# ICAF

## Review of Aeronautical Fatigue Investigations in Germany during the Period of April 2019 to May 2021


### Abstract

This review represents a compilation of abstracts on aeronautical fatigue investigations in Germany during the period from April 2019 to May 2021. 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.



HOMBERGSMEIER, Elke
elke.hombergsmeier@airbus.com

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# 1 INTRODUCTION

This review represents a compilation of abstracts on aeronautical fatigue investigations in Germany during the period from April 2019 to May 2021. It will be published on the ICAF website, because 2021 there was no physical Meeting of the International Committee on Aeronautical Fatigue, due to COVID-19 health restrictions. The next physical Meeting and Conference is postponed to 2023. All related information is available on the new ICAF Website https://www.icaf.aero/

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, D-21129 Hamburg, Germany, www.airbus.com |
| **HZG** | Institute of Materials Mechanics, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, D-21502 Geesthacht, Germany, www.hzg.de |
| **IMA** | IMA Materialforschung und Anwendungstechnik GmbH; Postfach 80 01 44, D-01101 Dresden, Germany, www.ima-dresden.de |
| **IVW** | Leibniz-Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str. 58, D-67663 Kaiserslautern, Germany, www.ivw.uni-kl.de |
| **PPI** | Institute of Product and Process Innovation, Leuphana University of Lüneburg, Universitätsallee 1, D-21339 Lüneburg, Germany, www.leuphana.de/en/institutes/ppi.html |

# 2 FATIGUE AND FRACTURE OF FUSELAGE PANELS

## 2.1 Single-Aisle Overwing-Door curved fuselage panel fatigue and damage tolerance tests

*Mirko Sachse, Silvio Nebel (IMA), Sven Berssin, Christian Göpel (Airbus Operations)*
*Contact: silvio.nebel@ima-dresden.de*

IMA Dresden performed a fatigue and damage tolerance test for Airbus Operations on a newly designed overwing-door curved fuselage panel (Figure 1a).

The test conditions covered a complex loading program consisting of combinations of internal pressure, axial tension, bending, shear and active frame loading. Due to the geometrical non-regularities incorporated in the panel, a specialized test concept was developed and fatigue and damage tolerance tests were performed (Figure 1b). The tests were finished in Q4/2020.

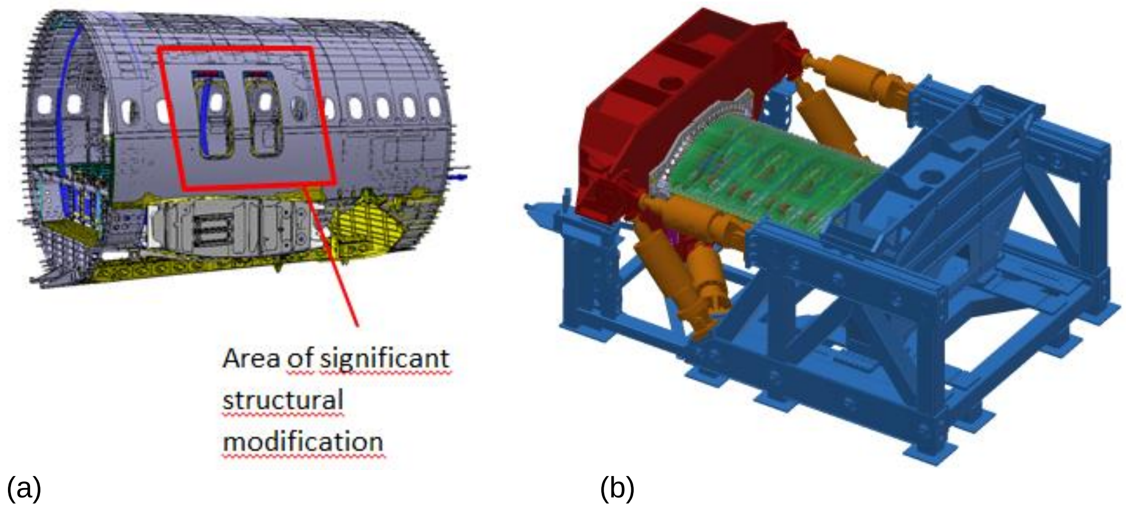



Figure 1: (a) Location of structural modification in center fuselage; (b) F&DT test rig with panel set-up

The test rig consisted of:

- A fixed load frame,
- A fixed bulkhead for panel installation at one side,
- A moveable bulkhead for panel loading (3 DOFs displacement, 3 DOFs rotation) powered by six hydraulic actuators offering movement and loading capabilities of a hexapod,
- A pneumatic system for pressure load application,
- An internal hydraulic loading system, to ensure correct loading and boundary conditions in the panel (e.g. frame and skin spreaders).

