

The fourth European Conference on the Structural Integrity of Additively Manufactured Materials (ESIAM26)

Probabilistic assessment of space components manufactured by PBF-LB

Lorenzo Rusnati^a, Guglielmo Landi^{b,c}, Mauro Ravaoli^b, Stefano Beretta^{a,d,*}

^aPolitecnico di Milano, Department of Mechanical Engineering, via La Masa 1, 20156 Milano, Italy

^bLEONARDO S.p.A. Space Business Unit, Via delle Officine Galileo, 1, 50013 Campi Bisenzio, FI, Italy

^cInternational PhD Programme, UNESCO Chair “Environment, Resources and Sustainable Development”, 80143 Naples, Italy

^dAuburn University, National Center for Additive Manufacturing Excellence (NCAME), Auburn, AL 36849, USA

Abstract

The use of additive manufacturing in aerospace fields is strictly linked to the capability to assess the harmful effect of process anomalies. In this sense, non-destructive evaluations permit the characterization of flaws, which can be employed in fatigue life estimates of parts considering their service lives. X-ray computed tomography proves particularly effective for metal powder bed fusion process, with the ability to recognize gas porosity and lacks-of-fusion from sub-optimal local printing parameters. Nonetheless, the accuracy of the inspection is strongly dependent on the achievable voxel size, which is determined from the part's bulk.

This study proposes a probabilistic fatigue assessment methodology to evaluate the fatigue life of additively manufactured components. This method discusses the reliability of the X-ray computed tomography in terms of probability of flaw detection and of sizing error. Through a suitable fatigue strength model and considering the various uncertainties within the approach, the methodology can estimate the failure probability of a part depending on the applied stress and on the required life. The relationship between stress, defect and life is based on fracture mechanics concepts, since it is built based on the characterization of material properties from experimental tests conducted on standard specimens.

The methodology is then applied to benchmark components, manufactured in laser powder bed fused Ti-6Al-4V. The components are brackets for satellite applications sustaining an optical payload. Once manufactured, the parts were inspected through X-ray computed tomography at two voxel sizes, 16 μm and 60 μm . The components were then tested in fatigue on a shaker in a setup that models the original configuration on the satellite; the fatigue load is injected as a sinusoidal excitation at constant frequency and acceleration. The experimental and predicted lives are hence compared, to evaluate the accuracy and bias of the estimates.

© 2026 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the ESIAM26 organizers

Keywords: Additive manufacturing; Fatigue; Non-destructive testing; Probability of failure

* Corresponding author. Tel.: +39-0223998246.

E-mail address: stefano.beretta@polimi.it

1. Introduction

Among the additive manufacturing (AM) processes, laser powder bed fusion (PBF-LB) is distinguished for its great versatility and net-shape possibilities. In recent years, metal components for aerospace applications have been manufactured by PBF-LB [Blakey-Milner et al. \(2021\)](#), supporting the wide expansion of the technology. The application of the PBF-LB process is hindered by the formation of anomalies, generated by localized sub-optimal manufacturing parameters. These anomalies present notable differences in formation cause, morphology and density; nonetheless, these flaws must be assessed to demonstrate an acceptable fatigue strength in light of the parts' qualification [Seifi et al. \(2016\)](#).

Fracture mechanics theory is the typical approach that is adopted for evaluating the structural integrity of components in relation to the presence of defects. Flaws are in fact treated as short cracks and assessed using the concept of stress intensity factor (SIF), linked to the [Murakami \(2002\)](#) size parameter $\sqrt{\text{area}}$, i.e. the square root of the defect area projected on the plane on which the stress is applied. Fracture control standards of relevant space agencies [NASA \(2025\)](#); [ECSS \(2021\)](#) prescribe the assessment of structural, fatigue critical components by crack propagation calculations adopting [NASGRO v10.0 \(2023\)](#). Under a deterministic perspective, these standards require the verification of parts with the application of a service life factor η of 4; the initial defect size is either observed by non-destructive evaluations (NDE) or bounded through the detection capability.

