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IAI Creating a Difference

TI-6AL-4V ADDITIVE MANUFACTURING MECHANICAL PROPERTIES AS INDICATION TO MEASURE OF QUALITY

31st ICAF Symposium
26-29 June 2023,
Delft,
The Netherlands

Commercially Sensitive

Outline

- The need to evaluate Additive Manufacturing (AM) defects for Fatigue.
- What are the AM defects to evaluate?
- The experimental campaign:
  Specimens / Findings / Evaluation.
- Conclusions.

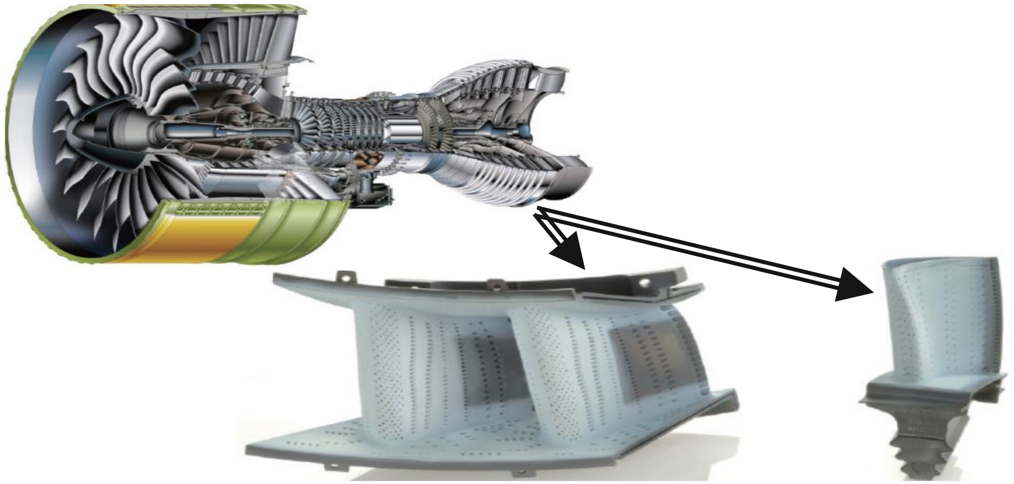
The need

AM Applications → Driven by quality control

Jet Engines - Primary Structure:

Quality as Computer-Tomography etc., to detect defects.

Turbine blade/nozzle, etc.



High-pressure turbine blade/ nozzle

Susceptible to fatigue cracking

Airframe - Secondary Structure:

Lack of generic, economic quality control methods, to detect manufacturing defects.

Cover bracket, connector etc.

Nacelle hinge bracket

(Copyright: Airbus)

Machined manufactured

AM manufactured

Ti cabin bracket connector (Copyright: Airbus)

NOT susceptible to fatigue cracking

What are AM the defects to be detected?

To develop generic inspections,
need to know, what to look for
(that will compromise Fatigue strength).

Ti-6AL-4V Powder Bed Fusion (PBF) / Selective Laser Melting (SLM)
for "Critical Defects" Criteria, to be Detected based on:
Experiments
Micro-CT inspections, &
SEM/Fractographic failure analyses.

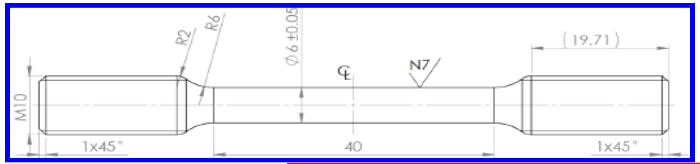
AM Defect Types:

- ❑ Pores (Local Voids), with/without trapped non-melted-powder {✱}.
- ❑ Lack of Fusion Surfaces {✱}.
- ❑ Inclusions (Contaminations) {✱}.
- ❑ *Residual Stress fields {✱✱}.*

{✱} Included in the study.

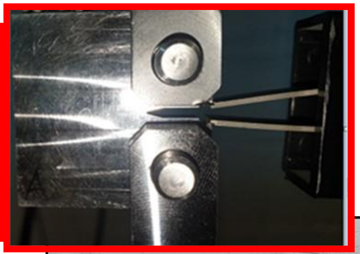
{✱✱} Not included in Study → Internal Stresses Relieved by:
Heat Treatment (HT) / Hot Isostatic Pressing (HIP)
50% of the Specimens: Heat Treatment (HT) of 800ºC for 2 hours.
50% of the Specimens: Hot Isostatic Pressing (HIP).

The experimental campaign

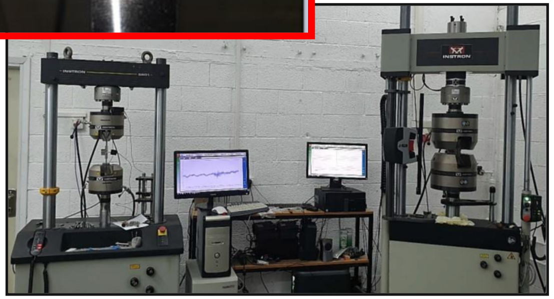


Type of Tests:

- ❑ Quasi-Static per ASTM E8.
- ❑ Crack Growth per ASTM E647−15;
  R=0.1, C(T) Specimen.

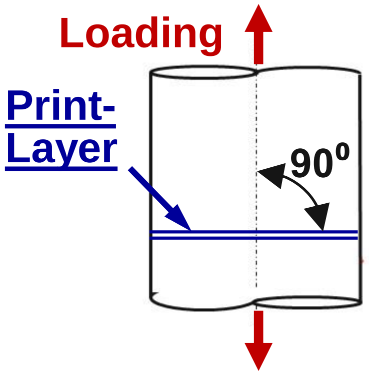


- ❑ Fatigue per ASTM E466-15;
  R=0.1; Kt=1.0.



Type of Specimens:

Ti-6Al-4V powder via SLM – PBF per ALM EOS M290 Machine (Laser-Power: 340W, Print-Layer-Thickness: 60µm).



8 AM different qualities → 8 Distinct Specimen Type:

- ❑ 4 AM Printing Parameters Sets
- ❑ 2 Thermal-Post-Processing procedures:
  50% of the Specimens: Heat Treatment (HT) of 800°C / 2 hours (Argon).
  50% of the Specimens: Hot Isostatic Pressing (HIP) per ASTM F3001.

