP&C Ti-6Al-4V Stress Relief	Z	920	1006	19	4
	Yes		Z	857	979	17	4

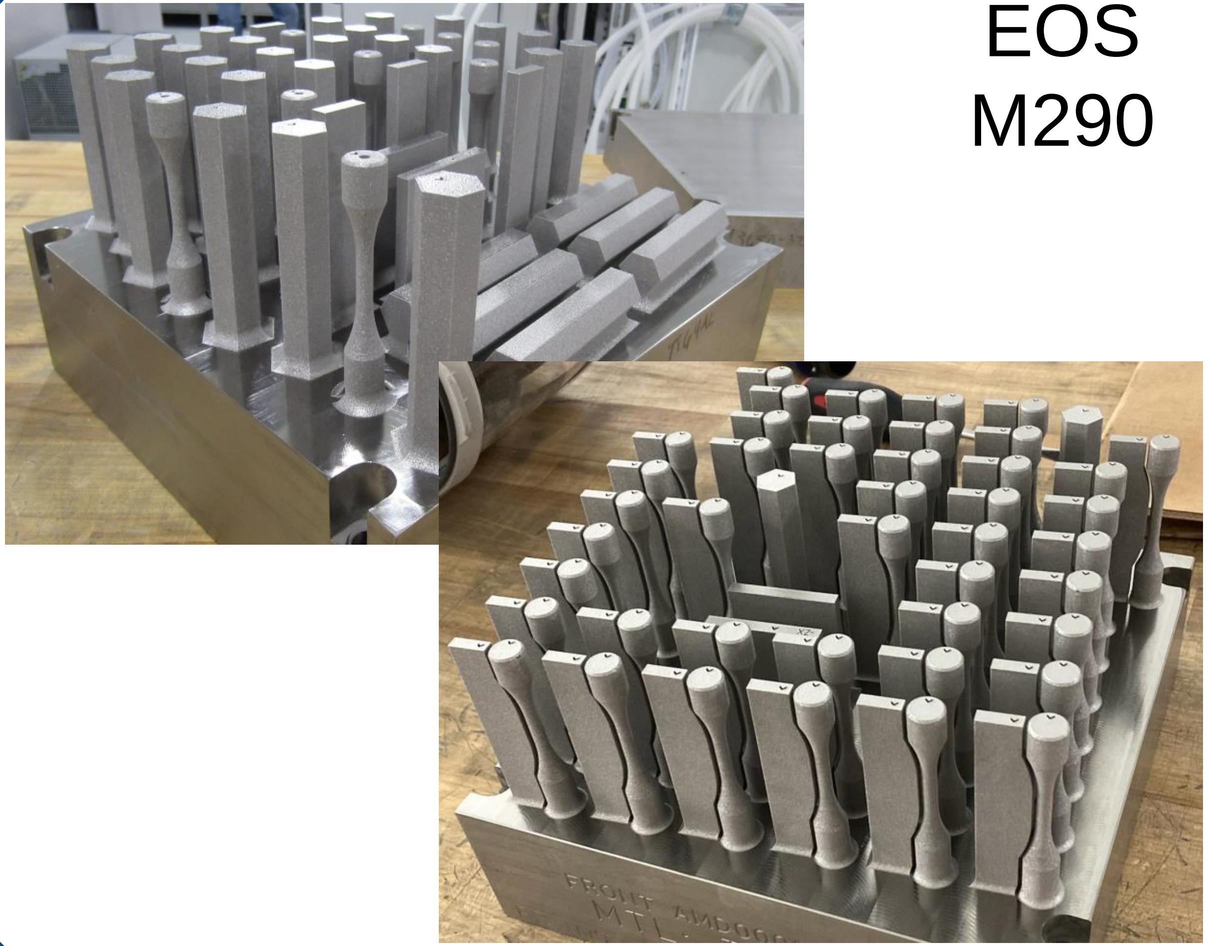


Tensile properties meet ASTM F2924-14 specification (powder bed fusion Ti-6Al-4V)

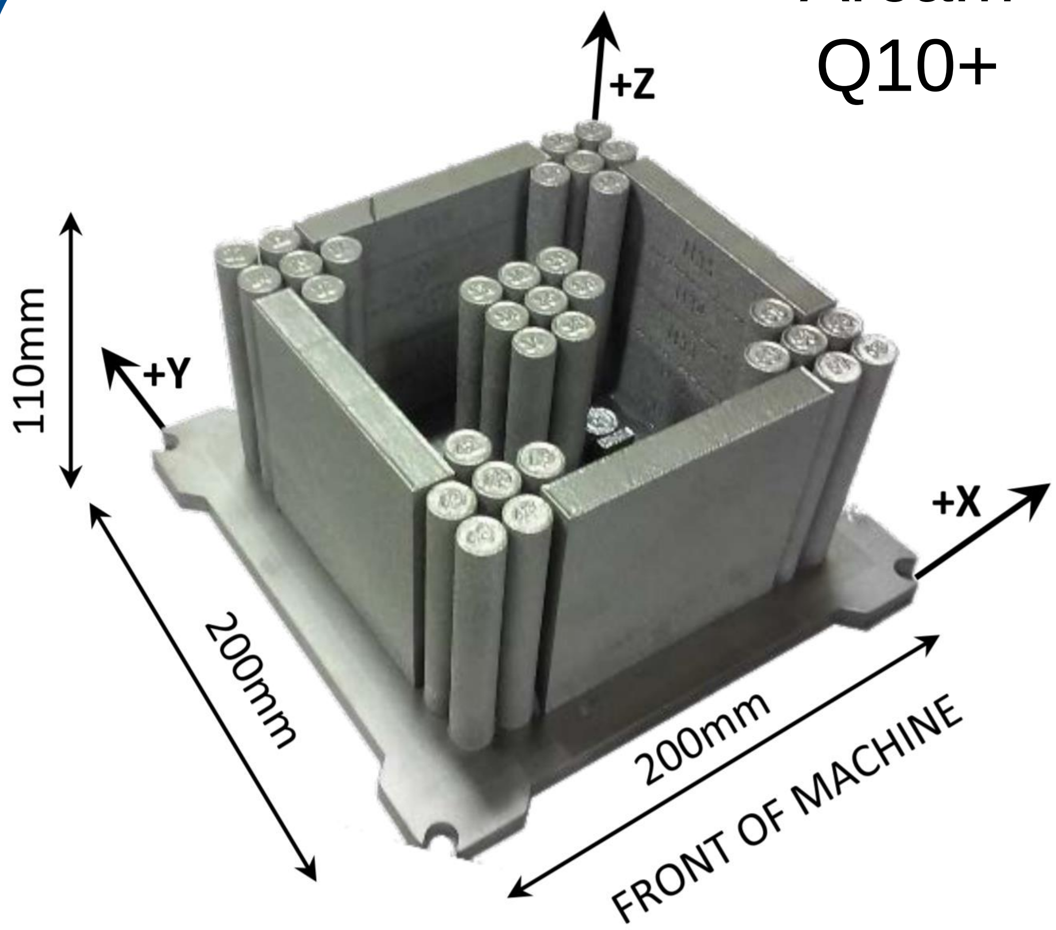
Systematic difference in tensile properties depending on position on the build plate - “exclusion zone”