The preferred inspection technique for the characterization of defect population in AM parts is X-ray micro-computed tomography (μ CT) [Han et al. \(2024\)](#). The method is in fact particularly favorable for the inspection of internal flaws, with a spatial resolution that is measured as the size of the voxel. The achievable resolution is affected, among other factors, by the bulk of the part and by the distances between X-ray source, scanned object and detector. The resolution impacts the minimum observable defect size [Senck et al. \(2020\)](#): false negatives may occur in larger number as the resolution lowers, and the size of the detections can be affected by a large scatter. These phenomena are evaluated through a probability of detection [Perghem et al. \(2025\)](#) and sizing error [Rusnati et al. \(2024\)](#) analyses, in which the results μ CT scans at multiple resolutions are compared.

The present work focuses on the manufacturing of aerospace components by PBF-LB/Ti-6Al-4V, their inspection by μ CT scan and the subsequent fatigue testing. The adopted component is an isostatic mounting device (IMD) bracket; the system, which is a proprietary technology of Leonardo S.p.A., is used to sustain the optical heads of spaceborne payloads by providing structural stiffness while ensuring an efficient thermal decoupling between the optical assembly and the surrounding spacecraft structure. This architecture effectively limits the transmission of thermo-elastic and hygro-elastic distortions, allowing the optical head to maintain its alignment stability. The mounting system is constituted of three brackets, a pair of which is identical, as displayed in Fig. 1a.

2. Experimental campaign

The IMD brackets were manufactured by PBF-LB in Ti-6Al-4V with a Renishaw AM500Q system equipped with four 500 W ytterbium lasers. A total of 5 parts were manufactured in a single job. The manufacturing occurred in an inert environment through Ar purge and with the baseplate pre-heated at 170 °C. The main manufacturing parameters were the same ones employed to characterize the fatigue and crack propagation performance of the alloy in a previous study by [Risposi et al. \(2025\)](#). After the completion of the job, the parts were stress relieved at 650 °C for 2 hours, followed by furnace cooling. The outcome of the manufacturing process is shown in Fig. 2. The parts' interface regions were then machined after the removal from the build plate. A set of 3 out of the 5 manufactured components was printed with a deliberately induced defect located in the part's most stressed region, labeled as "B" in Fig. 1b, at a depth of approximately 0.5 mm from the external surface. This artificial anomaly was obtained by seeding a spherical void with a radius of 0.45 mm in the CAD of the parts prior to their manufacturing.

All the components were inspected via X-ray micro-computed tomography (μ CT). The maximum resolution that was achieved with a full-scale inspection corresponded to a voxel size of 60 μ m. In addition, the components with the deliberately-induced anomaly were inspected at a higher resolution: the region of the CAD-seeded void was scanned with a voxel size equal to 16 μ m. The μ CT scans were analyzed with Dragonfly 3D World and segmented with global threshold values determined with the triangle method [Steinhilber et al. \(2024\)](#) to characterize their porosity.

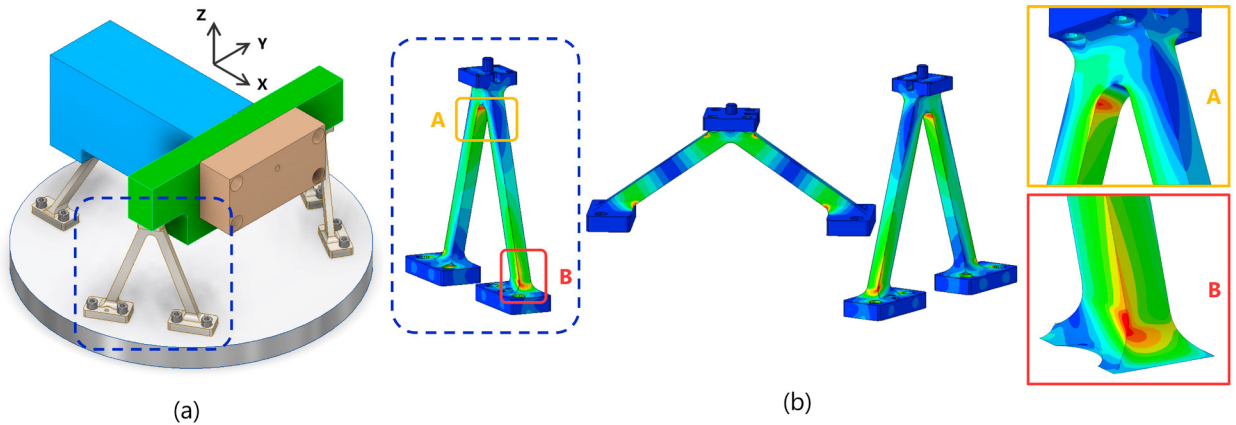


Fig. 1. Setup for the fatigue testing (a) schematics of the assembly; (b) FE analysis and detail of the most stressed locations.