During the fatigue and the damage tolerance test phases the panel was loaded with a flight-by-flight load spectrum, incorporating several 100 individual flight types. Comprehensive inspection programs were incorporated into both test phases. Prior to the tests an extensive optimization and calibration of test rig loads were performed, based on required stress and strain distributions in the panel. Based on these optimizations the tests could be performed beyond 3 Design Service Goal (DSG).

Purpose built routines for load monitoring, load optimization, test progress supervision and anomaly detection could be applied during the tests. The test program was accompanied by quasi-static surveillance tests.

# 3 FATIGUE AND FRACTURE OF METALLIC COMPONENTS

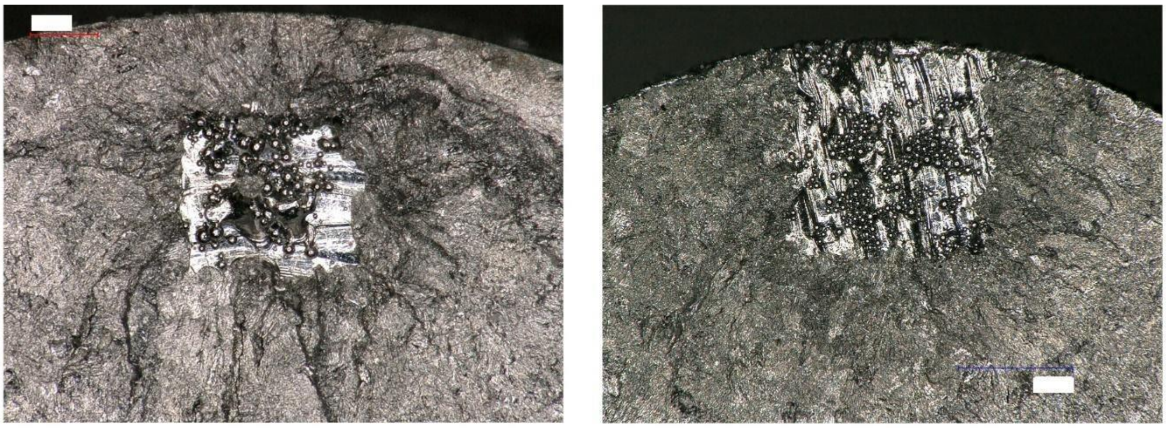
## 3.1 Effect of defects on the fatigue behavior of Additive Manufactured metal components: a zone based approach for tailored Non Destructive Testing

*N. Cersullo (Airbus, Technical University of Braunschweig), J. Mardaras, K. Nickel, P. Emile (Airbus Operations), C. Hühne (Technical University of Braunschweig)*
*Contact: nicola.cersullo@airbus.com*

In recent years, Additive Manufacturing (AM) processes and in particular Laser Powder Bed Fusion (LPBF) have received a lot of attention in the aircraft industry. Compared to conventional manufacturing techniques, the possibility of producing complex geometries with a relatively freedom in the design, the efficient use of material and resultant mass optimization represent the main benefits that are leading to the adoption of AM components for aerospace applications. Despite the numerous advantages, the characterisation of the Fatigue and Damage Tolerance (F&DT) behaviour still represents an open challenge in the widespread application of the technology in the aircraft industry for fatigue critical parts. Indeed, the entire production process needs to be properly mastered in order to minimise printed parts to be affected by process-induced characteristics such as defects or high surface roughness which have a detrimental effect on fatigue properties [1]. In order to ensure an adequate and robust F&DT quality of printed parts, several measures need to be put in place in the design and process, and additionally post-process steps may be required such as surface improvement processes, Hot Isostatic Pressing (HIP) and tight Non Destructive Testing (NDT) requirements, which considerably increase the cost in part production. NDT introduces additional difficulties in terms of part size that can be inspected, geometry accessibility and resolution to be adopted which further affect the inspection cost. In order to relax the current post-processing step requirements and reliably transition towards defect tolerant designs, an improved understanding of effect of defects is required which can lead to location specific NDT; internal stresses in every component are different, geometry features are not the same all over it and therefore the inspection size criteria needs to be adapted on a local base approach and considering target life of the component. In this optic, a model that is able to calculate those tailored requirements easily and reliably is needed, simplifying the part acceptance criteria process.