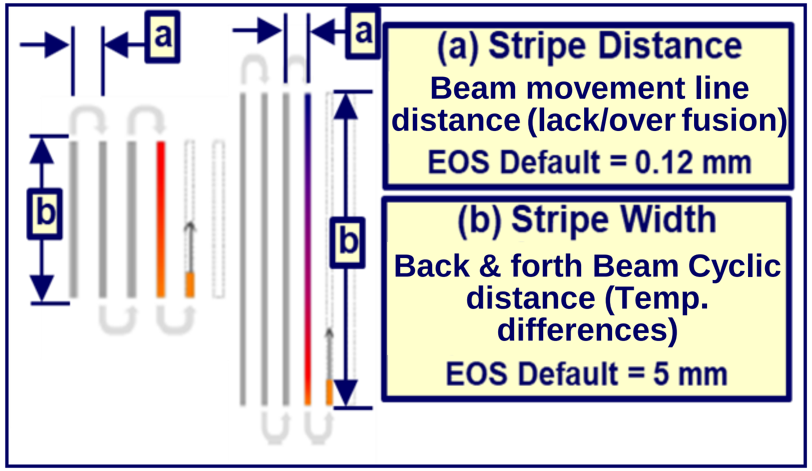
The 4 AM Printing Parameters Sets:

Tray #1 – All parameters per EOS recommendation **(Reference: good quality)**.

Tray #2 – Stripe Width, increased to double EOS recommendation **(best quality)**.

Tray #3 – Stripe Distance, increased to double EOS recommendation **(poor quality)**.

Tray #4 – Laser Power, decreased to half EOS recommendation **(the worst quality)**.



Note: The Trays #2 to #4 – all other Printing Parameters were per EOS recommendation.

The specimens were Machined per ASTM's.
Surface Roughness: N6 (32μin. 0.8μm).

Quasi-Static Test Results

ASTM F3302-18 tensile requirements for Ti-6Al-4V	Yield Strength $R_{p0.2}$, MPa	Tensile (UTS) Strength, R_m, MPa	Elongation (%) A (L_0=25mm)
	825 min	895 min	10 min

Ti-6AL-4V Linear-elastic/isotropic/homogeneous, as required of AM to replace Forges & Plates.

Tray #1 Specimens Default AM meets Elasticity/Elongation Req.

Specimen ID		Yield Stress 0.2p, MPa	UTS, MPa	Elongation (l0=25mm), %
P1m-03	Without HIP	1071	1111	13.5
P1m-05		1070	1114	13.2
P1m-07		1068	1115	13.3
av		1069.67	1113.33	13.33
std		1.25	1.70	0.12
P1m-02	With HIP	934	1012	11
P1m-04		922	1005	12
P1m-06		936	1013	12
P1m-08		931	1011	11.7
P1m-10		940	1013	10.7
av		932.60	1010.80	11.48
std		3.99	1.22	0.56

Tray #2 Specimens Improved AM better meets Requirements

Specimen ID		Yield Stress 0.2p, MPa	UTS, MPa	Elongation (l0=25mm), %
P2m-03	Without HIP	1050	1102	16.7
P2m-05		1056	1104	16.5
P2m-07		1053	1102	16.3
av		1053.00	1102.67	16.50
std		2.45	0.94	0.16
P2m-02	With HIP	916	1004	17.1
P2m-04		918	1006	17.3
P2m-06		920	1010	17.3
P2m-08		920	1011	17
P2m-10		917	1004	17.2
av		918.20	1007.00	17.18
std		1.47	3.16	0.12

Tray #3 Specimens Poor AM don't meet Elasticity/Elongation Req. For some, HIP increase Elongation to meet Req.

Specimen ID		Yield Stress 0.2p, MPa	UTS, MPa	Elongation (l0=25mm), %
P3m-03	Without HIP	898	909	0.5
P3m-05		920	978	4.0
P3m-07		912	978	4.0
av		910.00	955.00	2.83
std		9.09	32.53	1.65
P3m-02	With HIP	895	960	3
P3m-04		894	983	16.7
P3m-06		899	986	16.5
P3m-08		848	853	0.5
P3m-10		895	981	16.3
av		886.20	952.60	10.60
std		23.32	61.87	7.50

Tray #4 Specimens Worst AM don't meet Req. HIP don't "help"

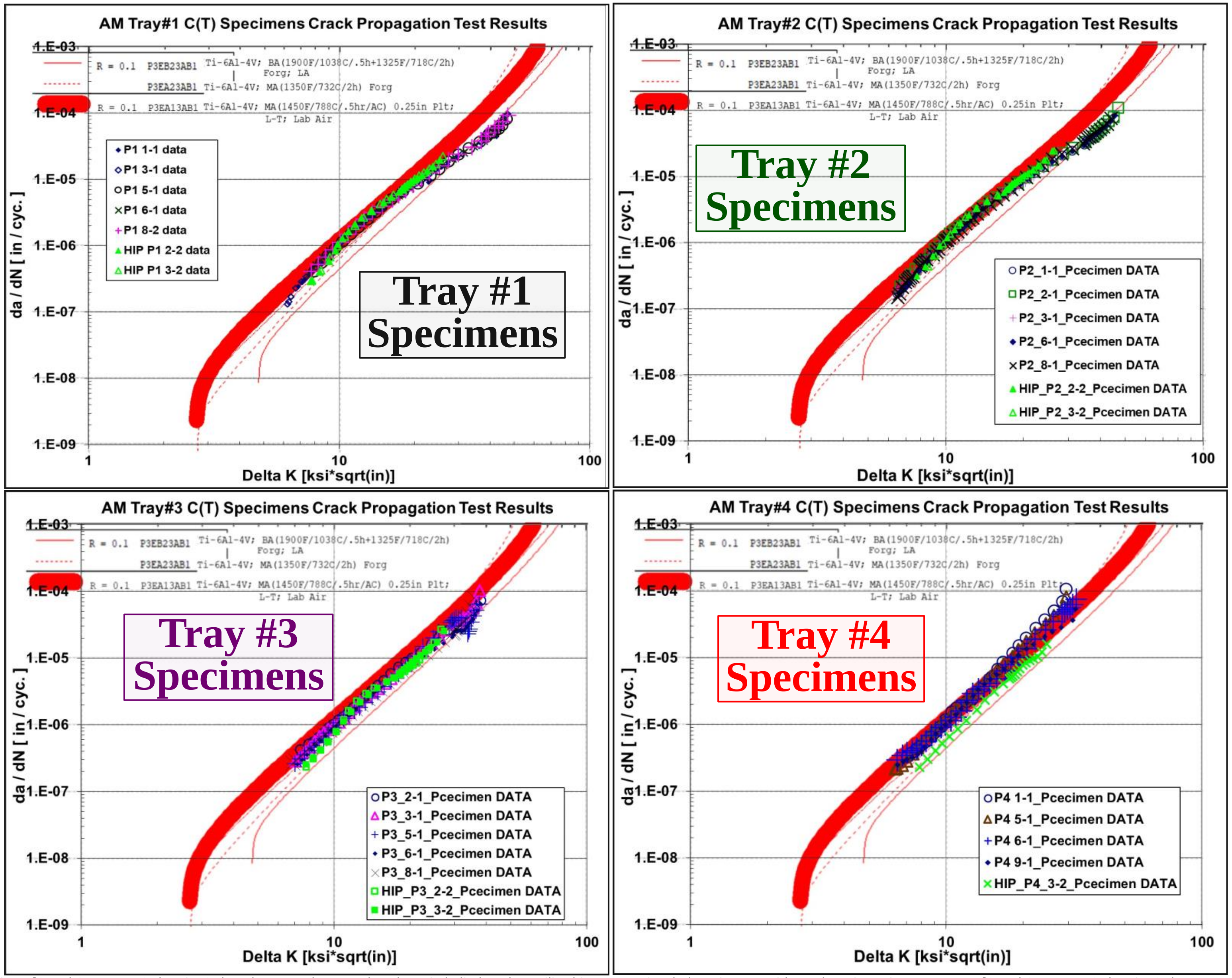
Specimen ID		Yield Stress 0.2p, MPa	UTS, MPa	Elongation (l0=25mm), %
P4m-03	Without HIP	768	809	0.5
P4m-05		818	876	1.5
P4m-07		824	881	1.5
av		803.33	855.33	1.17
std		25.10	32.83	0.47
P4m-02	With HIP	734	803	1.8
P4m-04		760	839	2.2
P4m-06		766	795	0.5
P4m-08		746	806	1.1
P4m-10		710	782	1.5
av		743.20	805.00	1.42
std		23.21	11.17	0.45