Build Lay-outs

EOS
M290



Arcam
Q10+



Material processing variables for fatigue testing

Fabrication process / AM Platform	Material source program	Heat treatment	Surface condition	Orientation[4,5]
LPBF / EOS M290	Current	SR[1]	LSG	Z / vertical[4]
LPBF / EOS M290	Current	SR[1]	as-built	Z / vertical[4]
LPBF / EOS M290	Current	SR[1]	LSG	X / horizontal[4]
EBM / Arcam Q10+	Current	HIP[2]	LSG	Z / vertical[4]
Plate forging / –	Current	MA[3]	LSG	long.[5]
Plate forging / –	Archival	MA[3]	LSG	long.[5]

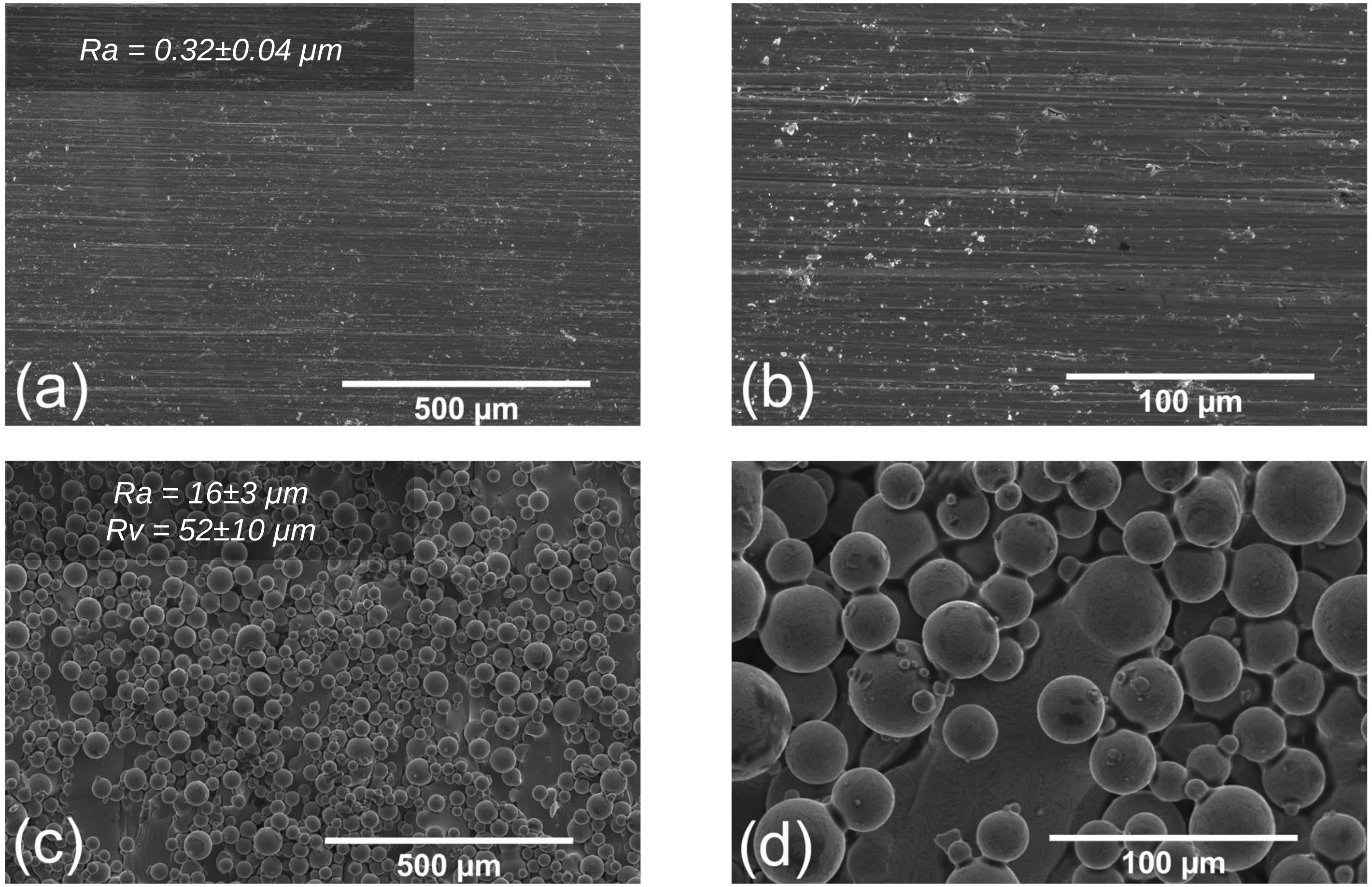
1. Combined stress-relief and solution heat treatment in vacuum
2. Hot isostatically pressed
3. Solution heat treat 932±14 °C / 1h + mill-anneal 704±14 °C / 2h
4. Z and X designate orientations parallel to build direction and to the build plane, respectively.
5. Long. designates parallel to the longitudinal direction of material flow during plate forging

