EVALUATING THE SEVERITY OF DEFECTS IN A METAL TO CFRP HYBRID-JOINT WITH IN SITU PASSIVE THERMOGRAPHY DAMAGE MONITORING

Jannik Summa1(*), Michael Schwarz1, Hans-Georg Herrmann1,2
1Chair for Lightweightsystems (LLB), University of Saarland, Saarbrücken, Germany
2Fraunhofer Institute for Nondestructive testing (IZFP), Saarbrücken, Germany
(*Email: jannik.summa@izfp-extern.fraunhofer.de

ABSTRACT
This work assesses the quality of a novel metal to carbon-fiber-reinforced-polymer (CFRP) hybrid-joint and the influence of production induced defects, which were artificially implemented within the resin-transfer-moulding (RTM) process. Quasi-static tensile tests with in situ passive thermography damage monitoring of the hybrid-joints without defects and such with 10° misalignment, pleat or delamination were carried out. This methodology enabled to evaluate the severity of defects on the mechanical performance of the hybrid-joint.

Keywords: Metal-CFRP hybrid, tensile tests, passive thermography.

INTRODUCTION
In contrast to many high load-bearing hybrid-joints applicable in aerospace, the introduced concept is suitable for series-production and addressed to automotive applications. The planar hybrid-joint is achieved by inserting a metallic structure with a thermoplastic injection-moulded coating of optimised geometry between the CFRP laminate-plies within the RTM-process.

Although mass of investigations had been carried out on each of the involved materials (Cantwell, 92; Senthil, 2013; Greenhalgh, 2015; Al-Khudairi, 2015) in the past decades, only few is known about the mechanical behaviour as well as damage mechanisms of metal to CFRP hybrid-joints. Among the state of the art works, most focused on the fatigue behaviour of adhesively bonded CFRP-laminates, cohesive failure was found to occur most-likely in the adhesive, which is a typical failure pattern related to slow fatigue crack growth (Casas-Rodriguez, 2008). Besides that competing damage mechanisms may be observed in this work, since delamination growth was reported being strongly promoted by penetrative reinforcements (Parkes, 2014), which is comparable to the al-insert within the CFRP-laminate. To overcome the lack of knowledge on mechanical behaviour as well as damage mechanisms of metal to CFRP hybrid-joints, this work’s main objective is to assess the quality of the hybrid-joint and to evaluate the severity of defects by combined application of mechanical testing with in situ passive thermography.

However, further investigations on the overall mechanical behaviour, which reflects the collaboration of the three materials, the interfaces, the gradient properties and the complex geometry, have to be carried out whereas non-destructive testing (NDT) focuses on the bonding zone between the components, which depicts the locus of structural attenuation due to gradient mechanical properties.
The subsequent task is to evaluate the influence of defects on the mechanical properties, e.g. tensile strength and fatigue strength as well as the damage mechanisms. A review on delamination growth in CFRP laminates with detection capabilities by NDT is given by Senthil (Senthil, 2013). Therefore a comparative study on the mechanical behaviour of hybrid-joints without and such with defects, e.g. 10° misalignment, pleat and delamination respectively, is shown by means of quasi-static tensile tests with passive thermography in situ damage monitoring.

EFFECTS OF DEFECTS IN CFRP

To evaluate the severity of aforementioned defects, previous investigations were carried out on the damage mechanisms and the influence of these defects on the mechanical properties of the used CFRP-laminate (Summa, 2016). The sample geometry and testing conditions were chosen according to DIN EN ISO 527-4:1997.

It could be observed, that missing roving as well as gapping had negligible impact, as damage patterns and mechanical properties weren’t affected in tensile tests; stiffness degradation and heat build-up measurements showed only slight deviations for fatigue experiments below $2 \times 10^6$ cycles.

In contrast to that significant decrease of mechanical properties, such as tensile strength (5%, 20%, 40% drop respectively) and stiffness, were found to occur in presence of 10° misalignment, pleat or delamination. It was further observed that matrix-cleavage appeared at the pleat for tensile loads above a specific threshold, which might lead to an asymmetric force flow within the samples.

Investigations on fatigue properties revealed severe impact caused by 10° misalignment, pleat and delamination. Compared to defect-free specimens, 10° misalignment caused a decrease in cycles to failure of about one decade, whereas highest decrease of fatigue resistance was found for pleat and for delamination. It was further observed that matrix-cleavage appeared at the pleat for tensile loads above a specific threshold, which might lead to an asymmetric force flow within the samples.