Crack Growth Test Results

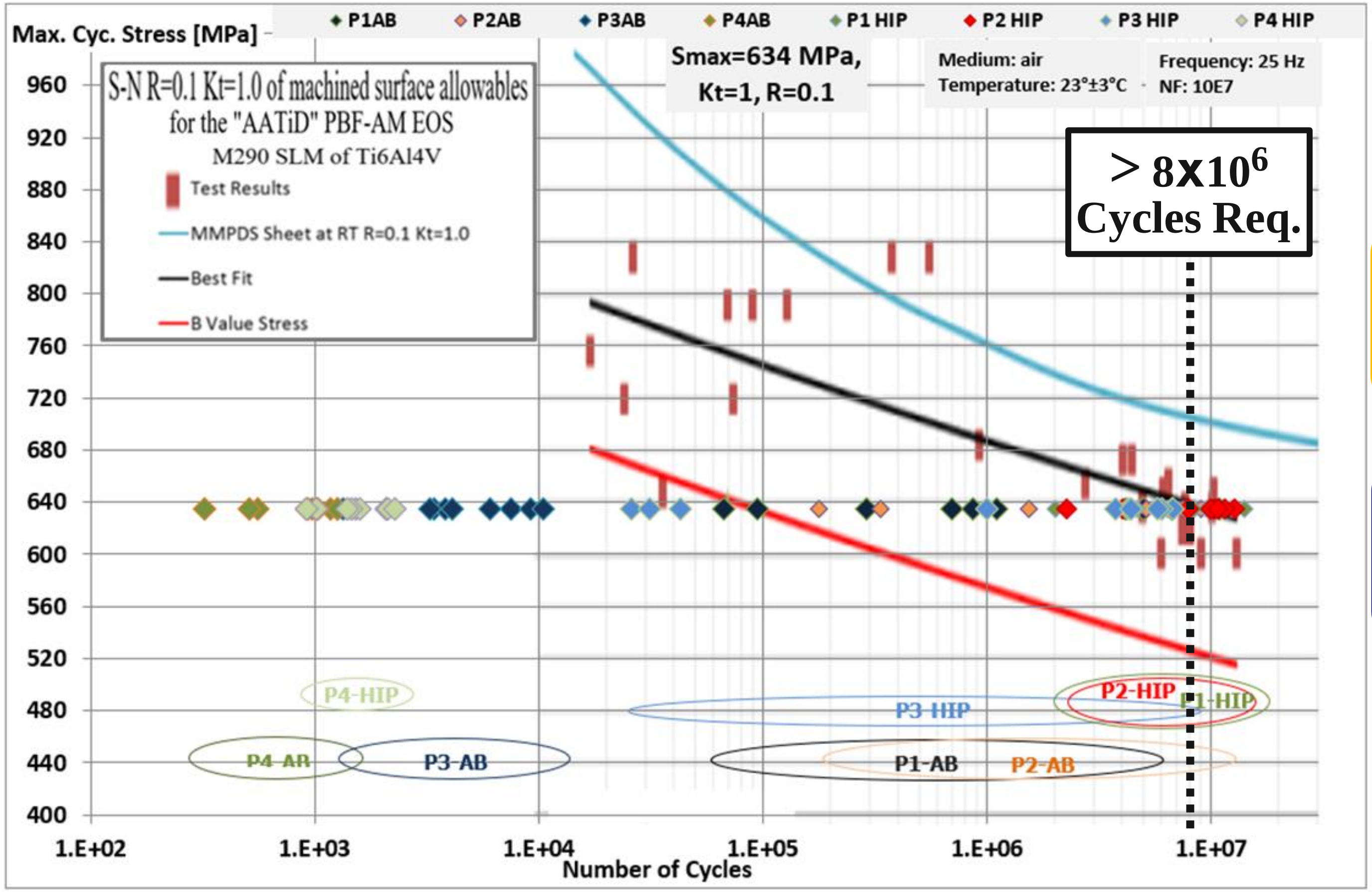
No practical differences for 8 distinct Specimen Types

&

All correlate well to NASGRO da/dN vs. ΔK Data.