SURFACE CONDITION

As-built vs LSG surfaces

Load axis

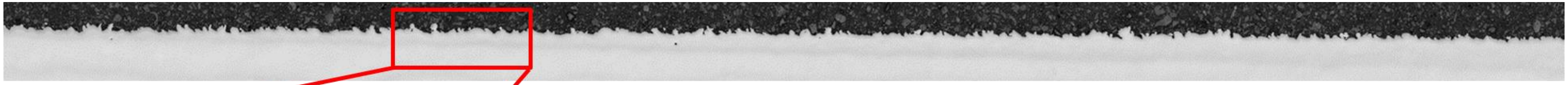
Low-stress grind

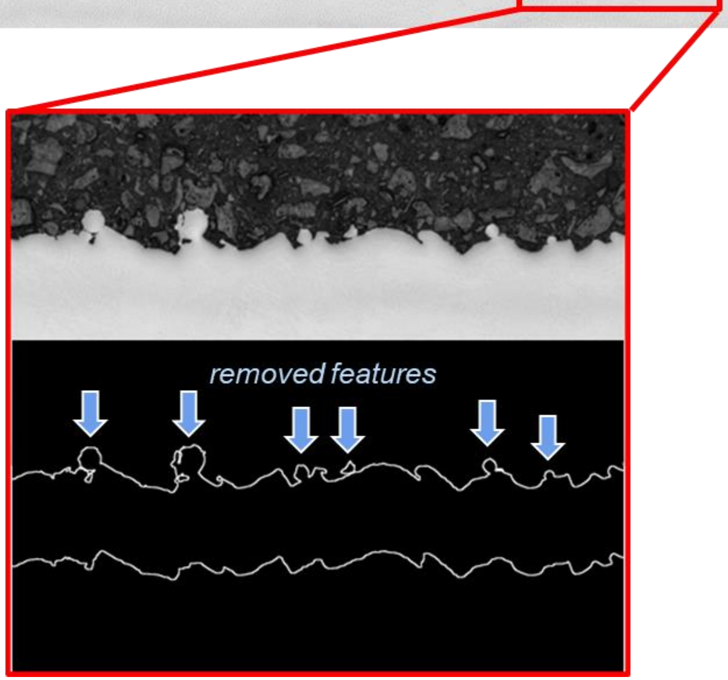


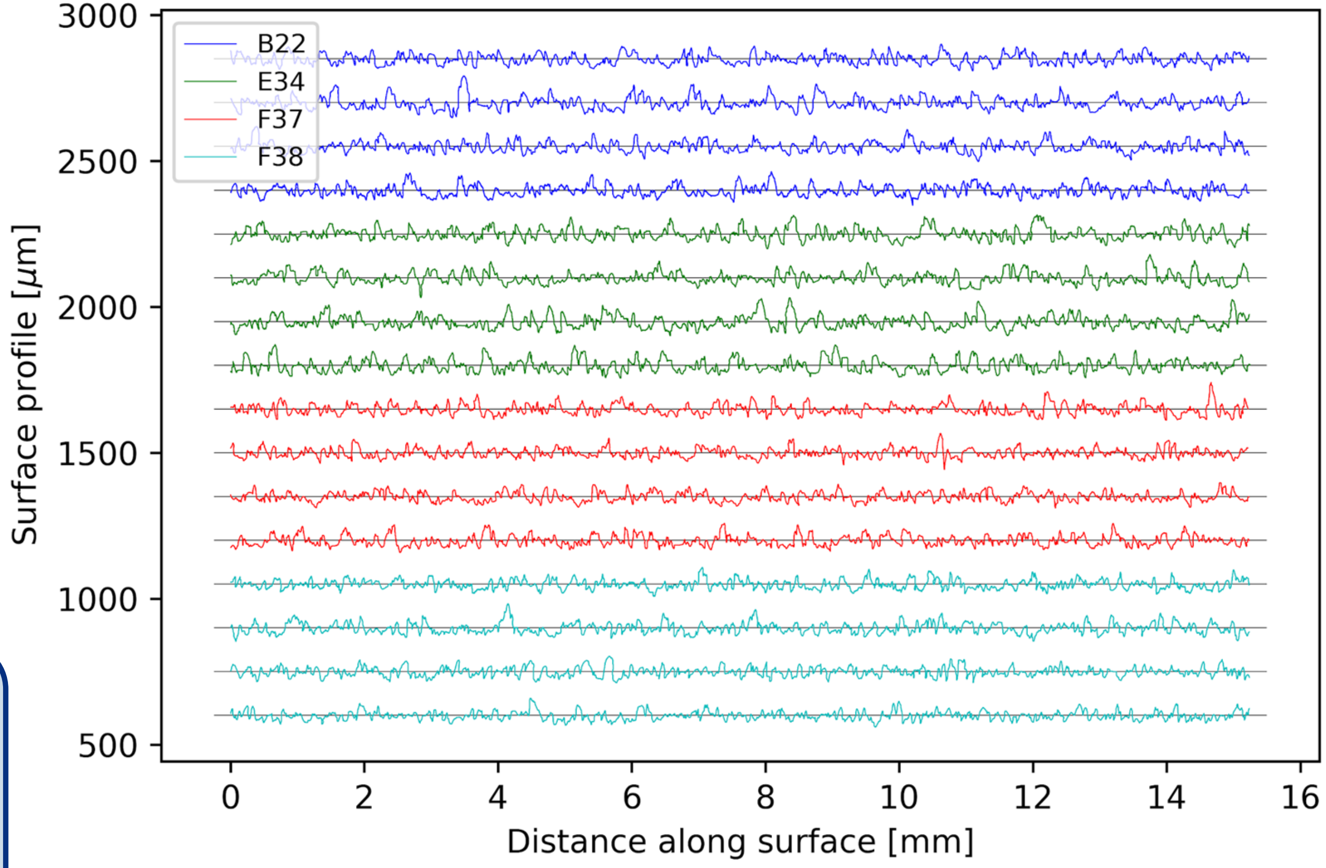
As-built

Orders of magnitude difference in roughness feature sizes due to machining

