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The effect of an elastomer interlayer thickness variation on the mechanical properties of Fiber-Metal-Laminates

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ABSTRACT

Fiber-Metal-Laminates with elastomer interlayers (FMEL) consisting of CFRP and Al 2024-T3 were manufactured with standard and thin elastomer interlayers to evaluate the mechanical properties of the FMELs. The elastomer layer thickness reduction was necessary to increase lightweight potential of the laminate. The layer thickness was reduced using a new process step. The thin elastomer layers were obtained using a solvent and deposited on the aluminum core layer before manufacturing the laminate. The effects of the additional manufacturing step and the thickness variation on the mechanical properties of the laminate were examined focusing on interfacial and flexural behavior. The FMEL were compared to FML to determine the impact of the elastomer interlayer. The FMEL with thin elastomer interlayers exhibited a higher flexural stiffness but lower strain to failure than the FML accounting for the lower deformation in the thinner elastomer layer. The interfacial properties showed a satisfactory quality after the solution step, which was presented by identical interfacial shear strength compared to the FML. The FMEL with thin elastomer interlayers could be manufactured through a solution step and the mechanical properties led to the desired results.

1. Introduction

Fiber-Metal-Laminates find application in aviation due to high specific mechanical properties, good dynamic behavior and low crack propagation rates [1]. The commercially available GLARE, which combines glass fiber reinforced polymer (GFRP) and aluminum layer, can be optimized using carbon fibers instead of glass fibers to enhance the mechanical properties through the higher stiffness and lower density of the carbon fiber [2]. However, the combination of carbon fibers with aluminum induces interfacial problems caused by the electrochemical potential and a mismatch of coefficients of thermal expansion (CTE-mismatch) [3,4].

The interfacial problems can be solved by an elastomer interlayer, as Sarlin et al. showed increased adhesion of the laminate constituents [5] and resistance to corrosion [6] in steel-GFRP laminates. The elastomer directly influences the corrosion resistance and prevents corrosion through high electrical resistance [7], but also has the ability to balance the CTE-mismatch through high strains [8] and influence the damping and vibration behavior [9].

The elastomer layer causes increasing specimen temperature in cyclic loading due to the damping properties [10], which can reduce

the temperature dependent polymer properties. The high strain and damping of the elastomer can also increase impact properties and reduce the damage area in laminates [11]. The elastomer interlayer properties can be altered due to aging, where the moisture is more crucial than the thermal damage [12].

However, the mechanical properties of the FML are reduced due to the low properties of the elastomer [13]. Therefore, a thin elastomer layer could solve the corrosion and CTE-mismatch problem, while enabling a high load bearing capacity of the laminate.

To obtain a FMEL with higher lightweight potential, the elastomer layer thickness had to be reduced using a new process step. For the laminate to achieve higher mechanical properties a thinner elastomer layer is essential proving the need for an additional manufacturing step to reduce elastomer layer thickness. The 0.5 mm elastomer sheets used in previous studies could not be manufactured in thinner sheets by roll forming. However, the elastomer layer was used in a pre-cured state, which enabled the possibility to solve the elastomer in benzene and manufacture thinner elastomer sheets. The thin elastomer sheets were desired to achieve identical interfacial properties as the FMEL [14] while surpassing FMEL in mechanical properties, especially in respect to flexural behavior.

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Fig. 1. FMEL specimen with CFRP face layers, elastomer interlayers and an aluminum core layer.

The interfacial quality of the laminates was assessed by the edge shear test [15], which loads the interface in shear loads to quantify the adhesive properties of the constituents. The mechanical properties were examined using flexural tests to compare mechanical properties of the FMEL with thin elastomer interlayers (tFMEL), FMEL and FML lacking the elastomer interlayer.

2. Materials and methods

2.1. Laminate manufacturing

The Fiber-Metal-Laminates with elastomer interlayers (FMEL) are a layered material consisting of stacked constituent materials. The face sheets consisted of biaxial carbon fiber reinforced polymer (CFRP) and the core layer was an aluminum sheet. The constituents were bonded by an elastomer interlayer as presented in Fig. 1. To inhibit warpage caused by the CTE-mismatch a symmetrical layer succession was selected. The constituents were stacked accordingly and consolidated in a press.

