# SURFACE QUALITY CHALLENGE FOR TI-6AL-4V ADDITIVE MANUFACTURED TOPOLOGIC OPTIMIZED LIGHTWEIGHT STRUCTURE

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## Abstract

Additive Manufacturing (AM) technology (also called 3D-Printing) enables to build airframe lightweight structures via topologic optimization, creating geometrically complexed shapes having "bionic"-like branching. Such AM items pose a challenge to surface treatments for achieving a required surface quality. This is since 3D-Printing creates rough and defective surfaces, of which inner and hidden surfaces cannot be adequately treated by mechanical and other traditional polishing techniques. This study presents an experimental evaluation procedure to examine innovative surface treatment techniques. The study shows that this challenge has not been met yet for air-frame structural requirements, by state-of-the-art surface treatment techniques. Additional combinations of surface treatment techniques are being suggested to be further evaluated by the presented procedure, using a Universal Component Specimen (as a generic testing specimen) representing typical shape complexity. This Research was supported by the Israel Innovation Authority ministry.

**Keywords:** Additive-Manufacturing, Topologic-optimization, Surface-treatments, Surface-quality

## 1. Introduction

Additive Manufacturing (AM) technology is gaining growing interest in aerospace industry as it allows lightweight structures manufacturing by durable metals as titanium alloys. AM topologic optimization enables lightweight structures design and provides material waste minimalization.

There is increasing demand for AM technology to produce airframe primary structural members that carry flight and ground cyclic loading being susceptible to fatigue cracking, of which such structures need to meet fatigue and damage tolerance regulations and requirements.

The surface quality of a structural member is a dominant factor influencing the fatigue strength (especially at a stress concentration locations). AM parts contain partly molten particles on their surface creating surface defects. Therefore, AM parts require post-processing procedures (after print completion) to attain the desirable surface quality. However, topologic optimization creates geometrical complexity to structural load-carry parts having "bionic" like shapes with branches and sub-branches introducing hidden surfaces, that conventional mechanical techniques (such as machining, grinding, lapping and sand or other particle blasting) are not applicable for surface quality improvement.

This study presents an experimental evaluation campaign done for European leading state-of-the-art surface treatment techniques. It is shown that these innovative state-of-the-art techniques do not yet present adequate surface improvements to meet airframe industry requirements, and it is suggested for further study using the Universal Component Specimen (UCS), as a generic testing specimen that was developed during this evaluation campaign.

## 2. The specimen for the experimental campaign

Figure 1 presents two practical typical examples for load carry items resulted in "bionic" like shapes by topologic optimization, compare to their conventional design.

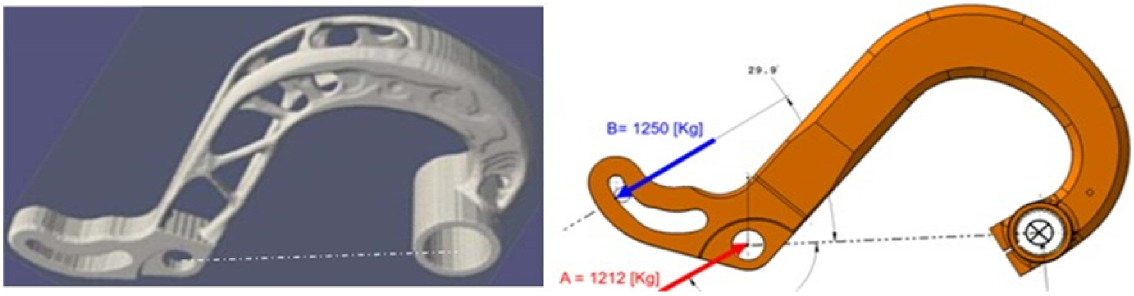


Figure 1a – "Gooseneck"-hinge-link example item.

**Note:** The very poor surface quality can be seen here for the AM part.

Figure 1b – Hinge for Elevator/Rudder example item.

Figure 1 – Examples for AM topologic optimization compare to conventional machining designs.

AM material's mechanical characteristics (Static & Dynamic), can be only partially evaluated by standard coupons per Quasi-Static [4], Crack-Initiation [5] and Crack-Growth [6] tests, for geometrically complex structures (as Figure 1 presents). Such standard coupons don't represent:

- Interactions between geometrical details (shapes, thickness gradients and radii) with AM manufacturing features (printing parameters and thermal mass gradients).
- Limited ability to improve surface quality at hidden radii and surfaces.