As-built vs LSG surfaces







AM surface roughness is a critical initiating feature

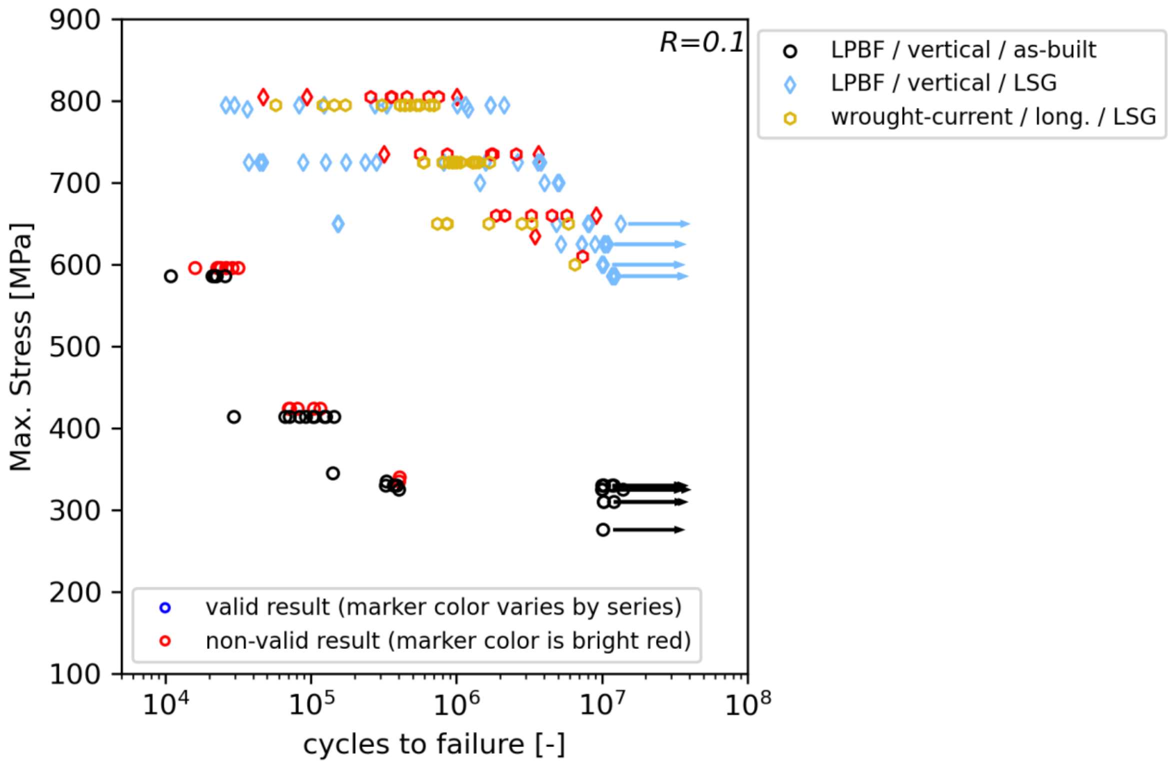
Methods in development for measuring

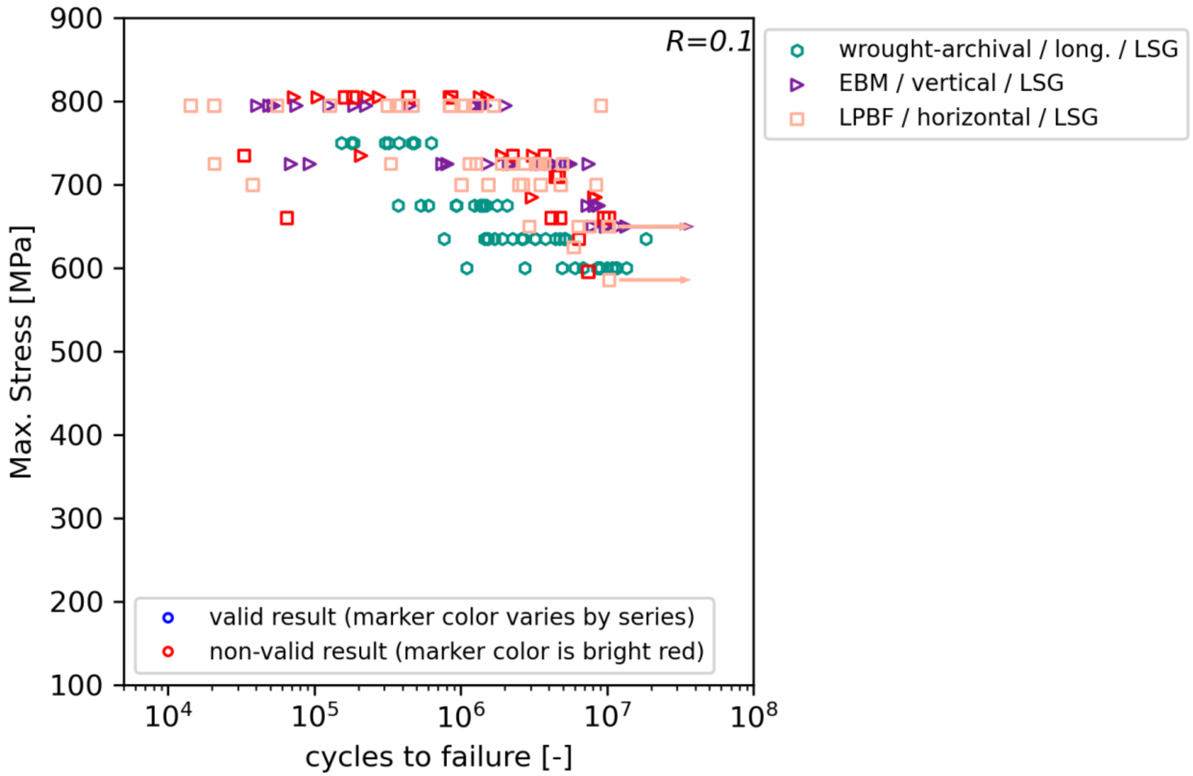
Extreme-values stats. for life prediction

FATIGUE TESTING RESULTS

Fatigue Test Results (S-N)