The laminates with an area of 300 mm × 300 mm were manufactured at the Institute of Production Science (wbk) of the Karlsruhe Institute of Technology (KIT) using a press type RP 400 OK 920 by Laufer. The curing cycle was conducted for 300 s at 150 °C and a pressure of 23 bar. The curing temperature of the prepreg was matched to the vulcanization temperature of the elastomer interlayer and no pretreatments or adhesives were used in the laminates. The specimens were cut out of the laminate using a Struers Accutom with water cooling and an aluminum-oxide cutting wheel.

2.2. Carbon fiber reinforced polymer (CFRP)

A Hexcel “M77/42%/UD90/CHS” prepreg was used for the CFRP layer in the laminate. The M77 epoxy resin had a fast curing cycle time, which prevented the usually long curing cycle times of commercial FML [16]. The CFRP contained a resin weight content of 42%, which resulted in a fiber volume fraction of 50%. The CHS (carbon high strength) fibers were oriented unidirectionally (UD90) in the prepreg. The prepreg layer had a cured thickness of 0.1 mm. The uni-directional layers were oriented biaxially to obtain 0.6 mm thick face layers of the laminate with the orientation [0°/90°/0°/0°/90°/0°].

The unidirectional CFRP layer had a density of 1.5 g/cm³ and a stiffness of 116.6 GPa in longitudinal and 7 GPa in transverse direction. The tensile strength in longitudinal direction was 2250 MPa, while the transverse direction had 90 MPa. The biaxial CFRP layer was examined in tensile tests according to DIN EN ISO 527-5 and the stiffness of the layer was 69.6 GPa ± 3.5 GPa with a strength of 1300 MPa ± 87 MPa.

2.3. Aluminum layer

The aluminum core layer of the laminate was chosen with regard to high specific mechanical properties as well as good comparability to FML. Commercial FML, like GLARE, often use the alloy 2024-T3, which was also chosen for this laminate because of high specific mechanical properties. The layer was commercially available in 0.3 mm thin sheets with a high stiffness of 73 GPa and a density of 2.7 g/cm³. The

mechanical properties were obtained in tensile tests according to DIN EN ISO 6892 with adapted specimen dimensions to account for the sheet. The specimen dimensions were 250 mm × 15 mm × 0.3 mm. The yield strength was 320 MPa ± 4 MPa and the tensile strength was 433 MPa ± 6 MPa.

2.4. Elastomer interlayer

The elastomer interlayer with the commercial name Kraibon by Kraiburg Holding GmbH & Co. KG, Waldkraiburg, Germany was used. The exact mixture was called SAA-9579/52 which was an ethylene propylene diene methylene (EPDM) elastomer and was optimized for good adhesion to the epoxy matrix and the aluminum layer. The elastomer was integrated in the FML to inhibit corrosion by high electrical volume resistance of $3 \cdot 10^{12} \Omega \cdot \text{cm}$ resistivity and to balance the CTE-mismatch through high strains.

The elastomer was used in a pre-cured state and it was vulcanized in the same process step as the CFRP was cured. The resulting layer thickness was 0.5 mm and the mechanical properties were determined in tensile tests. The stiffness was 50 MPa with a tensile strength of 8 MPa and a strain to failure of 200%.

The thin elastomer layer could not be examined without the aluminum substrate layer and no isolated mechanical properties were obtained. The thin elastomer had a thickness of 0.1 mm.

2.5. Laminate

The standard FMEL laminate consisted of 0.6 mm thick biaxially oriented CFRP face layers, a 0.3 mm aluminum core and 0.5 mm elastomer interlayers. The layup resulted in a laminate thickness of 2.5 mm.

The tFMEL had elastomer interlayers with 0.1 mm thickness with the objective to retain the positive aspects of the interlayer shown by the FMEL but reducing the negative effect on the mechanical properties caused by the interlayer. The aluminum and CFRP thickness was kept constant, which led to a tFMEL thickness of 1.7 mm.

The FML without elastomer interlayer used the identical CFRP and aluminum layers, which resulted in a thickness of 1.5 mm.

3. Experimental procedure

The experimental procedure contains the manufacturing of the tFMEL, because the feasibility to fabricate the tFMEL had to be examined. Subsequently the mechanical characterization of the FML, FMEL and tFMEL was conducted using edge shear tests to assess the interfacial properties and bending experiments to define the load bearing capability.

3.1. Manufacturing of the thin elastomer layers

The elastomer layers were supplied in a pre-cured state, which still enabled the possibility to use a solvent to obtain a fluid containing the elastomer precursor. The solution was applied onto the aluminum core layer in the desired amount to generate the thin layers. In order to obtain a pourable solution with high surface tension, the volumetric content of 16% elastomer in the benzene solution had to be achieved.