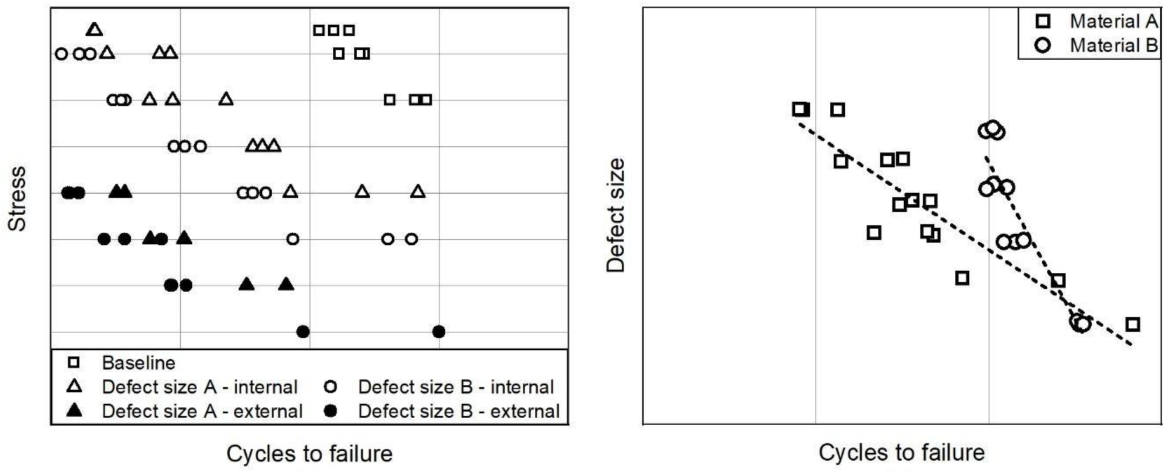
In the present work, a detailed comparison towards the defects' sensitiveness on the fatigue behaviour between two materials widely used in aircraft industry is provided. Fatigue coupons with artificially induced defects of different dimensions were produced by LPBF technique. In order to assess the defect position influence, the defect size scenarios considered were evaluated for two different positions: internal and directly exposed to the surface (see Figure 2).

Fatigue curves for several defect sizes were produced (Figure 3a). A particular focus was made on the trends at same stress level for defect size versus fatigue life where a different behaviour was observed depending on the material (Figure 3b).



(a) (b)

Figure 2: Fracture surface of two fatigue coupons made of the same material with a focus on the two defect position configurations: internal (a) and external (b)




(a) (b)

Figure 3: (a) Experimental fatigue results with a focus on the difference between internal and external defects for similar size; (b) Influence of internal defect size identified by fractographic analysis on the cycles to failure for a given stress level

Based on a purely fracture mechanics approach, a simplified stress-life-defect size model is finally devised. The experimental test results together with the information obtained from the fracture surface analysis of post mortem samples are used to validate the model predictions. A deep analysis was undertaken to assess the crack growth behaviour of the two materials in respect to the different propagation environment between the internal and the surface defects. Despite the simplified approach adopted, the proposed model correlates well with the experimental test data (see Figure 4).

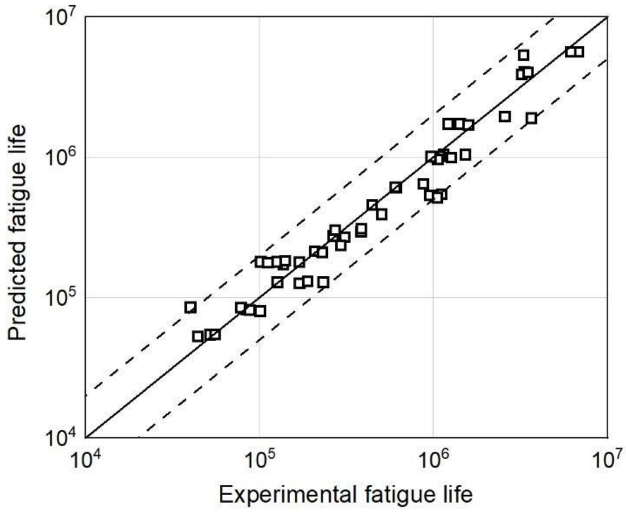



Figure 4: Comparison between predicted fatigue life from the proposed model and experimental fatigue life obtained from one of the materials investigated. Only internal defect configurations are reported here

The proposed methodology represents a key enabler for a zone based approach in NDT requirements. Indeed, the different behaviour in terms of defect sensitivity suggests the possibility to adapt defect acceptance criteria depending on the material printed. Additionally, the introduced simplified approach allows to easily compute the critical defect size map as a function of local stress and target life for a given component (Figure 5). Selection of NDT technique and required resolution can then be tailored correspondingly by minimising required effort and cost.

