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Ti-6AL-4V Additive Manufacturing Measure of Quality According to Fatigue Crack Initiation vs. Crack Propagation

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Abstract

Additive Manufacturing (AM) technology (also called 3D-Printing), is yet not mature enough to be adopted in the aviation industry as an extensive method to produce airframe load carry structural items. The main aspect of this immaturity is lack of generic efficient quality control methods, to economically detect manufacturing defects (that may compromise fatigue strength). This study provides basic "Critical-Defects" criteria (per defect type, size and distance from surface) for quality control detection requirements, to ensure product service life adequate fatigue strength. The study also shows that Fatigue-Crack-Initiation life results are strong indicator for AM procedure quality-measure, whereas, Fatigue-Crack-Growth life results do not necessary relate to AM procedure inherent defects and cannot provide indications for AM procedure quality-measure.

Keywords: Additive Manufacturing, 3D-Printing, Fatigue, Crack-Initiation, Crack-Propagation, defects.

1. Introduction

Additive Manufacturing (AM) technology for metal Airframe load carry items (Principal Structural Element – PSE per Regulation terminology [1]), is facing implementation challenges in the aviation industry. AM technology is not yet considered mature for PSE's serial production, mainly due to lack of generic economic efficient quality control methods, to detect manufacturing defects. PSE items are typically susceptible to fatigue cracking in service, and need to be inspected for defects in their production. AM technology is being used in Airframe industry today to produce secondary items (non-load carry members) of which are not susceptible to fatigue issues.

The well-established Non-Destructive Inspections (NDI) technologies such as: Ultra-sonic, Eddy-current, Liquid-penetrant, etc., cannot detect the AM technology inherent defects, of which triggers fatigue issues [2]. Detection of such AM technology inherent defects, may be achieved either by "tailor-made" technics per specific product (of which specific detection technics are being developed during the development phase of the product), or, using very expensive technologies, such as Computer Tomography (CT), etc. Either one of the above defects detection technics for AM technology, are too expensive to be used for serial production of PSE's in the Airframe industry. In order to be able to develop generic inspections capable to economically detect AM defects, first we need to specify and determine what are the minimal features of these defects (called: Critical Defects), that trigger fatigue failures. I.e., to specify what such inspections need to look for (per minimal terms).

This study discusses and presents Critical Defects features, for the AM of the Powder Bed Fusion (PBF) of Selective Laser Melting (SLM) technology for titanium Ti-6AL-4V, to enable development of generic economic quality control methods, based on an experiment program (for fatigue testing), accompanied by Micro-CT inspections and SEM/Fractographic failure analyses.

The Critical Defects criteria are combinations of the following three AM-process-induced defect, minimal features, causing early cracking:

- Defect Type – Pore (Local Void), Lack of Fusion Surface or Inclusion (Contamination).
- Defect Size.
- Defect Distance from Surface.

Another AM Defect Type is Residual Stress fields, that are known to have a strong impact on fatigue crack growth [3]. The study shows that via routine Heat Treatment (HT) procedures such as 800ºC for two hours or HIP (Hot Isostatic Pressing), Residual Stresses in the printed specimens are being practically eliminated. Since all the specimens AM procedures were completed with either HT of 800ºC for two hours at Argon atmosphere (and furnace cooled, via optimize temperature control with the inert gas chamber) or HIP per ASTM F3001, this Defect Type was apparently not included into this study.

As shown by [3], the Defect Types that were evaluated in this study (Pores, Lack of Fusion Surfaces and Contaminations) strongly affect fatigue strength via affecting the crack initiation. The experimental results data presented in this study strongly support this well-established knowledge. Pores, Lack of Fusion Surfaces and Contaminations does not influence fatigue crack growth, since they do not interact with the crack front. These defect types do have strong influence on crack initiation mechanics, since, they introduce stress concentration sites. Because crack initiation is strongly dependent on stress concentration, it is strongly dependent on the relation of defect size and its distance to the surface.

2. The Experimental Campaign Program

The experimental campaign was done by cooperation of industry: IAI (requirements and results evaluation for Airframe industry applications), and academia: Afeka Engineering College (inspections and failure analyses) & Israel Institute of Metals, Technion (specimens manufacturing and mechanical testing).

The following three mechanical tests were done via the following three specimens, to address Airframe structure industry needs:

- Quasi-Static Test per ASTM E8 [4]; Test specimen: 12 mm diameter round bar.
- Fatigue (crack initiation) Test per ASTM E466-15 [5], R=0.1, Round Bar specimen with continuous radius between Ends (Neck=5mm dia., Ends=10mm dia.), Kt=1.0.
- Crack Growth Test per ASTM E647−15 [6], R=0.1, Compact Tension C(T) Specimen having: Width=30 mm, Thickness=5 mm, Artificial notch length=5 mm.

In order to examine the AM Defects in the context of the mechanical testing results, the quality of the specimens was studied by Metallurgical and Micro Computer Tomography (Micro-CT), inspections, and failure analyses were conducted (Fractographic via SEM).

This study used AM technology of: Ti-6Al-4V powder processed via Selective Laser Melting (SLM) via Powder Bed Fusion (PBF) technology of ALM EOS M290 Machine (Laser-Power = 340W, Print-Layer-Thickness = 60μm). All specimens were printed with printing layer orientation perpendicular to specimen's loading direction (the weakest orientation), and machine processed to produce the required dimensions for each test (per relevant ASTM Specification), including N6 (32μin) surface roughness quality level.

8 distinct Specimen type were produced to examine effects of AM technology defects on mechanical properties. The distinct Specimen type were configured by:

- 4 different AM (Printing) Parameters Sets.
- 2 different Thermal Post-Processing procedures applied to each Printing Parameters Set.

Half the total number of Specimens produced for each one of the four different AM Printing Parameters Set, were Thermal Post-Processed by either one of the following two procedures:

- Heat Treatment for stress relief (HT) of 800ºC for two hours at Argon atmosphere.
- HIP procedure per ASTM F3001

The four different AM Printing Parameters Sets (for different printing qualities according to [7]):

- **Tray #1** – All printing parameters were the EOS Recommended parameters as defined by EOS for their printing machine used (ALM EOS M290 Machine).
  This specimen type was identified as: Default → **Reference**.
- **Tray #2** – The printing manufacture parameters were the Recommended parameters as defined by EOS, except of the following parameter: Stripe Width, of which was modified to be increased to double the EOS recommendation.
  This specimen type was identified as: Stripe Width +100% → **Best / improved quality**.
- **Tray #3** – The printing manufacture parameters were the Recommended parameters as defined by EOS, except of the following parameter: Stripes Distance, of which was modified to be increased to double the EOS recommendation.
  This specimen type was identified as: Stripes Distance +100% → **Poor quality**.
- **Tray #4** – The printing manufacture parameters were the Recommended parameters as defined by EOS, except of the following parameter: Machine Laser Power, of which was modified to be decreased to half the EOS recommendation.
  This specimen type was identified as: Beam Power -50% → **The worst quality**.

Distinct Specimen Type: Specimen Type is combination of the two thermal treatments & the four printing parameters sets (each printing parameters set is manufactured via different printing Tray).

Figure 1 presents: (a) The Laser beam travel printing parameters of Stripes Width/Distance graphics, (b) Four printed parameters sets, (c) Tensile Machines used & Fatigue / Crack Growth test specimens.

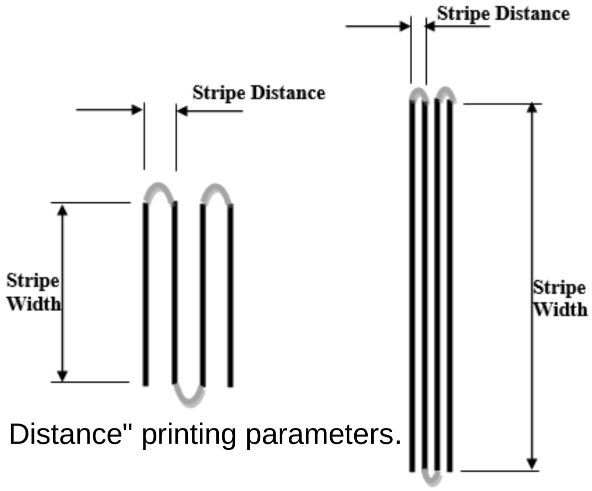


Figure 1a – "Stripe Width" & "Stripes Distance" printing parameters.

