THE IMPACT OF ENVIRONMENTAL STRESS ON THE MECHANICAL BEHAVIOR OF FIBER-METAL-LAMINATES WITH ELASTOMER INTERLAYERS (FMEL)

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Abstract
Fiber-Metal-Laminates (FML) combine a low density with outstanding dynamic resistance. The mechanical properties of commercially available laminates made from glass fiber reinforced polymer (GFRP) and aluminium can be increased by substituting the glass with carbon fibers. The combination of carbon fiber reinforced polymer (CFRP) and aluminum, however, induces possible contact corrosion and a mismatch of thermal expansion coefficients (CTE-mismatch). A passivating, adhesive elastomer layer is introduced to resolve the issue, thus creating the Fiber-Metal-Elastomer-Laminate FMEL. However, environmental loads may alter and age the polymer structures, reducing the mechanical properties. More importantly, the CTE-mismatch generates stresses in the interface, which potentially damage the laminate.
In this study, thermal cycling from -40 °C to 80 °C for 100 cycles is carried out to represent the environmental load. The temperatures were chosen accordingly to the thermal load range anticipated in an automobile.
The residual resistance was tested by flexural experiments. The tests induced tension stress in the CFRP and shear stress in the elastomer.
The residual resistance describes the change of mechanical properties in the respective components due to the thermal loads. The flexural modulus and strength of the thermally cycled materials remained unchanged after 100 thermal cycles.

1. Introduction

Fiber-Metal-Laminates (FML), often used in aviation (cf. glass laminate aluminum reinforced epoxy: GLARE), have outstanding resistance to crack propagation and excellent impact properties combined with low densities [1–3]. A further increase of specific mechanical properties could be achieved by replacing glass fibers with carbon fibers. This lightweight laminate introduces certain problems, such as contact corrosion between the carbon fibers and the aluminum layer as well as delamination [4–6] due to different coefficients of thermal expansion (CTE-mismatch)[7–9].
Additionally, the metal surface has to be elaborately prepared to increase adhesion. An elastomer interlayer, which absorbs the CTE-mismatch with high elastic strains and inhibits contact corrosion by electrical decoupling could resolve these issues.

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Furthermore, the elastomer has adhesive properties and is thus desired to improve the bond between the carbon fiber reinforced polymer (CFRP) and the aluminum. In order to prevent warpage caused by the CTE-mismatch, symmetrical laminates are generally realized (Figure 1).
As environmental loads can cause severe damage on FML [10], these materials are normally tested under thermal loads [11], after hygrothermal loads [12, 13] or after thermal cycling [14, 15]. Because of the additional elastomer layer and the carbon fibers, this research is not simply transferable to research carried out with GLARE. Only little work was conducted with carbon fiber reinforced aluminum laminate (CARALL) [12]. Due to the noted corrosion and CTE-mismatch, this material is hardly used. The carbon fiber and elastomer based material system has to be researched likewise to GLARE concerning the stability to thermal cycling to safely consider it as a material for structural application.

2. Materials

2.1. Laminate Architecture

The Fiber-Metal-Laminates with elastomer interlayers (FMEL) generally consist of CFRP face layers, elastomer interlayers and an aluminum core (c.f. Figure 1 left). In this paper the laminate consists of three layers (Figure 1 right). The succession is aluminum – elastomer – CFRP. This layup is altered for this paper to reduce the amount of layers to describe the behavior of each laminate sheet and the interfaces with a higher quality. In this research, the elastomer interlayer was varied between a standard configuration and a fast curing elastomer mixture to reduce production costs.

The FMEL was manufactured at the Institute for Production Science (wbk) at the Karlsruhe Institute of Technology (KIT). A Lauffer type RP 400 OK 920 machine press was used. Laminates were manufactured at 150 °C and 23 bar pressure with a curing cycle of 300 s. Slightly adapted parameters were used for the fast curing elastomer. The faster curing cycle offers the possibility to reduce the processing temperature (140 °C for 260 s at 23 bar).