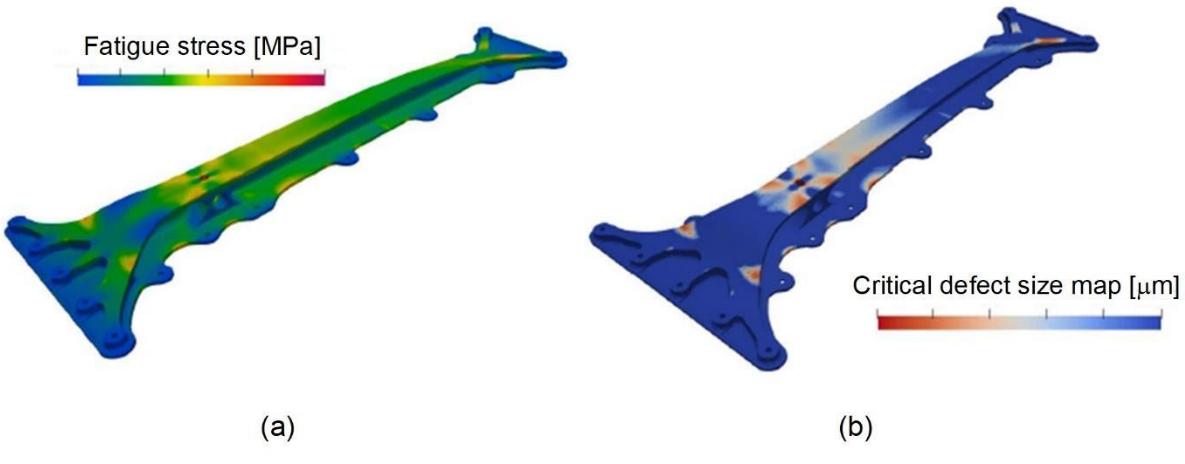



Figure 5: Example of critical defect size map as a function of stress and target life

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## 3.2 Effect of laser shock peening on fatigue properties of AA2024-T3 specimens with a fastener hole

*R. Sikhamov, F. Fomin, N. Kashaev (HZG), B. Klusemann (HZG, PPI)*
*Contact: nikolai.kashaev@hzg.de*

As the fatigue performance of airframe structures is an extremely important aspect for the safety of the aircraft, different techniques were developed to improve the fatigue performance of fastened joints such as cold expansion, interference fitting and laser shock peening (LSP) [1-2]. The aim of the accomplished study was to evaluate the effect of LSP on the fatigue behaviour of AA2024-T3 specimens with a fastener hole and to investigate the possibility of healing already existing cracks using LSP [3]. For this purpose, initial fatigue cracks of different lengths were generated within the specimens with a fastener hole. Deep compressive residual stresses were introduced into the specimens by applying LSP to both specimen surfaces (Figure 6a). Depth-resolved residual stress profiles were obtained by using the incremental hole drilling technique (Figure 6b). Three categories of specimens were investigated: (i) specimens with a fastener hole, (ii) specimens with an initial fatigue crack at the fastener hole of three different lengths 1.0 mm, 1.8 mm and 2.5 mm with LSP treatment, and (iii) specimens with a fastener hole without an initial fatigue crack and with LSP treatment.

Fatigue behaviour of undamaged base material specimens and specimens with an initial fatigue crack at the fastener hole were investigated by means of axial fatigue tests. Each specimen was tested at the same load level at room temperature. The maximum calculated stress level in the specimen cross-section without a fastener hole was 110 MPa at an applied stress ratio $R = 0.1$. For analysing the fatigue test results, the two-parameter Weibull distribution was used. The fatigue test results show that LSP significantly extends the fatigue life of specimens with an initial fatigue crack, but the effect of LSP depends on the crack length (Figure 6c). The larger the crack length, the weaker the effect of the subsequent LSP processing. The fatigue life of LSP-treated specimens with an initial crack of 2.5 ± 0.1 mm exceeds the fatigue life of base material specimens by a factor of 1.5, specimens with an initial crack of 1.8 ± 0.1 mm by a factor of 1.7, and specimens with an initial crack of 1.0 ± 0.1 mm by a factor of 3.3. The results of the present study clearly demonstrate the significant benefits and high potential of the LSP technique for fatigue life extension of specimens with a fastener hole.