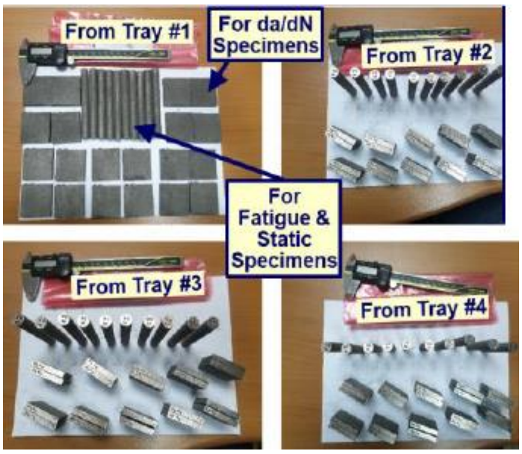


Figure 1b – Four printing parameters sets.

Figure 1c – Testing machines used & specimens.

Figure 1 – AM tested specimens, for the four print parameters sets and testing machines.

3. The mechanical testing results

3.1 The Quasi-Static Test Results

Table 1 presents total number of Specimens tested and Average Test results for each distinct Specimen Type.

Tray #	Printing Parameters	Number of Specimens		Remarks
		Stress relief HT	HIP	
P1	EOS Default Parameters	2	5	
P2	double increased stripes width [rest EOS Default Parameters]	3	5	Stripe Width +100%
P3	double increased stripes distance [rest EOS Default Parameters]	3	5	Stripe Distance +100%
P4	double decreased laser power [rest EOS Default Parameters]	3	5	Beam Power - 50%

Specimen Type		Modulus [Gpa]	Tensile Strength (UTS) [Mpa]	Yield Strength $R_{p0.2}$ [Mpa]	Elong. ε_f [%]
Tray #	Thermal Post-Processing Status				
1	Stress relief HT	118	1,113	1,070	13.3
	HIP	118	1,011	933	11.5
2	Stress relief HT	118	1,103	1,053	16.5
	HIP	118	1,007	918	17.2
3	Stress relief HT	105	955	910	2.8
	HIP	114	953	886	10.6
4	Stress relief HT	95	855	803	0.8
	HIP	95	805	743	0.9
ASTM F3302-18 Requirements		110	895 Min.	825 Min.	10 Min.

Table 1 – Quasi-Static Test Average Results & Number of Specimens Tested par Specimen Type

The following can be seen from Table 1 Test results:

- **Elasticity Modulus:** For the Good quality Specimens (Printing Trays #1 & #2) the Elasticity Modulus, meets ASTM Requirements and is unchanged (independent) for either performing the HIP Post-Processing or performing the two hours 800ºC with no pressure HT. For Printing Tray #3 Specimens, the HIP process had increased the Elasticity Modulus and improved it to meet the ASTM requirements, while for Printing Trays #4 Specimens HIP did no managed to improve Elasticity Modulus and all Trays #4 Specimens did not meet ASTM Requirements.

  Note: It is assumed of linear-elastic, isotropic and homogeneous material, as would have been expected (preferred) for AM as replacing Forges & Plates conditions.
- **Tensile & Yield strength:** For all Specimens (per all the Printing Trays), the HIP Post-Processing, had cause a decrease in the Tensile & Yield strength, relative to HT of 800ºC for two hours with no pressure (the same trend had been shown also at study [3]). For the Good quality Specimens (Printing Trays #1 & #2), the % decrease in the Tensile & Yield strength are about 9% & 13%, respectively, and still meets well the ASTM Requirements.

- **Elongation:**
  - Printing Tray #1 Specimens meet the minimum ASTM Requirement.
  - Printing Tray #2 Specimens present relatively high level of elongation (24% to 50% higher than Tray #1 Specimens).
  - Printing Tray #3 Specimens meet minimum ASTM Requirement only after the HIP process, while via the two hours 800ºC with no pressure HT, the elongation is low and far from meeting ASTM Requirement.
  - Printing Tray #4 Specimens, for both the Post-Processing thermal treatments, the elongation is very low and very far from meeting ASTM Requirement.
- All the Tray #4 Specimens, doesn't meet any of the minimum ASTM Requirements, for both the Post-Processing thermal treatments.

3.2 Fatigue (Crack Initiation) & Fatigue-Crack-Growth Test Results

Fatigue (crack initiation) and Crack-Growth Tests were done on Round Bars (Kt=1) and C(T) Specimens, respectively. Fatigue and Crack-Growth Specimens were Printed via the same four different Trays (of the four printing parameters sets per the four mentioned above different AM printing qualities), and having the two different mentioned above HT procedures. These tests were done in order to evaluate the Fatigue Resistance capabilities for the eight different Specimen Type (per combinations of four printing qualities and two HT procedures as detailed above).

The number of Specimens tested per each Specimen Type, for the fatigue (crack initiation) tests and for the crack-growth tests, are presented in Table 2 and Table 3, respectively.

Printing Parameters Tray #	Number of Specimens Tested	
	Stress Relieved HT (as specified above)	HIP per ASTM F3001
Tray #1	10	10
Tray #2	9	9
Tray #3	9	10
Tray #4	9	10

Table 2 – Number of Specimens Fatigue (crack initiation) Tested par Specimen Type

Printing Parameters Tray #	Number of Specimens Tested	
	Stress Relieved HT (as specified above)	HIP per ASTM F3001
Tray #1	5	2
Tray #2	5	2
Tray #3	5	2
Tray #4	4	1

Table 3 – Number of Specimens Crack-Growth Tested par Specimen Type

Figure 2 presents the Fatigue (crack initiation) Test results for number of cycles to failure per Max. Cyclic Loading Stress (R=0.1, Kt=1), for all specimen tested, presented by the diamond-dots (via eight different colors per the eight Specimen Types), in comparison to:

- Results of testing program conducted via the "AATiD" Consortium [7], of which present their Specimens results via brown color stripes and are accompanied with "Best Fit" curve (black color curve) & "B Value Stress" curve (red color curve), that are in accordance to the "AATiD" Consortium results.
- MMPDS Handbook Data [8], presented by the light-blue color curve.

Figure 2 also presents results of Weibull Statistical analysis done for each Specimen Type (per its seven to 10 individual Specimens results), in the terms of the "Characteristic-Life" and the Variance level (shape parameter). It should be noted that the Statistical analysis included, or not-included, the following Specimen results (for some Specimen Types, not all their nine or 10 specimen results were accounted into the Statistical analysis), as follows:

- If, for a specific Specimen, Micro-CT inspection & Failure analysis (per Fractographic via SEM) reviled that the Specimen contained "very-excessive" defects (relative to the others of its Type), that caused "extremely-low" Fatigue result, then, that Specimen represented an example for a produce to be Rejected, and that result was not included into the statistics of that Specimen Type. Such "excessive" defects are candidates for evaluations of definitions for "critical" defects that should be detected by quality control procedures (to derive Rejection). The Specimen Types of: "P1-no-HIP" & "P2-no-HIP", did not include two specimens results, into their statistics.

  More candidates for such evaluations are the Trays #1 & #2 Specimens that their Fatigue results were below 3 X 10^6 cycles (5 X 10^6 cycles may be considered accepted Minimum Fatigue result; above 8 X 10^6 cycles, is the required Fatigue result).
- The statistical analysis accounted number of cycles that caused specimen failure, and also accounted (differently) number of cycles that did not cause specimen failure (i.e. the specimen either did not fail, or failed in the Tensile Machine Grips). The total number of Specimens (failed + not-failed) over the number of Specimens that were accounted as not failed, are specified as: "(n/s)".

Figure 2 also presents eight oval shapes in the different colors as are for the eight distinct Specimen Types, to represent the spread (variance) of the Fatigue results (in term of number of cycles to failure), for each of the eight distinct Specimen Types.