Fig. 2 a) visualizes the solution process, where the elastomer was brought into solution under constant stirring. In part b) of the image the solution of elastomer and benzene was deposited on the aluminum layer, which was not only the core layer, but also served as substrate for the elastomer solution. The solvent was subsequently evaporated, like visualized in c), leaving only the elastomer layer behind. The aluminum with the elastomer coating was flipped to repeat the procedure with the other side to obtain the central three layers for the five-layer-laminate. The desired elastomer layer thickness could be regulated with the volumetric amount of elastomer solved in the benzene.

The obtained aluminum core with elastomer interlayers was

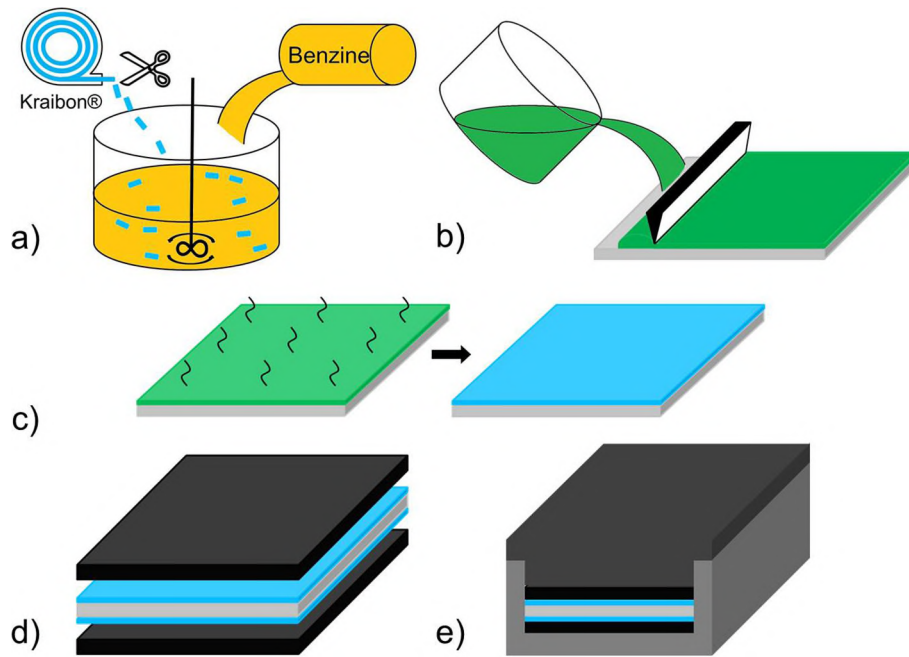


Fig. 2. Manufacturing process for tFMEL in five steps with a) solution in benzine b) coating of the aluminum c) evaporation of the benzine d) stacking of the constituents and e) pressing the laminate.

finished with two biaxial CFRP face layers visualized in Fig. 2d) to form the laminate. The subsequent curing process in e) was conducted for 300 s at 150 °C and 23 bar.

3.2. Mechanical characterization

3.2.1. Edge shear tests

Edge shear tests according to Weidenmann et al. [15] were used to define the interfacial properties of the laminates. The experiment loaded the hybrid interface of the laminate in shear loading as presented in Fig. 3. The characteristic values defining the adhesion were the shear strength, which resembled the maximum interfacial load and the shear energy, the area under the stress strain curve, which was associated with the absorbed energy to failure [14].

Fig. 3a) presents the schematic of the edge shear test and the shear load induction into the specimen. The guiding plates on both sides of the laminate (b), were used to define the shear plane of the test. A ZwickRoell Zmart.PRO 100 kN universal testing machine was used with a 20 kN load cell. The strain was measured with an inductive strain transducer which represents Δx in Fig. 3c). The distance h of the shear gap is set to the thickness of the elastomer layer for each specimen. The

experiment was conducted at 1 mm/min crosshead velocity. The experiment was started after a force of 10 N was applied. The failure criterion was a force decrease of 20%. Ten specimens were tested per laminate.

3.2.2. Bending experiments

Three point bending experiments according to DIN EN ISO 14125 [17] were conducted to assess the flexural properties of the laminates. A tactile strain transducer was used to measure the deflection. The experiment was carried out on a ZwickRoell universal testing machine with a 2.5 kN load cell. Fig. 4 presents the test setup, which loaded the specimen with 5 N before testing and the failure criterion was a 20% force decrease. Ten specimens were tested for every laminate.

