International Committee
on Aeronautical Fatigue
and Structural Integrity

ICAF

Review of Aeronautical Fatigue Investigations in Germany during the Period of April 2021 - April 2023

Abstract

This review represents a compilation of abstracts on aeronautical fatigue investigations in Germany during the period from April 2021 - April 2023. It will be published on the ICAF website, as well. The contribution of summaries by German aerospace manufacturers, governmental and private research institutes, universities as well as aerospace authorities was voluntary, and is acknowledged with sincere appreciation by the author of this review. Enquiries concerning the individual contents shall be addressed directly to the author of the corresponding summary.

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1 INTRODUCTION

This review represents a compilation of abstracts on aeronautical fatigue investigations in Germany during the period from April 2021 - April 2023. It will be published on the ICAF website https://www.icaf.aero/ and presented during the ICAF 2023 – the 38th Conference and 31st Symposium of the International Committee on Aeronautical Fatigue and Structural Integrity. All related information is available on the ICAF 2023 Website https://www.icaf2023.nl/

The contribution of summaries by German aerospace manufacturers, governmental and private research institutes, universities as well as aerospace authorities (Table 1) was completely voluntary, and is acknowledged with sincere appreciation by the author of this review.

Enquiries concerning the individual contents shall be addressed directly to the author of the corresponding summary.

Table 1: Overview of contributing companies and institutes

Abbreviation	Details
AIRBUS	Airbus Operations GmbH; Kreetslag 10, 21129 Hamburg, Germany, www.airbus.com
AIRBUS CRT	Airbus Central Research & Technology, Willy-Messerschmitt-Strasse 1, 82024 Taufkirchen, Germany, www.airbus.com
HZH	Institute of Materials Mechanics and Institute of Materials Physics, Helmholtz-Zentrum Hereon, Max-Planck-Str. 1, 21502 Geesthacht, Germany, www.hereon.de
IABG	Industrieanlagen-Betriebsgesellschaft mbH, Einsteinstraße 20, 85521 Ottobrunn, Germany, https://www.iabg.de/en/
IFL	Technische Universität Braunschweig, Institute of Aircraft Design and Lightweight Structures (IFL), Hermann-Blenk-Str. 35, 38108 Braunschweig, Germany, https://www.tu-braunschweig.de/ifl
IVW	Leibniz-Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str. 58, 67663 Kaiserslautern, Germany, www.ivw.uni-kl.de
PPI	Institute for Production Technology and Systems, Leuphana University of Lüneburg, Universitätsallee 1, 21335 Lüneburg, Germany, www.leuphana.de/en/institutes/ppi.html

2 FATIGUE CRACK GROWTH AND LIFE PREDICTION METHODS

2.1 Acceleration of Large Scale Fatigue Tests: LUFO 6.2 Project Rapid EF Enablers

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The development time of current aircraft design is driven by time consuming major fatigue tests (EFx) to validate the structural integrity under fatigue loading. In the scope of development time reduction for new aircraft below 5 years the major fatigue test has to be performed in an earlier time frame than before and the test preparation, run time and inspection down time has to be reduced significantly.

The state of the art test and validation methods do not have currently the potential for further improvements to reach the 5 years development time goal. New test methods need to be created and prepared using enhanced digitalisation (Big Data), automation and simulation (digital twins) and enhanced quicker control system means.

In the frame of the aerospace research program LUFO 6.2 Airbus and a partner network are addressing this challenge with the public-funded project “Rapid EF Enablers” (Fig.:1). The goal is to reduce the lead-time of a large-scale fatigue test by improving the individual phases and avoiding or minimizing the need for interruptions of the test progress.

Figure 1: Rapid EF Enablers partners

The ambition is to achieve the performance of 1 fatigue life before the first flight of the aircraft (Fig.:2). The project is organized in three work packages addressing the test preparation, the cycling, and the downtime for interventions and inspections.

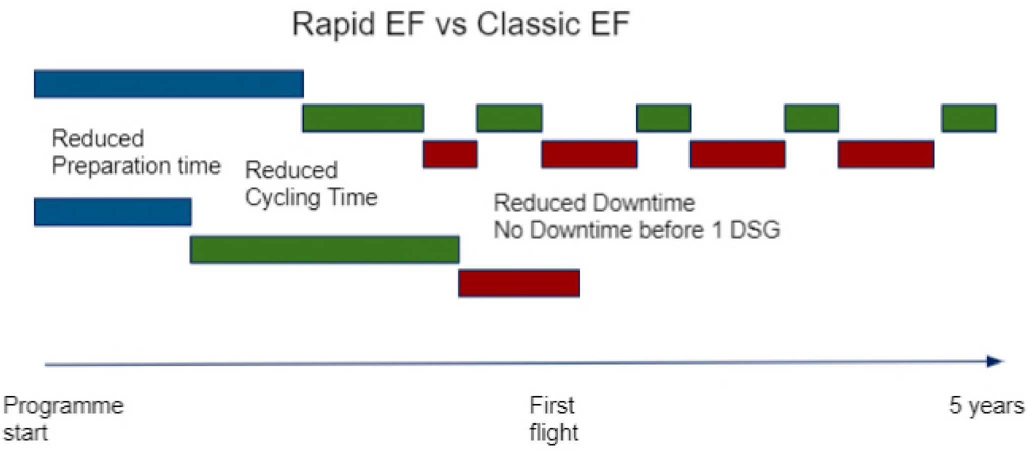

Figure 2: Major Fatigue Test Lead Time reduction

The main methods investigated in the three work packages are:

1. Reduction of the test preparation time by using virtual sensors
   Virtual sensors will be used in structural areas with limited access after manufacturing. They will use a digital twin of the specimen under simulated testing conditions. The digital twin calibration is locally supported by physical measurements (strain gauges, DIC methods) in order to allow an enhanced prediction of the specimen deformation and deflection in areas that would require difficult and time consuming instrumentation.

2. Reduction of the test cycling time by allowing operation close to resonance
   For long and slender test specimens (e.g. wings, stabilizers) the first resonance frequencies of the test set-up will become relatively low. An excitation with a frequency close to this would result in excessive deformation and unrealistic fatigue up to structural overloading. The prediction of the response function of the test specimen including the test rig allows for an adapted excitation that provides realistic specimen behavior closer to the resonance frequency.than today.

3. Reduction of the test downtime by using automated inspection and data analysis
   Non-contact automated inspection methods and health monitoring methods allow surveillance of the test specimen without interrupting the fatigue test cycling. In addition, the automated analysis of the captured data using AI algorithms will allow detecting potential damages before becoming critical, thus removing the need for regular inspection stops.

The three project work package pillars are shown in Fig.:3.