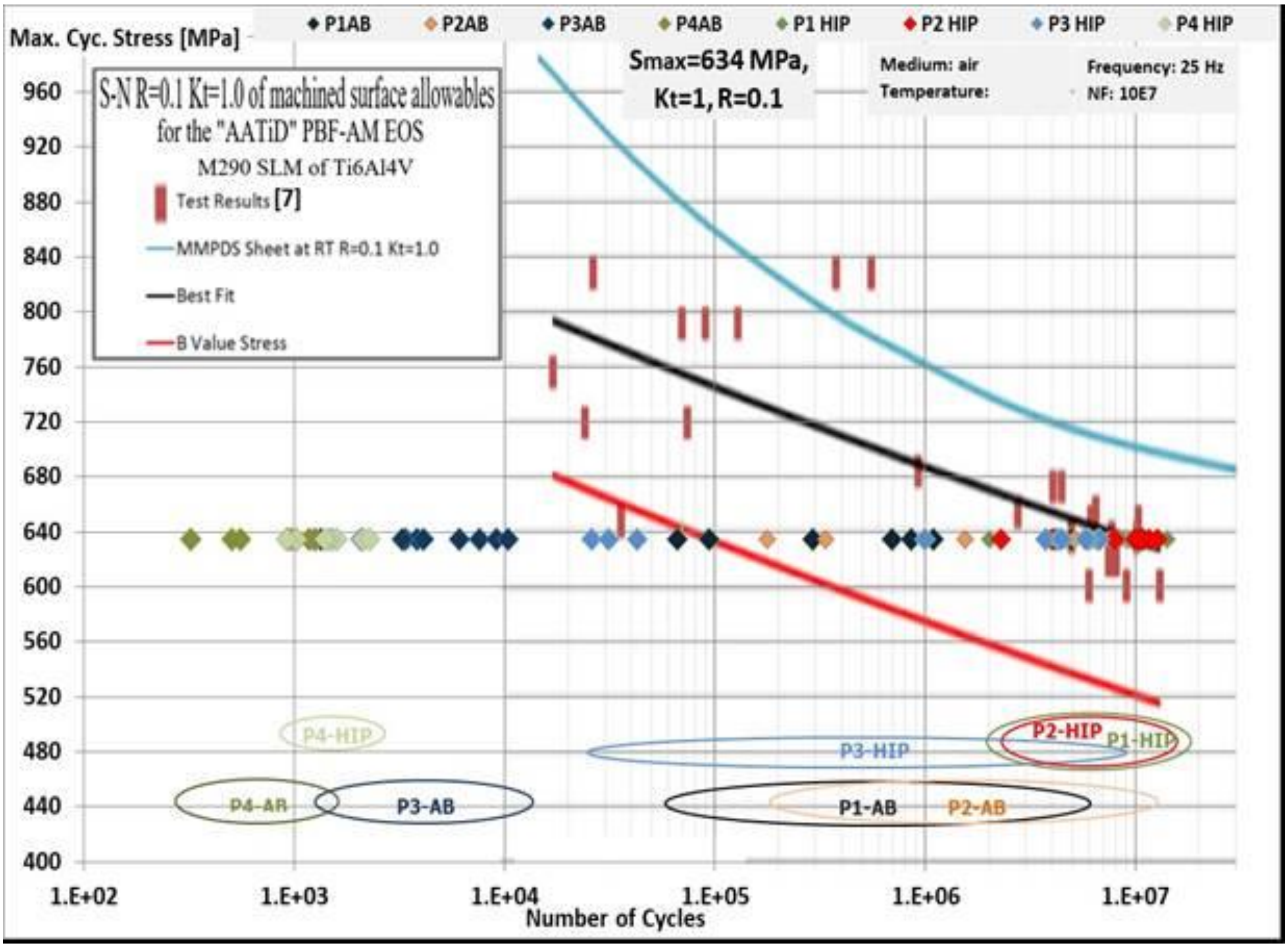
Table 4 presents crack initiation test results observations that can be seen in Figure 2.

Note: The phrase "Corresponds well to "AATiD" results", means to say that the test results at this study resembles (corresponds well) to previous program test results documented in Ref. [7].

	Characteristic-Life	Variance (spread) Level
Tray #2 Printing		
HIP –	Corresponds well to "AATiD" results	Low
NO-HIP(*) –	Corresponds well to "AATiD" results	Very High
Tray #1 Printing		
HIP –	Corresponds well to "AATiD" results	Low
NO-HIP(*) –	~ 0.5 Factor of "AATiD" results	Very High
Tray #3 Printing		
HIP –	~ 0.3 Factor of "AATiD" results	Very High
NO-HIP(*) –	Extremely low	Low
Tray #4 Printing		
HIP –	Most extremely low	Extremely Low
NO-HIP(*) –	Most extremely low	Low
(*) Stress Relieve Heat Treatment of 2 hours at 800ºC with no pressure applied.		

Table 4 – Crack initiation test results observations per Fig. 2

Figures 3 to 6 present the crack growth test results, in terms of crack growth rate (Inches of crack length per number of applied loading cycles, da/dN) vs. Stress Intensity range (in units of KSI X√Inches, ∆K). Each of the 3 to 6 Figures, present the Crack Growth Test results of HIP and non-HIP Specimens (via different dots) for each Printing Tray (#1 to #4). The crack growth test results are presented in comparison to NASGRO computer program da/dN vs. ∆K data [9] (that is well accepted and extensively used in the Airframe industry) for Ti-6AL-4V Forges & Plates (red curves present NASGRO data).



P1m – Printing Tray #1	P2m– Printing Tray #2	P3m – Printing Tray #3	P4m – Printing Tray #4	Thermal Procedures:
The 2nd Best Quality All EOS Default	The Best Quality EOS Default & Change Stripe Width +100%	The 2nd Worst Quality EOS Default & Change Stripe Distance +100%	The Worst Quality EOS Default & Change Beam Power -50%	2Hr. 800°C HT No Press. (AB) HIP per ASTM F3001 (HIP)

Weibull Statistical Distribution Data					
2 hours 800°C Heat Treatment with no Pressure			HIP procedure per ASTM F3001		
Tray #	Shape Parameter / Variance (n/s)	Characteristic Life	Tray #	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

Figure 2 – Fatigue (crack initiation) Test Results for all eight Specimen Types

The following should be noted: ASTM E647 formulation and C(T) Specimens usage, is done under the assumption that the Ti-6AL-4V printed material is linear-elastic, isotropic and homogeneous (as we would have preferred it, for replacing the Ti-6AL-4V Forges & Plates). The da/dN vs. ΔK test data, presented in this article, is for comparison purposes (of the eight distinct Specimen Type) rather than crack growth analyses usage. Further investigation may be needed to validate this assumption.

The following results can be seen in Figures 3 to 6:

- All Crack Growth Test results (of HIP & non-HIP Specimens from all Printing Trays) correlate well to the NASGRO computer Program da/dN vs. ΔK data, to all the ΔK range tested.

  Note: Two Specimens from Printing Tray #4 presented some higher da/dN's for the relatively higher ΔK's, compare to the NASGRO computer Program data.
- Neither the four different Printing Parameters Sets (four Printing Trays) nor the two HT (of HIP vs non-HIP), had any significant different effects or influences on the crack growth rate results.

