Virtual and experimental hybrid thermoforming of GFRP and aluminum

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VIRTUAL AND EXPERIMENTAL HYBRID THERMOFORMING OF GFRP AND ALUMINUM

M. Grubenmann[1], J. Heingärtner[2], A. Rieb[3], and P. Hora[4]

[1] inspire AG, Institute of Virtual Manufacturing, Technoparkstrasse 1, 8005 Zurich, grubenmann@inspire.ethz.ch, www.inspire.ethz.ch
[2] inspire AG, Institute of Virtual Manufacturing, Technoparkstrasse 1, 8005 Zurich, heingärtner@inspire.ethz.ch, www.inspire.ethz.ch
[3] Bond-Laminates GmbH, Am Patbergschen Dorn 11, 59929 Brilon, arthur.rieb@lanxess.com, www.bond-laminates.de
[4] ETH Zurich, Institute of Virtual Manufacturing, Tannenstrasse 3, pavel.hora@ivp.mavt.ethz.ch, www.ivp.ethz.ch

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ABSTRACT

In this work, a hybrid thermoforming process consisting of a glass fibre-reinforced thermoplastic and aluminum outer layers is investigated. To guarantee interlaminar adhesion of the two materials, a multi-layered thermoplastic adhesive film is used. Both materials are thermo-mechanically tested to calibrate the corresponding material model. In-plane tensile tests and bias extension tests, as well as out-of-plane cantilever tests, are used to characterize the behaviour of the organosheet. For the characterization of the aluminum alloy AA5182, uniaxial tensile tests at various temperatures and strain rates in relation to rolling direction are performed. A flat tool pressing process is chosen to show the flexural behaviour of the hybrid component in a three-point bending test, whereas lap shear tests are used to investigate the interlaminar shear strength carried by the adhesive film. In both validation experiments, it is shown that increased temperature and low applied pressure leads to increased flexural strength and interlaminar shear strength. A V-shaped two-dimensional geometry is used to apply this hybrid approach to a deep-drawing process. After the forming process, microscopic pictures of the cross-sections are manufactured to investigate the consolidation of the GFRP layer and evaluate air void formation. Being independent of the consolidation pressure, heating the GFRP layer up to 10 °C above melting temperature of the matrix material causes high void fraction and low fraction of bonding area between the GFRP and aluminum layer. Applying higher temperatures up to 280 °C leads to continuous bonding contact of all layers and only few and small void formations. Based on two simple geometries, a feasible hybrid thermoforming process of GFRP and aluminum is demonstrated.

1 INTRODUCTION

In the automotive industry, efforts are undertaken to develop new lightweight approaches to lower CO2 emissions and fulfil the average emission limits within the EU. Novel multi-material designs enable new lightweight technologies in the field of component design but also lead to new challenges in material and process modelling. An appropriate modelling of the considered manufacturing process and the material behaviour can prevent time and cost consuming trial-and-error approaches in the designing phase of a component. The idea of taking advantage of a mixed material approach based on a combination of fibre-metal laminates (FML) has been pursued for several decades and was successfully implemented in the aviation industry [1]. The usage of fibre-reinforced thermoplastic materials in an FML lay-up and conventional stamp forming tools allow short cycle times and therefore the high production rate needed. Literature is limited to several studies which investigated the deep-drawing of FMLs on a mainly experimental level. MOSSE et al. have determined in various studies [2, 3] the influence of different process parameters such as tool temperature and blankholder force on the shape error and replicated these results using Finite Element Analysis (FEA). In comparison to conventional metallic deep-drawing parts, the FML parts showed 75 % less shape error. TEKKAYA et al. [4] and BEHRENS et al. [5] have shown successful deep-drawing of FMLs to cup shapes. The major challenges were wrinkling as a consequence of too low blankholder forces and fracture due to too high blankholder forces. Both defined a process window based on experimental data.