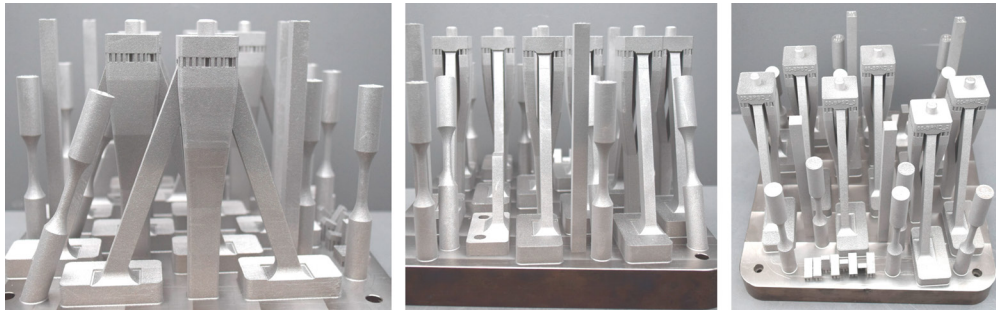


Fig. 2. Outcome of the manufacturing process.

The components with artificial defect were tested in high cycle fatigue regime on the Ling Dynamic System V960 shaker, equipped with 80 kN of dynamic excitation capacity. The fatigue tests were conducted with a constant frequency, constant amplitude sine vibration, below the first resonant mode of the unit under test consisting of IMD and dummy mass to simulate the mechanical behavior of the optical head. The acceleration was injected at the IMD interface through an interface plate. The frequency and acceleration amplitude were selected to achieve a stress range equal to 360 MPa in region "B", with region "A" reporting a stress range of 336 MPa. For the fatigue tests, the IMD comprised of a PBF-LB component, two conventionally manufactured parts to complete the isostatic mounting and a dummy 26.6 kg mass (see Fig. 1a). Each test was preceded by a resonance search to confirm the magnitude of the eigenfrequencies. The tests were monitored using PCB tri-axial accelerometers mounted on the dummy mass and interface plate and through mono-axial strain gauges attached on the component. The interruption of the tests was ruled by a change in acceleration response, which would be followed by liquid penetrant inspection of the artificial defect's region to inspect the crack's extent. After fatigue failure, fracture surfaces were observed through SEM to identify and measure the failure-initiating defects.

Following the execution of the fatigue tests, a component's leg was used for surface roughness measurements in the down-facing areas (i.e., the inner part of the leg and the upper cusp region). The measurements were done by focal variation microscopy using Alicona system.

Along with the components, fatigue specimens were manufactured with the same parameters and conditions of the IMD brackets. In total, 24 specimens were produced. Half of the specimens was manufactured in vertical orientation, the other half with an inclination of 70° with respect to the build plate (same orientation of the components' legs). Prior to their fatigue testing, all the specimens were inspected by μ CT at a voxel size equal to 16 μ m to determine the distribution of the internal anomalies. The specimens were tested under a uniaxial load at a stress ratio equal to