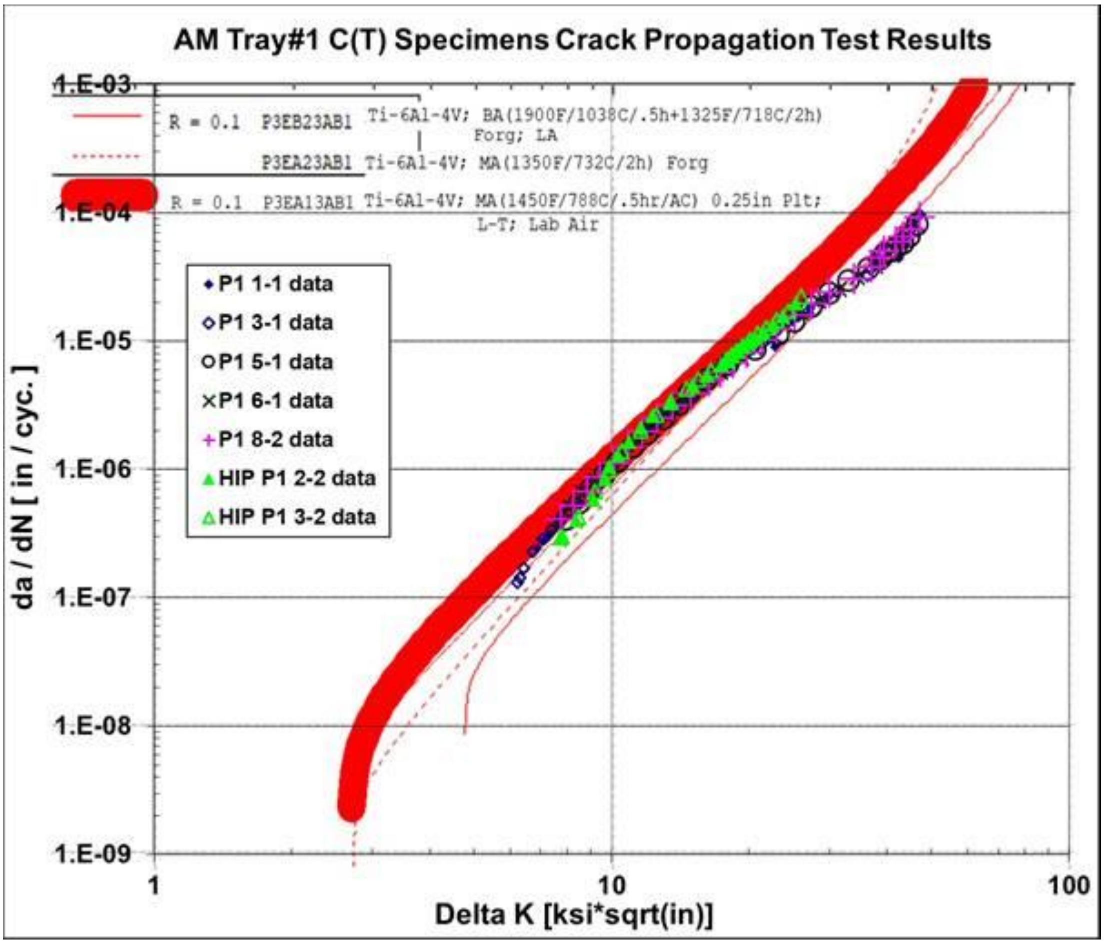


Figure 3 – Crack Growth Test Results for Tray #1 Specimen Type (No-HIP & HIP).

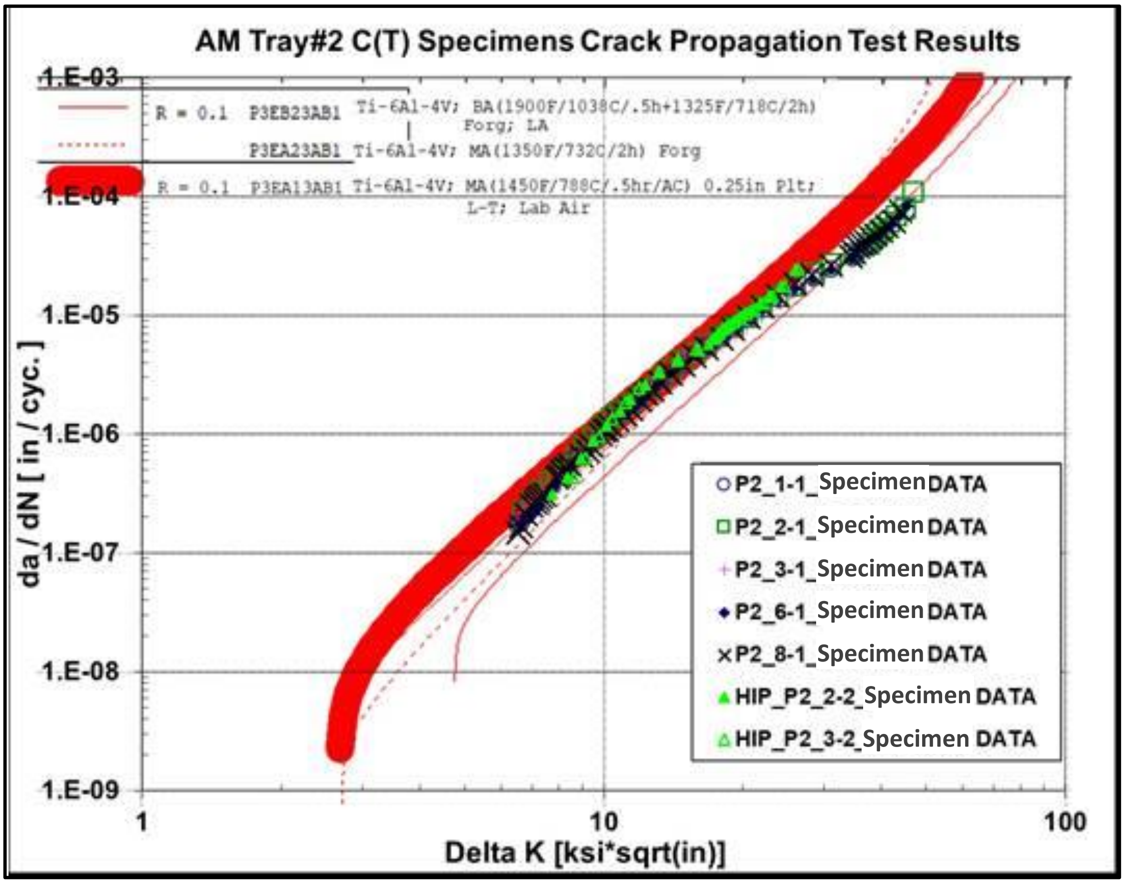


Figure 4 – Crack Growth Test Results for Tray #2 Specimen Type (No-HIP & HIP).

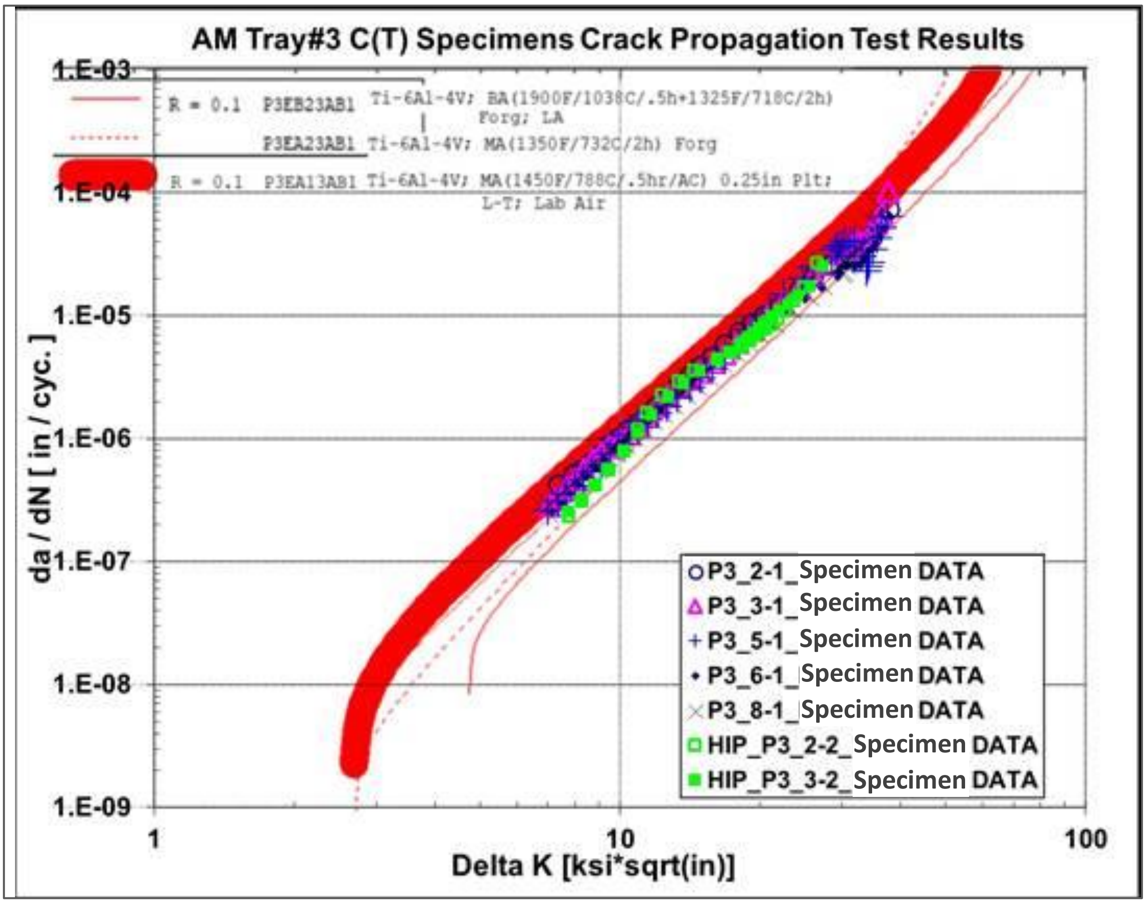


Figure 5 – Crack Growth Test Results for Tray #3 Specimen Type (No-HIP & HIP).