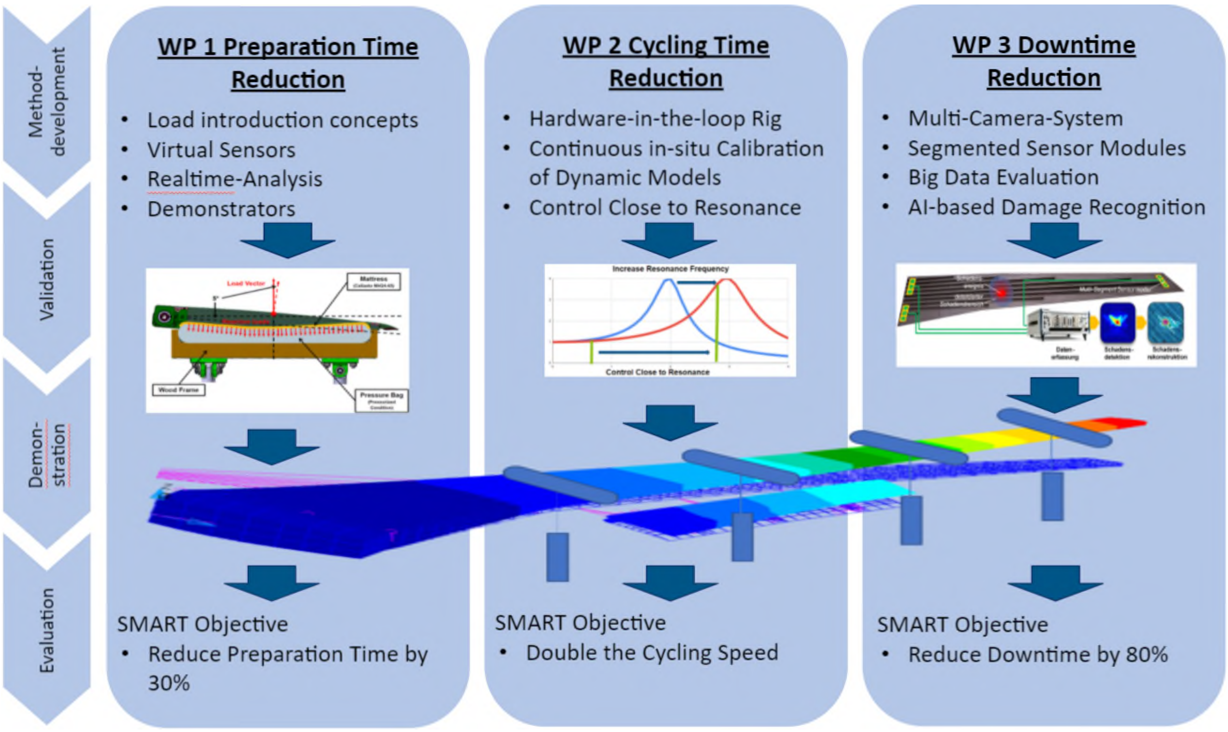

Figure 3: Rapid EF Work Package structure

The project Rapid EF Enablers has been granted in 2022 by the German ministry of Economic Affairs and Climate Action and is currently progressing on all three work packages.

3 LIFE EXTENSION AND MANAGEMENT OF AGING FLEETS

3.1 IABG Integrity Management in the Context of Service Life Enhancement for the German Air Force Tornado Fleet

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The excellence in reconnaissance, low-level flight and air to ground attack of the **W**eapon **S**ystem (WS) Tornado are key competences of the **G**erman **A**ir **F**orce (GAF) tactical capabilities. Additionally, extensive in-service experience, continuous system development and amortization have led to operational efficiency on both, the tactical and financial domain. All this makes the WS Tornado still attractive to extend the in-service usage up to 8000 **f**light **h**ours (FH) until the **O**ut of **S**ervice **D**ate (OSD). The so-called **S**ervice **L**ife **E**nhancement (SLE) program was finally established in the year 2016. IABG has supported the GAF in terms of integrity management for the WS Tornado since its entry into service in the early 1980s, and now also in all questions regarding structural integrity for the SLE with a special National Structure Integrity Team. The IABG roles in terms of structural integrity management are blue highlighted in Figure 4.

Figure 4: IABG Integrity Management Support for the German Air Force Tornado Fleet and the key Contribution from SHM

Strategies were developed in close collaboration with the System Design Responsible Companies (Airbus Defense & Space, BAE Systems, Leonardo), the military airworthiness authority and with the GAF to extend the service life up to 8000 FH.

The WS Tornado was originally designed for 4000 **P**erformance **D**esign **R**equirement flight **h**ou**r**s (PDR-hrs). The fatigue capabilities of **S**tructural **C**ritical **I**tems (SCI), representing safety or mission critical parts, have been proven in the qualification process:

- by the **M**ajor **A**irframe **F**atigue **T**est (MAFT performed by IABG, left hand picture in Figure 2) for the primary structure,
- in several component tests (e.g. for control surfaces, undercarriage, taileron, etc.) for the secondary structure,
- and/or by analysis.

Structural **H**ealth **M**onitoring (SHM) provides the contribution in the context of exploiting the structural integrity, and especially in the realization of SLE for an aging aircraft by allowing a comparison between the fatigue qualification and the in-service usage. Thus, the life consumption can be determined and hence the potential for SLE (Figure 5) can be identified.

As mentioned above the primary structure has been qualified by the MAFT. Totally 20988 simulated flight hours were tested, which resulted in a qualification of 5247 PDR-hrs, considering a **s**catter **f**actor of SF = 4 and the structure is free of damage. Findings during the MAFT are therefore less qualified and are monitored by the IABG during in-service operation. These SCIs need special measures, such as inspection, modification or even replacement, to reach the SLE goal of 8000 FH. The MAFT spectrum is driven predominantly by maneuver loads (g-loads) and aircraft weight. These parameters, and in addition to other flight parameters, are recorded and monitored by the Tornado SHM System “OLMOS” (**O**nboard Life **MO**nitoring **S**ystem). In general, the SHM demonstrated that the in-service spectrum is at least 33% less severely damaged compared to the MAFT spectrum. This results in the capability of SLE up to estimated 8000 equivalent safe flight hours if the mission profile does not change significantly until OSD ($\frac{5247\, PDR-hrs}{(1-0.33)\frac{PDR-hrs}{FH}}$).

A basically same approach is applied for the unmonitored structures (secondary structure) to estimate the SLE capability. The fatigue damage is less depending on the OLMOS parameters for the unmonitored structure – it is more driven by its characteristic function. The **U**sage **I**ntensity **P**rofile (UIP), which may be monitored by the **F**light **D**ata **R**ecorder (FDR), has to be determined to estimate the life consumption and therefore the SLE capability. If UIP data are not existing, special measures have to be performed:

- Performance of an **O**perational **L**oad **M**easurements (OLM) to determine the life consumption and to estimate the SLE capability.
- Application of artificial intelligence to get UIP, using training and validation data from other sources such as OLM data from the Royal Air Force, to determine life consumption.

- Strict execution of measures according to the fatigue qualification, performing inspections, modifications, and replacements after fixed flight hour intervals.