Fatigue (ini.) Test Results



P1AB P1HIP
Printing Tray #1
2nd Best Quality

P2AB P2HIP
Printing Tray #2
Best Quality

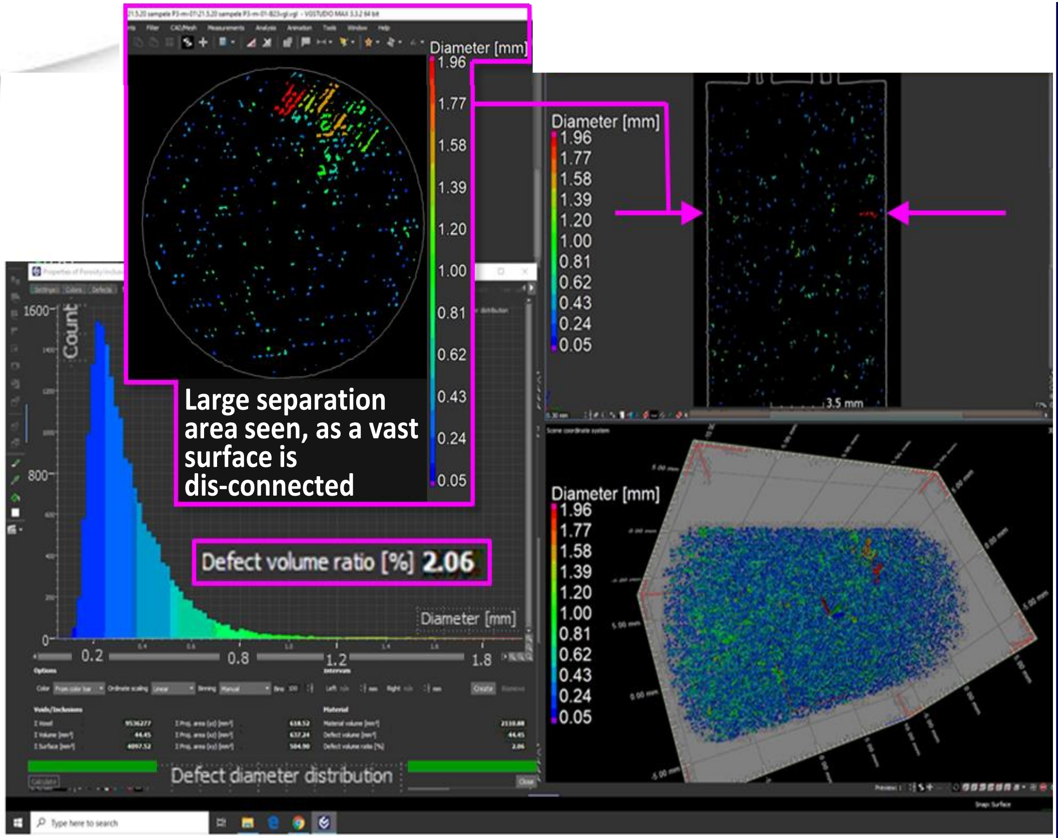
P3AB P3HIP
Printing Tray #3
2nd Worst Quality

P4AB P4HIP
Printing Tray #4
Worst Quality

Weibull Statistical Distribution Data

(AB) HT of 800ºC / 2 Hr. (No-HIP)				HIP			
Specim	Shape Parameter / Variance	(n/s)	Characteristic Life	Specim	Shape Parameter / Variance	(n/s)	Characteristic Life
P1	0.787 (8/2)	◆	5,194,789 Cycles	P1	3.067 (10/3)	◆	10,417,260 Cycles
P2	1.485 (7/3)	◆	9,455,652 Cycles	P2	2.502 (9/4)	◆	12,190,150 Cycles
P3	1.630 (9/0)	◆	6,101 Cycles	P3	0.515 (10/0)	◆	2,610,585 Cycles
P4	2.380 (9/0)	◆	1,014 Cycles	P4	3.448 (10/0)	◆	1,699 Cycles