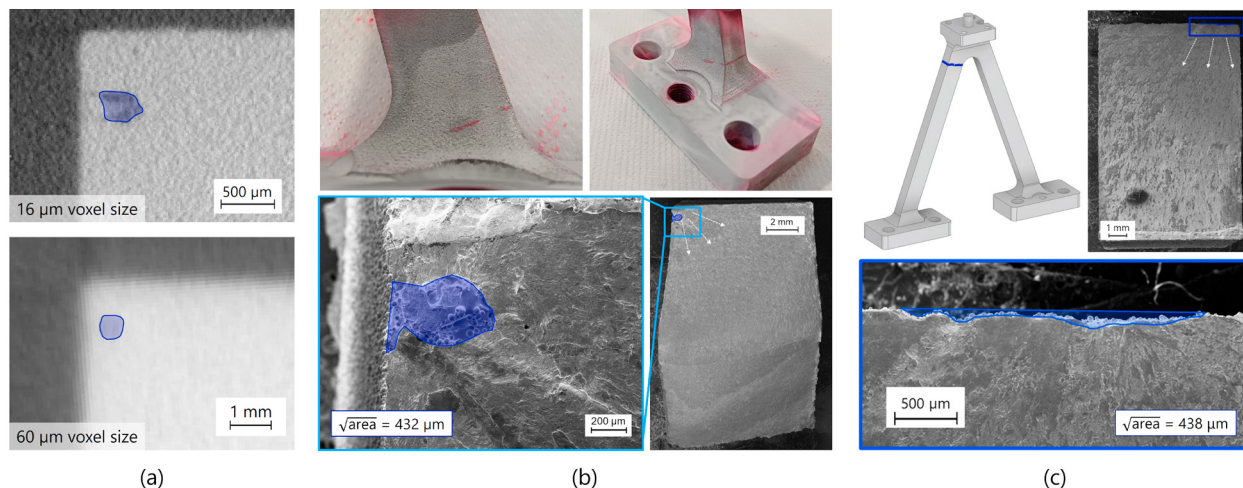


Fig. 3. Experimental results on components: (a) example of deliberately induced flaw observed through multi-resolution μ CT; (b) fatigue failure of a part from liquid penetrant testing and SEM observation of the artificial defect; (c) fatigue failure of component 3 from a surface anomaly.

-1. Eventually, scanning electron microscopy (SEM) was employed to inspect the fracture surfaces and to observe the failure-initiating flaws.

3. Results

Only the components with deliberately induced anomalies were tested. The outcome of the tests is listed in Tab. 1 in terms of experimental life and type of failure-initiating defect. As seen, two components had their artificial defects as points of failure initiation, whereas component 3 failed from a naturally-occurring net-shape surface anomaly located in region "A". Fig. 3a and Fig. 3b show the outcome of the experimental campaign of component 2 in terms of μ CT, liquid penetrant testing and SEM observation of the fracture surface. Fig. 3c, instead, shows the location of failure and the crack-initiating anomaly of component 3.

Table 1. Outcome of the fatigue tests.

Component	Seeded defect type	Experimental life	Failure from artificial defect?	Predicted life (NASGRO)
1	Surface-breaching	395,000 cycles	YES	360,000 cycles
2	Sub-surface	451,000 cycles	YES	386,000 cycles
3	Embedded	415,000 cycles	NO - surface feature	

Concerning the μ CT inspections, the CAD-seeded voids were successfully observed at both 16 μ m and 60 μ m voxel size (see Fig. 3a). The scans revealed some variations in the outcome of the seeded flaws: in one case, the void was located in the intended position, with a ligament of approximately 0.1 mm from the free surface; in another example, the edge distance was higher, classifying the defect as internal; lastly, one anomaly was exposed to air because of the thin ligament. With reference to the fatigue specimens, porosity data from μ CT scans were analyzed with the statistics of extremes to determine the distribution of the internal anomalies. The peak-over-threshold technique was employed to fit a two-parameter negative exponential function, as reported Fig. 4c and in Tab. 2.

The results of tests on fatigue specimens were initially analyzed by separating the samples by their inclination. The S–N curves showed little differences in slope and fatigue limit, as seen in Fig. 4a. All the anomalies at the root of failure were therefore aggregated and analyzed through extreme values statistics by fitting a largest extreme values distribution (LEVD) (Fig. 4b). The control volume pertaining to the failure initiating defects was the volume of the