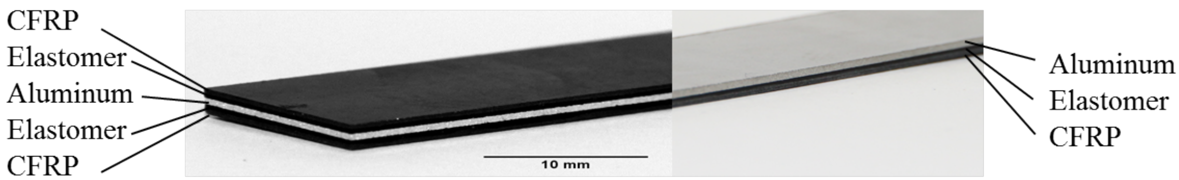

Figure 1. FML with elastomer interlayers, layer succession on the left: CFRP - Elastomer - Aluminum - Elastomer - CFRP. This sequence is used for dimensional stability as the CTE-mismatch does not deform the FML. Layer succession on the right: Aluminum – Elastomer – CFRP. This, reduced, layup is used in this study to better research each component and interface

For the bending tests an asymmetrical layup was used. So, the elastomer layer was situated in the neutral fiber in order to be purely loaded by shear stress. Additionally, the CFRP could be loaded by tension, which should be preferred for FRP layers to inhibit micro buckling [16].

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2.2. Carbon Fiber Reinforced Polymer

The CFRP used in this study is a Hexcel M77/42%/UD90/CHS prepreg with unidirectional high strength carbon fibers and an optimized resin for fast curing cycles to counteract the usually long curing cycles of FML. For the application in the FMEL a low sheet thickness of 0.1 mm was essential to guarantee a variable layup of the CFRP layer in laminate.
The curing temperature of the epoxy matrix was matched to the curing temperature of the elastomer interlayer to ensure the best production quality of the FMEL. Due to the high strength fibers and a fiber volume content of 50 % the CFRP has high specific mechanical properties. The resulting density was 1.5 g/cm^3. The Young's Modulus of the unidirectional CFRP sheet is 120 GPa and the tensile strength is 2250 MPa. The unidirectional prepreg sheets were arranged to a biaxial CFRP layer with 1 mm thickness. Production technology and the thickness forces a layup where the biaxial sheet does not have the same properties in both directions (0°/90°/0°/90°/0°/0°/90°/0°/90°/0°). The stiffer direction will be called "in fiber direction", because it is the predominant fiber direction. The other direction, named "perpendicular to fiber direction", is anticipated to have generally lower mechanical properties.
The recommended curing cycle for this prepreg is 120 s at a temperature of 150 °C and a pressure >5 bar. At 140 °C, the curing cycle is increased to 180 s.

2.3. Elastomer

The elastomer used in this research was provided by Kraiburg. The registered trade name is Kraibon. It is optimized for applications with CFRP. The chosen mixture, SAA-9579/52, does not only possess enhanced adhesion to CFRP with epoxy matrix but also to aluminum. Another elastomer mixture, SAA-9530/70, with lower mechanical properties but a faster curing cycle, was taken into account. It can be associated with the possibility of lower production costs.
Both elastomer interlayers promise inhibited corrosion, balancing of CTE-mismatch and increased adhesion. The elastomer layers have thicknesses of 0.5 mm and their curing temperature is fitted to the curing temperatures of the Hexcel M77/42%/UD90/CHS. The duration of the curing cycle for the FMEL is defined by the elastomer, as it is the slower curing component of the FMEL. The resulting duration is 300 s at 150°C, respectively 260 s at 140°C.

2.4. Metal

The metal considered in this study was chosen according to high resistance to sheet bending combined with a low density. The selection process was restricted by the requirement to be able to roll the metal to a 0.3 mm thin sheet. An aluminum 2024-T3 was chosen to ensure comparability, as many structural applications use this alloy [1, 2]. The alloy has extraordinary specific strengths and good availability in rolled thin sheets. The minimum thickness of 2024-T3 commercially available is 0.3 mm, being sufficient for the FMEL.