for clarity: results split into two plots; non-valid results displaced +10MPa



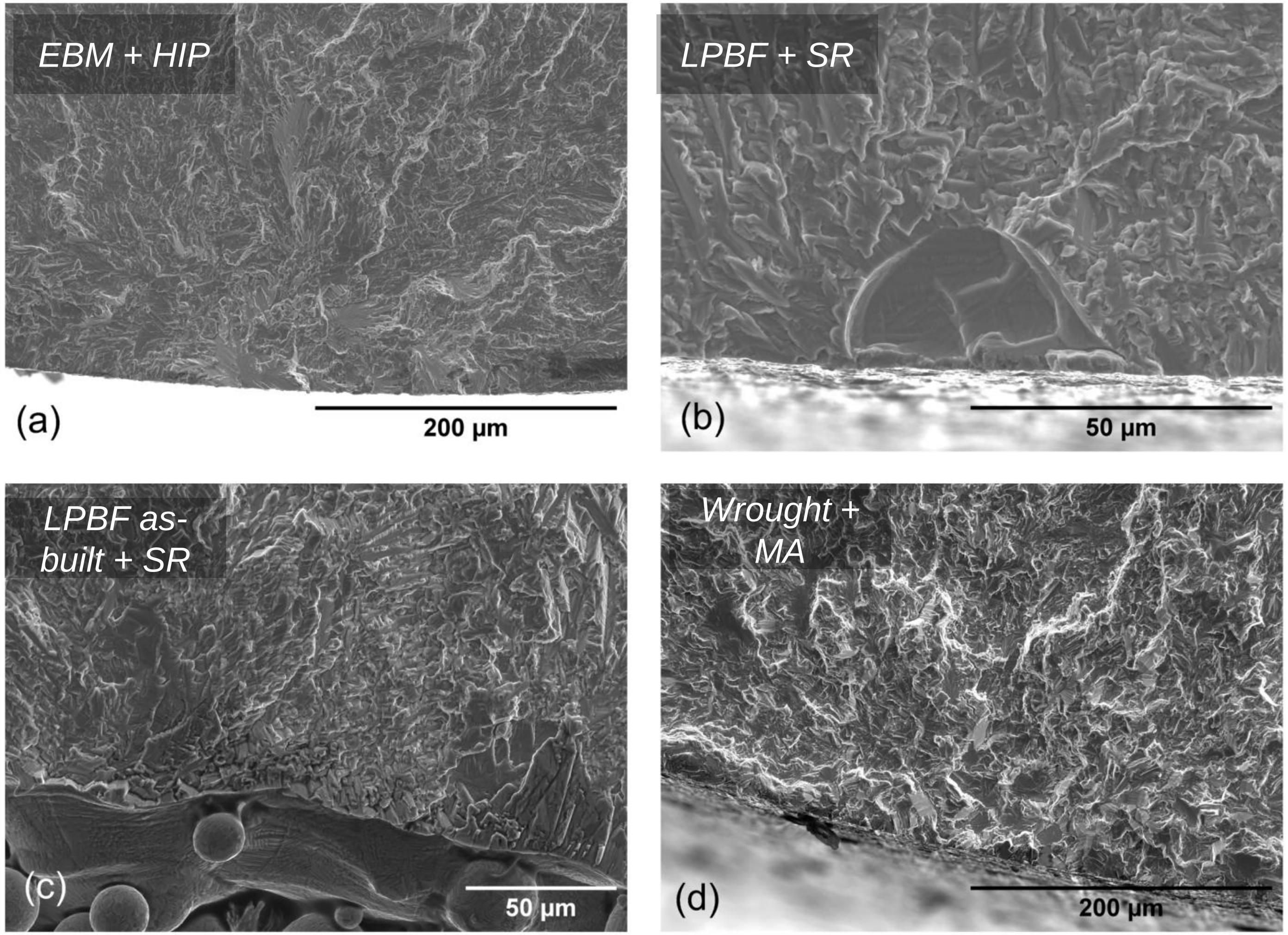


58% of as-built sample tests are non-valid

Rough as-built surface → run-out stress halved vs. LSG surface

Machined specimens: N_f distributions broader for AM than for wrought

Initiation features at N_f ~$3x10^5$ cycles

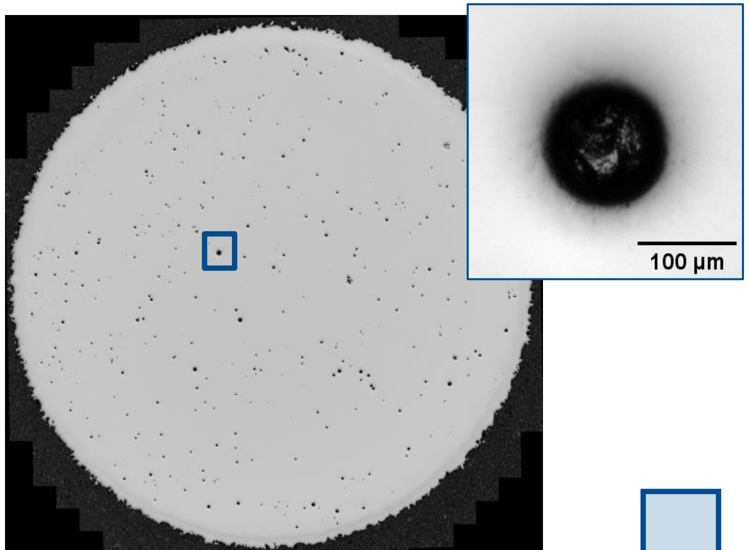


Initiations at *surface* when $N_f < 1x10^6$

Initiations are *internal* for $N_f > 1x10^6$, except for as-built specimens

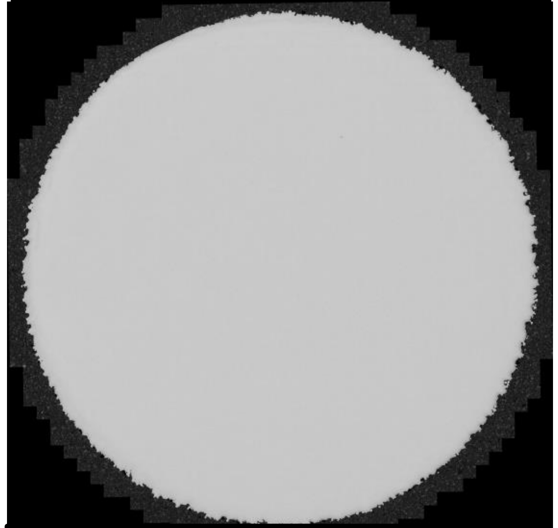
Initiation feature class varies by fabrication and post-processing

EBM porosity: failure to heal?