IABG acts in the context of SLE as the data collector and data analyst for the GAF, provides a lifetime estimation and suggests measures for the safe SLE of the monitored and unmonitored structure up to 8000 FH. IABG does also align the requirements (e.g. special technical order due to in-service incidents) with the existing measures, e.g. inspection. All the examinations are summarized in technical memorandums and in proformas, which are the basis for further discussion with the GAF and SDR partners and for the approval by the military airworthiness authority to fulfill the SLE requirement of 8000 FH.

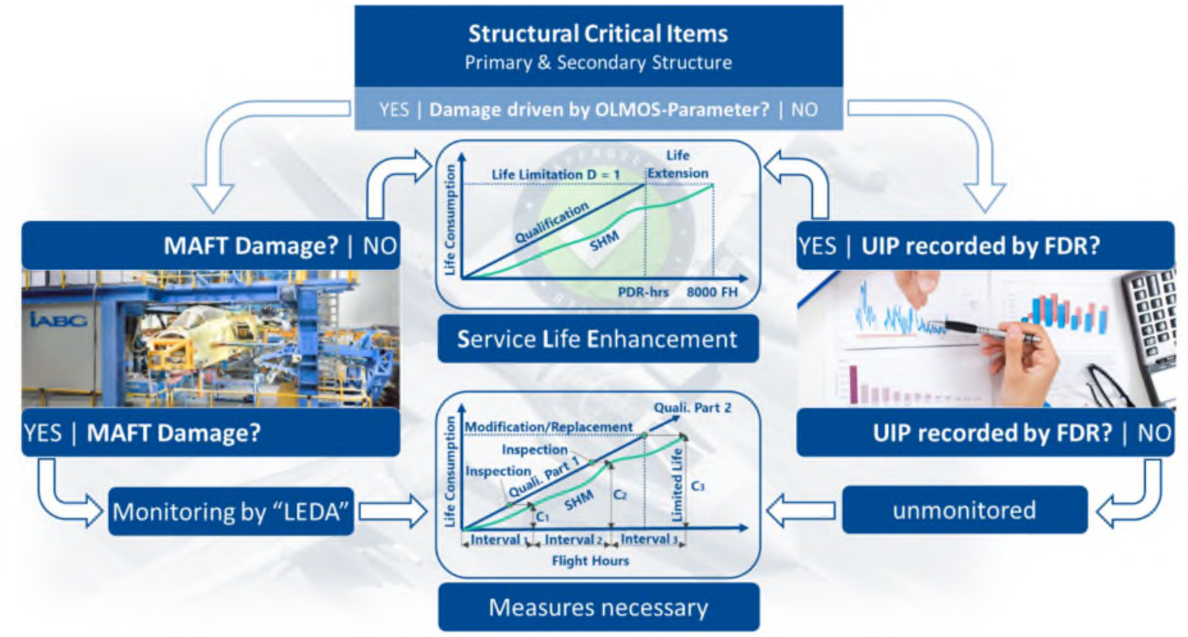

Figure 5: General Strategy of Tornado Service Life Enhancement

4 STRUCTURAL INTEGRITY OF COMPOSITE LAMINATES

4.1 Testing of a Co-Cured Composite Frame Panel by the Application of Vacuum as an Alternate to Frame Bending Test

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The Frame Bending Test (FBT) of fuselage panels is plagued by complex design at load introduction regions, high workload for assembly of specimen to test rig and the need for disassembly for access to stiffened structure. An alternative to the FBT was explored by the application of vacuum on the skin side of the panel using a metallic fixture while the frame side of the panel is subjected to atmospheric pressure. The vacuum level can be controlled to obtain the desired differential pressure.

A curved composite panel was designed with three co-cured corrugated frames and eight stringers under the InFuSe (**In**tegral **Fu**selage **S**h**e**ll Concepts) Project between CSIR-NAL and Airbus. The shear clips, to stabilize the frame web laterally, were eliminated by the corrugation of the web. A metallic fixture was developed to mount the panel to enable application of vacuum. The finite element (FE) analysis of the panel mounted on the fixture was carried out to understand the structural response. The desired circumferential strains in the panel were achieved by the proper sizing of the vacuum fixture. The location of strain gauges, Digital Image Correlation (DIC) regions and dial gauges were guided by FE analysis. Acoustic Emission (AE) was also monitored during the test.

Two vacuum tests were carried out with vacuum levels of 100 mbar and 20 mbar. The structural responses were measured both during loading and unloading. The first test was stopped at 100 mbar vacuum pressure because of increased AE activity. Post-test ultrasonic scan of cocured joints showed disbonds in the frame and stringer crossover regions in proximity to metallic fixtures. Rivets were installed on disbonds to prevent the further growth. Subsequently, the panel was loaded up to 20 mbar vacuum pressure and the panel withstood the vacuum pressure successfully. Ultrasonic scan was carried out on co-cured joints and showed no disbonds. The structural response in terms of deflections and strains were correlated well with FE simulations.

The proposed Vacuum Test (Figure 6) has advantages like smooth and uniform load introduction, quick assembly and economical. It also allows quick access to specimens for DIC, NDE and other sensors on frame side during the test and presents itself as an alternative to FBT.

Figure 6: Test set up of a fuselage panel tested by Vacuum Test

5 ADVANCED MATERIALS AND INNOVATIVE STRUCTURAL CONCEPTS

5.1 Investigations on Multiple Fatigue Influences and Limits of Cross-Ply Laminates under VHCF

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The research in the Very High Cycle Fatigue- (VHCF-) regime is scarce, because of difficulties in testing specimens and structures up to 10^8 load cycles (LC). The most important ones are long testing times (up to 231 days under 5 Hz), specimen heating under high testing frequencies and self-fatigue of the test equipment.
To overcome these difficulties Adam et al. [1] developed a specialized four-point bending test rig using an electrodynamic actuator. The test rig is capable of determining the in-situ bending modulus and damage states over the total fatigue test time. Adam and Horst [2-3] conducted test series with cross- and angle-ply laminates with multiple specimens on different load levels up to 10^8 LC. The used glass fibre/epoxy composite provides excellent transparency and enables damage detection via transmitted light photography.

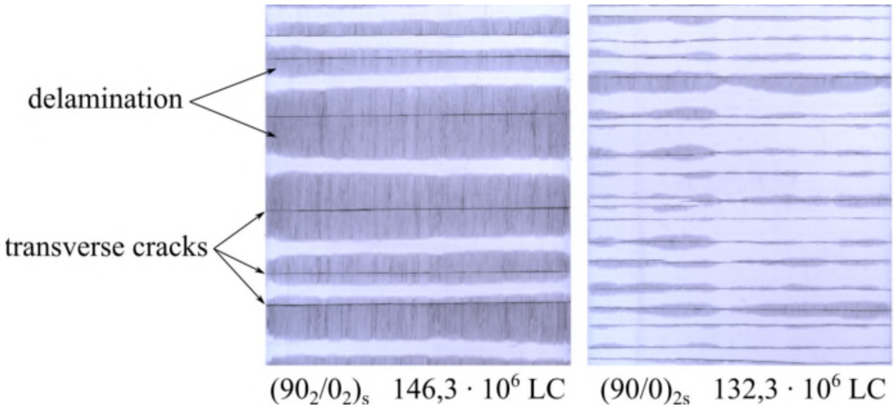

Figure 7: Typical damages for two cross-ply laminates with 0.5 mm (left) and 0.25 mm ply thickness

Fatigue damages in cross-ply laminates under four-point bending are mainly transverse cracking in the outer 90° layer and from the crack tip growing delamination along the interface to the adjacent 0° layer. These damages are visible in Figure 7 for two specimens with low crack density as well as large delamination areas (left) and vice versa (right).