3. Methods

The residual mechanical properties of the laminate were characterized with flexural tests. The bending test was designed to specifically load the CFRP with tension stress. The elastomer was situated close to the neutral fiber and therefore loaded with shear stress. The interfaces of the FMEL are also loaded primarily with shear stress superimposed with lower values of tensile respectively compression stress according to the position of the interface.

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Furthermore this chapter features a description of the thermal cycling of the specimen, which is used to induce stresses through the mismatch of coefficients of thermal expansion (CTE-mismatch). Additionally, the mechanical properties of the elastomer and the CFRP can be altered by the thermal load. This change in mechanical properties is supposed to be monitored by bending experiments.
Delamination, a premature failure due to insufficient adhesion, does not use the full potential of the laminate components. Thus the desired specimen failure is tension failure of the CFRP component in contrast to a possible delamination of the components.

3.1. Bending

The 3-point-bending experiments were carried out using a ZwickRoell ZwickiLine Z2.5 universal testing machine with a 2,5 kN load cell. The bending experiments were carried out at ambient temperature of 22 °C and according to DIN EN ISO 14125 [17].
The experimental setup consists of two support bars, a loading bar and an inductive measuring sensor. All bars had a radius of 5 mm. The experiments were carried out with a cross head velocity of 1 mm/min to achieve quasi static testing conditions. During the test, the CFRP was loaded in tension, the aluminum in compression (c.f. Figure 2).

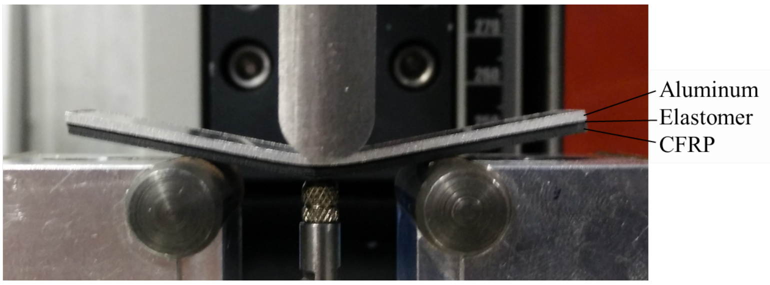

Figure 2. Experimental setup for bending tests on an asymmetrical FMEL specimen

The distance between the support bars was altered from the specification in DIN EN ISO 14125 [17] to 40 mm to ensure specimen failure. The specimen thickness was measured using a measuring screw before testing for an accurate calculation of flexural modulus and strength. Five specimens were tested for each configuration, fiber direction and thermal load.

3.2. Environmental Load

In order to completely characterize and understand a material, quasi static experiments are not sufficient, but dynamic and environmental tests have to be carried out accordingly. Environmental loads have to be applied to the specimens in order to quantify the possible damage of the structure. In this paper, the sole focus is the change in mechanical properties caused by thermal cycling.
The thermal load range for automobiles (-40 °C to 80 °C) is chosen as a characteristic temperature range, which is applied to FMEL. The thermal load is applied over time prior to mechanical testing. The change in mechanical properties is calculated using reference specimens without thermal loading.

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3.2.1. Thermal Cycling

The thermal cycling was carried out in a Vötsch VCL 7010 climatic chamber. A complete cycle from -40 °C to 80 °C and back to -40 °C was carried out in 1,5 hours. The cycle includes 15 minutes holding time at each turning point to ensure the application of the whole temperature range to the specimen. The temperature change rate was 4 °C/min between the two extreme values. The thermal cycle is comparable to the work of da Costa [14], who was applying an aviation temperature range. The thermal cycle was repeated 100 times.