HYBRID-JOINT WITH THERMOPLASTIC INTERLAYER

The concept of the hybrid-joint presented in this work is addressed to series production, i.e. automotive applications. In contrast to many high load bearing compounds that are joined by expensive or time consuming bolting, riveting or adhesives, the hybrid-joint in this work aims to compromise fast and cheap production-cycles with good mechanical properties, especially fatigue resistance.

Therefore a metallic insert, EN AW 6082 aluminum (AlMgSi1), is encased with a polypropylene (PP, Moplen HP500N by lyondellbasell) by direct injection-ouvermoulding and inserted subsequently between the middle plies of the CFRP-laminate within the RTM process. The CFRP-laminate consists of four layers $[0/90°, \pm 45°]$, of 30 vol% 3K plain weave Torayca FT300B carbon fiber embedded in an epoxy matrix (Biresin CR170/CH150-3). To achieve the coupling of the three components, the aluminium-PP insert was subjected to
geometrical optimisation resulting in a tight fit. Additional aims of the optimisation were minimised contact pressure concentrations and a homogenous stress distribution.

The benefits of this technique are a fast and cheap process chain with improved metal to PP adherence by microscale mechanical interlocking (Grujicic, 2008). Moreover the thermoplastic polymer is capable of function integration, i.e. better drapery or surface structuring; it improves the corrosion resistance (Amancio-Filho, 2009) and reduces the gap in stiffness, which counteracts the gap in mechanical properties between the aluminum and laminate-plies.

However by introducing the thermoplastic component as a force coupling agent two interfaces are generated. Since the mechanical interlocking contributes to adherent bonding between the metal and the PP, the PP-CFRP interfaces depict the regions of the hybrid-joint, where damage is most-likely to occur due to gradient mechanical properties. Additional affections of these interfacial regions may be caused by production induced defects.

In order to evaluate the effects of defects in the hybrid-joint different types of defects, 10° misalignment and pleat, are implemented into the upper ply, delamination between first and second ply respectively within the RTM process.

**EXPERIMENTAL SETUP**

Prior to mechanical testing the hybrid-joints were subjected to active thermography characterising the defects, which were artificially implemented into the CFRP-laminate within the RTM process, in terms of type, size and location.

After defect characterisation by active thermography, mechanical testing with passive thermography damage monitoring was carried out on the hybrid-joint. Thereby specimens were mounted with screw side-action grips with a clamping length of 25 mm from both sides. According to DIN EN ISO 527 tensile tests were driven displacement controlled with 2 mm/min cross-head speed.

Figure 1 shows the geometric parameters of the 4 mm thick metallic insert encased with a 2 mm PP layer and the insert implemented within the middle plies of the 1 mm thick CFRP-laminate.

![Fig. 1 - left) geometric values of metallic insert with PP layer, right) insert implemented between the middle plies of the CFRP-laminate](image-url)
The mechanical testing was complemented with an InfraTec VarioCam® HD Head bolometer camera with a resolution of 1024 x 768 pixels, spectral sensitivity in the range of 7.5 to 14 µm and a temperature resolution below 0.05 K (at T= 303.15 K).

Thereby thermography and mechanical testing data were synchronised by triggering the bolometer camera at t = 0 with 3 Hz image acquisition. Thus, changes in the IR images could be attributed to events in force-displacement diagrams at corresponding times. A picture of the experimental setup is shown in Figure 2.

**ACTIVE THERMOGRAPHY**

For the measurement with thermographic methods there are two general possibilities: passive and active thermography.

To achieve a thermal contrast with active thermography an external excitation is needed. As excitation sources laser, halogen lamps, eddy current, flash generators or ultrasonic can be used. The specimens in this work are excited with a flash generator. To capture the thermal radiation after the specimen is excited an infrared camera with Stirling cooler is used. The utilised infrared camera is a special Dualband camera which is suitable to capture radiation from the midwave (4.4 - 5.2µm) and the longwave (7.8 - 8.8µm) infrared. Since defects act like thermal barriers they are depicted as bright areas in the infrared image. Thus defect identification in terms of type, size and location is enabled. An example is given in Fig.3, which shows the comparison of a defect-free specimen with one containing a pleat.