3.2.3. Fractography analysis

In order to investigate the failure behaviour of the specimens in more detail, SEM images were prepared after the shear edge tests. For this purpose, the fracture surfaces of two opposing shear surfaces were analysed on a laminate without elastomer (FML), with thick (FMEL) and with thin elastomer (tFML).

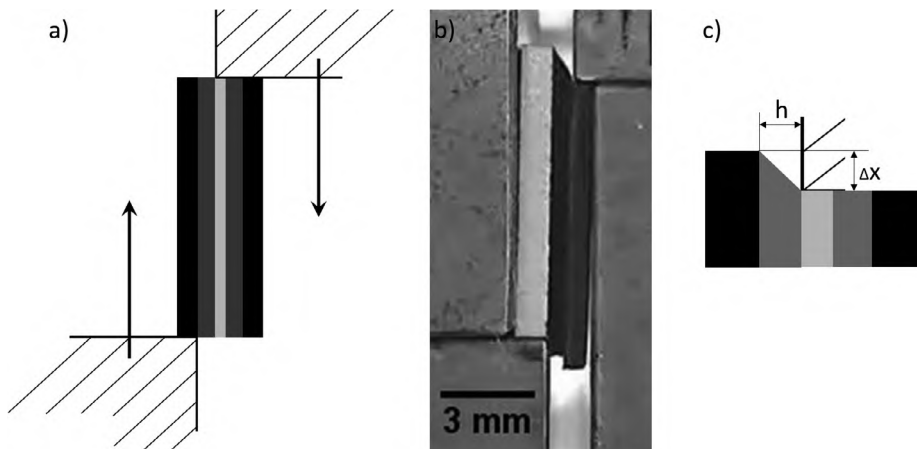


Fig. 3. a) Schematic of the edge shear test b) an asymmetric laminate in the experiment showing the strain of the elastomer c) schematic of the displacement Δx and the shear gap h .

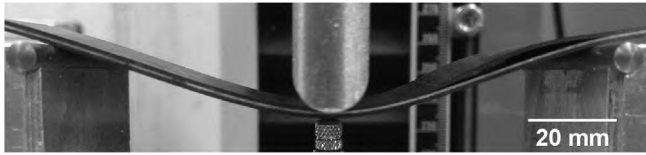


Fig. 4. Setup for three point bending tests with a FML failing due to delamination on the right side.

4. Results

The results of this study are presented concerning the feasibility of the tFMEL manufacturing process and towards the mechanical properties compared to FMEL and FML.

4.1. Manufacturing of FMEL with thin elastomers

The manufacturing of Fiber-Metal-Laminates with thin elastomer interlayers through solving the elastomer in benzene to reduce the layer thickness was successful. Optically flawless laminates were manufactured using the identical curing process as with FMEL and FML. The resulting microsection images are presented in Fig. 5.

The manufacturing process of the tFMEL was successful, as consolidated laminates were obtained. The solution process was optimized finding 16% elastomer content, which enabled a constant layer thickness through pourability, but was convenient to handle because of high surface tension. The subsequent curing process was invariant and not sensible concerning the thin layer.

4.2. Mechanical properties of tFMEL, FMEL and FML

The influence of the elastomer interlayer thickness was examined through mechanical properties. The adhesive properties were additionally evaluated to assess differences caused by the solution step.

4.2.1. Interfacial properties

The interfacial properties of the different laminates were assessed first to account for the adhesive properties between the constituents and define the manufacturing quality of the tFMEL. Fig. 6 shows a representative shear stress displacement curve for each laminate obtained in the edge shear tests. The FML specimen exhibits the stiffest behavior due to the lack of the shear soft elastomer interlayer. With thicker elastomer layers it can be seen that the interface becomes less stiff. From these curves the maximum shear strength can easily be deduced, the shear energy is calculated by the area under each curve.