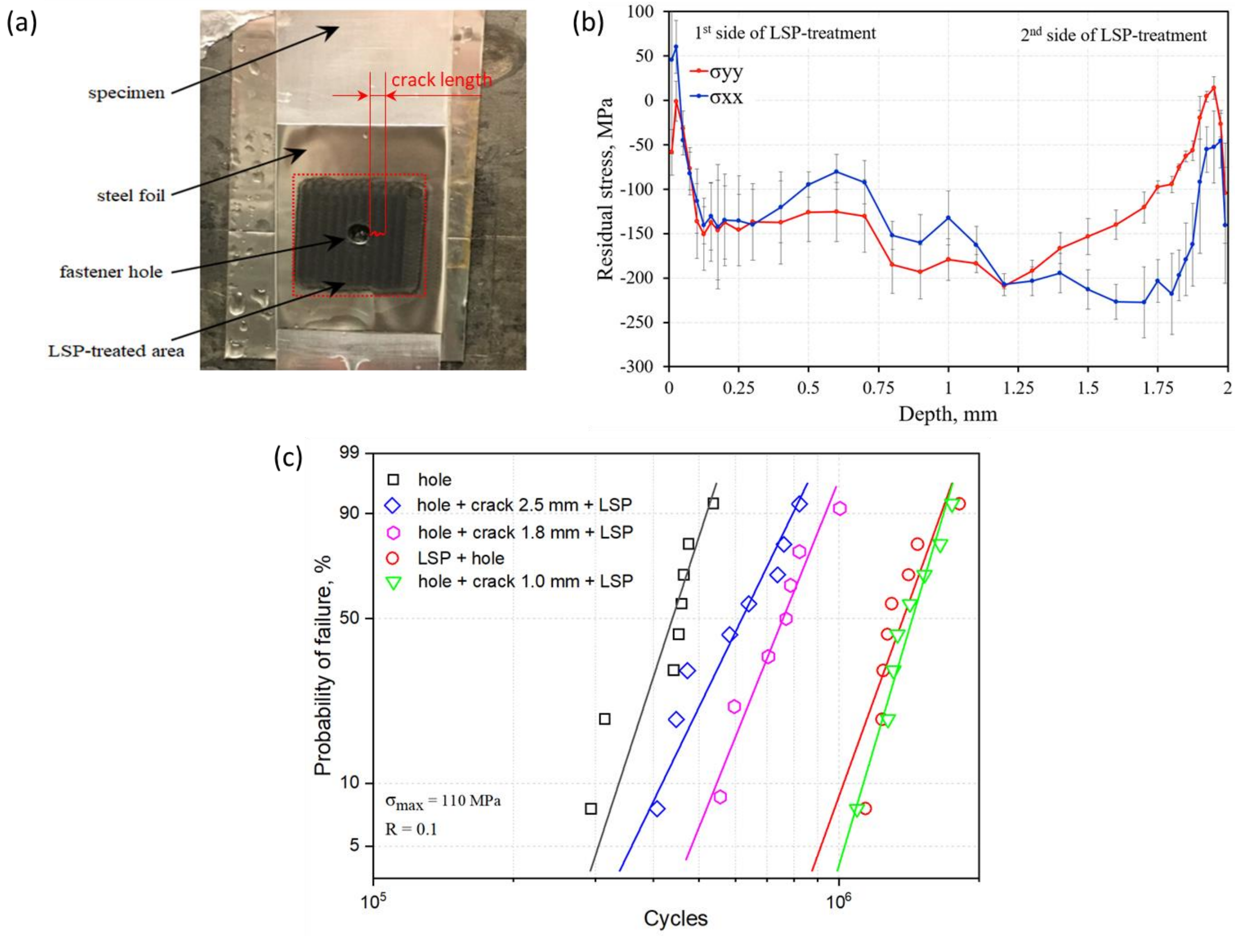


Figure 6: (a) AA2024-T3 specimen with a fastener hole after LSP, (b) depth resolved residual stress profile in LSP-treated specimen and (c) fatigue test results of the base material specimens (hole), the specimens with initial crack and LSP (hole + crack + LSP), the specimens only with LSP (hole + LSP).

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[3] R. Sikhamov, F. Fomin, B. Klusemann, N. Kashaev. The Influence of laser shock peening on fatigue properties of AA2024-T3 alloy with a fastener hole. Metals 10 (2020) 495.

## 3.3 Recovery of fatigue life of laser welded AA6056 specimens with surface fatigue cracks through laser shock peening

*N. Kashaev, D. Ushmaev, V. Ventzke, F. Fomin (HZG), B. Klusemann (HZG, PPI)*
*Contact: nikolai.kashaev@hzg.de*

Laser beam welding (LBW) as an efficient manufacturing technology is already established for lower fuselage applications in Airbus aircrafts [1]. Laser beam welded structures show better buckling behaviour under compression loading in comparison to riveted structures. The reason why the application of LBW is still limited for lower fuselage applications is their inferior damage tolerance behaviour under tensile loading. In case of LBW, the fatigue critical zones are located in the weld, where the crack can be initiated due to possible welding defects and in case of aluminium alloys due to reduced strength within the welding zone in comparison to the sheet material. Additionally, LBW introduces tensile residual stresses. One promising way to improve the fatigue behaviour of welds is to introduce compressive residual stresses, whereby laser shock peening (LSP) represents an effective residual stress engineering method to generate deep compressive residual stress fields within metallic materials.