4. Results

The effect of the thermal cycling was evaluated using 3-point-bending experiments with novel and thermally cycled specimens. All specimens failed through tension failure in the CFRP sheet and not through delamination of the laminate components. The specimens with the different elastomer interlayers will be regarded separately.

The flexural modulus and the flexural strength were measured to characterize the FMEL. The modulus was measured from 0.05 % strain to 0.25% strain. The modulus was regarded in relation to the predominant fiber direction. The cycled specimen are compared to the reference specimen without any prior treatment to show changes in mechanical properties.

The values are anticipated to be higher with specimen in the predominant fiber direction compared to specimen perpendicular to it.

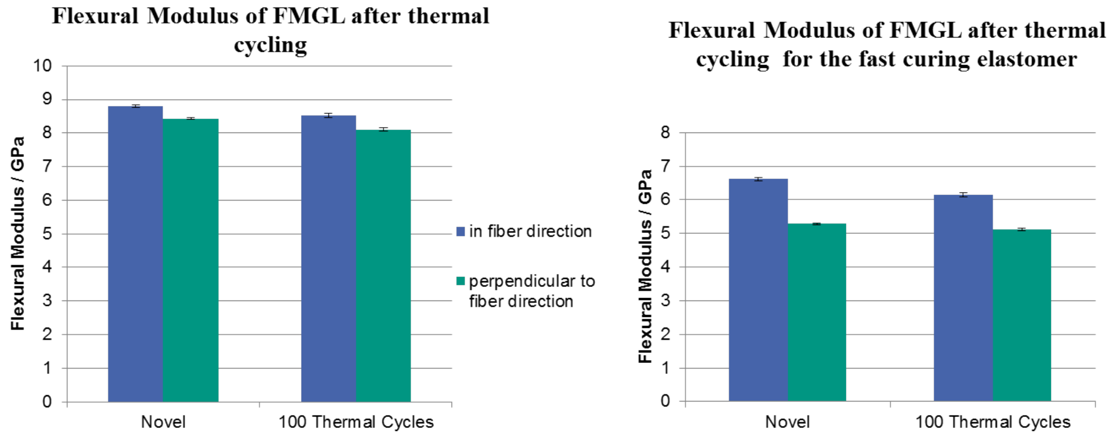

Figure 3. Flexural Modulus of novel and thermally cycled FMEL with standard (left) and fast curing elastomer (right)

A small reduction of approximately 3 % of the flexural modulus was observed when testing the flexural modulus of the FMEL using the standard elastomer interlayer. The difference between the modulus in fiber direction and perpendicular to fiber direction is also insignificant. The marginal reduction in modulus of the thermally cycled specimens is consistent with the fiber directions. The absolute values of the flexural modulus of the FMEL with the fast curing elastomer are lower compared to the FMEL with standard elastomer. This FMEL also shows a marginal decrease of approximately 5 % in flexural modulus after 100 cycles. The decrease is also consistent with the fiber directions. The difference in modulus in relation to the fiber direction is more prominent compared to the results with the standard elastomer.

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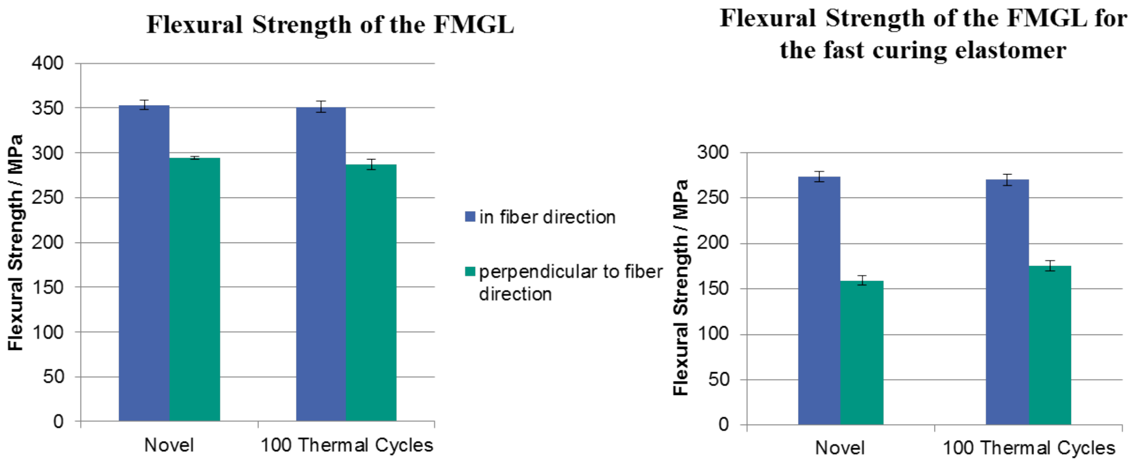