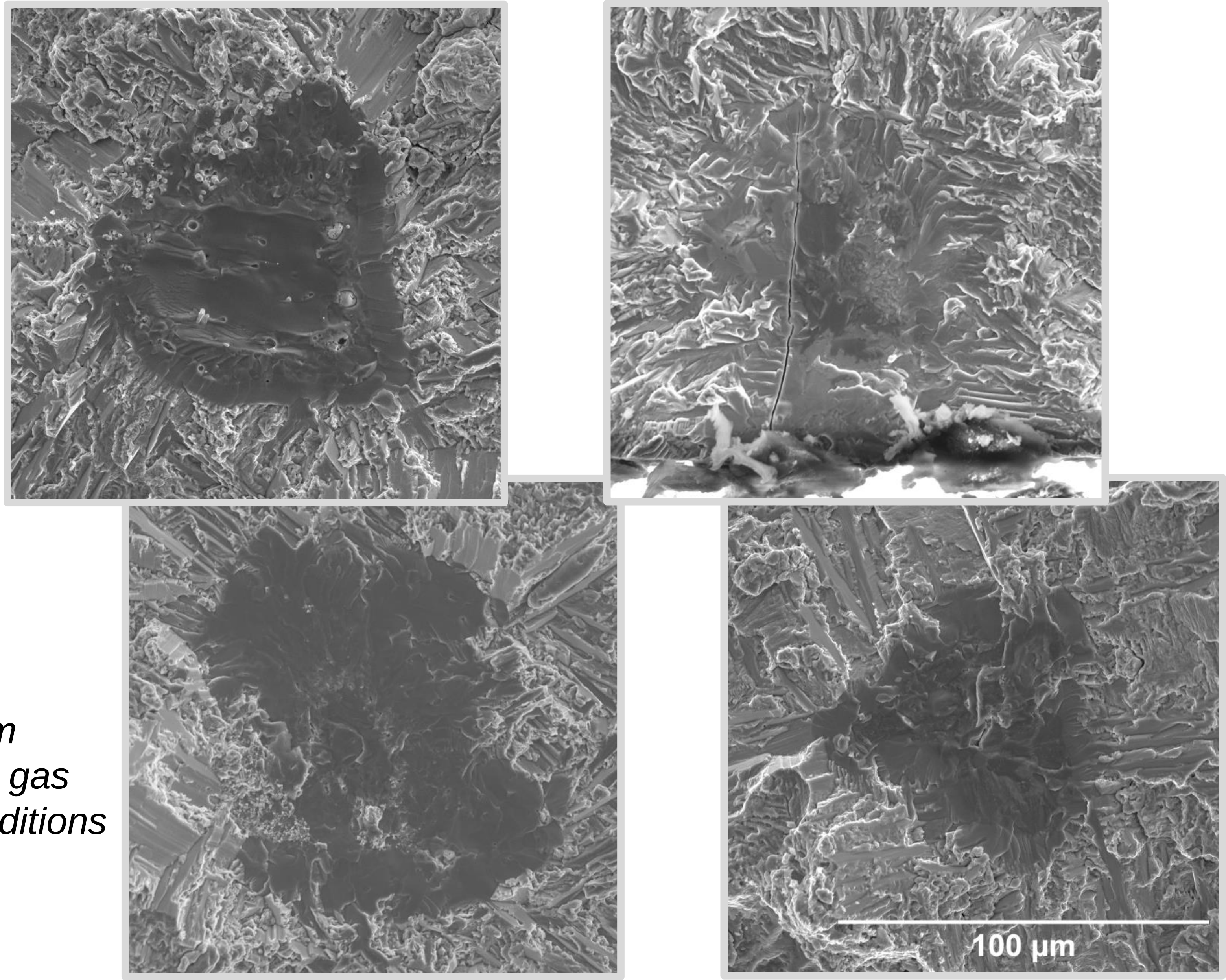
0.4% porosity as-printed

HIP

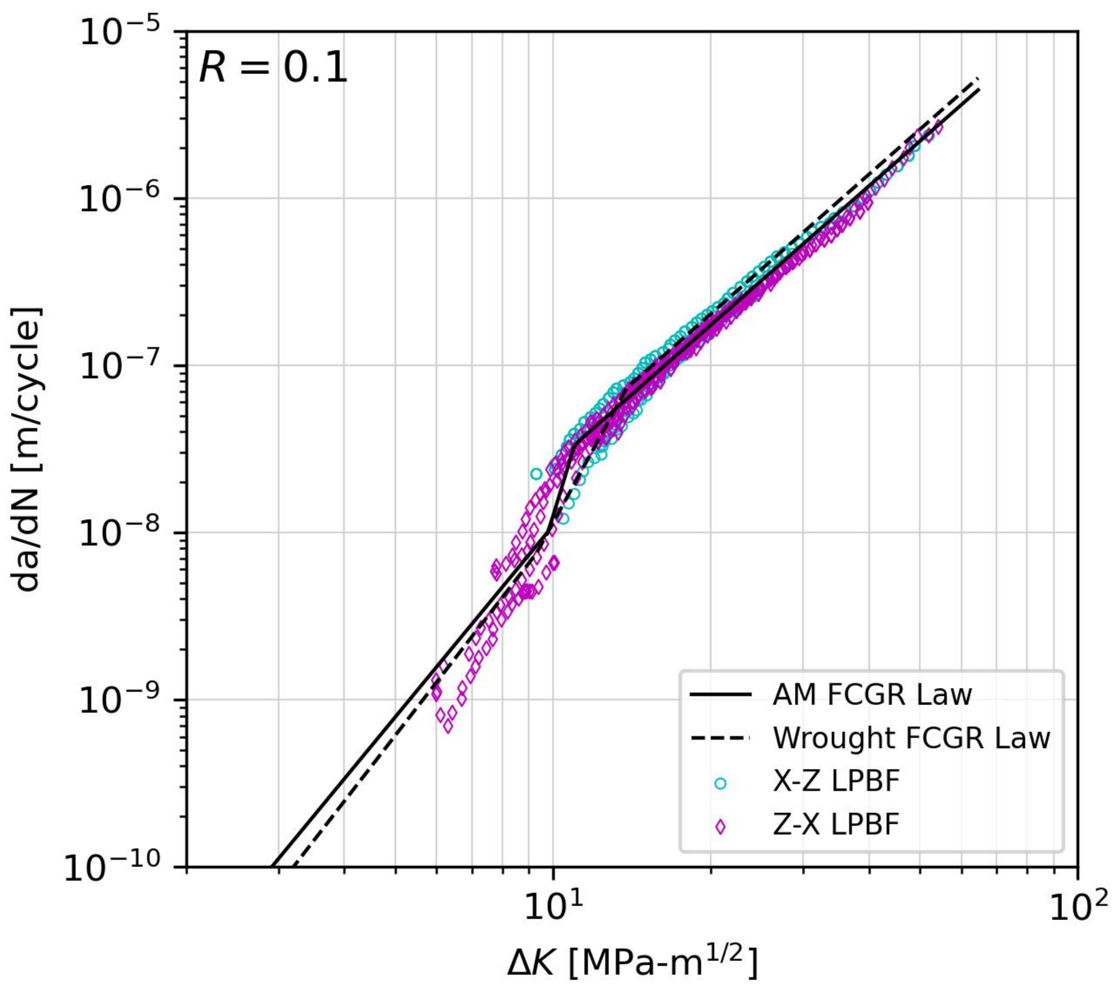


~0% porosity HIP'ed

100μm→0.1μm
Δd_{pore} for ideal gas
under HIP conditions



FCGR results, and model

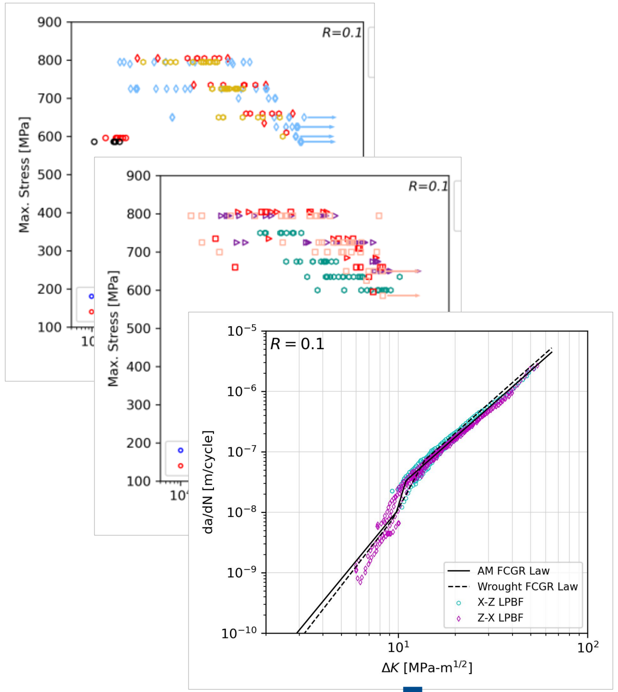


Features, shortcomings
- Continuous three-part piecewise Paris-law fit
- NASA EBM data[1] used for lowest-ΔK branch
- Small-crack behavior treated as extrapolation to arbitrarily small sizes
- Wrought data from prior AFRL effort[2] fitted
- All AM data pooled – currently only R=0.1, LPBF

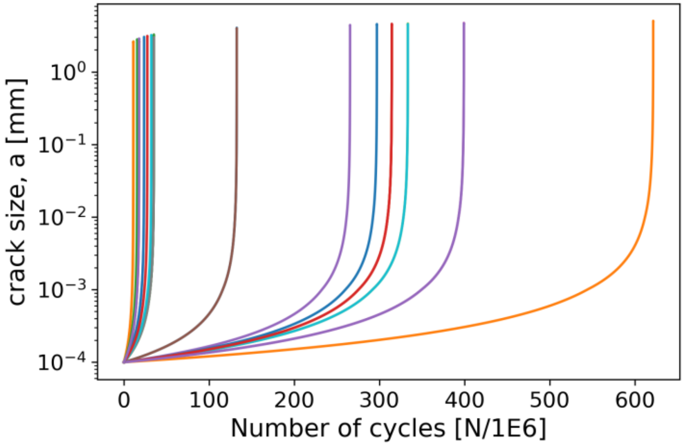
Pending refinements
- Small crack growth treatment
- Multiple R
- Differentiation of EBM, LPBF
- Internal vs. external CGR law