Fig. 7 presents the interfacial properties of all FML, FMEL and

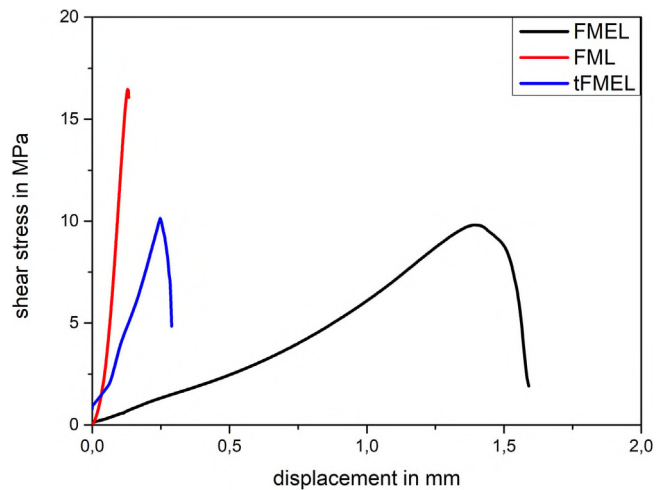


Fig. 6. Shear stress – displacement (Δx) curves of the tFMEL, FMEL and FML in the edge shear test.

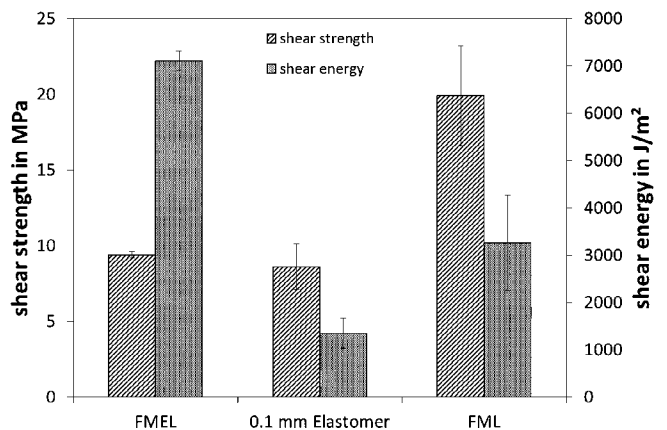


Fig. 7. Interfacial properties of the FMEL with different elastomer thickness and the FML.

tFMEL specimens in the edge shear test. The FMEL and tFMEL had identical shear strengths, with a higher scattering for the tFMEL specimens. The FML had significantly higher shear strength with the highest scatter.

The FMEL had the highest shear energy, while the tFMEL had the lowest value and the FML exhibited the intermediate performance with

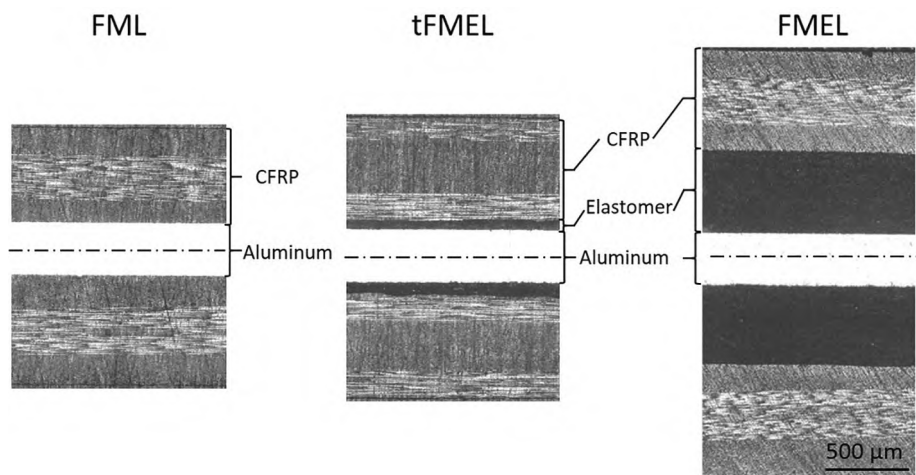


Fig. 5. Cross-section images of an FML, tFMEL and FMEL specimen.

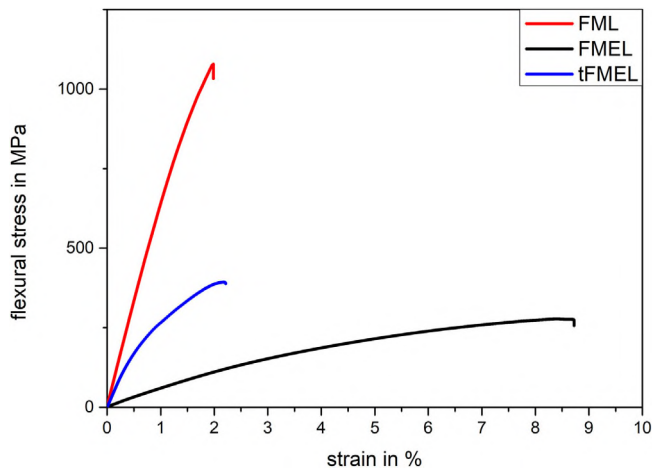


Fig. 8. Flexural properties of the tFMEL, FMEL and FML in the three point bending test. Strain and flexural stress are calculated for the outer fiber of a homogeneous material.

the highest scattering.