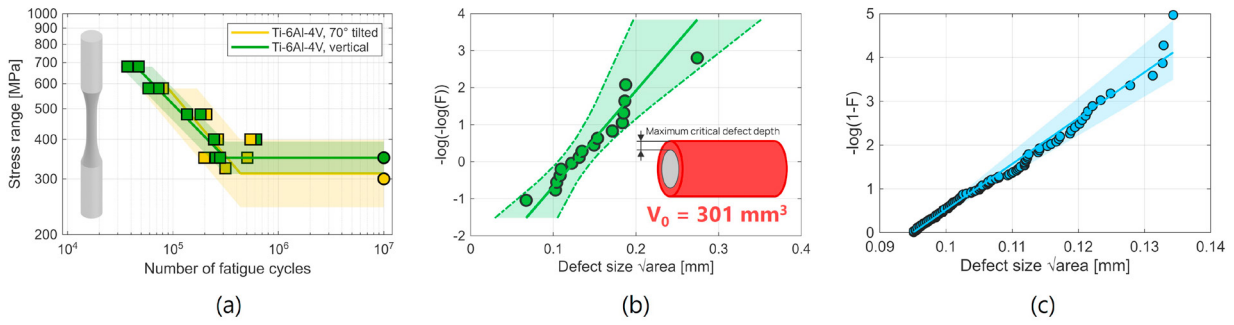


Fig. 4. Results from the experimental campaign on fatigue specimens: (a) S–N curve; (b) extreme values statistics of the failure-initiating anomaly sizes; (c) extreme values statistics of the internal defects detected by μ CT scan.

hollow cylinder identified by the gauge region's diameter and by a depth equal to the maximum critical defect's depth (200 μm).

Surface roughness measurements conducted on the components were analyzed with a similar approach: block maxima sampling of the depth of valleys, S_v , permitted the description of the LEVD fitting the largest surface features in the two regions. The S_v parameter was translated into an equivalent $\sqrt{\text{area}}$ value by scaling it by $\sqrt{10}$. The parameters of the different distributions are listed in Tab. 2.

Table 2. Extreme values distributions of the different populations of anomalies, with indication of the source.

Anomaly population	Source	Distribution type	Position parameter	Scale parameter	Control parameter
Internal defects	μ CT scan of specimens	Negative exponential	$u = 95 \mu\text{m}$	$\sigma = 9.6 \mu\text{m}$	$V_{ref} = 452 \text{ mm}^3$
Surface defects	Fractography	LEVD	$\lambda = 125.8 \mu\text{m}$	$\delta = 38.7 \mu\text{m}$	$S_{ref} = 301 \text{ mm}^2$
Surface defects – cusp	Roughness measurement	LEVD	$\lambda = 537.3 \mu\text{m}$	$\delta = 147.9 \mu\text{m}$	$S_{ref} = 2 \text{ mm}^2$
Surface defects – down-facing	Roughness measurement	LEVD	$\lambda = 195.0 \mu\text{m}$	$\delta = 89.4 \mu\text{m}$	$S_{ref} = 2 \text{ mm}^2$

4. Discussion

The test campaign on the components revealed two remarkably different defects at the origin of the failures. On two cases, the artificial flaw was responsible for the rupture of the part, whereas the third component's fracture revealed a surface-related shallow anomaly. The two deliberately induced voids at the root of failure were observed with the μ CT inspection, while the roughness defect was not detected. Because of these differences, as discussed by Park et al. (2024) in a NASA technical memorandum, two assessment routes were established to assess the life of these parts: the undetected critical defect imposes a fully probabilistic assessment, whereas the evaluation of the detected deliberately induced anomalies follows a NDE-informed approach.

As a common trait, all the assessment routes relied on a predetermined stress-defect-life relationship. This link was derived from the application of fracture mechanics theory. Two separate crack types, surface and embedded, were propagated under a fatigue load of constant amplitude in a section which is representative of the component's critical region. By recording the number of fatigue cycles to failure for varying stress amplitudes and initial crack sizes, a full material database was obtained. The procedure had been outlined in a previous work by part of the authors Rusnati et al. (2026) and tested on different PBF-LB items of various alloys. From the same article, the authors collected the uncertainty related to the presented fatigue strength model, devised as a coefficient of variation $CV_{\Delta\sigma_{w,0}}$ and determined by analyzing the scatter of the predicted lives in comparison with experiments. For this alloy, with identical manufacturing and post-processing parameters, the value was 0.08.