This study evaluation campaign required a testing element representing wide range of different complex structural features. This was achieved by using a Universal Component Specimen (UCS), as a generic specimen, for AM structural durability testing, developed at Israel Aerospace Industries (IAI) and printed at The Technion's Israel Institute of Metals, to fatigue evaluate different surface treatment techniques. The UCS represents the following structural features:

- Multiple load paths via branching and junctions ("bionic-like"), introducing 8 tensile stress concertation locations of Kt=3.16 (enables statistical distribution per specimen).
- Surface conditions presenting: (a) Geometrically complex structure having hidden radii and surfaces (not-accessible). (b) AM for "As-Build" print conditions (no surface treated), featuring poor surface texture and surface defects (of about 10 µm Ra roughness, whereas to meet fatigue requirements, surface quality should have Ra roughness less than 1.6 µm level).
- Local thermal mass and gradient rate differences (via thickness gradients) influencing powder solidification, to enable geometry details and AM-SLM technology interactions

UCS was printed by Titanium (Ti-6AL-4V) Powder Bed Fusion (PBF) of Selective Laser Melting (SLM) technology (by EOS M290 machine of 340 W Laser-Power, providing Print-Layer-Thickness of 60 µm), with the mechanically weakest axis, as parallel to part loading axis.

Figure 2 presents the UCS dimensions (2a), print tray arrangement and a close-up on the poor print surface quality (2b), and a unit loaded "StressCheck" [8] FEM stress analysis results (2c).

All UCSs were residual stress relieved Heat-Treated (Argon atmosphere chamber 2 hrs. 800ºC & optimize temperature control furnace cooled) with no pressure applied (no HIP procedure done).

Note: The specimens that were send to undergo Surface-Improvement-Treatments, all their diameter dimensions were increased by 0.3 mm to 0.5 mm.

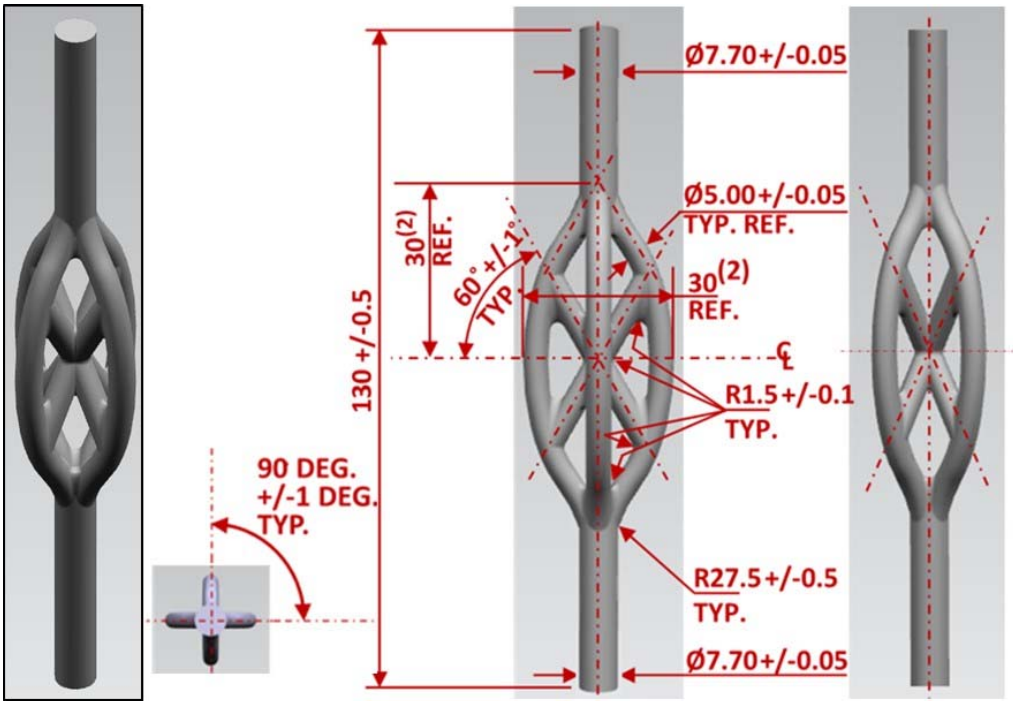


Figure 2a – UCS dimensions (in mm units).

Figure 2b – UCS printed ("AS-BUILD").