4.2.2. Flexural properties

The flexural properties of the laminates were used to compare the load bearing capability of the laminates with the different elastomer thicknesses. The flexural stiffness, strength and strain to failure were assessed to describe the behavior of the laminates. The mechanical properties of the laminates are presented in Fig. 8, where a representative curve of each laminate of the bending experiments is visualized. The strain and stress describe the fictional values for a homogeneous material with the same thickness. The FML had the highest properties in stiffness and strength followed by the tFMEL and FMEL. The strains to failure were contrary to the high strength. The tFMEL was able to show higher mechanical properties than the FMEL due to the thin elastomer layers, but for a linear interpolation of the properties, the strain to failure was reduced.

In Fig. 9 the flexural properties of all tFMEL, FMEL and FML are presented. The flexural stiffness values for the FMEL were the lowest, tFMEL presented the intermediate stiffness and the FML had the highest stiffness. The scatter was very low with the FMEL specimens, higher with tFMEL and very high with FML. The flexural strength of the FMEL and tFMEL were nearly identical and the FML presented significantly higher properties. The scatter behaved like the strength values nearly constant for FMEL and tFMEL, while the FML had high scattering. The strain to failure was high with FMEL specimens and low with tFMEL and FML specimens.

The failure in FMEL and tFMEL was tension and compression failure

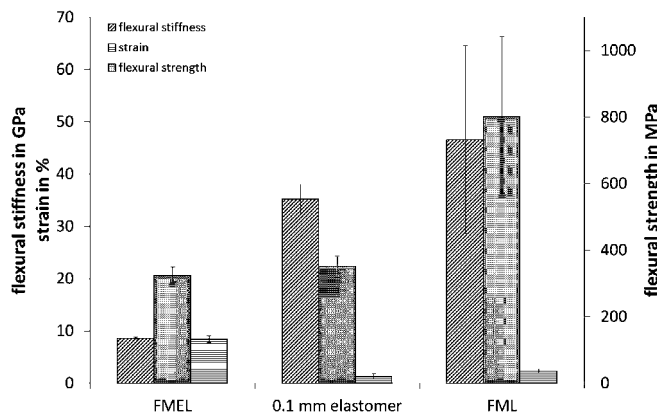


Fig. 9. Flexural properties of FML, tFMEL and FMEL.

in the outer fibers, while the FML failed due to delamination (see Fig. 4).

4.3. Fractography analysis

The results of the SEM analysis can be seen in Fig. 10 and in Fig. 11 for different magnitudes. The direction of the carbon fibers can be easily recognized in Fig. 10 for all three specimens by the horizontal running textures. For the tFMEL and the FMEL these are the imprints of the carbon fibres in the elastomer or the fibres themselves. For the FML, these are fractured resin-rich areas that adhere to the aluminum (Fig. 10c) or represent a breakout in the CFRP (figure 10f). In Fig. 11 it can be seen, that the specimens with elastomer failed in the interface between CFRP and elastomer as the imprint of the carbon fiber can be clearly seen for the pictures with CFRP underneath (a,b). However, for the tFMEL slightly more elastomer adheres to the CFRP layer underneath. For the FML, the imprint of the vertical running direction of rolling of the aluminum can be detected, that was imprinted to the epoxy resin during the consolidation process (c). On the aluminum side the resin-rich areas also show few adhering fibres (f) top left.

5. Discussion

The manufacturing process of the tFMEL using benzene in the solution to generate thin elastomer layers was shown. The manufactured laminate did not show any visual impairments and the layers of the laminate were homogeneous and constant in thickness over the manufactured sheet. The additional manufacturing step, which was included, did not affect the process cycle.

The FML had a high strength and high stiffness compared to the other laminates. The FMEL and tFMEL had similar strengths but different fictional strains in the flexural tests and different displacements Δx in the edge shear test. The different fictional strains originated from the elastomer layer thickness. Under bending stress, all CFRP and aluminium layers of the FMEL and tFMEL specimens are bent around their own central axis because nearly no shear forces can be transferred by the soft elastomer layer. The failure in the tFMEL and FMEL in the bending experiments was compression and tension failure in the outer layer, which proved sufficient interfacial properties as the interface did not fail prematurely. The FML, on the other hand, failed due to delamination, causing a sudden failure because of the brittle interface.