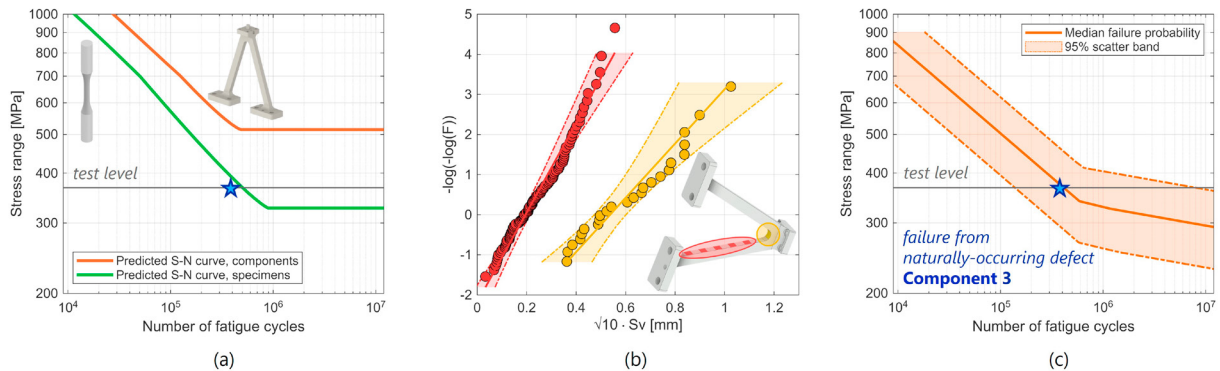


Fig. 5. Steps of the probabilistic assessment of the IMD bracket: (a) considering the expected defect size from the surface flaws' population; (b) statistics of extremes for the down-facing regions (red) and cusp region (yellow); (c) output of the zone-based assessment through ProFACE software.

4.1. Probabilistic assessment

The probabilistic analysis of the components shall rely on the possibility to predict their fatigue life on the basis of the fatigue specimens' data. In this sense, the statistics of extremes allow the transfer of distributions of defects' populations on different scenarios. With this perspective, the IMD brackets were analyzed employing the distributions of surface failure-initiating anomalies determined on fatigue specimens' fracture surfaces. The distribution was extrapolated on the component's V_{90} , i.e. the volume subjected to the top 10th percentile of maximum principal stress, determined through the FE analysis and equal to 3.64 mm³. Because of the smaller volume, the expected median defect size $\sqrt{\text{area}_{50\%}}$ resulted to be 40 μm , significantly lower than the median anomaly size of specimens (127 μm). Fig. 5a reports the expected S–N curve of the components, determined by querying the stress-defect-life relationship with the median flaw size. It is clear that the prediction fails to capture the fatigue failure of component 3.

To establish an accurate prediction of the failure from the naturally-occurring defect, a zone-based fully probabilistic assessment strategy was adopted. For this task, ProFACE software was used. The software processes the results of the FE analysis of the part (stress and volume) to derive the failure probability of the item through a weakest-link approach. In detail, the statistics of extremes is adopted to determine the likelihood of occurrence of a defect in a model's sub-region (either volume or surface). In this application, it was chosen to exploit a zone-based assessment: different areas of the component were associated with different defect populations, using the database listed in Tab. 2. Volumetric defects from μCT scans were linked to the evaluation of the volume, the distribution of roughness obtained on the cusp region was adopted for the same zone (see Fig. 5b, yellow area), the population of down-facing surfaces was associated with the inner surfaces of the legs (Fig. 5b, red area) and the surface defects from SEM imaging of specimens was linked to every other surface. The fatigue cycles associated with a 50% failure probability are shown in Fig. 5c for a varying applied stress. The graph is complemented with the bilateral 95% band of the probability of failure. It is evident that the zone-based assessment manages to accurately predict the fatigue failure occurred from the surface roughness feature.

4.2. NDE-informed assessment

The fatigue failures of components that were initiated by CAD-seeded voids were analyzed adopting a NDE-informed framework. The goal was to predict the fatigue failure of the parts on the basis of the detection of the defects by low resolution μCT . Following the assessment route prescribed by fracture control of aerospace parts, the deliberately induced flaws were assessed with NASGRO [NASGRO v10.0 \(2023\)](#) software.