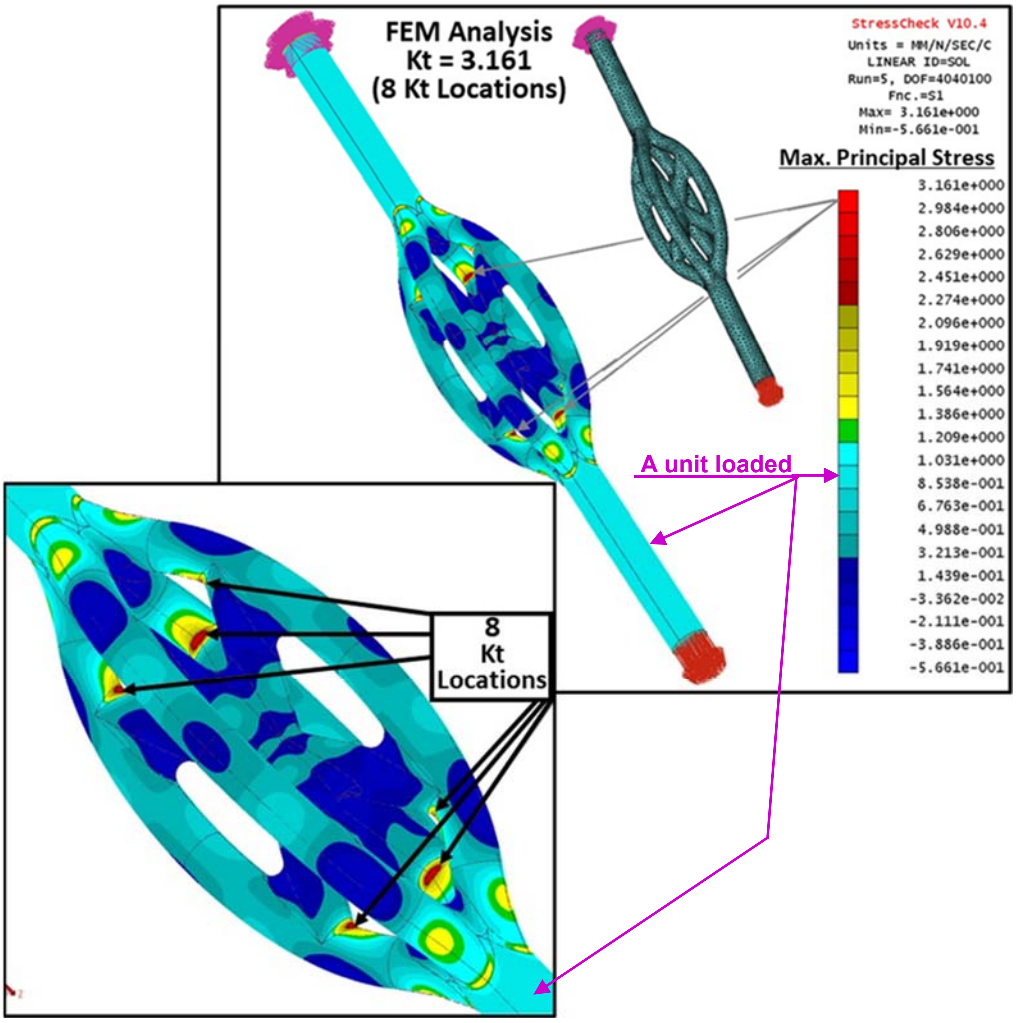


Figure 2c – UCS Finite Element Model (FEM) stress analysis results.

Figure 2 – Universal Component Specimen (UCS) used for AM structural durability fatigue testing.

## 3. The experimental procedure and results

UCS were cyclic tested (at The Technion's Israel Institute of Metals) for application of different state-of-the-art Surface-Improvement-Treatment-Techniques, to determine the influence of these techniques on fatigue resistance. As reference, also non-surface-treated specimens (i.e. printed "AS-BUILD" condition), were tested. The cyclic loading was for R=0.1 by Max. load of 2,650 Lb., providing 36.7 ksi as "remote-gross" stress at the 7.7 mm Diameter bar section, introducing 116 ksi at the stress concentration points. The test campaign is presented at Table 1, for the number of specimen's fatigue tested per each Treatment-Technique, and the test results presenting results range and the Weibull Statistics Characteristic-Life. The Treatment-Techniques are briefly described as follows:

- Chemical Electrochemical Liquid Media 1 & 2 (2 stands for an improved revision of the method) – Purely chemical & electrochemical process on bases of liquid media (non-mechanical grinding process).
- High-Frequency Movement in Liquid Media – A mechanical chemical process, of which the part moves relatively to a stay-still water-based media having small particles.
- Dry Electropolishing – Dry electropolishing is based on solid media for grinding and polishing metals by ion transport using free solid bodies (no usage of liquid).
- Plasma electrolytic Polishing (PeP) – Using a chemically neutral, non-toxic, water-based weak salt (i.e. ammonium sulphate) solutions as an electrolyte, of which the chemical composition of the used electrolyte is determined for each polished alloy specifically.
- Powder Blasting combined with PeP (PBPeP) – Prior to the above PeP procedure, a powder blasted (PB) procedure, having blasting material of spherical and irregular stainless-steel particles is applied, in order to reduce initial surface roughness before PeP.