2 MATERIAL CHARACTERIZATION

The symmetrical layup of the hybrid blank consists of the organosheet Tepex dynalite 102-RG600(2)/47% with a thickness of 1.0 mm as core material and AA5182 as outer layers with a thickness of 0.5 mm. In this chapter, the thermo-mechanical material properties are presented. The thermal properties of the materials, the heat transfer mechanisms as well as the friction model will not be discussed in detail in this study.

2.1 Organosheet

The considered organosheet consists of a polyamide 6 matrix reinforced with 47 vol. % fibre content. The fabric is an E-Glass roving in twill 2/2 style. The temperature dependent material behaviour in 45° to the main fibre direction is shown in Figure 1. For the determination of the shearing behaviour, bias extension tests and digital image correlation (DIC) are used to track the shearing angle. Cantilever tests help to determine the temperature-dependent bending behaviour of the material. Detailed in-plane and out-of-plane material properties are presented in [6].

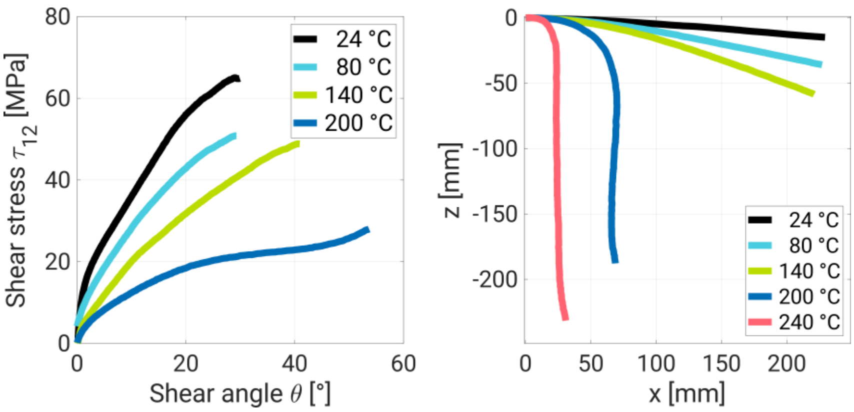

Figure 1: Temperature dependent material behaviour in 45° to main fibre direction in-plane (left) and out-of-plane (right).

*MAT249 in LS-DYNA™ is used to describe the material response during the forming process. By reallocating the integration points, the low bending stiffness at elevated temperatures can be reproduced.

2.2 Aluminum alloy AA5182

To model the considered aluminum alloy, strain rate dependent tensile tests at various temperatures are performed. To ascertain the hardening behaviour at higher strains, a bulge test is executed to extend the uniaxial yield curve. These uniaxial flow curves are approximated by equation 1 according to Hockett-Sherby.

$$\sigma_y = S_{sat} - (S_{sat} - S_0)exp(-me^n) \tag{1}$$

To describe the plane-stress flow behaviour the YLD2000 yield locus, which was proposed by BARLAT et al. [7], is chosen. Figure 2 shows various experimental uniaxial flow curves. It can be seen that the aluminum alloy is not strain-rate sensitive at room temperature but its dependence is cumulative with increasing temperature. The normalized YLD2000 approximation of the yield stresses at room temperature is given on the right-hand side of the figure with its calibrated model parameters. This yield locus is valid for the entire temperature and strain-rate range.