**Fig. 2** - left: Hybrid-joint mounted with screw grips, right: bolometer camera adjusted for damage monitoring

**Fig. 3** - Comparison between defect free sample (left) and sample with pleat (right)
In the left picture of Fig.3 a hybrid sample without artificial defects is depicted. Besides the metal-thermoplastic insert, the fibre orientation can be determined very well. In the right picture the metal-thermoplastic insert as well as the fibre orientation are easily visible as in the left picture. Furthermore there is a pleat under the upper “arm” of the fir tree structure. This pleat is brighter than the surrounding and stands out.

PASSIVE THERMOGRAPHY DAMAGE MONITORING

Passive thermography is used as a sophisticated method monitoring the damage progression without the necessity of external excitation, since the heat-generation originates from internal excitation of the specimen due to friction and deformation processes. The mechanically induced heat can be described as a superposition of the thermo-elastic temperature variation, the heat dissipation $\Delta T_{\text{diss}}$ and heat exchange with the environment $\Delta T_{\text{loss}}$ (Rösner, 2004).

Since no adiabatic conditions are reached in tensile tests, thermoelasticity is further neglected. For dissipative processes Chrysochoos (Chrysochoos, 2000) developed the local heat conduction equation based on the Clausius-Duhem inequality, as:

$$\rho C_{\varepsilon,\alpha} \frac{dT}{dt} + \text{div} q = d_i + \rho T \psi_{\varepsilon,\alpha} \frac{d\varepsilon}{dt} + \rho T \psi_{\alpha,\alpha} \frac{d\alpha}{dt} + r_e$$

(1)

With $\rho$: density, $C_{\varepsilon,\alpha}$: specific heat capacity at constant $\varepsilon$ and $\alpha$, $q$: heat influx vector, $\psi$: Helmholtz free energy, $r_e$: external heat supply, $\varepsilon$: strain, $\alpha$: state variable, $d_i$: intrinsic thermal dissipation, which can be correlated to the difference of anelastic and stored energy rate:

$$d_i = W'_a - W'_s$$

$$W'_a = \sigma : D - \rho T \psi_{\varepsilon,\alpha} \frac{d\varepsilon}{dt}$$

$$W'_s = \rho T \psi_{\alpha,\alpha} \frac{d\alpha}{dt}$$

(2)

Where $\sigma$ is the Cauchy stress tensor, $D$ the Eulerian strain rate tensor, $W'_a$ the anelastic energy rate and $W'_s$ the stored energy rate.

Based on this equation measurements of local temperature changes can be correlated with irreversible deformations quantitatively by means of the Eulerian strain rate tensor.

Jegou (Jegou, 2013) inferred a simplified relation of (1) for the prediction of Wöhler-curves based on dissipative heat build-up measurements. It has also been shown that passive thermography damage monitoring improves the capabilities characterising the damage evolution due to spontaneous heating during CFRP tensile tests (Roche, 2012). Thereby the crack location could be identified with a lateral resolution of approximately 1 mm.

RESULTS

Good identification of the damage propagation by passive thermography is achieved by data optimisation. Fig.4 shows different contrasts for a defect-free sample at the event of delamination growth due to mechanical loading. The raw data (Fig.4 left) is clearly improved by calculating the differential T-image, which refers to the initial sample temperature before loading. Further improvement of the image contrast is visible by introducing a T-threshold, which dyes pixels grey that lie beneath the threshold.
Tensile test with passive thermography damage monitoring of a defect-free specimen is shown in Fig. 5. Events of damage propagation can easily be identified by passive thermography images (Fig. 5 right), as spontaneous heating accompanies the characteristic stick-slip behaviour, especially at newly generated fracture surfaces. Applying differential T-image ($\Delta T$), referring to the initial sample temperature and an isothermal T-threshold simplifies the identification. Moreover the triggered synchronisation enables to correlate events of damage progression with the development of the force-displacement diagram.