The aim of the accomplished study was to investigate to what extent the fatigue behaviour of laser beam welded AA6056-T6 butt joints with an already existing surface crack can be improved through LSP [2]. Crack tip diffraction, using the ultrasonic phased array system investigated in this study, was proven as promising approach to monitor fatigue crack growth during fatigue tests. The ultrasonic technique was calibrated on introduced notches in the specimens using electro discharge machining. It was possible to accurately measure the fatigue crack depth starting from a depth of 0.5 mm. The chosen procedure allowed preparation of welded specimens with an initial surface fatigue crack of approximately 1.2 mm in depth.

Fatigue test results showed that surface fatigue cracks introduced in laser beam welded specimens significantly reduce their fatigue limit. A presence of a semi-elliptical fatigue crack of approx. 1.2 mm in depth leads to a reduction in fatigue strength in the endurance limit of approx. 20% in comparison to the specimens in as-welded condition (without initial fatigue crack). Through the application of LSP treatment on both surfaces of the pre-cracked specimens, Figure 7(a), it was possible to generate deep-compressive residual stresses in AA6056 sheet material of 6.2 mm thickness up to a depth of approx. 2 mm. The fatigue performance of the pre-cracked specimens after the LSP treatment was recovered and even better in comparison to the fatigue behaviour of as-welded specimens without fatigue cracks, Figure 7(b).

The results of the study propose LSP as an efficient technique to repair structural components, where small cracks can be detected by non-destructive testing such as ultrasonic testing. In this context, LSP treatment can be used to improve the fatigue behaviour of structural components, where fatigue cracks can be initiated in critical areas such as welds. Next to the application illustrated within this study, another possible application scenario for LSP is a prophylactic residual stress engineering approach to extend the fatigue life of critical structures in ageing aircrafts, where the fatigue cracks have not reached the detectable size. In this regard, LSP treatments could reduce the required safety margins (safety factors) of fatigue critical component or structure.

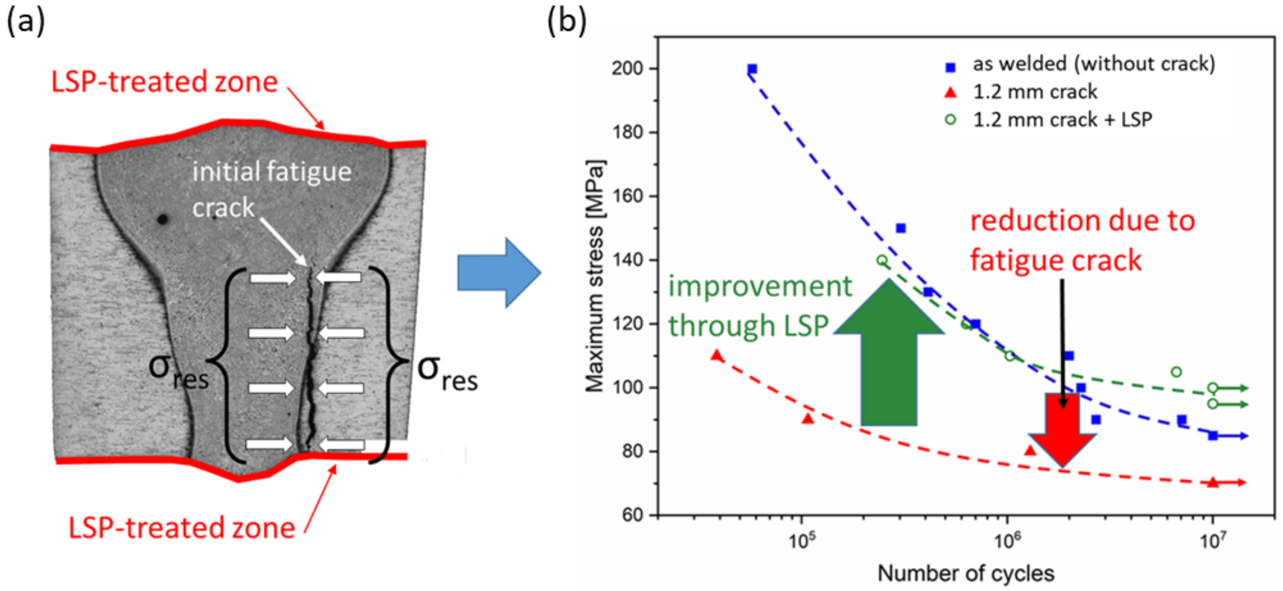


Figure 7: (a) Schematic of the specimen with an initial surface fatigue crack and (b) fatigue test results of laser beam welded specimens, laser beam welded specimens with the fatigue crack and laser beam welded specimens with the fatigue crack after LSP-treatment.