Micro-CT Results Example



Tray #3 Specimen No HIP

2.06% Defect Density

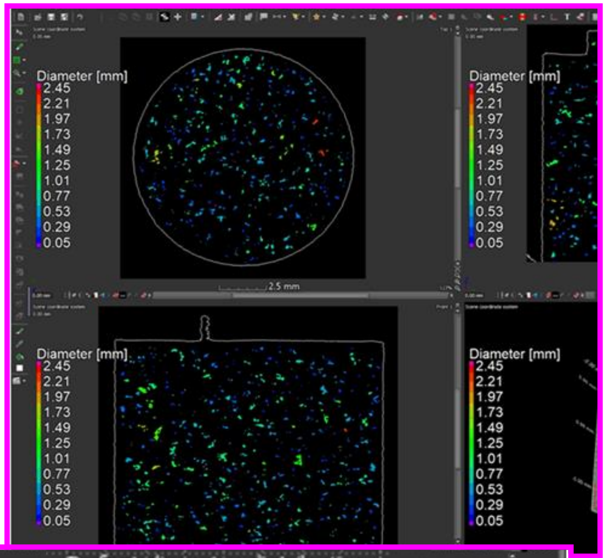
97.94% **Relative Density**

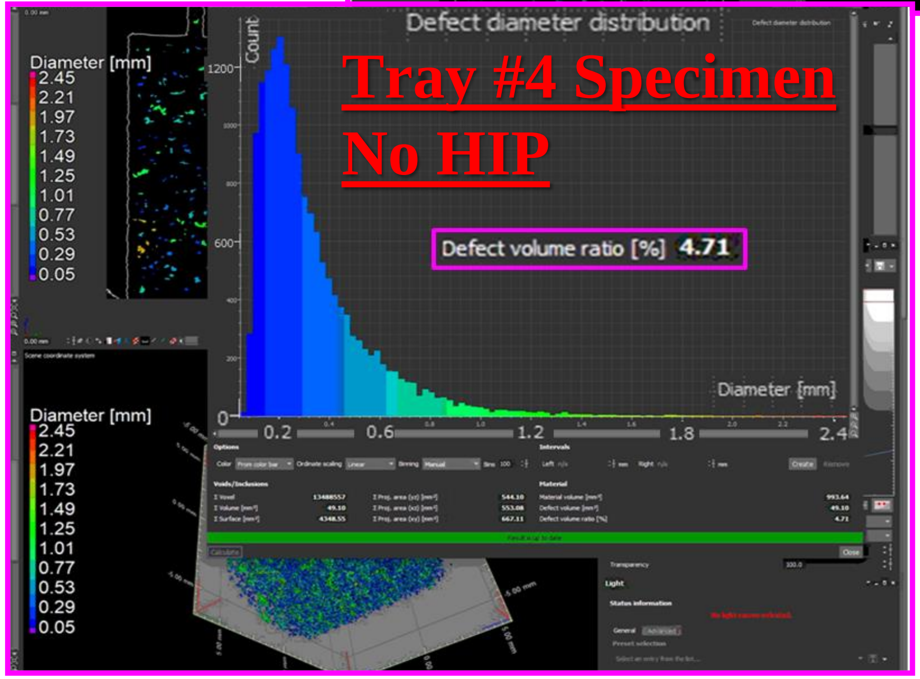
High defect count & large sizes

4.71% Defect Density

95.29% **Relative Density**

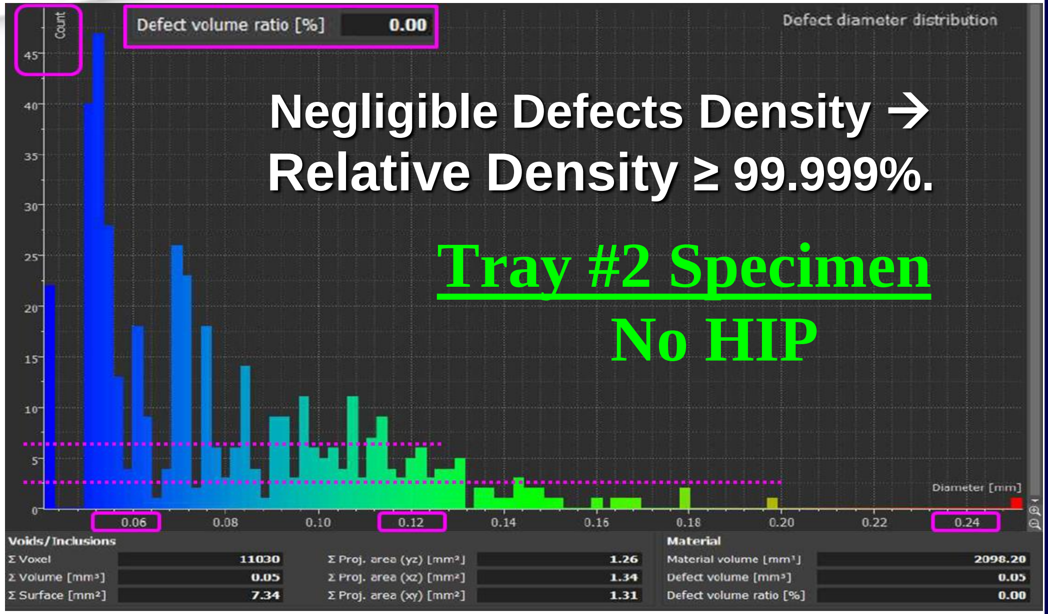
High defect count & large sizes

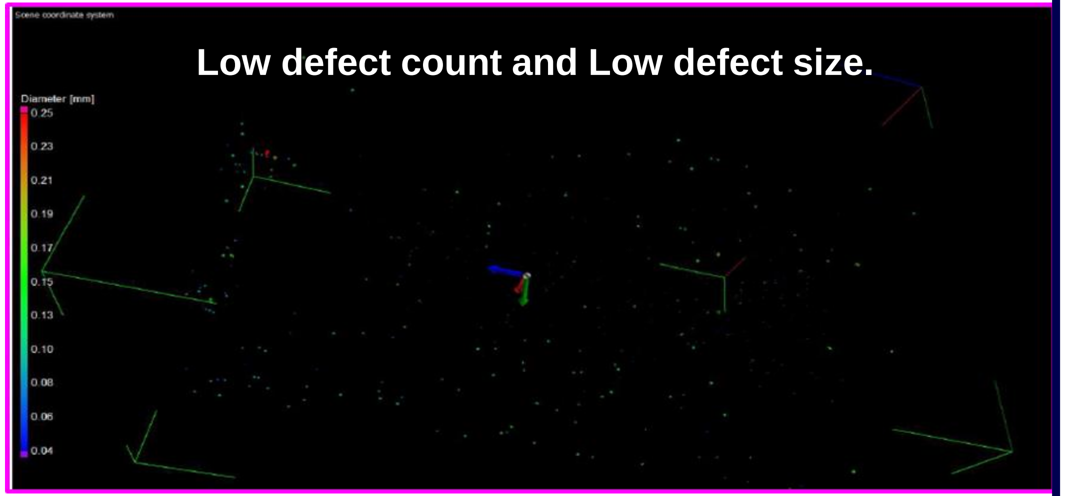




Tray #4 Specimen No HIP

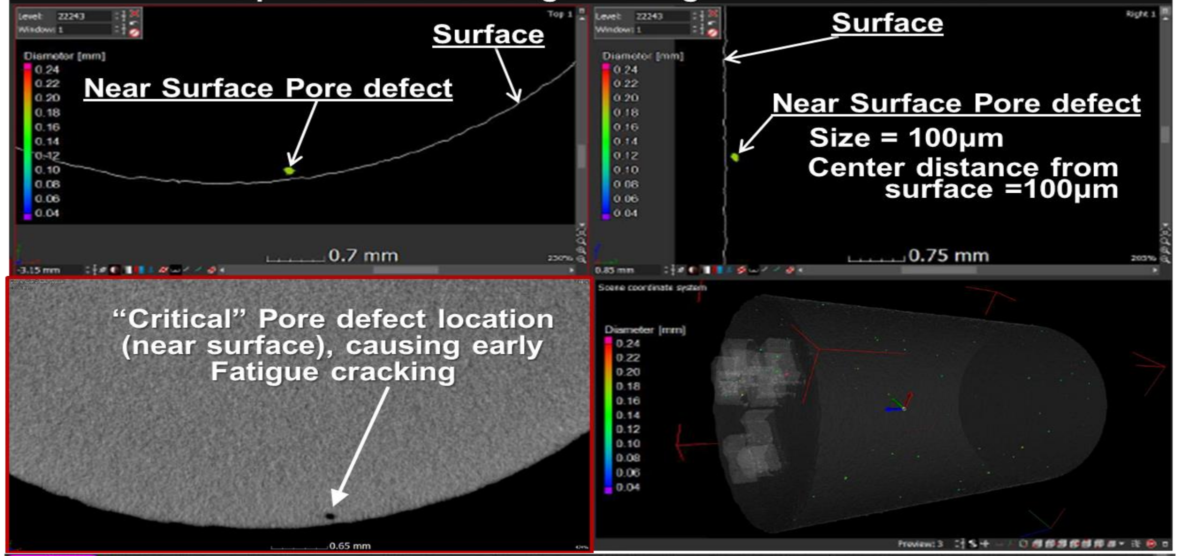