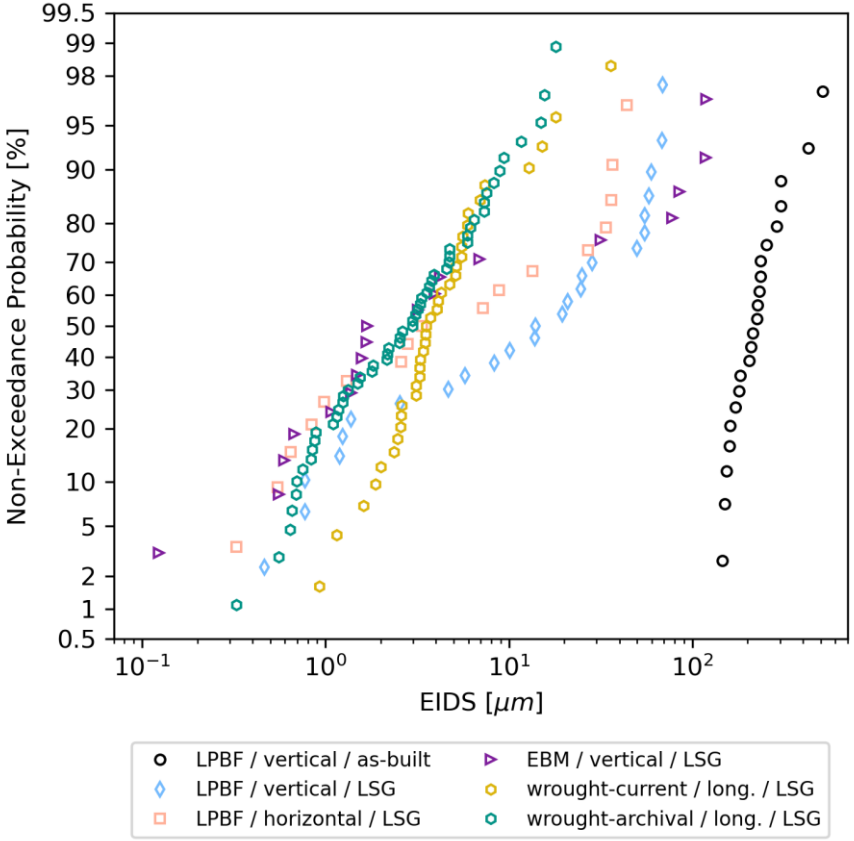
1. *S. Draper, et al., NASA/TM-2016-219136, 2016.*
2. *J.H. Gallagher et al., AFRL-ML-WP-TR-2001-4159, 2001.*

EIDS calculation methodology



Newman-Raju K solution for semi-elliptical surface crack embedded in a rod in tension





EIDS comparisons

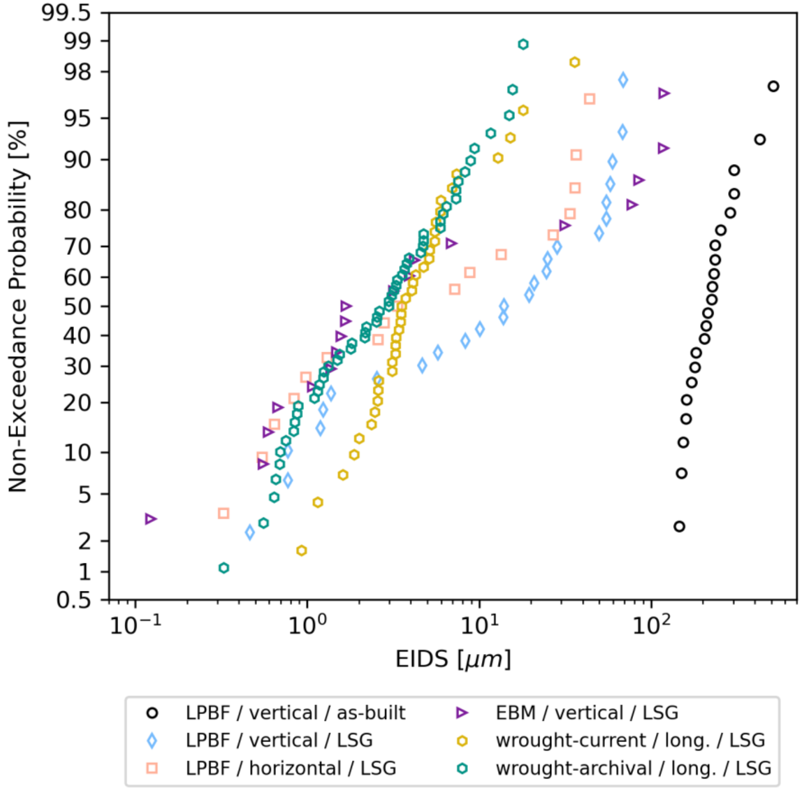


Table 1: Damage sizes for DADT crack growth analyses[1]

Part Criticality	Durability requirement		Damage Tolerance requirement	
	P_{exceed}	$EIDS_{min}$ [µm]	P_{exceed}	$EIDS_{min}$ [µm]
NC	$1x10^{-1}$	250	–	–
FC or DC	$1x10^{-3}$	250	$1x10^{-7}$	1300

1. AFLCMC/EZ, Structures Bulletin EZ-SB-19-01, (2019).

EIDS$_{max}$ relationships

As-built AM ≈ 4-12x machined AM
Machined LPBF ≈ 1-2x machined wrought

Table 4: Maximum EIDS values for each specimen class

Specimen class	Total number of specimens	Number of valid, non-runout specimens	Number of specimens in EIDS plot[1]	$EIDS_{90}$ [µm][2]	$EIDS_{max}$ [µm][3]
LPBF / vertical / as-built	53	22	22	426	512
LPBF / vertical / LSG	57	40	25	68	69
LPBF / horizontal / LSG	50	34	17	36	44
EBM / vertical / LSG	57	39	19	118	119
wrought-current / long. / LSG	58	37	37	13	36
wrought-archival / long. / LSG	75	75	75	9	18

1. EIDS data are plotted for tests that were valid, not run-outs, and which exhibited surface initiation
2. Smallest value in the EIDS distribution having a probability of non-exceedance of at least 90%
3. Maximum value in the EIDS distribution for the number of samples in the EIDS plot

SUMMARY

Summary

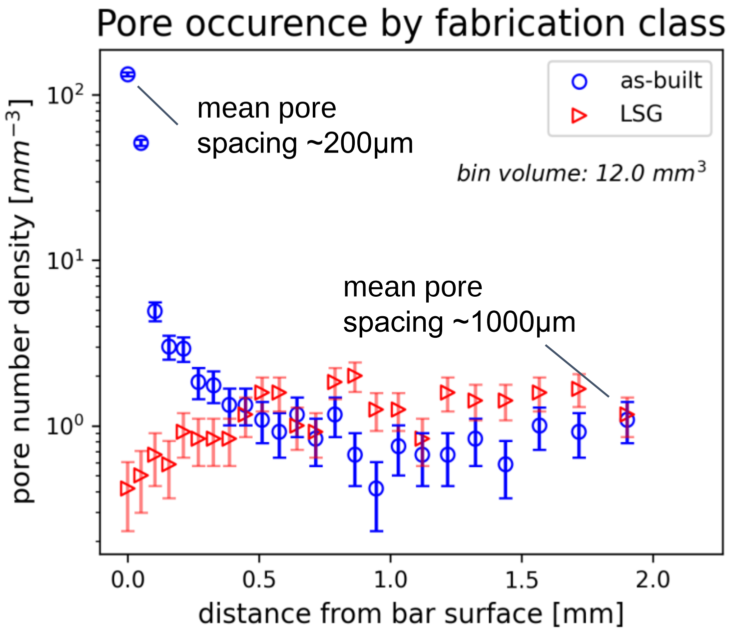
- ~500 bars being fatigue tested, paired with FCGR curves to produce EIDS values
- Fabrication variables: AM Modality (+ forging), as-built surface, orientation, bar size*, heat treatment*, load mission*