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# 4 FATIGUE AND FRACTURE OF COMPOSITE COMPONENTS

## 4.1 Understanding potential pitfalls in compression fatigue test data of composite materials

*Andreas Baumann, Joachim Hausmann (IVW)*
*Contact: andreas.baumann@ivw.uni-kl.de*

The tension dominated part of the constant lifetime diagram is the main focus of most fatigue studies on composite materials. A better fatigue performance under tensile loads and easier test set-ups maybe one of the reasons. However, misuse loads or unexpected loading conditions might lead despite a tension dominated component design to compressive loading. An extensive literature study [1] revealed a gap in the literature with respect to compressive fatigue loading. This is in stark contrast to quasi-static compression testing where a lot of research can be found [2]. Instabilities on different length scales globally (lab-scale specimen) and locally (e.g. fiber kinking) can interact and could make characterization results set-up dependent. This assumption stems from the two main testing strategies for lab scale testing. A small gage length specimen with a free length smaller than the critical length at the given load or a large gage length specimen with a lateral support. Both strategies are designed to avoid global buckling but should not alter damage growth or type. This suggest that all failure modes other than global buckling are regarded as material strength even though some of the damage modes are micro- or mesoscopic instabilities. It is therefore important that the methods do not effect bifurcations on the small length scales. Our research focused on the method of supporting the large gage length specimen with an anti-buckling guide. To verify the influence analytical models for different damage modes supplement the experimental results.

Typically anti-buckling guides consist of two metal plates with a PTFE film in-between to reduce friction. This additional layer is in contact with the specimen's surface and its elastic-plastic behavior defines the constraints, which could prohibit localized damage. Slightly modified analytical models on the kink band propagation stress and the constrained buckling by a thin film were used to verify this effect. A twill-weave glass fiber reinforced polyamide 6 was characterized by compression-compression fatigue tests and additional load increase creep tests. The material showed to be prone to localized instabilities as pre-failure damage.

For the set-up an aramid honeycomb material as intermediate layer between the supporting plates and the specimen is used. A relatively low stiffness and crushing stress are assumed to be favorable to limit the constraining effect for localized damage modes and at the same time avoid global buckling. From the testing results it could be concluded that global buckling was successfully avoided for all specimens tested. Pre-failure damage on the specimen's surface suggested a pronounced interaction of fatigue and creep.

This fatigue-creep interaction was than further investigated by load increase creep tests. These experiments were also used to characterize the effect of different constraints (i.e. intermediate materials) on the failure load. In a first step, it was verified that the load increase creep test resulted in similar damage modes as the compression-compression fatigue test. For the material under investigation matrix creep seems limiting for the compression strength of the composite material. This

observation was also valid for the typical PTFE layer and a second aramid honeycomb material with different properties. However, the highest failure load correlates to the stiffest supporting material. This is in agreement with the analytical models.
The effect the supporting structure has might also be explained by the contact pressures between specimen and anti-buckling guide. A second set-up with a pressure sensitive film instead of PTFE or any other intermediate material was used. The results in term showed that the localized instability developed over a period of several minutes (~42 min) and finally lead to collapse of the specimen, due to load redistribution.
From our current findings it was concluded that the constant lifetime diagram without the factors time or frequency might miss the effect creep has on the compressive part of the diagram. Furthermore, by including localized instabilities into the material's strength the recipient and user of testing results must be aware of the testing set-up with which the results were obtained. This means that the transfer from lab-scale testing to component design can only be made if the same constraints act in both cases.