Based on the work of Adam and Horst, the further development of the test rig and six test series are conducted, to research the influences of different

- materials (presented at DLRK22, article appearance in CEAS mid 2023),
- ply thicknesses (ICAF23),

- stress ratios (ICCM23) and
- loading types

in the VHCF-regime.

In case of different materials, it can be shown that an improved fiber-matrix-adhesion leads to higher damage initiation limits and lower crack densities, but also to stronger delamination growth. For thinner ply thicknesses the commonly known fact that thinner plies encourage higher crack densities can be extended to the VHCF-regime.

A rare investigation is the comparison between alternating and swelling loads. Four point bending under swelling loads enables the differentiation between compression and tension on the two sides of the specimen. It is found that even for the highest load level, no damage occurred on the compression side. On the tension side the crack densities are lower compared to the alternating tests, but the delamination areas are larger. Using a numerical transverse crack and delamination simulation (FEM), it can be shown that the dominant damage mechanism, concerning bending modulus degradation, changes from cracks to delaminations. Comparing uniaxial tension fatigue to four-point bending, first damages occur at lower loads for tension loading.

Another focus of the investigations is the determination and prediction of fatigue limits. At first, the crack initiation prediction model developed by Hosoi and Kawada [4] is verified for four-point bending with good accordance between initiation predictions for both loading types.

Furthermore, an approach for determination of a crack growth limit using a linear regression of crack growth rates under different load levels is made. Using the normalization of the crack initiation model from Hosoi et al., the crack growth limit of the different stress ratios and loading types can be matched. To normalize the influence of ply thicknesses, the approach has to be further advanced. In the end a delamination growth limit is specified in terms of stress intensity factors, using fatigue damage saturation states.

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5.2 Fatigue Analysis of Overmolded Hybrid Composite Structures

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Overmolding of reinforcing elements enables the designers to optimize the design of a component by choosing different fibers and matrices based on load application. The main advantage of this technique includes net shape potential, short cycle time and high production rate. In this process, continuous fiber reinforced inserts are pre-heated and overmolded with short fiber reinforced composite through injection molding. Topology optimization is required to determine highly loaded areas where the continuous reinforcement could be placed. [1] Hence, these parts show high integration possibilities with localized high structural mechanical strength, which makes it popular for aircraft parts. However, preheating and overmolding develops residual stresses in the part, which in turn reduce the fatigue life. Due to the combination of two different manufacturing processes and materials, the prediction of fatigue life is challenging.

Therefore, the focus of this study was to analyze the lifetime of a hybrid composite structure and its failure mechanism. An exemplary hybrid composite coupling rod is taken for this study as a demonstrator [2, 3]. This demonstrator is made by molding of short glass fiber reinforced polyamide 6 (PA6) over a circular loop made by UD tape of continuous glass fiber reinforced PA6 with higher fiber volume fraction (Fig. 8). Such types of coupling rods are used in different actuation tasks in aviation as well as for chassis in commercial vehicles. The design is optimized taking consideration of realistic load variations. However, the fatigue test is done for only one stress ratio and loading frequency currently.

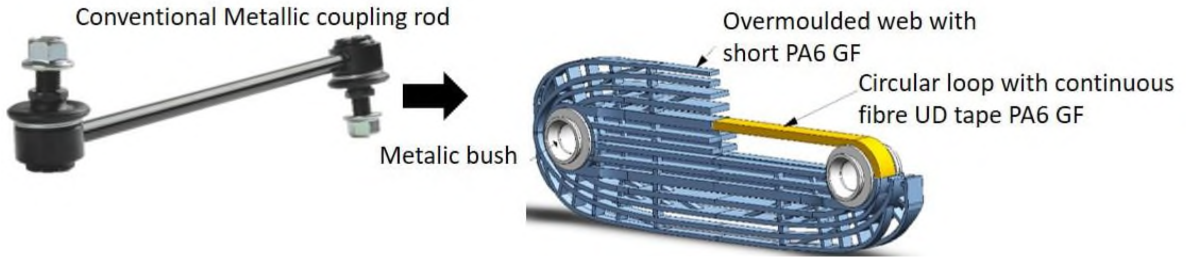

Figure 8: Overview of the demonstrator used for lifetime analysis

The demonstrator is around 420 mm long and 140 mm wide. A test fixture is manufactured to conduct fatigue testing. Special arrangement is made in the test fixture to assure inline movement of the specimen. Tensile and compression tests are done using the same test fixture to determine quasi-static failure loads. A hydraulic testing machine PSB 250 was used. The maximum tensile load was 122 kN whereas compressive load was 51 kN. The higher tensile load is due to the presence of the circular loop of UD laminate. In case of compression, the specimen failed due to delamination between loop and short fiber reinforced web. Hence, the load ratio selected for fatigue testing was not -1 but the ratio of quasi-static tensile and compressive load which is R = -0.42.

For fatigue testing, the maximum and minimum load are +38 kN and -16 kN, respectively, at 1 Hz frequency. Visual inspection to determine delamination and its growth for such a big component was costly and time consuming. Moreover, the delamination growth measurement under cyclic loading is extremely challenging, as crack initiation can only be visible if it propagates to the surface. Hence, compliance variation is recorded to detect the initiation of the fatigue delamination following ASTM standard D6115. To avoid non-linearity that might appear during experimental testing, continuous monitoring of dynamic compliance is recorded. The test has been stopped when the specimens delaminated near the circular loop and overmolded web, or fracture occurred at the area of the metallic bushings. Otherwise, the test continued till the compliance increased to 105% of initial compliance or completed 110,000 cycles with a frequency of 1 Hz.