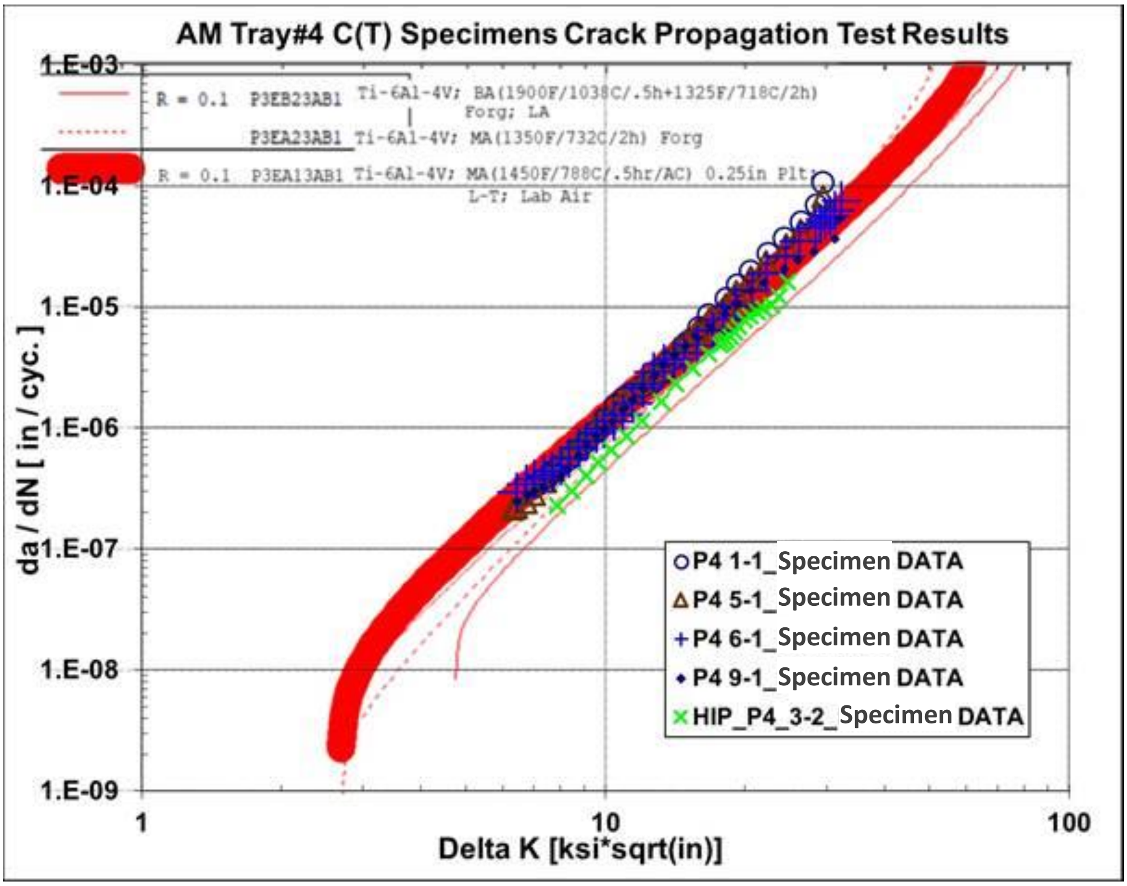


Figure 6 – Crack Growth Test Results for Tray #4 Specimen Type (No-HIP & HIP).

4. Fatigue Tests Results Discussion

4.1 Fatigue-Cracking-initiation Test Results Discussion for the Printing-Parameters and the HIP Procedure Effects

- Printing Parameters Sets of Trays #1 & #2:

  The HIP procedure was effective in regard of changing the Fatigue test results from being very spread (very high Variance level) for HT with no pressure applied, to be having low spread level (low Variance level) for HIP application. It should be mentioned that whereas for Tray #2 Printing Parameters, the HIP procedure only slightly improved its "Characteristic-Life", for Tray #1, the HIP procedure dramatically improved its "Characteristic-Life" (by Factor of 2).

  This HIP procedure effect suggests that the dominant type of defects introduced by the Printing Parameters Sets of Trays #1 & #2, are such that the HIP can "repair". Such defects are Pores (Local Voids), that the pressure application can "close" (Pore size diameter reduction to below 50 μm up to below detection limit of 22 μm, depending on initial As-Built Pore size) [10]. This is in contradiction to defect type of Lack of Fusion Surfaces and Inclusions (Contaminations), that HIP procedure cannot create "complementary" Fusion or eliminate Contaminations to repair. I.e., the dominant defect type are Pores, and the minority defect type are Lack of Fusion Surfaces and Inclusions (Contaminations). This suggestion is proven (as further presented) by the Micro-CT inspections and the SEM/Fractographic failure analyses.

  The conclusion from this finding is that Airframe primary structural members being manufactured via Trays #1 & #2 Printing Parameters, will be expected to have more defect type of Pores (Local Voids), relative to less defect type of Lack of Fusion Surfaces and Inclusions. But still, Specimens to be further Micro-CT inspected & Failure analyzed (via Fractographic SEM analyses), for Critical Defects investigation, should look for: Pores, Inclusions and Lack of Fusion Surfaces. Such Critical Defects investigation was focused on the Specimens which their Fatigue results were below 3 X 10^6 cycles (5 X 10^6 cycles may be considered accepted Min. Fatigue result; above 8 X 10^6 cycles, is the required Fatigue result)

- Printing Parameters Set of Tray #3:

  The HIP procedure had an opposite effect compare to its effect upon the Printing Parameters Sets of Trays #1 & #2. The HIP procedure changed the Fatigue test results from having low spread level (low Variance level) for HT with no pressure applied, to be very spread (very high Variance level) for the HIP application. This HIP procedure effect suggests that the Tray #3 Printing Parameters Set introduced both defect types of: Pores vs. Inclusions and Lack of Fusion Surfaces, with no one being the dominant. Specimens having both defect types in the same extent level, was dramatically reducing their Fatigue life (and had such low Variance level). Application of HIP procedure "repairing" the Pore defects but not "repairing" the other defect types, improves Fatigue life results for some Specimens but not for others. Thus, increases the Fatigue life results Variance level. This suggestion is proven by the Micro-CT inspections and the SEM/Fractographic failure analyses. It should be mentioned that the HIP procedure dramatically improved the "Characteristic-Life", but yet the "Characteristic-Life" is still well below required level (~ 0.3 Factor of "AATiD" results [7])

- Printing Parameters Set of Tray #4:

  The HIP procedure had a very marginal effect on the Fatigue life results. It slightly decreased the Variance level, and very slightly increased the "Characteristic-Life", of which is extremely below required level. This HIP procedure effect suggests that the Tray #4 Printing Parameters Set introduces much more defects of the Lack of Fusion Surfaces type (and maybe Inclusions), relative to the Pores defect type (but yet some Pores defect type are introduced). The vast extent of such defects, was extremely dramatically reducing the Fatigue life. This suggestion is proven by the Micro-CT inspections and the SEM/Fractographic failure analyses. It should be mentioned that Tray #4 Printing Parameters included reduction in the Laser Printing Power to half of the EOS recommendation. So, it is expected to have lots of Lack of Fusion Surfaces defect type in these Specimens

- Contribution to Critical Defects Study:
  There is a need to specify and determine minimal features for AM defects that reduces fatigue strength, in order to enable development of serial production quality control procedure (to economically detect AM defects). These Fatigue (crack initiation) test results does provide useful information for this study, since the defects that exist in the Specimens (Pores, Inclusions and Lack of Fusion Surfaces) did significantly impact the Fatigue test results. Trays #1 & #2 Printing parameters Specimens, which showed significant reduction in the Fatigue strength (to not accepted levels in the Airframe industry) were further evaluated for Critical Defects features, via detailed Micro-CT inspections and SEM/Fractographic failure analyses, to the Pores, Inclusions and Lack of Fusion Surfaces type defects.

4.2 Crack-Growth Test Results Discussion for the Printing-Parameters and the HIP Procedure Effects

- All four Different Printing Parameters Sets (Trays #1 to #4) & HIP vs non-HIP:
  The reason that the four different Printing Parameters Sets, did not have significant different effects or influences on crack growth rate results, is that both the HT (HIP & non-HIP) had eliminated Residual Stress defects. Residual Stress defects has strong impact on fatigue crack growth, whereas Defect Type of Pores & Lack of Fusion Surfaces does not influence crack growth (only crack initiation), as study [3] showed.