The sub-surface deliberately induced defects were analyzed adopting NASGRO software's crack mode "EC04", whereas the surface-exposed flaws with "SC31" crack type. In all cases, a bivariate stress intensity factor solution was used to model the stress state of the part's section. Crack propagation and threshold parameters were obtained

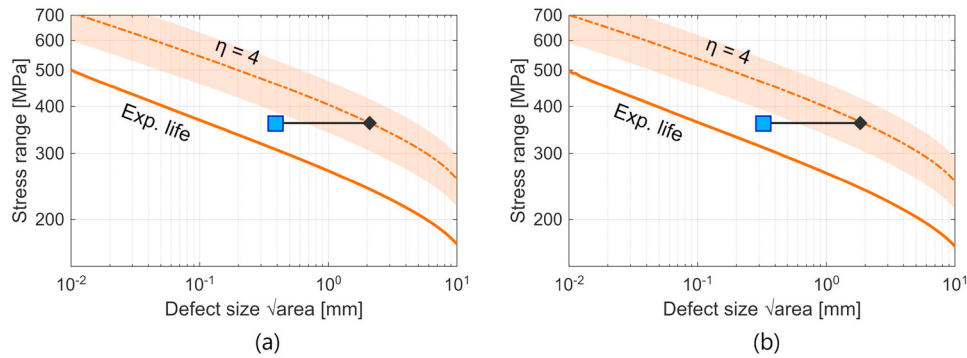


Fig. 6. NDE-informed assessment of: (a) component 1; (b) component 2. The solid line represents the critical defect curves calculated for the fatigue life of each component, the dashed line marks the critical defect sizes with the application of a service life factor η of 4 and the shaded region indicates the 95% bilateral scatter of the fatigue strength model.

by Risposi et al. (2025) with fatigue crack growth specimens. The maximum principal stress applied to the section containing the defect was derived from the FE analysis. In absence of an automatic transition between different crack types, the sub-surface crack was manually converted into a surface ("SC31") and then corner ("CC09") type at the interruption of each propagation caused by the exceedance of the solution validity range; this operation was conducted without substantially altering the crack dimensions.

As the assessment was performed from the size determined by the low resolution μ CT, a statistical analysis of the detection capabilities was conducted. The sizing error was derived by evaluating the bias and scatter of the 60 μ m voxel size inspections of parts with artificial defects, with respect to 16 μ m voxel size inspections of the same items. A set composed of 2 components and 6 fatigue specimens was used for the analysis; all the parts had deliberately induced anomalies, seeded with the same strategy and dimension. The $\sqrt{\text{area}}$ parameter of the artificial flaws was found to have a negligible bias (-1.4 μ m), while the dispersion of the inspected size was $\sigma_{\sqrt{\text{area}}} = 32.6 \mu\text{m}$.

The results of the predictions are listed in Tab. 1. For both components whose failure-initiating defect was detected the experimental outcome is accurately predicted, maintaining a conservative trend mainly ascribed to the crack nucleation cycles.

Alternatively, defects' criticality can be captured by a NDE-informed analysis that considers the stress-defect-life relationship based on the crack propagation database. Fig. 6 shows the sizes (from the 60 μ m voxel size scans) and stresses (from the FE analysis) pertaining to the two artificial defects with the blue marker. These flaws are displayed in relation with the critical defect curves computed for the respective experimental lives. In addition, the graphs report the critical defect curves derived from the application of the required service life factor of 4. From the diagrams, it is possible to observe the prediction of the critical condition for the two anomalies, located beyond the critical curve. Additionally, by considering the $\eta = 4$ curve, for the same applied stress level the acceptable defect size would be 1.9 mm and 2.13 mm for the two components.

5. Conclusions

This work explored the assessment methodologies for the evaluation of defects in an aerospace component manufactured in Ti-6Al-4V by laser powder bed fusion. The isostatic mounting device brackets were inspected by X-ray micro-computed tomography and subsequently fatigue tested through dynamic stressing on a vibration shaker. The main results can be summarized as follows:

- The components were successfully manufactured with nominal printing quality and with deliberately induced anomalies, located in critical regions.
- A fully-probabilistic assessment with a zoning logic managed to estimate the fatigue life of parts with naturally-occurring flaws.