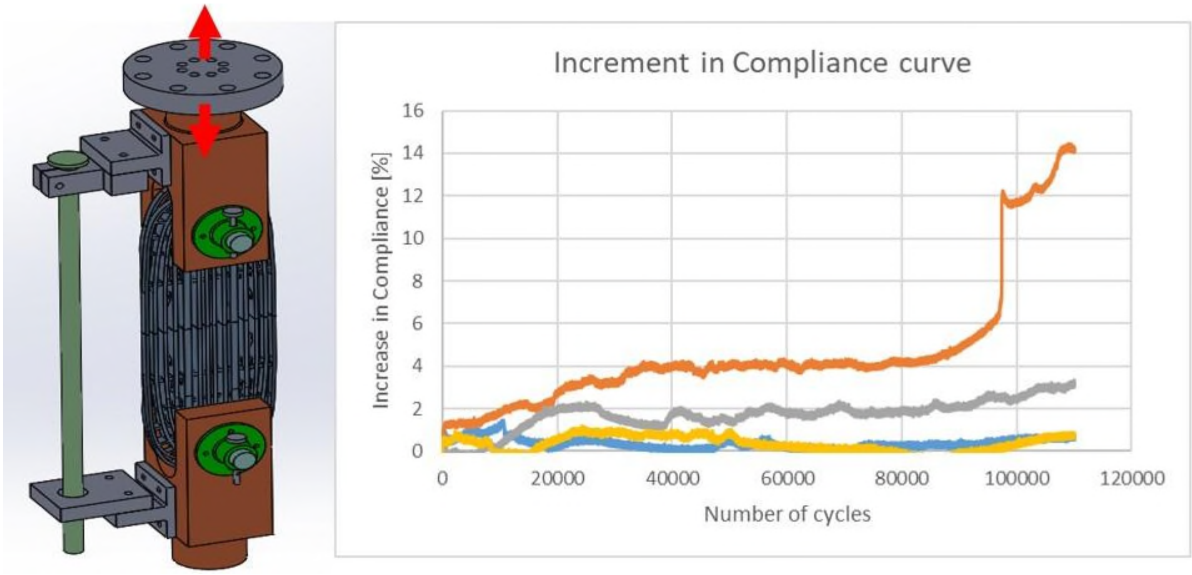

Figure 9: Testing fixture designed for mechanical testing for the demonstrator (left) and increment in compliance curve for few specimens (right).

As shown in Figure 9, almost all demonstrators have successfully passed the cyclic test for 110,000 cycles except one due to occurrence of delamination propagation at 100 k cycles. Fatigue fracture either initiated due to delamination near the region at the connection point of the UD laminate loop and injection molded web or near the connection point of aluminum bushing and UD laminate. Compliance increase by 1% and 5% has been monitored. Only one specimen has shown compliance increase of more than 5%. Hence, delamination growth is slow and stable. Therefore, the results are showing that the overmolded demonstrator is durable.

Currently achieved load ratio was -0.42 due to the low compressive strength of the component. Further optimization in the design is recommended to achieve fully reversible cyclic loading.

The use of such hybrid structures for aerospace applications require critical analysis on onset of delamination growth. Due to overmolding, residual stresses should also be controlled to increase the fatigue life of the component.

Acknowledgment

The project “pro-TPC-Struktur – Development Process Chain for the Optimized Use of Fiber Reinforced Thermoplastics in Functionalized Structural Components” (funding reference: 84002807) is supported by the European Regional Development Fund (ERDF) and the Ministry of Economic Affairs, Transport, Agriculture and Viniculture (MWVLW) of Rhineland-Palatinate.

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5.3 Application of Laser Shock Peening for the Fatigue Life Extension of AA2024 Lap Joints Welded with a Refill Friction Stir Spot Joining Process

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Refill friction stir spot welding (refill FSSW) is a solid-state joining process that was developed and patented by Helmholtz-Zentrum Hereon [1]. The process can join two or more sheet materials in an overlapped configuration and is recognized as a potential alternative for riveting [2]. However, the use of structural weldments presents a significant challenge for the implementation in a damage tolerance design, where a complete understanding of crack initiation and growth is imperative for the application of the refill FSSW in the aerospace industry. In the previous study, the refill FSSW process was optimized to achieve the maximum ultimate lap shear strength of similar AA2024 lap joints. However, under cyclic loading, the fatigue strength of the joints was only 15% of the ultimate lap shear strength [2].

The present work investigated whether an application of laser shock peening (LSP) as an innovative residual stress engineering technique can improve the fatigue life of refill FSSW joints [3]. For this purpose, the fatigue tests were performed on BM specimens, joint in overlap configuration via refill FSSW (Fig. 10a) as well as on specimens treated afterwards with LSP (Fig. 10b). The specimen geometry for the fatigue tests included a lap joint with one weld (Fig. 10a-b). The LSP treatment was applied on the upper part of the specimen, where the pin during the refill FSSW process penetrated. An area of 20 mm × 20 mm around the weld was LSP-treated twice with a square laser spot of 1 mm × 1 mm. Two LSP processes with the laser energy of 3 J and 5 J were applied, which resulted in the power densities of 15 GW/cm^2 and 25 GW/cm^2, respectively, considering a constant laser pulse duration of 20 ns (full-width at half maximum). For the LSP treatment, the material surface was covered with a laminar water layer used as a confining medium for the plasma. No ablative layer was used.

The uniaxial fatigue tests were performed using a 10 kN servo-hydraulic testing machine at a frequency $f \approx 20$ Hz, a constant load ratio $R_F = F_{min}/F_{max}$ of 0.1, and at room temperature. The fatigue test results as a function of maximal load F_{max} of cyclic loading on the number of cycles until failure were analyzed using the Basquin equation [4] to calculate the survival probability of 50 % at 2 × 10^6 (Basquin fatigue strength) loading cycles (Fig. 10c). The fatigue test results showed that through the application of the LSP treatment, the fatigue behavior of the refill FSSW lap joints can be significantly improved. Both LSP treatments resulted in a nearly comparable improved fatigue behavior. In terms of Basquin fatigue strength, LSP treatment at 5 J resulted in an improvement by a factor of 1.7.

In conclusion, LSP represents a promising post-processing technique to increase the service life of refill FSSW joints without adding weight to the structure, thus making this innovative joining technique a competitive replacement for classical riveting.

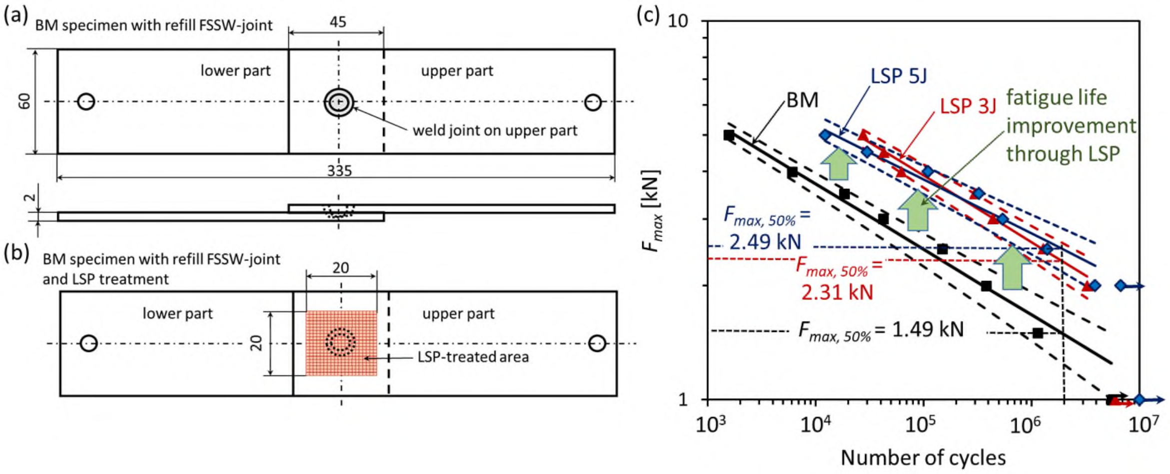

Figure 10: (a)-(b) Sketch of the investigated specimens: (a) BM specimen with overlap refill friction stir spot joint (refill FSSW), (b) BM specimen with overlap refill FSSW joint and LSP treatment of the joint area on the upper part. All dimensions are in mm. (c) Fatigue test results. In the diagram the mean S-N curves (survival probability of 50 %) with the values of maximum loads at 2 × 10^6 loading cycles (Basquin fatigue strength) together with 10% and 90% confidence intervals for the three investigated cases – BM specimen with refill FSSW joint, BM specimen with refill FSSW joint and LSP treatment at 3 J laser energy and at 5 J laser energy – are shown.