- Contribution to Critical Defects Study:
  The Crack Growth test results did not provide useful information for this study, since the defects that exist in the Specimens (Pores & Lack of Fusion Surfaces) does not impact the Crack Growth (for Macro-Cracks).

5. AM Defect Findings by Micro-CT Inspections & SEM/Fractographic Failure Analyses

Figures 7 to 10 present the Micro-CT inspection results for specimens printed via printing parameters of Trays 1 to 4, respectively (having HT with no pressure, i.e. no HIP done to these inspected specimens). The Figures show Micro-CT inspection results for the defects count, sizes and locations.

The Micro-CT inspection results evaluation, of which is stated here, is under the evidence gained via the SEM/Fractographic failure analyses done to the specimens that had completed the Fatigue (crack initiation) Tests (presented and discussed further in this article).

The reductions in Pores/Defects count (per volume unit) and Pores/Defects size, is having the following Step-Function effect on the Fatigue strength (behavior per crack initiation mechanism being a statistical phenomenon):

- Relative Density < 99.999% → Fatigue strength will most likely not meet the Airframe industry requirements.
- Relative Density ≥ 99.999% → Fatigue strength will meet the Airframe industry requirements, only if, no Defect will be above "Critical-Defect" criteria (specified further in this article for size vs. distance from surface).

Definition of "Relative Density": The ratio of the density of an Additive Manufactured Ti-6AL-4V to the density of Ti-6AL-4V made from Forges (or Plates).

Figures 11 and 12 present examples for the SEM/Fractographic failure analysis results. Figures 11 and 12 present examples for failure analysis results of specimens printed via printing parameters of Tray #3 (HIP applied) and Tray #2 (HT with no HIP applied), respectively.

Figure 11 presents – A Tray #3 Specimen Type, that had undergone the HIP procedure, but, since it contained many internal Lack-of-Fusion Surface defects, the HIP procedure could not "repair" it (as so, these Specimens remained having porous structure even after HIP). Such internal structure caused this kind of Specimens to have very low Fatigue results (Specimen I.D. P3-m-F2 was only 42,887 cycles to failure Fatigue tested).

Figure 12 presents – A Tray #2 Specimen (No-HIP), that happened to have an internal defect having an estimated size of ~90μm, and that defect was having about 850-to-900μm distance from the Specimen surface. This detect was the source for fatigue crack initiation. The Fatigue result for this Specimen (I.D. P2-m-F17) was high, as expected for the cyclic loading applied (and as required for Airframe structures), as 9,758,414 cycles to failure. This fatigue result shows that such a defect (size & distance from surface), is not critical-for-fatigue.

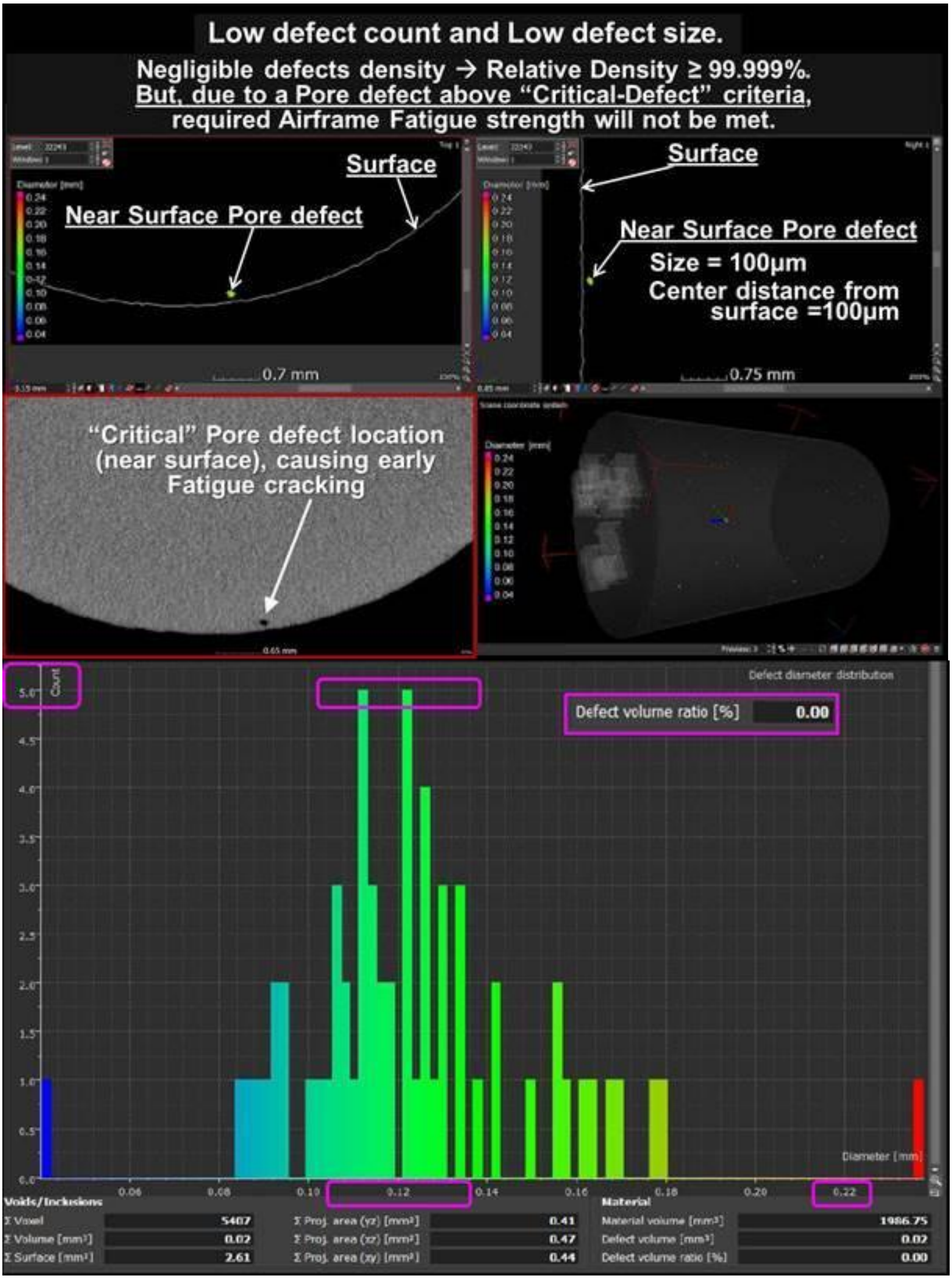


Figure 7 – Tray #1 Specimen Type (No-HIP) Micro-CT Defect Analysis Count Result (size & location) and an Example for "Critical" defect.

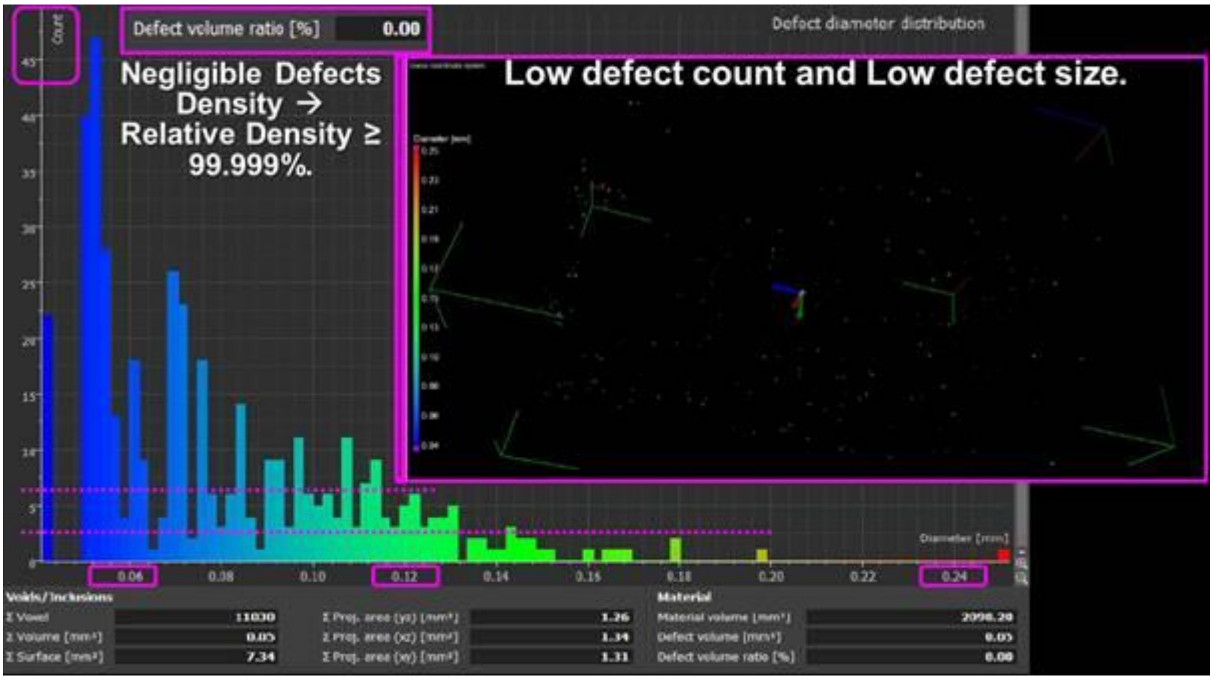


Figure 8 – Tray #2 Specimen Type (No-HIP) Micro-CT Defect Analysis Count Result (size & location).