These results reveal that the first stage is significantly determined by linear elastic behaviour until approximately 4 kN. Before reaching the maximum load bearing capability, first damages emerge beneath the lowest arm of the insert. With this onset of debonding located at the lowest point of the joining-zone between PP and the CFRP, radial mode-I delamination starts to propagate until the fir tree formed insert is fully delaminated from the CFRP-laminate and the load bearing capability vanishes. This indicates, that mode-I delamination is induced due to the pull-out effect of the insert, which is in good agreement with the observations of Parkes [Parkes].
Introducing a calibration length into the T-images, determination of the delaminated area is viable. Therefore the residual load bearing capability is plotted against the delaminated area (Fig. 5 left). It is evident that the load bearing capacity decreases linearly with increasing delamination area. Note that for the first data point the initial delamination was assumed to have the size of the insert geometry.

Fig. 6 summarizes the results of tensile tests on hybrid-joints with 10° misalignment, pleat delamination as well as defect-free ones. The first stage is dominated by linear elastic behaviour until first damage occurs at approximately 4 kN. Moreover the initial compliance is slightly affected by the implemented defects, as it can be seen from the inserted detailed diagram. It is evident that the maximum load bearing capability hardly decreases due to the pleat whereas 10° misalignment caused a decrease of 25 % and delamination of 20 %. All four curves show several drops in the force-displacement development which are related to events of damage. It can further be concluded that the damage enters at higher displacements for the defect-free specimen.

Fig. 6 - (a) Force-Displacement Diagram of uniaxial tensile tests of Hybrid-joints with detailed vision of the linear region; (b) residual load bearing capability plotted against the area of delamination, determined from passive thermography image.
The area of delamination was determined for each of the specimens and plotted against the corresponding force (Fig. 6 right). The load bearing capability is found to linearly decrease with the area of delamination. Until a delaminated area of about 6000 mm$^2$ has developed, differences in the load bearing capacity are visible, which decreases from the defect-free specimen to pleat, delamination and 10° misalignment. Below 6000 mm$^2$ the load bearing capacity as well as the decrease rate seems not to depend on the defects, implemented within the hybrid-joint. From this results it can be assumed that 10° misalignment and implemented delamination accelerate the mode-I delamination growth of the CFRP-laminate. To acquire broad knowledge on the effects of defects further investigations, especially considering fatigue properties, have to be carried out on this subject.

**CONCLUSIONS**

A metal to CFRP hybrid-joint is introduced, where the connection is achieved by inserting a polypropylene layer between the metal and the CFRP-laminate. Quality assessment and defect characterisation of the metal to CFRP hybrid-joint were enabled by active thermography. Good detectability was found for a pleat in the upper laminate-ply due to high contrast.

Investigations on the influence of artificially implemented defects on the mechanical properties of the hybrid-joint were carried out with *in situ* passive thermography damage monitoring. Thereby passive thermography analysis was improved by differential T-image with additional application of a temperature threshold. This methodology also enabled to determine the area of delamination that grew during tensile tests.

From the mechanical results the hybrid-joints were found to fail in a stick-slip manner. It was further observed that weakening of the mechanical properties were caused by implemented defects, especially the maximum load bearing capacity was significantly decreased, which was reached just before delamination growth commenced.

Plotting the residual load bearing capacity against the area of delamination, which was determined from passive thermography images, a linear decreasing dependence was evident. The decrease rate development indicates that mode-I delamination of the CFRP-laminate is slightly accelerated by 10° misalignment and implemented delamination until a characteristic level of delamination has reached.

It also evident from the investigations on the influence of defects that 10° misalignment and delamination affect the mechanical properties, whereas no strong deviations of mechanical properties were found to be caused by pleat. The fact that earlier works reported severe property deviations of pure CFRP-laminate caused by artificially implemented pleat arouses suspicion that the weakening effect of the pleat may depend on geometrical parameters.

However, to acquire a broader knowledge on the effects of defects in the introduced hybrid-joint, further investigations have to be carried out, especially considering fatigue properties.
ACKNOWLEDGMENTS
The authors gratefully thank Deutsche Forschungs Gemeinschaft for the funding of this work and our colleagues from wbk KIT, LKT Dortmund and Fraunhofer IZFP Saarbrücken.

REFERENCES
[1]-Cantwell W.J., Morton J., the significance of damage and defects and their detection in composite materials: a review, Journal of Strain Analysis, 27 (1), 1992


[8]-Amancio-Filho S.T., dos Santos J.F., Joining of Polymers and Polymer-Metal Hybrid Structures : Recent Developments and Trends, Polymer Engineering and Science, p. 1461-1467, 2009