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5.4 Prediction of Fatigue Crack Growth based on Weight Functions for AA2024 Specimens with Residual Stresses induced by Laser Shock Peening and Laser Heating

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This study deals with the prediction of fatigue crack growth (FCG) for thin specimens of Al alloy AA2024 (Fig. 11) with residual stresses induced by the two promising residual stress engineering techniques - laser shock peening (LSP) and laser heating (LH). Various weight functions are applied to calculate the stress intensity factor due to the presence of residual stresses. By calculating the total stress intensity factor considering the applied loads and residual stresses, a superposition principle is used. FCG is predicted using Paris' law based on the effective stress intensity factor, considering the effect of residual stresses by changing the ratio of the total stress intensity factor.

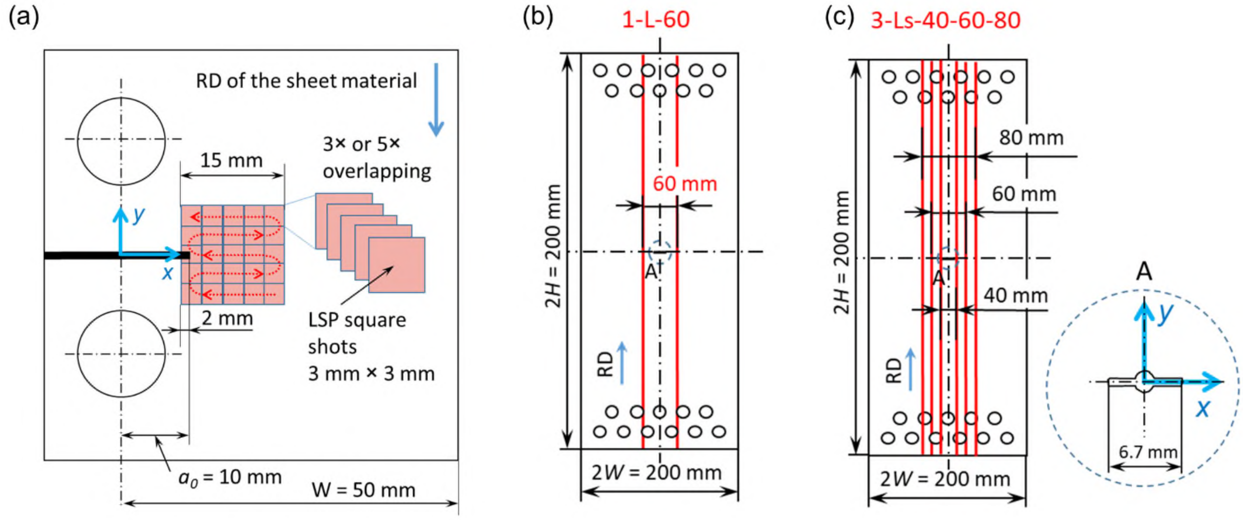

Figure 11: Sketch of the investigated specimens. (a) Laser shock peening (LSP)-treated C(T)50 specimen (specimens LSP 3× and LSP 5×), (b) M(T) specimen with one laser heating (LH) line on each specimen side (specimen 1-L-60), (c) M(T) specimen with three LH lines on each specimen side (specimen 3-Ls-40-60-80). The abbreviation RD denotes the rolling direction of the sheet material.

The obtained results show that by using weighting functions, good results can be obtained regarding the prediction of FCG for specimens with residual stresses induced by LSP and LH (Fig. 12). One reason for the small differences between the experimentally determined and predicted values in terms of FCG rate and crack length can be attributed to the scatter of the experimentally determined values for FCG as well as residual stresses. This study published in [1] shows that weight functions are a powerful tool for predicting FCG in thin specimens with residual stresses as long as the gradient of residual stresses in the loading direction is moderate. Concerning the studied specimen geometries with residual stresses, the following conclusions can be drawn:

1) For accurate calculation of the stress intensity factor for C(T) specimens, a weight function that considers the specimen with finite width should be used.
2) For the M(T) specimen geometry used in the present study, results for the stress intensity factor can be obtained with sufficient quality by using the weight function without considering the finite specimen width/length.
3) The stress intensity factors calculated in this way allow accurate FCG prediction for LSP-treated C(T) specimens as well as for M(T) specimens with LH lines.