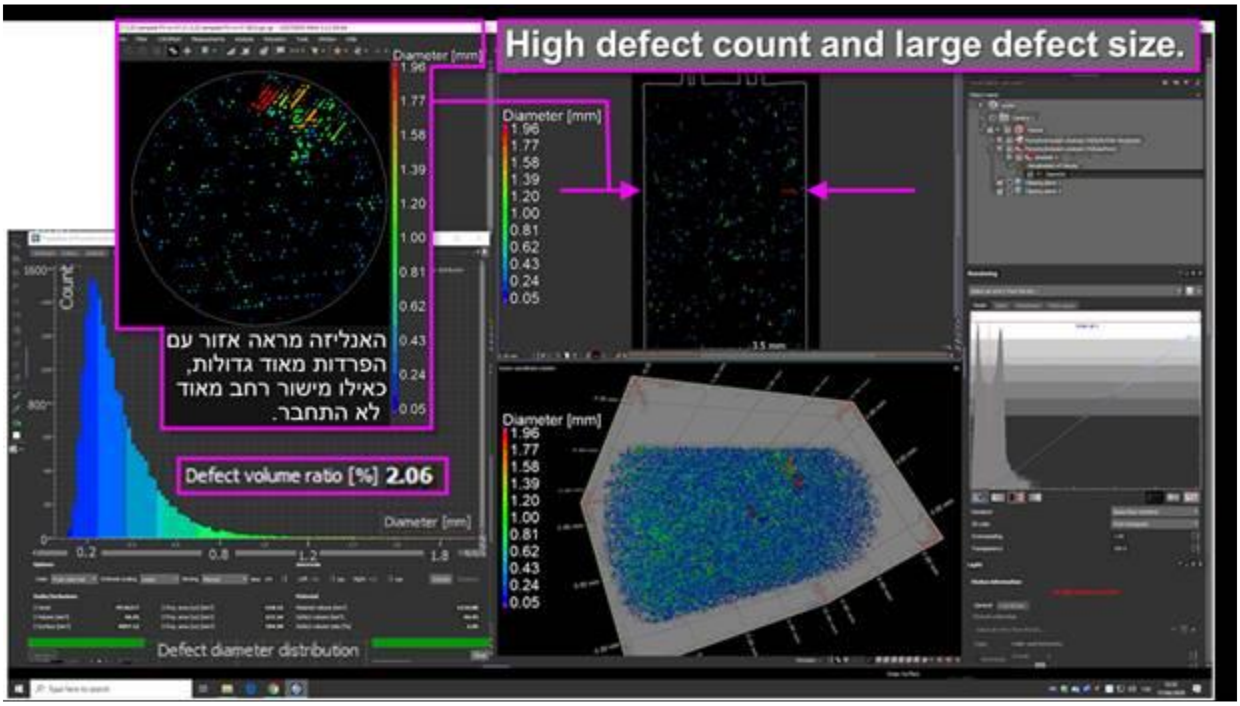


Figure 9 – Tray #3 Specimen Type (No-HIP) Micro-CT Defect Analysis Count Result (size & location).

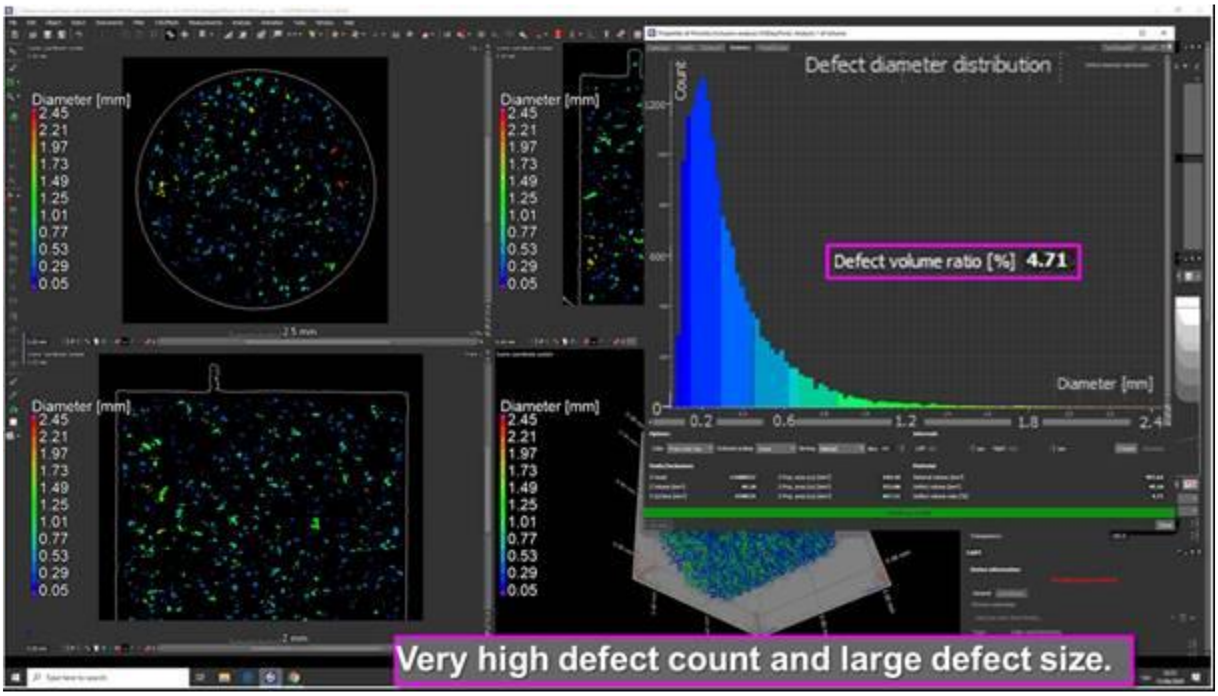


Figure 10 – Tray #4 Specimen Type (No-HIP) Micro-CT Defect Analysis Count Result (size & location).

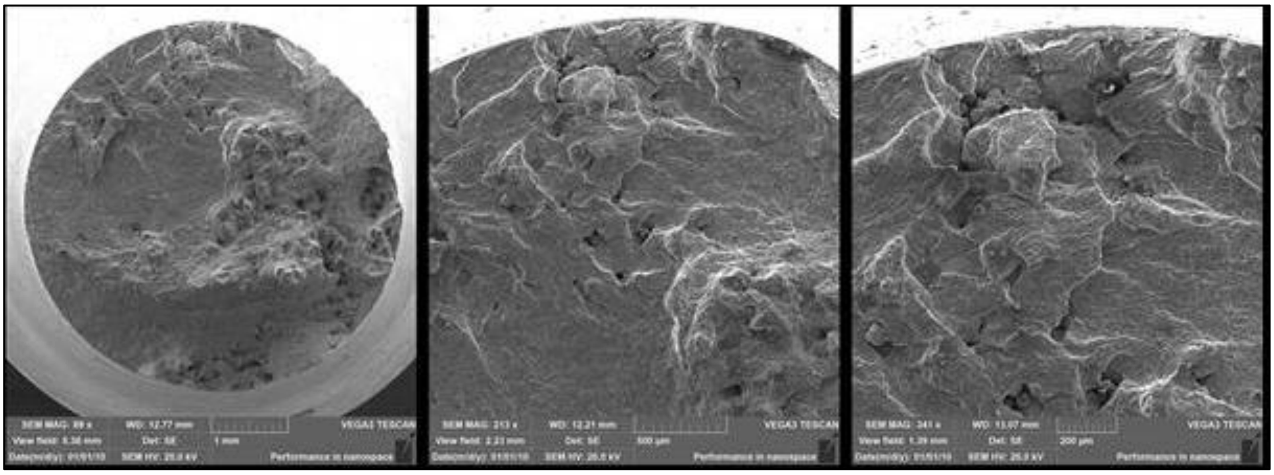


Figure 11 – Tray #3 Very-Early-Failure (Very-Low-Fatigue-Life) Specimen Type (HIP) SEM/Fractographic failure analyses.