Micro-CT Results Example

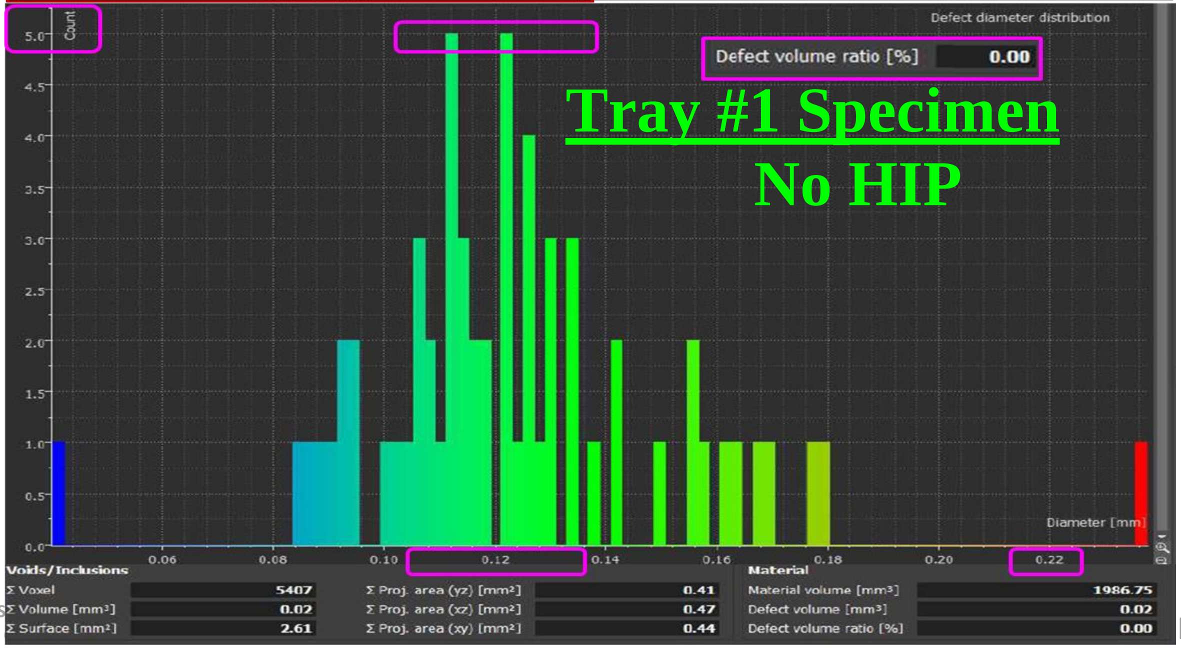




Low defect count and Low defect size.

Negligible defects density → Relative Density ≥ 99.999%.
<u>But, due to a Pore defect above "Critical-Defect" criteria,</u>
required Airframe Fatigue strength will not be met.

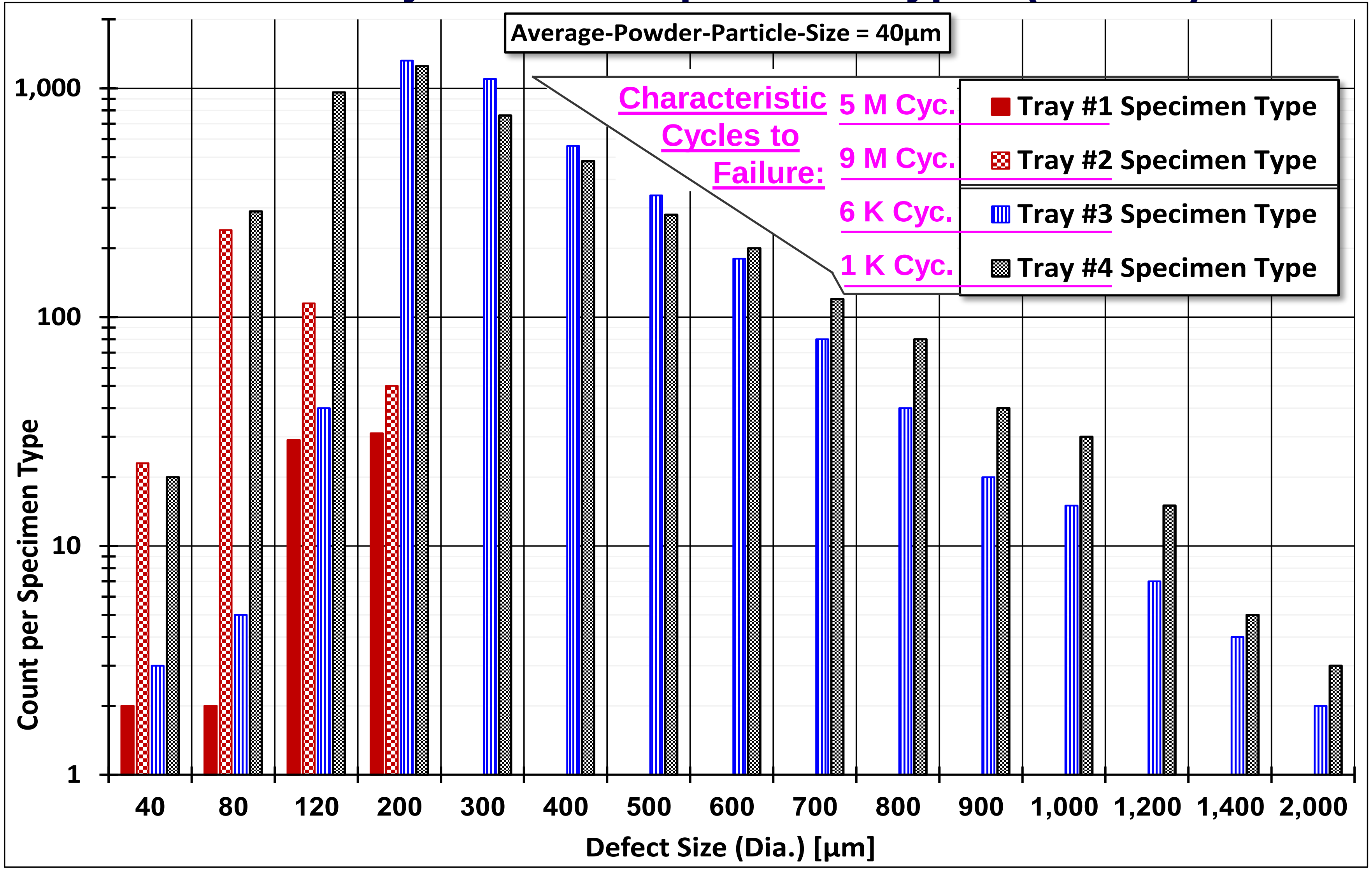




Micro-CT Inspections

Defect Count per Size Results (per unit of 2,000 mm^3 Specimen Section)

Trays #1 to #4 Specimen Types (No-HIP)