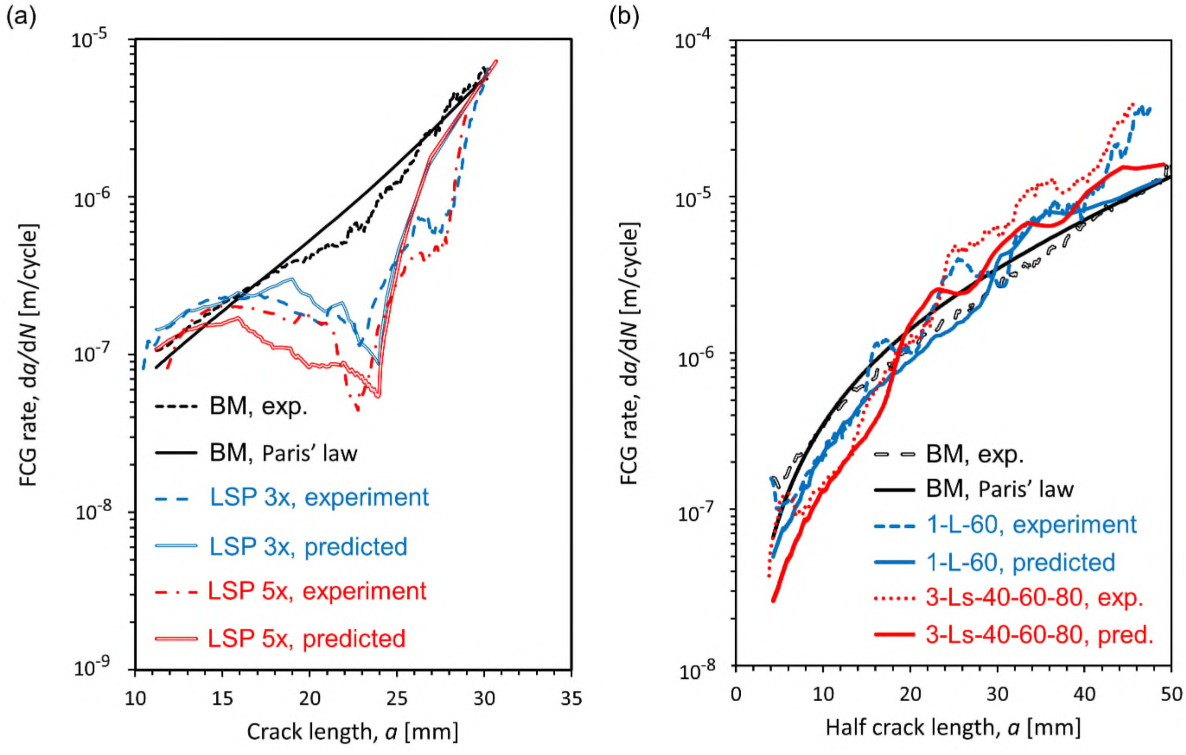

Figure 12: Predicted and experimentally obtained fatigue crack growth (FCG) test results for (a) base material (BM) and laser shock peening (LSP)-treated C(T) specimens and (b) for M(T) base material (BM) specimen and specimens with laser heating (LH) lines.

References

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5. 5 About the Problematic of Material Properties Assessment and Load Bearing Capabilities of 3D-printed (LPBF) Test Bodies

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Since about 20 years there has been an increasing interest in using additive manufacturing (AM) to produce complex parts in near net shape. Especially powder bed based laser beam melting (LPBF), a layerwise product creation approach becomes more and more popular because the tremendous hardware improvements over the last 5 years now enable larger complex parts already sized partially beyond 1000 mm in length. In addition the development of tailored and adaptable material concepts like **Scalmalloy** (AlScMg(Mn)ScZr) or **Scancromal** (AlScCr(Mo)Zr) which were established and high performant based on the rapid solidification propensities of the layerwise material generation in LPBF are disclosing new opportunities for extreme light weight design and/or new integrated functions. The principle possibility of more than 500 MPa yield strength in combination with nearly no short transverse strength/ductility limitations which are well known as well accepted from 7xxx T7x plate material applications motivate aerospace OEMs to rethink more and more parts classically designed in airframe structures.

However there are some certain fundamental challenges in AM which need to be realized, understood and respected (and finally mastered). For most of the engineers 3D-printing like LPBF starts in the computer with the virtual design of an often complex (bracket) part which was drafted with help of particular software, then step-wise geometrically optimized using bionicle augmented topography optimisations. Then the design is sliced into layers which reflects the build layers the LPBF machine is repeatedly melting until the part is finalized. This is meanwhile world wide well known but the conversion of a virtual 3D body with the help of layerwise powder melting using a 3D-printing device process chamber into a real near net shaped part includes always a very 1st and important processing step: The material creation for the 3D-printed part. The quality of this material creation, specifically its maximized density (ideally ~ 100%) and layerwise defined microstructure consisting of freshly solidified metal and remelted metal as well reheated metal, represents the base for any part properties. We can modify such a metallic material by post-LPBF process heat treatments, can try to make it even more dense by so-called hot-isostatic pressing but we will never achieve the microstructure conditions of an incumbent classical wrought metal product or semi-product like plate, sheet, extrusions, etc.. Owing the thermo-mechanical processing of established pre-products such materials feature a “fine-tuned” recrystallised microstructure with secured properties proven in an “acceptance certificate” where strength and ductility values (or more) are production batch-wise controlled and confirmed to the customer. Designers as well as strength/stress engineers are relying on these material properties as they build the fundament of any strength driven product development.

For more than 15 years all over the world scientists & engineers have been trying to develop high performance Al-alloys which shall be better suited for direct manufacturing schemes like laser powder bed fusion (LPBF). Meanwhile there are many different approaches disclosed but all of them are suffering on the same issues: Highly unstable melt puddle dynamics due to laser light energy transfer instabilities (==> conversion of the laser power into melting heat) and resulting material inconsistencies (insufficient density after solidification) so that the LPBF 3D-printing approach in Al-alloys remains challenging and still for many target applications immature. In addition, caused by the detrimental interaction of LPBF originated process imperfections (i.e. “lack of fusion”) with oxides & hydrogen contaminations that are mainly transferred from improper powder feedstock into the directly generated bulk material, the resulting LPBF material properties (strength, ductility & fatigue) are compromised. Consequently, the predicted extended industrial application of strength driven 3D-printed Aluminum-parts is still impeded. But it is not only the bulk material properties which are of concern. LPBF processing typically generates 3D parts or test bodies which inherently show a pretty peculiar surface (s. Figure 13).

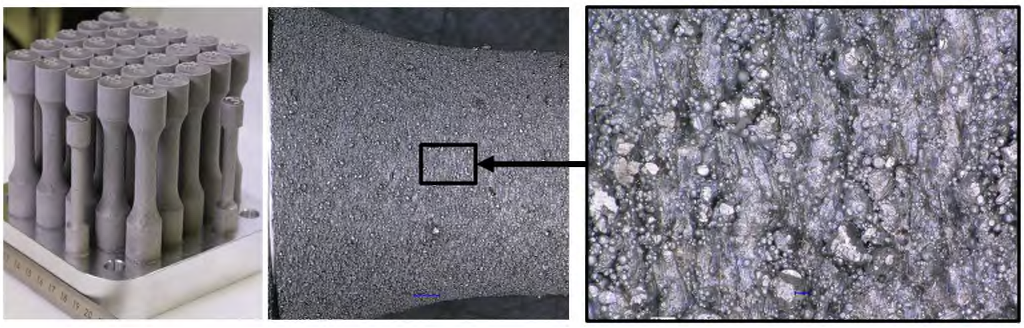

Figure 13: “As built” surface of Scalmalloy high strength Al-alloy test geometries

This surface differs significantly from machined surfaces because it displays beside a strong inhomogeneous roughness many other imperfections (s. Figure 14) which can act as a strong stress riser in the sub-surface region. Even after cleaning by sand blasting and chemical milling the principle roughness of the LPBF product remains incompatible with established surface roughness standards.

However those (machined) smooth surfaces are a prerequisite for reliable material property testing and evaluation verified in many studies over more than 100 years. All CAD designs and stress modeling done to assess or predict static strength or fatigue behavior depends on the accuracy and reliability of such measured (material performance) data. Therefore strength testing of 3d-printed test bodies though nominally seem to comply with given standard test geometries like “dog-bone type” test specimens are inherently invalid because they don’t fulfill the accepted geometry (surface) conditions for a “material-mechanically clean” property (strength & ductility) assessment.