Table 1 – Test Results per Surface-Treatment-Technique & Number of Specimens Tested.

| **Treatment-Technique Specimen Type** | | **Number of Specimens Tested** | **Fatigue Test Results** | |
|---|---|---|---|---|
| **Surface-Improvement-Treatment-Technique (Abbreviation)** | **Extra material all-around (extra per Diameter)** | | **Life Range to Fatigue Failure: Minimum – Maximum [Cycles]** | **Weibull Characteristic-Life to Fatigue Failure [Cycles]** |
| No Surface Treatment – AS-BUILD Condition (AS-BUILD) | 0.00 mm (0.0 mm) | **8** | **33,081 – 36,778** | **35,000** |
| Chemical Electrochemical Liquid Media – 1 (CELM-Rev.1) | 0.15 mm (0.3 mm) | **7** | **49,197 – 66,909** | **60,000** |
| Chemical Electrochemical Liquid Media – 2 (CELM-Rev.2) | 0.25 mm (0.5 mm) | **7** | **71,494– 128,286** | **106,000** |
| High-Frequency Movement in Liquid Media (HFMLM) | 0.15 mm (0.3 mm) | **6** | **60,149– 98,468** | **90,000** |
| Dry Electropolishing (DE) | 0.15 mm (0.3 mm) | **6** | **31,259 – 43,392** | **40,000** |
| Plasma electrolytic Polishing (PeP) | 0.25 mm (0.5 mm) | **8** | **66,687 – 92,962** | **84,000** |
| Powder Blasting combined with PeP (PBPeP) | 0.25 mm (0.5 mm) | **4** | **58,609 – 73,188** | **68,000** |

Figure 3 shows surface quality evaluation study (done at Afeka Engineering College) for "AS-BUILD" specimens (Ra per ISO4287/4288 was measured as15.12 µm surface roughness), and representative examples for the different Surface-Treatments. It should be mentioned that the quality of the different Surface-Treatments done could be fully evaluated only by the fatigue testing results. This was since surface roughness information wasn't fatigue strength indicative, for the following reasons (as fatigue strength is dependent on localize surface quality existing at stress concentration locations, i.e. the relevance of average surface quality results for majority specimen area has very limited meaning to fatigue strength level):

- Non-uniformity of the Treatments for the different specimen's surface areas (per outer to inner/hidden surfaces and per different shapes, thickness and radii).
- AM Defects emergence, as: dimples, indentations, tunnel-holes, powder remanence, etc.

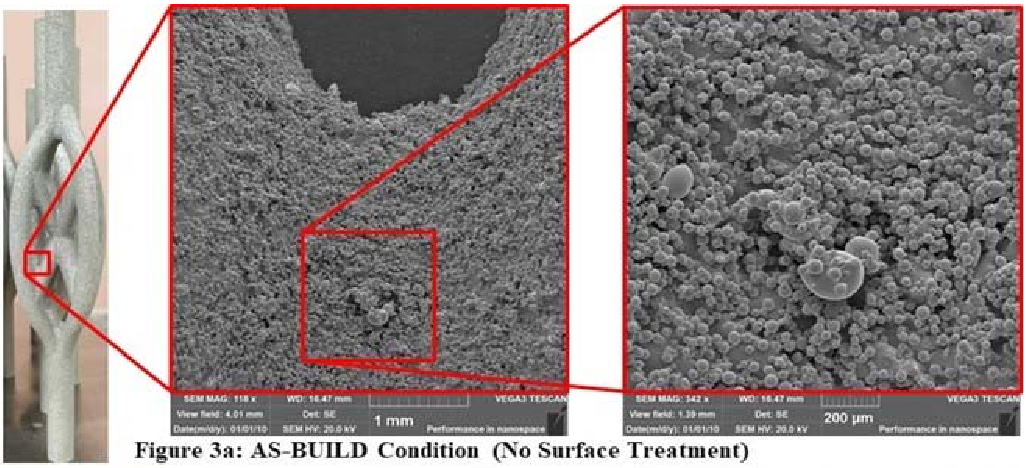


Figure 3a: AS-BUILD Condition (No Surface Treatment)