To compare the results of the edge shear test of the two laminates with elastomer, the shear strain γ is calculated from the elastomer thickness h (which was identical to the shear gap) and the displacement Δx by $\gamma = \frac{\Delta x}{h}$. However this estimation is only possible to for a positive shear gap (> 0) and thus for specimens with elastomer. The resulting curve for tFMEL and FMEL is shown in Fig. 12 with error bars showing the variation of the curves. A slight difference in elastomer thickness can cause a lower strain, which led to an overestimation of the stress properties causing the tFMEL curve to be shifted to higher values compared to FMEL. It can be seen that the maximum shear strain in almost the same for both elastomers and also the stiffness of the elastomeric interlayer is not influenced by the solution step. It is therefore concluded, that the adhesive properties of the elastomer layer with the additional solution step was identical to the elastomer in the FMEL, because the shear strength, maximum shear strain and shear modulus was constant. The solution step did therefore not influence the adhesive properties of the elastomer. The SEM analysis in Figs. 10 and 11 also showed similar failure mechanisms for both elastomer thicknesses. However, slightly more elastomer adhesion was seen in the tFMEL on the CFRP layer beneath, than on the FMEL. This may be due to increased adhesion between CFRP and elastomer, or reduced cohesion in the elastomer of the tFMEL. A decrease of the shear strength could not be determined thereby, though. However, the shear energy of the FML was higher than the tFMEL but could not surpass the FMEL. The higher shear energy of the FML compared to the tFMEL was caused by higher

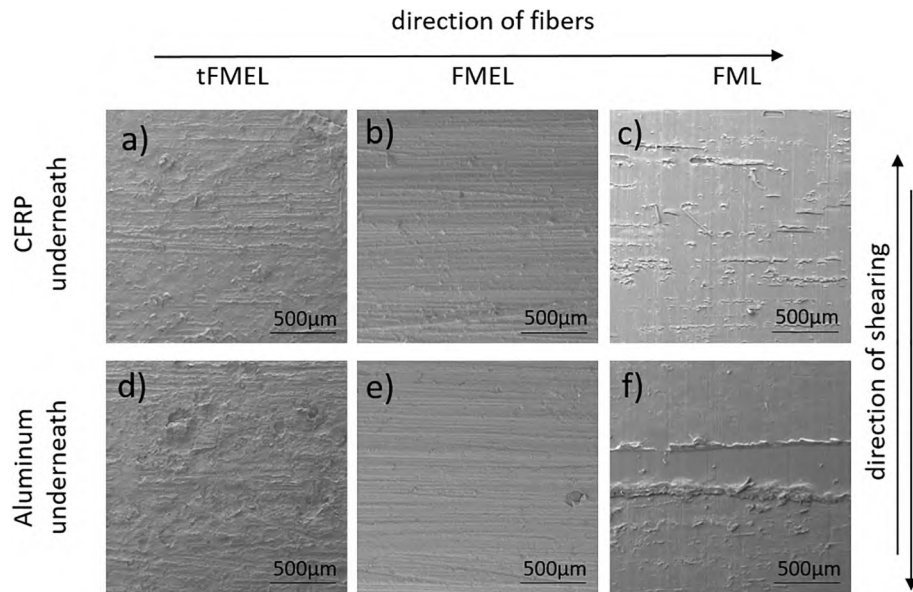


Fig. 10. SEM analysis of the fractured surfaces with either CFRP or aluminum as underneath following layer. 50× magnification.