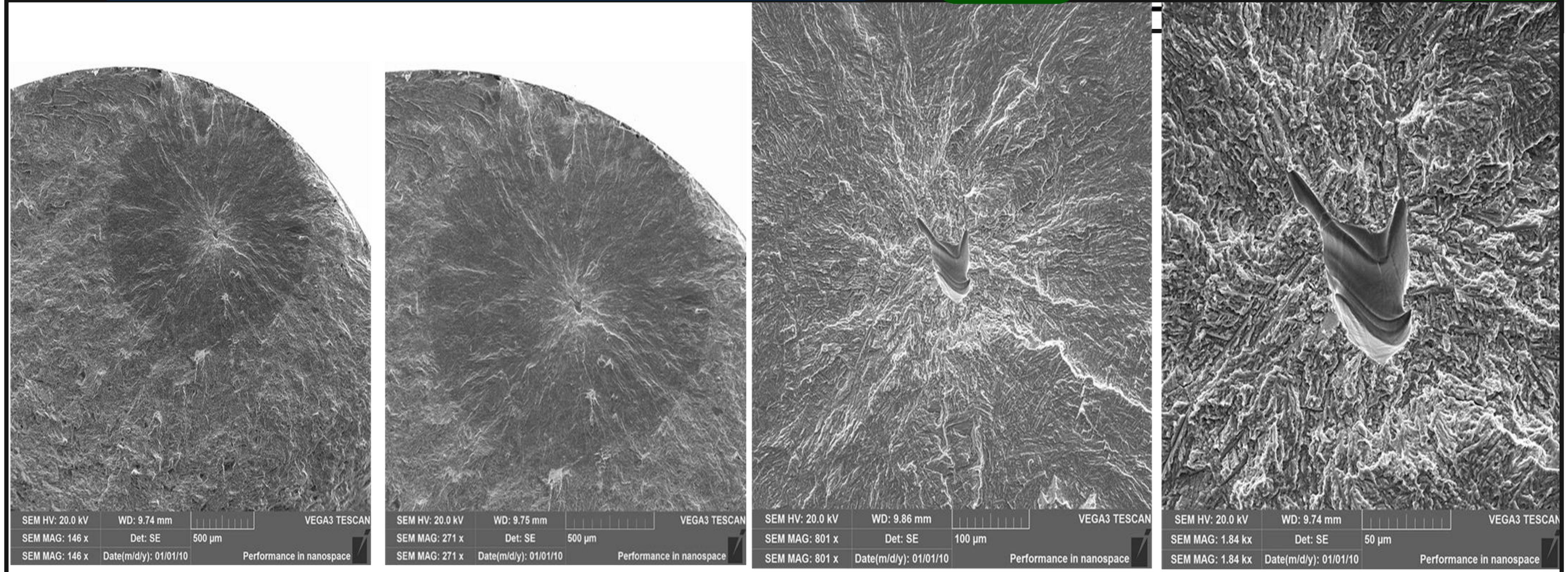


Failure Analyses Example

Tray #2 Specimen Type (No-HIP) High-Fatigue-Life of ~10x10⁶ cycles (as Required)

Manufact. I.D.	Specimen Type		Initiation Test Result	
	Manufacturing Configuration	Thermal Post-Process.	Notes	Cycles, N
P2 m F17	Stripe Width +100% *	No-HIP		9,758,414

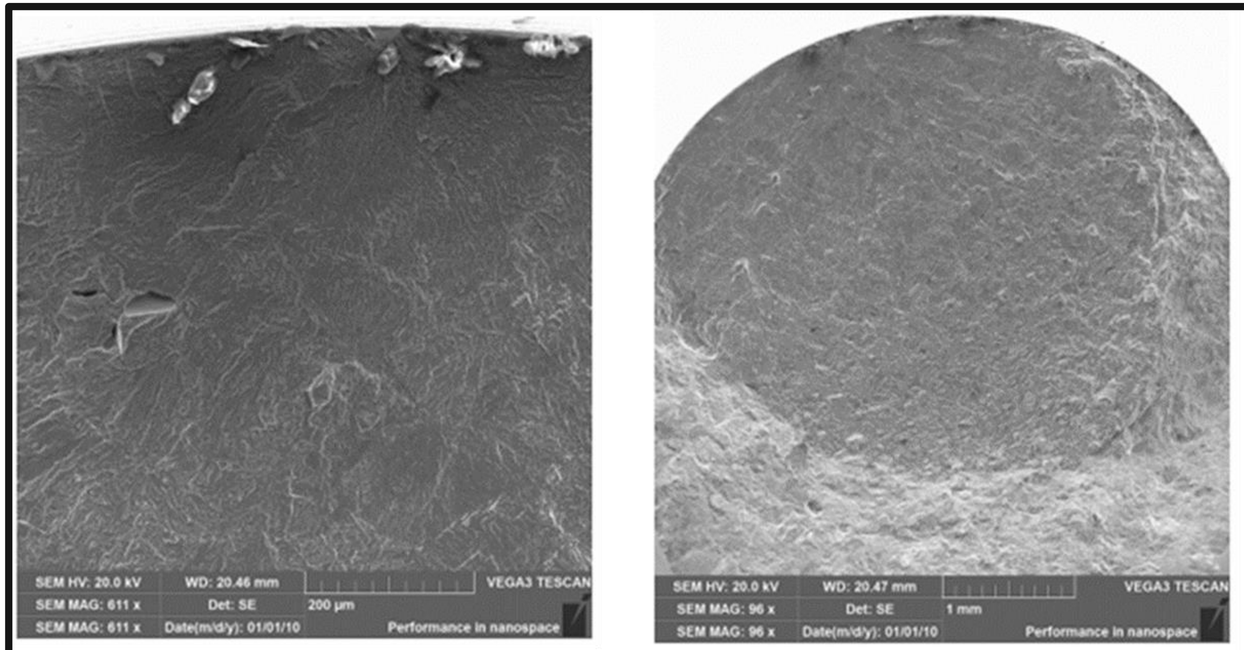
Defect size = ~85µm
Defect Distance from Surface = ~850µm



Crack Initiation source: Inclusion/Contamination that prevented solidification joining

Failure Analyses Example

Tray #2 Specimen Type (No-HIP) Very-Early-Failure (Very-Low-Fatigue-Life)

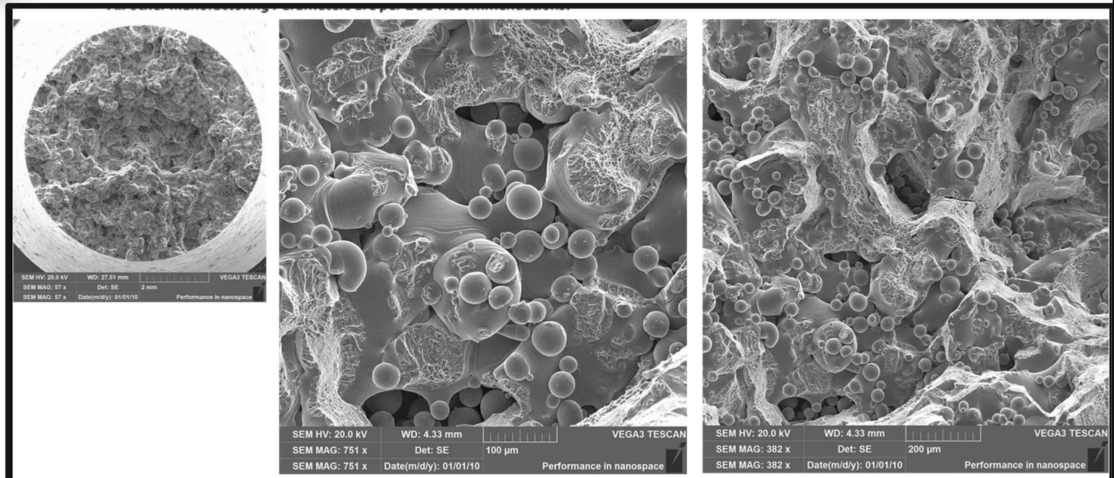


Crack Initiation source: Specimen Surface defect of lack of melt faces

	Specimen Type		Initiation Test Result	
Manufact. I.D.	Manufacturing Configuration	Thermal Post-Process.	Notes	Cycles, N
P2 m F1	Stripe Width +100% *	No-HIP		177,424