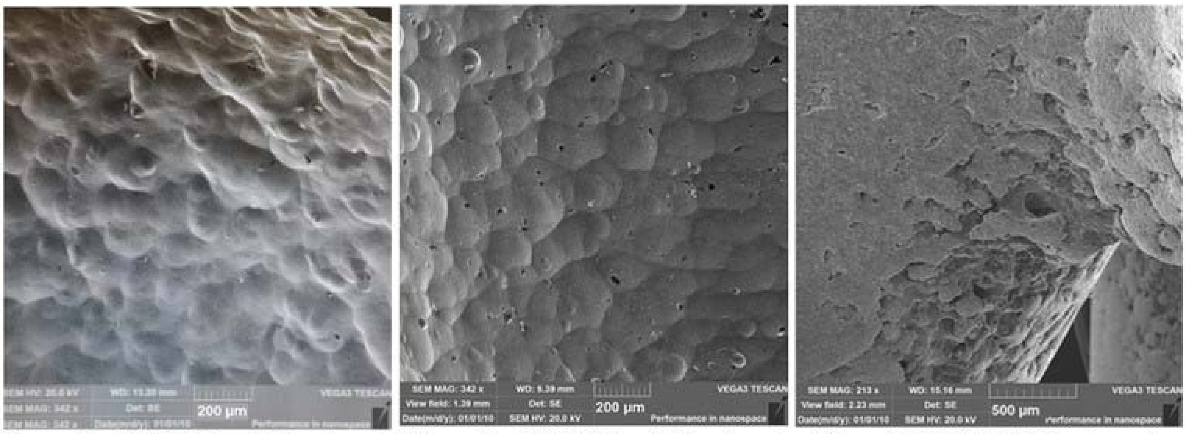


Figure 3b: CELM-Rev.1 Treatment Figure 3c: CELM-Rev.2 Treatment Figure 3d: HFMLM Treatment

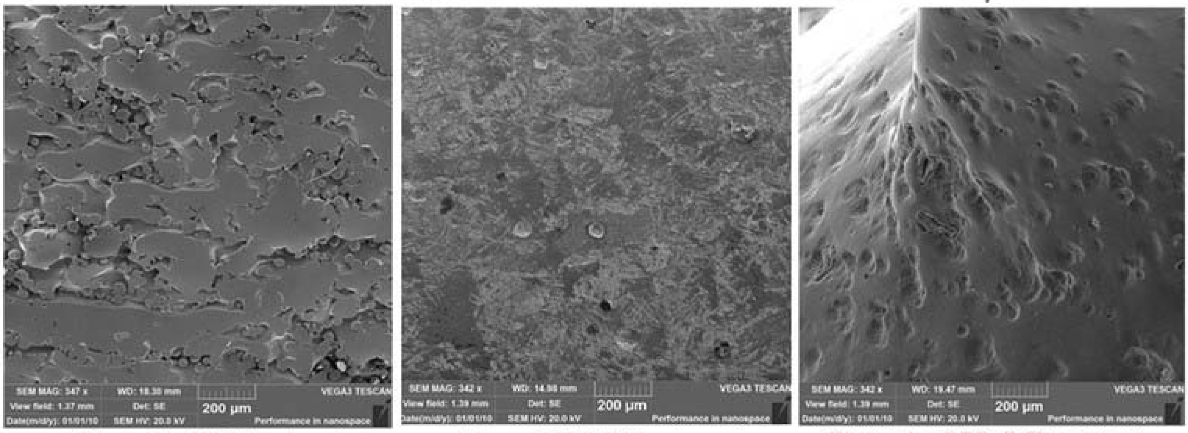


Figure 3e: DE Treatment Figure 3f: PeP Treatment Figure 3g: PBPeP Treatment

Figure 3 – Typical results for the different Surface-Treatment-Techniques

## 4. The experimental results evaluation

The fatigue test results were evaluated analytically (by IAI) and by a fractographic failure study (done at Afeka Engineering College). It was found that the surface treatments had shown fatigue improvement in a statistical sense that while the "AS-BUILD" surface condition had simultaneously developed primary cracking at all four branches of the specimen, for the surface treated specimens only one of the four specimens' branches had developed primary crack and other branches developed secondary cracking. But still, it was clearly seen that these surface treatments fatigue improvement was not enough in the statistical sense that: always there was one branch having surface defects compromising the required fatigue strength. Figure 4 presents the failure study results for the "AS-BUILD" surface condition specimens, showing: all four branches having significant fatigue cracking of more than 50% per each cross-section area (Fig. 4a), and fatigue cracking sources to be of surface furrows, and also fatigue ruptures at crack front propagation (Fig. 4b). On the other hand, Figure 5 presents the failure study results for the PeP surface treatment specimens (as a typical representation for the different surface treatments done), showing: that only one of the four branches had shown significant fatigue cracking, for about 90% of its cross-section area (while other three branches had shown secondary fatigue cracking of about 65%, 25% and 5% per each branch cross-section area). Figure 5 shows fatigue cracking sources to be of surface dimples and indentations (that may be caused by surface treatment), and also shows fatigue ruptures at crack front propagation.