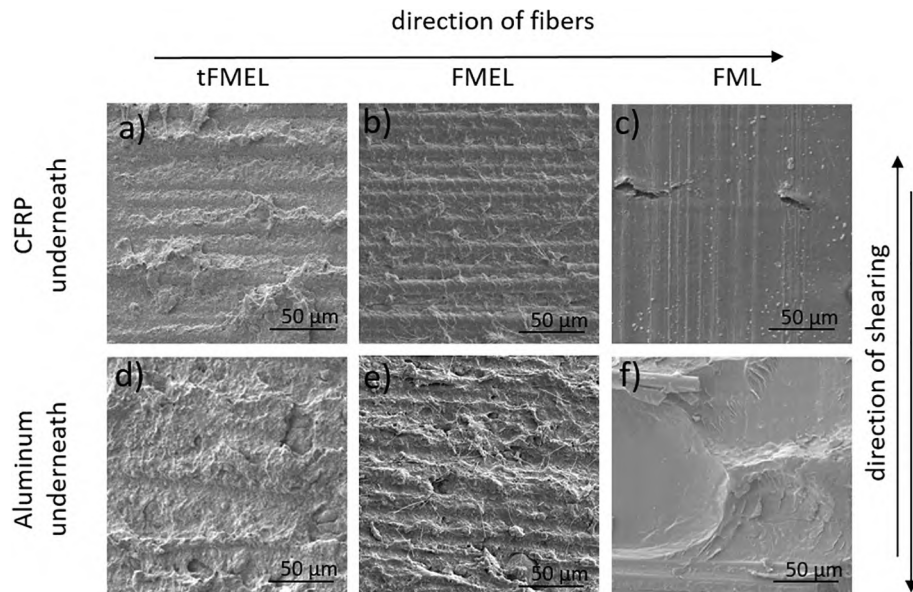


Fig. 11. SEM analysis of the fractured surfaces with either CFRP or aluminum as underneath following layer. 500× magnification.

shear strength. The benefit of the elastomer interlayer on the interfacial properties was nullified through the lower layer thickness in the tFMEL, because shear strength and energy were lower compared to the FML and the FMEL. In terms of flexural properties the thinner elastomer however leads to a higher stiffness and lower weight.

As most commercial available FMLs like GLARE or ARALL have thin ply thicknesses to increase the quantity of aluminium and fiber reinforced layers over the thickness and hence increase impact and fatigue properties, it seemed also promising to manufacture FMELs with thin individual layers.

6. Conclusion

The standard elastomer layer thickness reduced mechanical properties of the laminate. A thickness reduction of the elastomer was desired to increase laminate properties. However, the elastomer thickness could not be reduced by roll forming. The proposed solution was a dissolution step of the elastomer in benzene to obtain lower elastomer

thicknesses. Elastomer could be dissolved in benzene to obtain thin elastomer interlayers in FMELs. The basic manufacturing principle was proven, as optically flawless laminates could be produced. A thickness of 0.1 mm was selected for the elastomer interlayer, but the thickness can be varied at will using this technique. The mechanical properties of tFMEL, FMEL and FML were compared concerning interfacial behavior and flexural properties to assess the elastomer properties and the overall load bearing capability. The tFMEL had good adhesive properties and maximum shear strains, which matched the FMEL showing that the solution of the elastomer in benzene did not affect the adhesive properties negatively. The shear strain of the thin layer was identical to the thick layer, proving comparable mechanical properties leading to the possibility to tailor the laminate properties to the application. The flexural properties of the tFMEL increased the FMEL performance caused by the thinner elastomer interlayer, but did not reach the FML lacking the elastomer. The intended increase of the FMEL performance could be obtained by the thinner interlayer. The tFMEL could enhance the properties of the FMEL, but the electrochemical decoupling and the

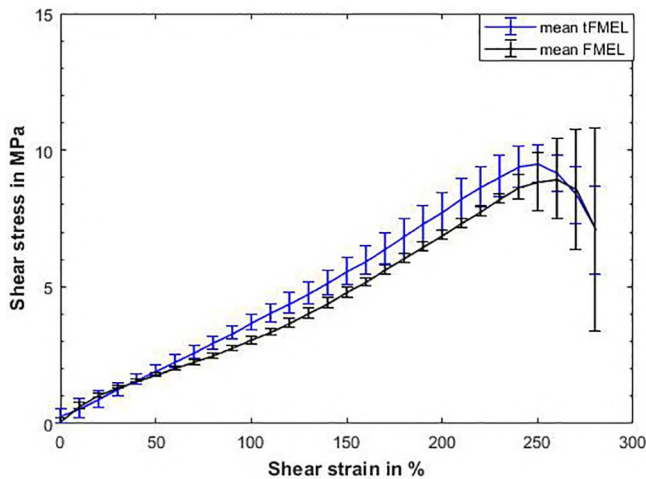


Fig. 12. Shear stress – shear strain curves of the elastomer layers for tFMEL, FMEL in the edge shear test.

compensation of thermal expansion coefficients must still be validated for thin elastomer layers. The objectives set for the thin layer could be reached and resulted in desired mechanical properties.

Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.compstruct.2019.03.042>.

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