Failure Analyses Example

Typical Tray #4 Specimen Type (No-HIP & HIP)

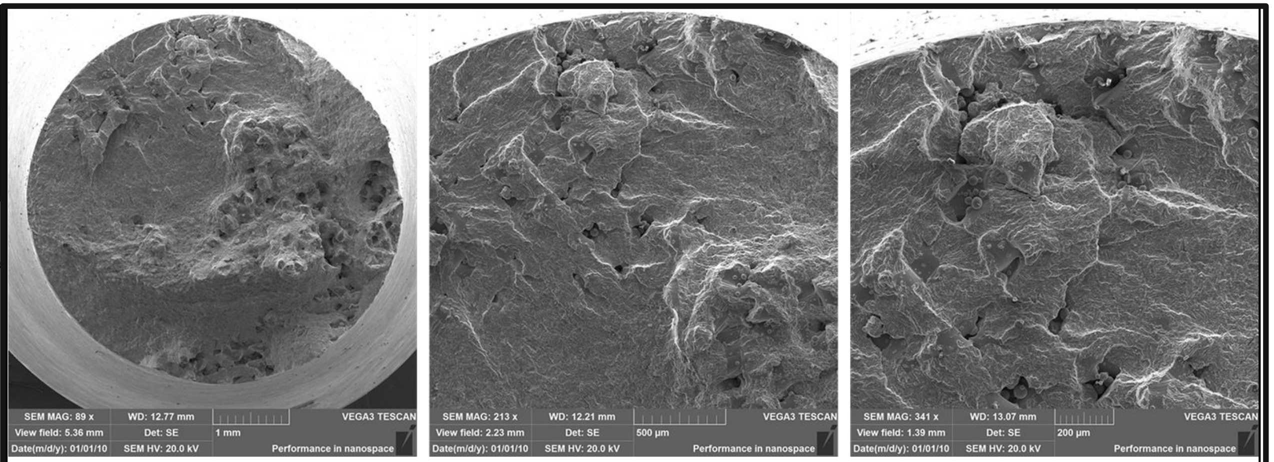


The Specimens are Full-of-Lack-of-Fusion Surfaces and powder-grains contained; porous fracture

Manufact. I.D.	Specimen Type		Initiation Test Result	
	Manufacturing Configuration	Thermal Post-Process.	Notes	Cycles, N
P4 m F1	Beam Power 50% *	No-HIP		323

Typical Tray #3 Specimen Type (HIP) of: Very-Early-Failure (Very-Low-Fatigue-Life)

Manufact. I.D.	Specimen Type		Initiation Test Result	
	Manufacturing Configuration	Thermal Post-Process.	Notes	Cycles, N
P3 m F2	Stripe Distance +100% *¹	HIP		42,887



The fracture faces are Full-of-Lack-of-Fusion Surfaces, Crack Initiation source is out of these Surfaces ; porous fracture

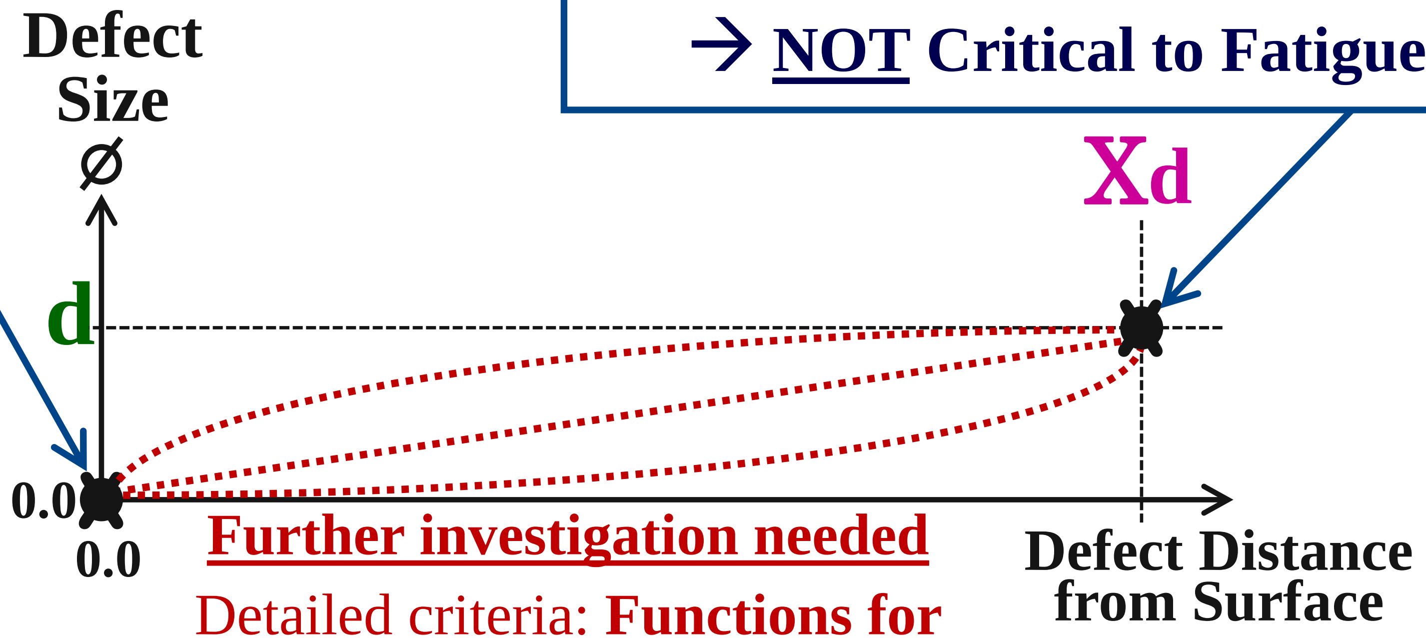
Conclusions: Critical-Defects Features

1) **Fatigue crack-growth isn't compromised by AM Defects of: Pores, Inclusions, Lack-of-Fusion, but Crack-initiation is → Enables quality control criteria.**

2) **The study suggests an approach for an allowed defects characterization.**

Very near Surface Defects:
Any Type / Size
→ **Critical to Fatigue.**

Defects of: d < 120 µm & X > 10d
→ NOT Critical to Fatigue.



Further investigation needed

Detailed criteria: **Functions for Defect Type & Size per Surface Distance.**

Thank you all for your attention

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