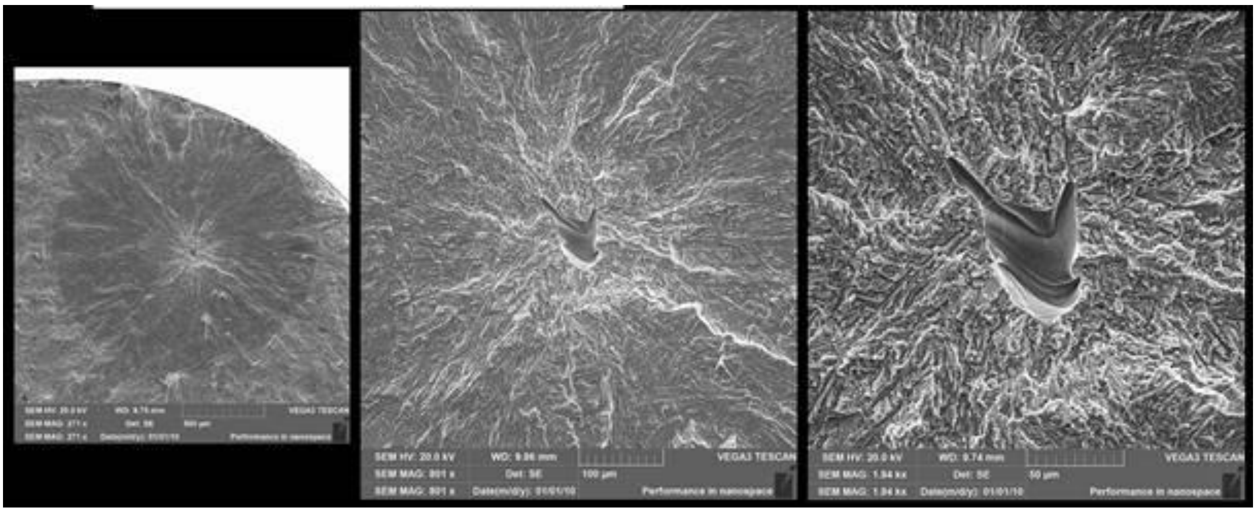


Figure 12 – Tray #2 Specimen Type (No-HIP) High-Fatigue-Life (as Required for Airframe Structure) SEM/Fractographic failure analyses.

Table 5 presents result summery of the Micro-CT inspections, for specimens printed by the four printing parameters sets, via Trays #1 to #4 (for specimens having HT with no pressure, i.e. no HIP done to these specimens). These data serve as complementary information to the SEM/Fractographic failure analyses findings. Table 5 presents Micro-CT inspection results for typical specimens printed via Trays #1, #3 and #4, and for four specific specimens printed via Trays #2 (specimens I.D.: P2m1, P2m3, P2m17, P2m9). The table also presents the Fatigue tests cyclic life (either as specific life of specific specimen or as Characteristic life per Weibull distribution for statistics of a Tray specimens). The Micro-CT inspection results are presented in terms of defects count, for defect diametric size per number of its occurrences. It can be seen that typical specimens of Trays #3 and #4 contain large defect size (up to 2.4 mm diameter), and lots of smaller defect sizes. It can be seen that specimens of Trays #1 and #2 contain much smaller defect sizes, of up to 0.25 mm diameter (having specimen I.D P2m1 as an exception). In addition, it can be seen that the specimens of Tray #2 relative to typical specimens of Trays #1 and #3, tended to contain more defects for the defect sizes up to 0.12 mm diameter. Combining with the information gathered by the SEM/Fractographic failure analyses, this finding supports the conclusion that defect sizes of up to 0.12 mm diameter, may be not critical for Fatigue, under condition that defects are far from the specimen surface (as specified in the conclusions Section).

Defect-Count per Defect-Size, for 2,000 mm^3 Specimen Section (No-HIP)

Defect-Count

Typ. Specimens Tray #4 (Characteristic Life [Cycles] 1,070)	Typ. Specimens Tray #3 (Characteristic Life [Cycles] 6,651)	Tray #2 Specimens (Characteristic Life [Cycles] 9,393,125): Specimen P2m1 177424 cyc	Tray #2: Specimen P2m3 335993 cyc	Tray #2: Specimen P2m17 9758414 cyc	Tray #2: Specimen P2m9	Typ. Tray #1 (Characteristic Life [Cycles] 2,049,233)	Defect-Size Ø [mm]
18	2	> Resolution	> Resolution	> Resolution	22	1	0.04
280	4	415	153	39	239	0	0.04-0.08
960	40	267	81	37	115	29	0.08-0.12
1,250	1,320	111	20	8	50	31	0.12-0.25
760	1,100	2	0	0	0	0	0.293
480	560	0					0.4
280	340	1					0.475
200	180	0					0.6
120	80						0.7
80	40						0.8
40	20						0.9
30	15						1.0
15	7						1.2
5	4						1.4
1 - 3	1 - 2						1.6 – 2.4

Table 5 – Trays #1 to #4 Specimen Type (No-HIP) Micro-CT Defect Count Analysis Results.

6. Summery and Conclusions

This study purpose was to establish AM defect characteristics, for Ti-6AL-4V Airframe principal structural items, that quality control should detect, in order to reject disqualified items, that will not meet required fatigue strength, for a fluent serial production procedure.

Serial production quality control should detect the AM technology inherent defect types of: Pores (Local Voids), Lack of Fusion Surfaces and Inclusions (Contaminations) that will compromise required fatigue strength. The product development design phase should make sure that the Residual Stress Type of defects, will not be existed in the product, via proper relevant Heat Treatment application (HIP procedure is recommended). Heat Treatment (via proper control system), will eliminate Residual Stresses in the printed product.

Based on [3] and in accordance with this study, the following Ti-6AL-4V AM relations to fatigue-strength-quality-measure can be said –

Strong indicator for AM quality-measure:

- Cyclic Life Results for Fatigue Crack Initiation.
- Findings in regard to Critical Defects Criteria per: Type, Size and Distance from Surface.

No indicator for AM quality-measure:

- Cyclic Life Results for Fatigue Crack Growth.
- Findings in regard to material density: Density similarity to Ti-6AL-4V made from Forges/Plates will not necessarily guarantee good compliance to fatigue-strength requirements (compliance to fatigue-strength strongly relates to "Critical Defects Criteria"). It should be mentioned that low density (relative to Forges/Plates) will most likely guarantee of not meet the Airframe industry fatigue strength requirements.

Critical-Defects (Fatigue strength) criteria –

According to this study fatigue (crack initiation) tests, Micro-CT inspections and SEM/Fractographic failure analyses, combined information, it can be said that the defect characteristics/features of Pores (Local Voids), Inclusions (Contaminations) and Lack of Fusion Surfaces, that a serial production quality control system, should detect are as follows:

- Surface Defects –

  Any type of defect and of any size, will cause early fatigue cracking, that will prevent to meet the fatigue requirements for Airframe structures.

  The surface defects themselves are not of interest for the aspiration to develop generic economic quality control methods to detect these defects, since there are already such methods (as Liquid Penetrant NDI). The purpose of discussion about surface defects is to emphasize the trend of: As a defect is being closer to surface, smaller defect sizes will become critical for fatigue strength.

- Internal (volumetric) Defects –

  Defects that their size is up-to 120μm and their distance from surface is more than 10 times their size, will not cause early fatigue cracking, and will allow to meet the fatigue requirements for Airframe structures.

  Further investigations are needed to extend that criterion to more detailed criteria, for having functions of defect size per distance from surface, to each of the above specified defect type (Pore, Inclusion, Lack of Fusion Surface).

Note: The study evaluated AM defects per the dominant phase determining Fatigue strength, as:

- The phase up to crack initiation (nucleation & "Micro-cracking" formation up to cracks of an "engineering size" i.e. "Macro-crack") – Dominant phase → Evaluated in the study.
- Crack growth phase (from an "engineering size" crack) – Typically much shorter cyclic life compare to crack initiation phase (<< 1/10) → Not evaluated in the study.

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8. Copyright Statement

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