Figure 6 presents the fatigue test results for the tested specimens, analytically evaluated per Ref. [3] and the data of the MMPDS Handbook [7] (the reasoning for using Ti-6AL-4V Kt=3 Sheet-Configuration MMPDS data, is presented in Figure 6 per [2]). The analytical evaluation accounts for the test maximum cyclic load providing of 36.7 ksi as "remote-gross" stress (σrem.) at the specimen's 7.7 mm diameter bar section, of which introduces 116 ksi at the stress concentration points of Kt=3.16 (Ktσ) for 36.7X3.16=116 ksi. The stress level to be accounted via the MMPDS for Kt=3, is 116/3=38.7 ksi. For the plasticity effects converting the geometric Kt to account for the material's sensitivity to fatigue, a Plasticity Factor of 1.192 (per [3]), is used as 1.192X38.7=46.1 ksi for acquiring the required fatigue life out of the MMPDS(Kt=3) to be 600,000 cycles (to be considered as the minimum required fatigue life). Figure 6 presents by different colors the fatigue test results and Weibull Characteristic life for each of the Surface-Improvement-Treatment-Technique tested and for the reference specimens having the "AS-BUILD" surface condition (including also an equivalent stress level presentation corresponding to each specified fatigue life).

An airframe load carrier structural item (considered as a primary structural member caring flight and ground cyclic loading) needs to meet fatigue requirements and regulations, as Principal Structural Element (PSE) per [1]. Usage of AM technology to produce such PSE that benefits from topologic optimization design (creating complex geometries), must undergo surface quality improvement (by innovative surface treatments) being effective and efficient to meet the fatigue requirements. Efficiency factor of a surface treatment technique can be evaluated by fatigue tests campaign for Fatigue-Improvement (FI) results in terms of:

FI = [Surface treated fatigue life] / ["As-Build" print condition fatigue life].

For this study, the minimum required Fatigue-Improvement (FImin.), was:

FImin.=17 (per 600,000 cycles of analytical min. life / 35,000 cycles per "As-Build" life)

None of the state-of-the-art surface treatment techniques tested, efficiently eliminated surface-defects, to meet the fatigue requirements, as all this study surface treatments tested resulted in: Minimum FI = 1.14 ; Maximum FI = 3.03.

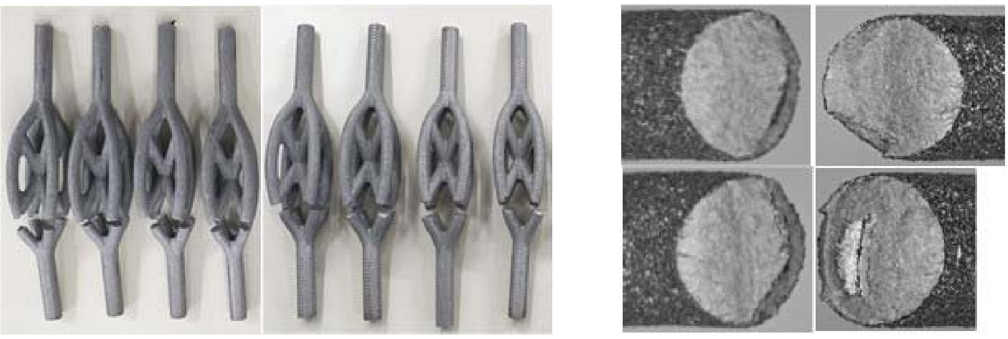


Figure 4a – Macro-view on the four specimens' branches.

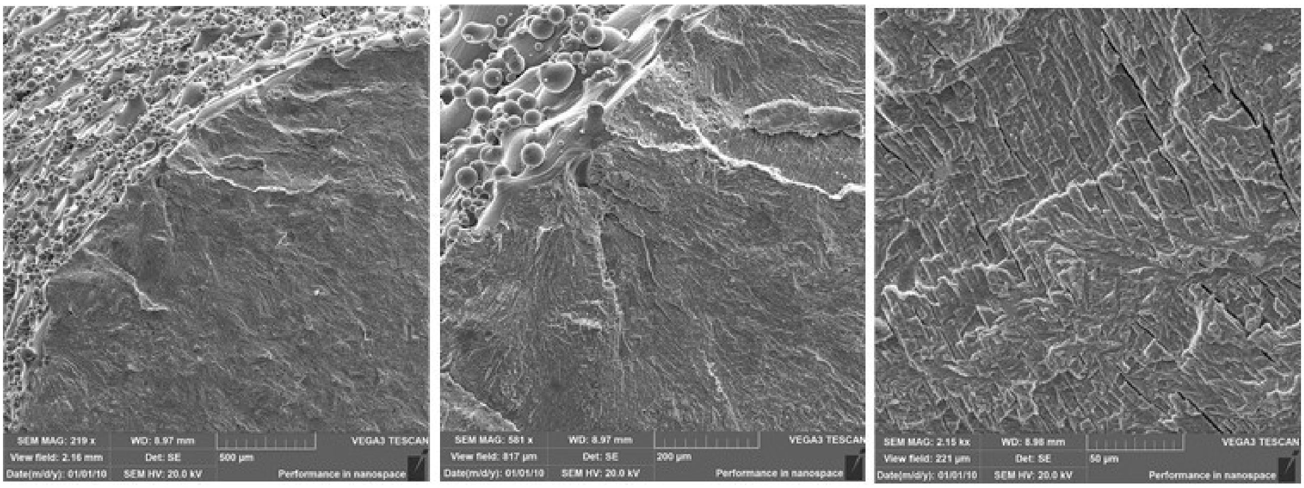


Figure 4b – Fractographic failure study results.