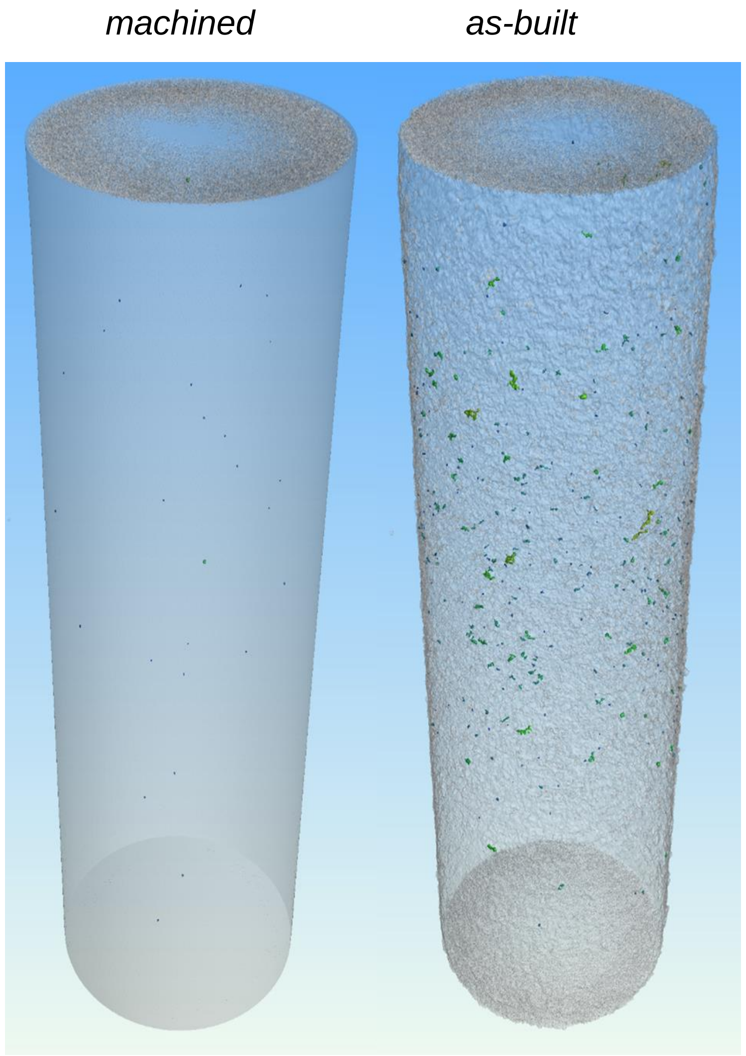
  **Testing is pending*
- Initiating features are specific to fabrication modality (surface roughness, crystallographic, as-deposited porosity, HIP-unhealed porosity, alpha particles)
- Fabrication-specific EIDS trends emerging – formal analysis of distribution pending

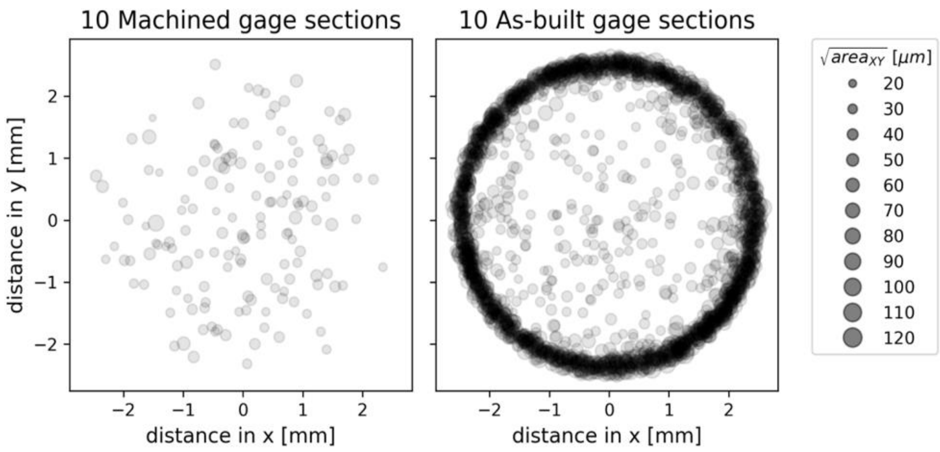
QUESTIONS?

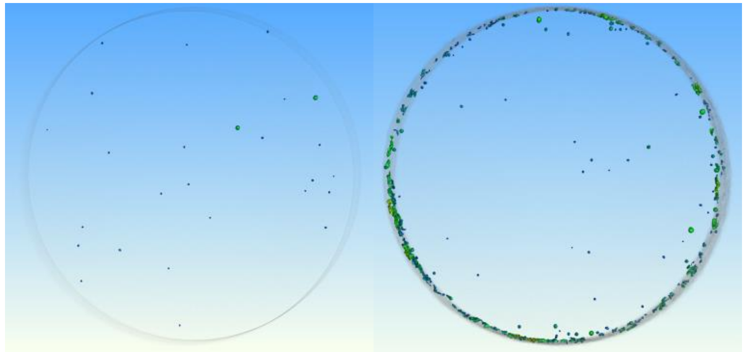
BACK-UP

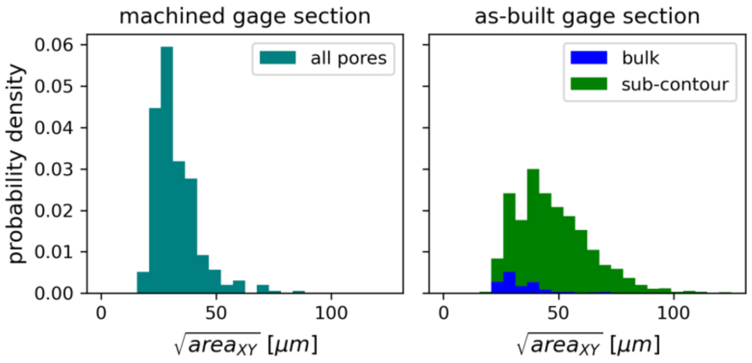
LPBF porosity measured by CT











- Baseline porosity content ~1mm^{-3}
- As-built bars have significant sub-contour porosity
- Beam hardening may be affecting pore detection near surface