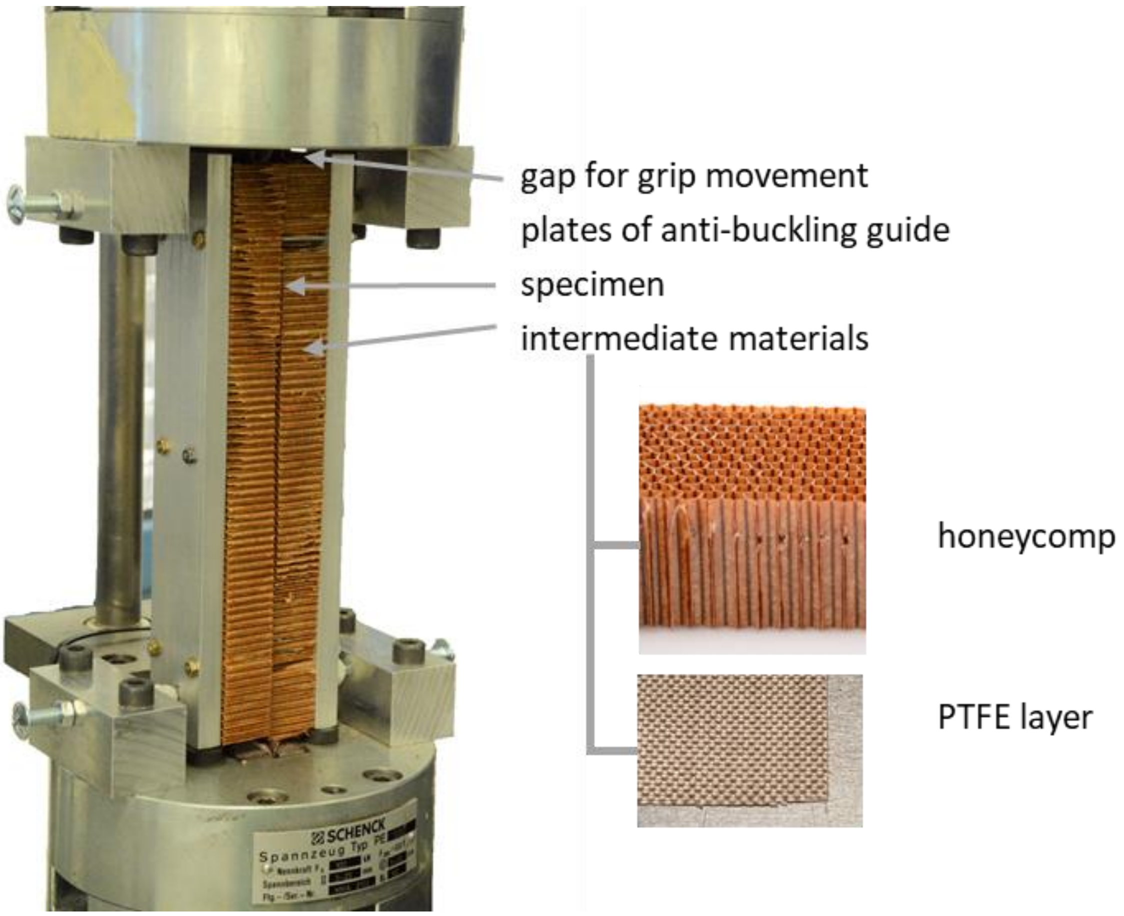
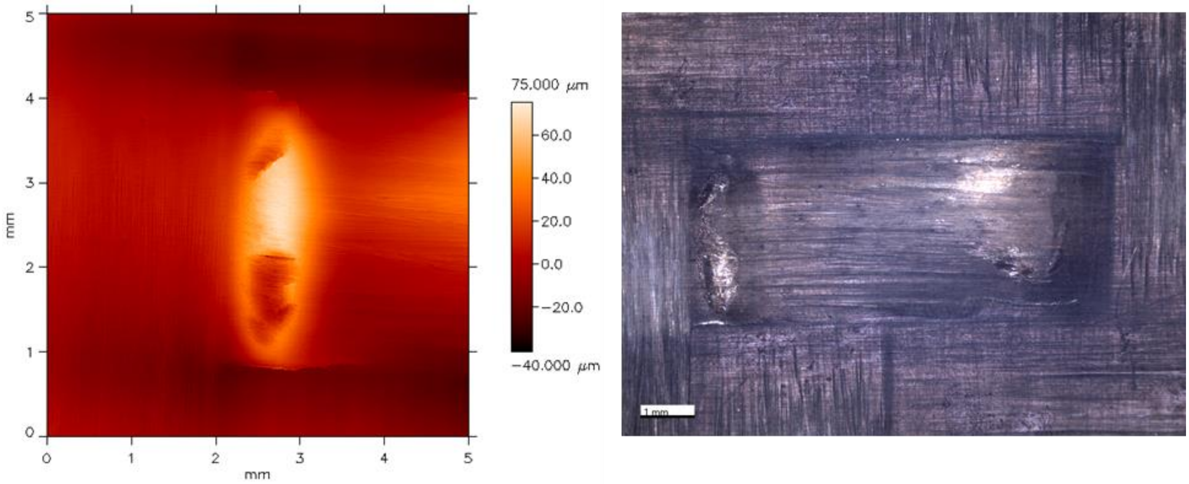



Figure 8: Test set-up with anti-buckling device and examples for intermediate materials




(a) (b)

Figure 9: Topographic diagram by white light inferometry (a) and macrosopic photograph (b) of a localized instability

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