Figure 4 – Failure study results for the "AS-BUILD" surface condition specimens.

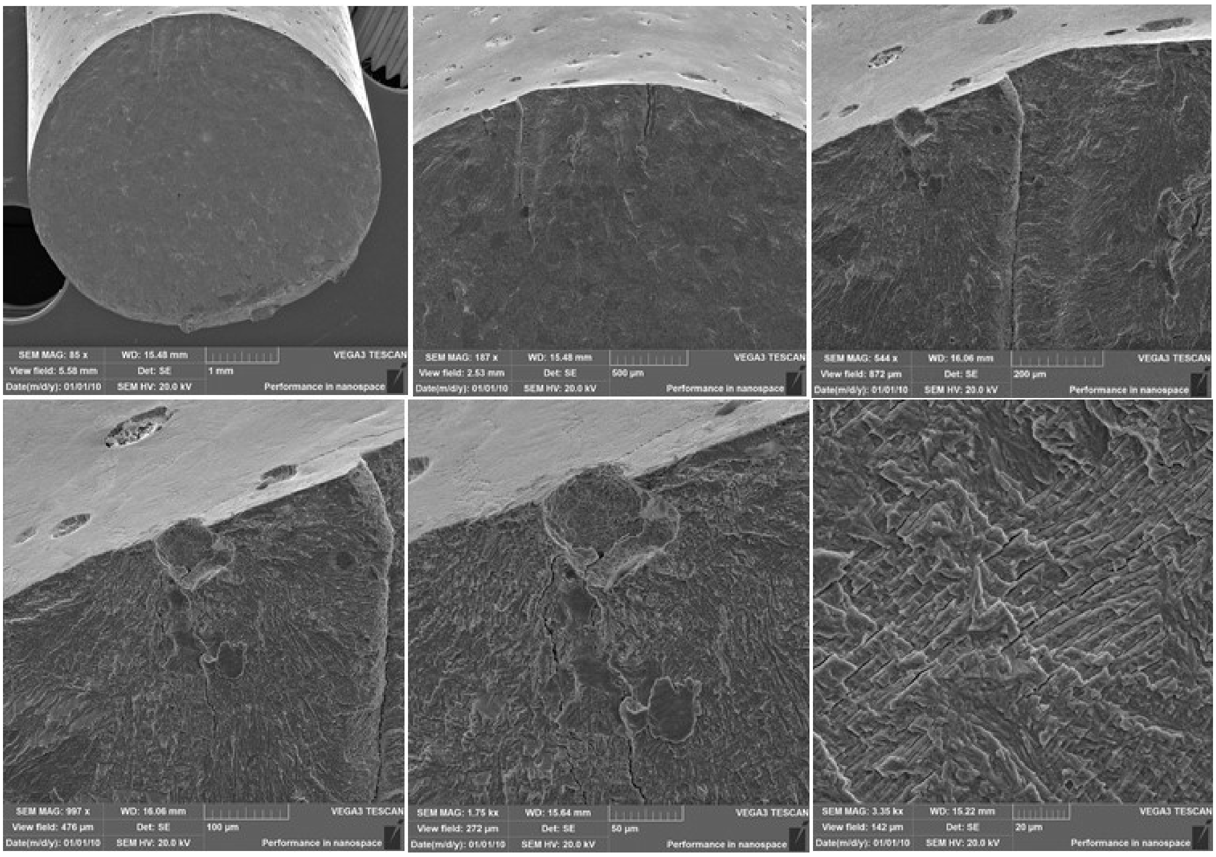
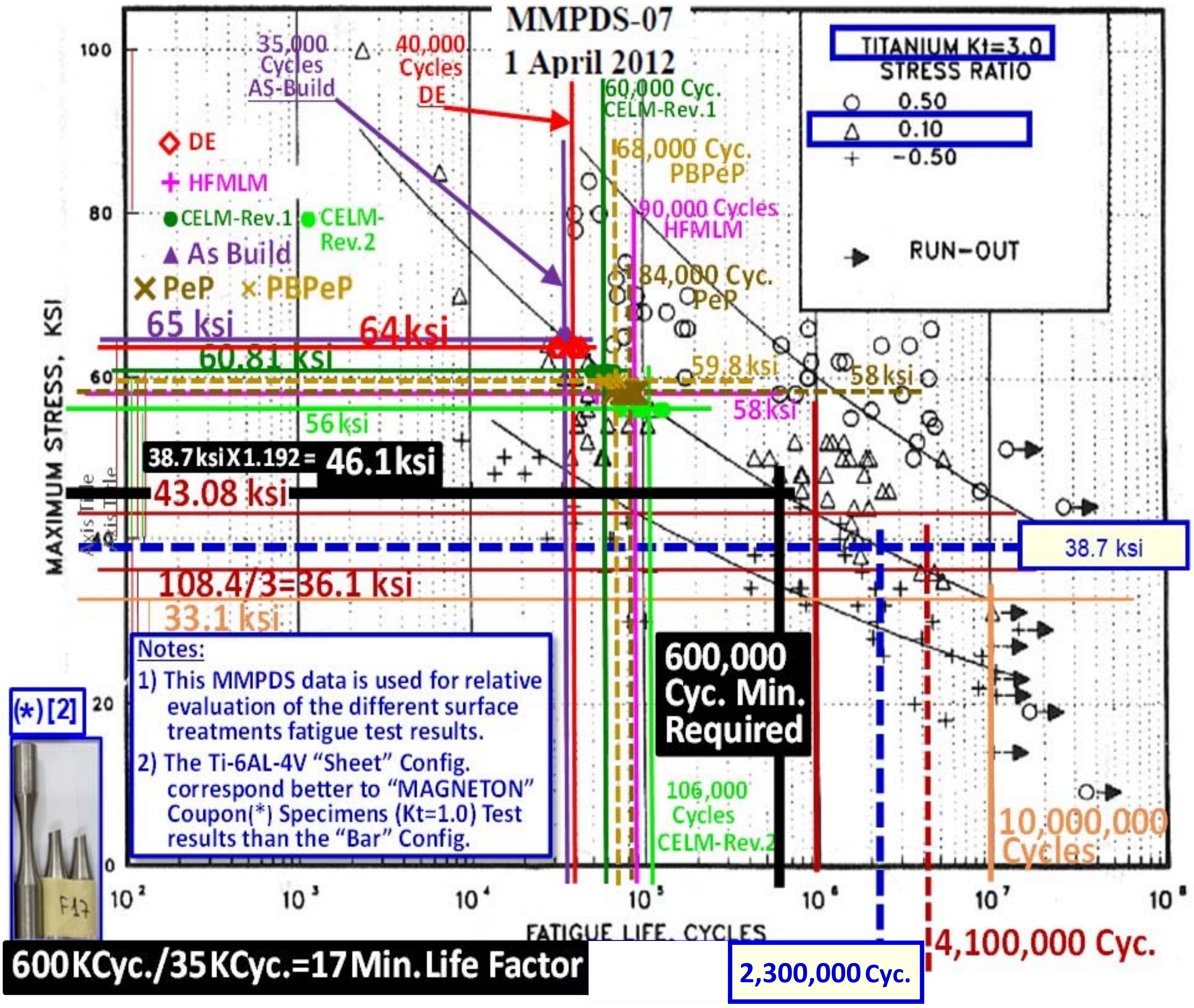