- Micro-computed tomography was able to observe the artificial defects, and a sizing error analysis was established using inspections at multiple resolutions.
- In light of the reduced sizing error, the low resolution inspection was successfully employed for the detection-based assessment of defects through NASGRO software; the results showed the critical condition of such flaws and the prospective acceptable defect size using a service life factor of 4, as per fracture control regulations.

Acknowledgements

The activities presented in this work were supported by the European Space Agency under AO/1-11042/22/NL/AR grant agreement (Smart-ProFACE project, in partnership with: Politecnico di Milano, The Manufacturing Technology Centre, BEAMIT, Leonardo and Thales Alenia Space - France).

References

- Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F. and Du Plessis, A., 2021. Metal additive manufacturing in aerospace: A review. *Materials & Design*, 209, p.110008.
- Seifi, M., Salem, A., Beuth, J., Harrysson, O. and Lewandowski, J.J., 2016. Overview of materials qualification needs for metal additive manufacturing. *Jom*, 68(3), pp.747-764.
- Murakami, Y., 2002. *Metal fatigue: effects of small defects and nonmetallic inclusions*. Academic Press.
- ECSS-E-ST-32-01C Rev. 2. Space engineering - fracture control. 30 July 2021, p. 1–105.
- NASA-STD-5019A w/CHANGE 4. Fracture control requirements for spaceflight hardware. Approved: 2024-07-29, Revalidated: 05-09-2025, National Aeronautics and Space Administration.
- Han, S., Dinh, T.D., De Baere, I., Boone, M., Josipovic, I. and Van Paepegem, W., 2024. Study of the effect of defects on fatigue life prediction of additive manufactured Ti-6Al-4V by combined use of micro-computed tomography and fracture-mechanics-based simulation. *International Journal of Fatigue*, 180, p.108110.
- Senck, S., Hapfl, M., Reiter, M., Scheerer, M., Kendel, M., Glinz, J. and Kastner, J., 2020. Additive manufacturing and non-destructive testing of topology-optimised aluminium components. *Nondestructive Testing and Evaluation*, 35(3), pp.315-327.
- Perghem, D., Salehnasab, B., Beretta, S., Shao, S. and Shamsaei, N., 2025. ML-based detection of critical defects in additively manufactured parts via X-ray computed tomography. *Materials & Design*, p.115184.
- Rusnati, L., Yosifov, M., Senck, S., Hubmann, R. and Beretta, S., 2024. Anomaly detection by X-ray tomography and probabilistic fatigue assessment of aluminum brackets manufactured by PBF-LB. *Materials & Design*, 248, p.113467.
- Risposi, T., Rusnati, L., Patriarca, L., Hardaker, A., Luczyniec, D. and Beretta, S., 2025. Fatigue of Ti6Al4V manufactured by PBF-LB: A comparison of failure mechanisms between net-shape and electro-chemically milled surface conditions. *Engineering Failure Analysis*, 172, p.109403.
- Steinhilber, F., Lachambre, J., Coeurjolly, D., Buffiere, J.Y., Martin, G. and Dendievel, R., 2024. A methodology for the 3D characterization of surfaces using X-ray computed tomography: Application to additively manufactured parts. *Additive Manufacturing*, 84, p.104144.
- Park, A.M., Tilson, W.G., Wells, D.N., Lang, C.G. and Kantzos, C.A., 2024. Agency Additive Manufacturing (AM) Certification Support Team (AACT) Risk Reduction-Safe Life Category: Fracture Control Framework for Un-inspectable Fracture Critical AM Parts (No. NESC-RP-21-01678).
- Rusnati, L., Minerva, G., Patriarca, L., Miccoli, S. and Beretta, S., 2025. Comparison of methods for the determination of fatigue critical flaw size and implementation for probabilistic fatigue assessment. *International Journal of Fatigue*, p.109252.
- South West Research Institute. NASGRO reference manual version 10.0. 2023.