Figure 4. Flexural Strength of novel and thermally cycled FMEL with standard (left) and fast curing elastomer (right)

The flexural strength of the novel and thermally cycled FMEL are illustrated in Figure 4 on the left hand side. The strength strongly depends on the fiber direction for the novel as well as for the thermally cycled specimens. But the thermally cycled specimens shows no reduction of flexural strength compared to the novel specimens.
Figure 4 on the right shows the flexural strength of the FMEL with the fast curing elastomer layer. The dependency of the strength on the fiber direction is visible. The thermal cycling, however, has no major impact on the strength.

5. Discussion

The production process and the thermal cycling are assumed to not have altered the mechanical properties of the aluminum. The curing cycle duration and the thermal cycling temperature were not sufficient for heat treatment in aluminum. Likewise, it is assumed that the CFRP matrix was not damaged [14].
The thermal cycle used by da Costa et al. was conducted in only two chambers with the minimum and maximum temperature, neglecting the controlled heating and cooling, generating a much faster cycle duration of 20 minutes. With the higher duration in this study, a lower cycle count of 100 was achieved in comparison to 1000 and 2000 cycles. The constant mechanical properties of the laminate show, that the properties of the matrix and aluminum remained the same. Due to the missing CTE-mismatch no other comparisons are possible.
The thermal cycling in this study induced stresses and strains into the elastomer and the interface. Possible damage in the elastomer and interfaces would show in a decrease of strength and specimen failure by delamination. The failure occurring in the CFRP layer shows that the thermal cycling combined with the CTE-mismatch did not result in a delamination, proving a sufficient interface strength.
The results show a dependency of mechanical properties to the dominant fiber direction. The outer fiber layer, with the highest stresses, was in this direction. Failure perpendicular to fiber direction occur at lower stresses, resulting in lower overall strengths.
The mechanical properties of the FMEL with the fast curing elastomer were lower compared to the standard elastomer. This can be explained by better mechanical properties of the standard elastomer as noted in chapter 2.3.

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However, the measurements in modulus were not conducted in other studies. The modulus was slightly changed, but this marginal trend has to be proven by subsequent experiments with specimens thermally cycled for 1000 cycles. The nearly constant modulus shows that the mechanical properties of the elastomer remained constant, assuming the constant elastic properties of the aluminum and CFRP.

6. Conclusion

The FMEL was subject to thermal cycling from -40 °C to 80 °C and the effect of this thermal load on flexural properties was evaluated.
The mechanical properties of the FMEL specimen have a dependency on the predominant fiber direction. The dependency is stronger with the flexural strength values compared to the modulus, as the maximum stress is located in the outer layer which endures higher stresses in fiber direction. Since the specimens all failed in the CFRP component, the interface properties remained sufficiently good after thermal cycling. The FMEL specimens exposed to the thermal cycling retain their original flexural strength. Consistent with the assumption that aluminum and CFRP were not affected, the additional elastomer layer and the interfaces therefore also kept the properties.
The flexural modulus remains approximately unchanged, but with a tendency for a lower value. This tendency has to be proven by an extended experiment with 1000 thermal cycles, which also allows better conclusions concerning the flexural strengths.

Acknowledgments

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