Figure 5 – Failure study results for the PeP surface treatment specimens.



Notes:
1) This MMPDS data is used for relative evaluation of the different surface treatments fatigue test results.
2) The Ti-6AL-4V "Sheet" Config. correspond better to "MAGNETON" Coupon(*) Specimens (Kt=1.0) Test results than the "Bar" Config.

Figure 6 – Fatigue test results evaluation for the tested specimens

## 5. Conclusions

This study evaluation, to meet fatigue strength requirements, for airframe load carrier structural items intended to be produced by AM technology, conclude that:

- The state-of-the-art surface treatment techniques tested, did not provide adequate surface quality improvement.
- The generic Universal Component Specimen, developed for this study, is useful for future surface treatment developments evaluation.
- Applicability of needed surface quality improvement technique, should be considered in early design phase.
- Surface quality improvement techniques should consider combination of:
  Surface-Improvement-Technics (as may be further developed technics per this study) +
  Surface-Enhancement-Technics (as Laser-Shock-Peeing, Phot-Peening, etc.), which should be further studied and tested.

## 6. Contact Author Email Address

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## 7. Copyright Statement

## References

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[6] ASTM E647-15, Standard Test Method for Measurement of Fatigue Crack Growth Rates.

[7] MMPDS Handbook - Metallic Materials Properties Development and Standardization (MMPDS): The primary source of statistically-based design allowable properties for metallic materials and fasteners used for commercially and military aerospace applications (recognized by certifying agencies within their limitations: including FAA, DoD and NASA).

[8] "StressCheck" FEM Computer Program, Version 10.1, June 2014, by ESRD.