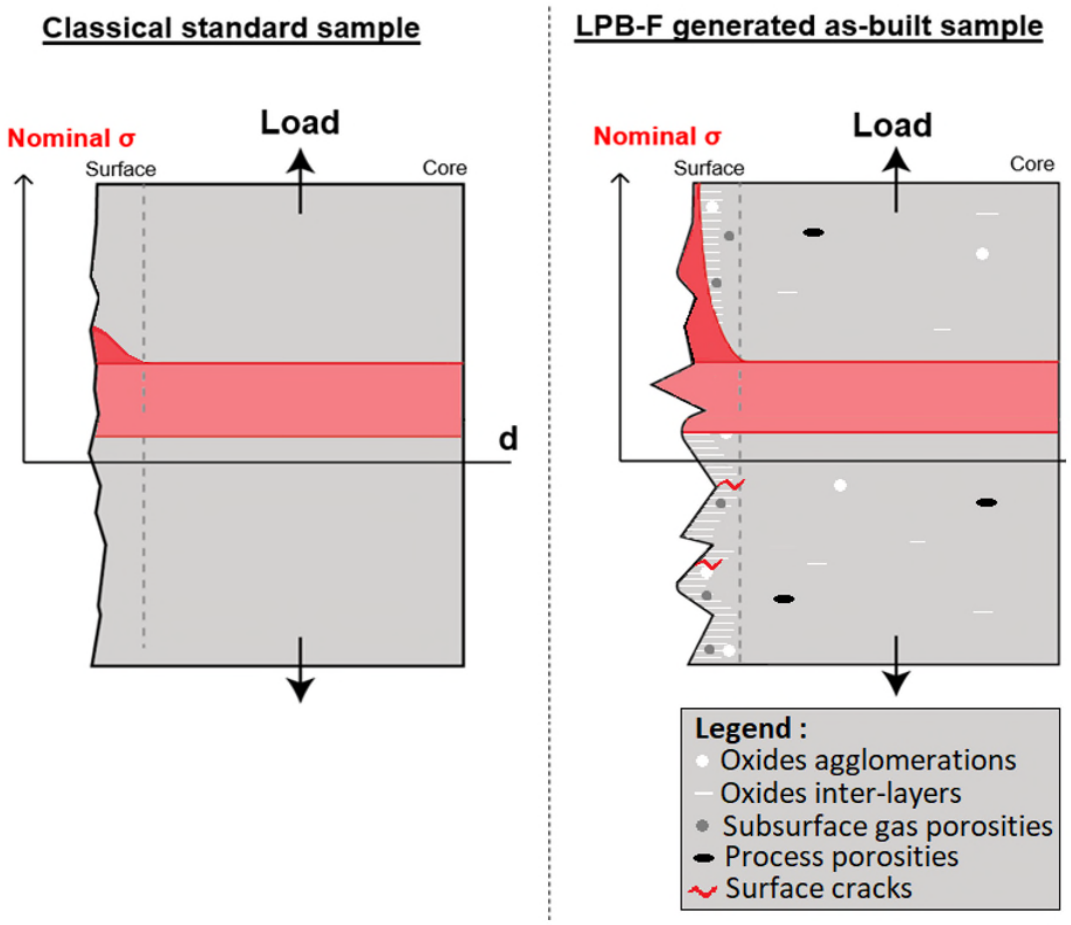

Figure 14: Modellized surface zone of a LPBF manufactured part or test body with extended rough- ness as well other imperfections like (tiny) cracks or oxid driven bonding defects ⇒ Comparison of a machined surface defined surface roughness ⇔ LPBF generated surface

Testing can only be performed w.r.t the so-called loading bearing capabilities of the test body as this refers to gross geometry of the tested sample. A detailed description of max. achievable stress at failure which requires a valid & accurate measurement of the loaded cross section is simply replaced by the max. load the test element can accommodate until it will fail. And this is the established way of conducting any static or dynamic durability test if a complex part or test body (where it is impossible to define a proper cross-section) will have to be analyzed. Hence, strength investigation on 3D-printed parts, it could be a dog-bone type sample geometry or a very complex mounting bracket, is always a classical part or product testing where “only” max. load bearing capabilities are tracked & recorded until failure of the part. But for (CAD) design purposes it is necessary to bridge from load bearing capabilities to strength and ductility (or even fracture toughness) values.

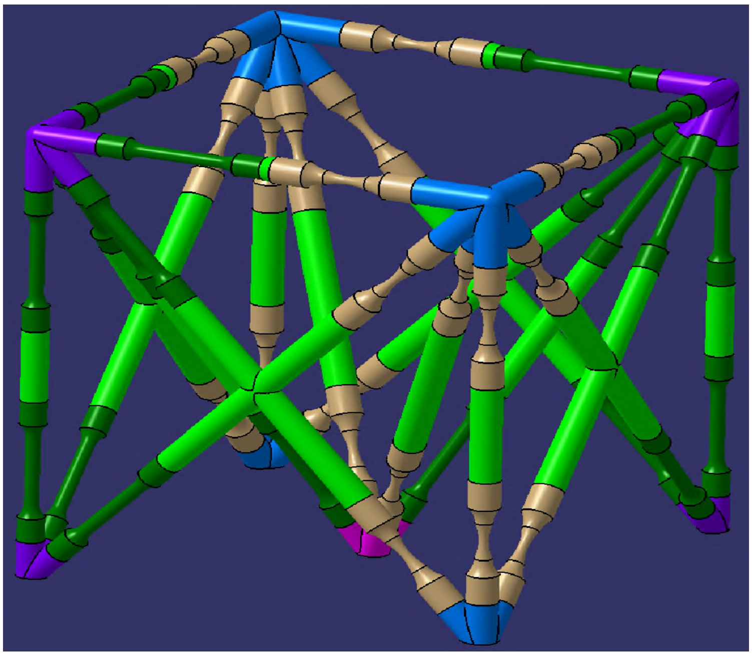

Figure 15: CAD-file of a scalable generic "test sample lattice beam structure" consisting of different test bodies to asses LPBF process parameter & hardware impact on directly generated material

This becomes possible if we compare defined prepared (machined) test bodies which are in line with the known material testing regulations with 3D-printed ones having in both cases the same nominal geometry. Doing so we then can deduce knock-down factors which enables designers a proper stress estimation for the 3D-printed part although its global and local notch situation cannot be handled precisely. Figure 15 is showing a 3D-printable **test sample lattice beam structure** consisting of static dog-bone ((green coloured) and hour-glas shaped fatigue test samples (beige coloured) which can be used to investigate the impact of LPBF process parameters on a "virtual component". Extracting all test bodies from the cube structure, machining the half of them for defined cross-sections, and then running the intended loading trials deliver the requested load bearing capabilities as well as the desired strength values (load versus cross-section). So we can properly deduce **knock-down factors** which are caused by the intrinsic LPBF bulk material properties and the impact as well interactions of the complex (defect prone) subsurface region and its related surface artifacts.

Astonishingly, the above mentioned material-mechanic challenge is very often disregarded in many scientific publications or even there is no awareness about this product and material problematic in the context of additive manufacturing and material property assessment.