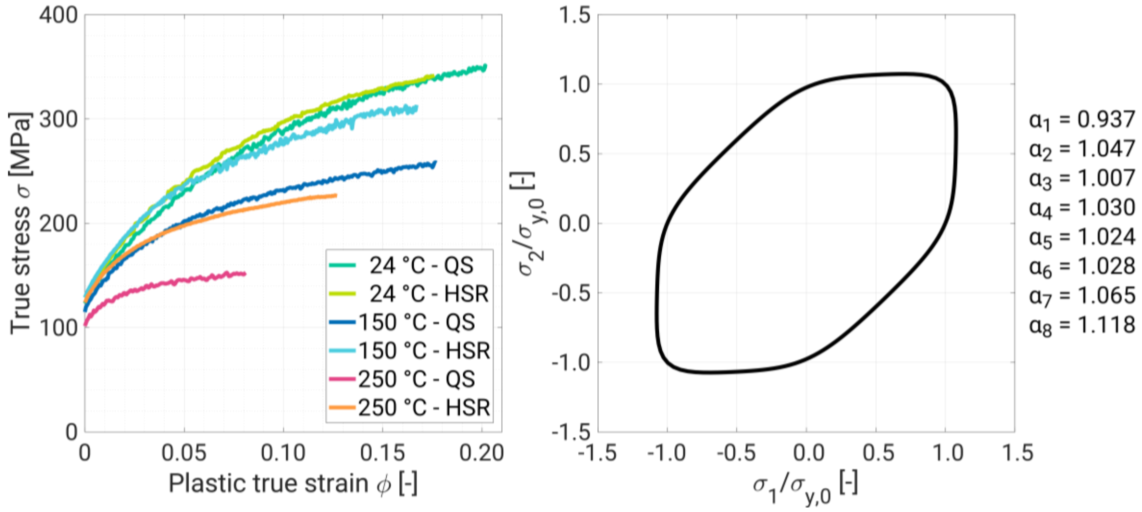

Figure 2: Experimental results of temperature and strain-rate dependent uniaxial tensile tests (left) and calibrated yield locus YLD2000 (right).

3 PROCESS MODELLING

In the preparation of the lay-up, the single material layers are stacked on each other. To guarantee good adhesion between the aluminum and the organosheet core, an adhesion layer of 0.1 mm is chosen. This thermoplastic hot melt foil nolax A22.5011 is supported by nolax AG. The multi-layer adhesive film is based on copolyamides and modified polypropylene. After preparation of the single layers to one blank with a total thickness of 2.2 mm, the hybrid blank is heated in a convection oven over the melting point of PA6 at 220 °C. The blank is then transferred to the press and placed between the tools that are held at room temperature. After the forming step, the hybrid component is held under constant pressure until the core material has reached room temperature and can be demolded. An overview of the process chain is given in Figure 3.

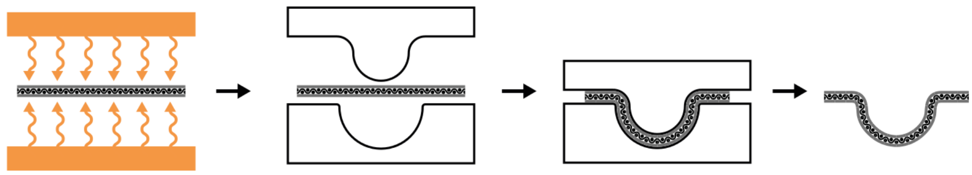

Figure 3: Hybrid thermoforming process consisting of the single steps heating, forming, cooling, and demolding.

The aim of this study is to determine the optimal process parameters for the case of two geometries. Besides the optimal process parameter, a process window should be defined, in which the process is feasible. For this reason, a flat tool pressing and a V-shaped deep-drawing process is considered.

4 FLAT TOOL PRESSING

For the flat tool pressing, an initial panel size with a length of 220 mm and a width of 100 mm is chosen. The main fibre direction is oriented along the long edge of the specimen. The varying process parameters are initial blank temperature and applied pressure in the forming process. A full factorial design with temperatures of 230 °C, 245 °C, and 260 °C as well as pressure of 0.1 MPa, 0.3 MPa, and 1.0 MPa is chosen. Figure 4 shows the temperatures at different locations during the process stages. The convection oven is heated to 300 °C to allow a short heating period of 200 s. The time lag of temperature T3 in the core of the organosheet must be considered when heating the composite blank to a specific temperature. In this case, the extraction temperature T1 is set to be 245 °C whereas T1 is at 236 °C. Therefore the matrix material can be considered fully melted. After heating, the blank is transferred to the press and placed on the lower tool within seconds. The closing speed is appointed to be 400 mm/min which allows closing of the tools in 5 seconds until the distance of 2.2 mm between the tools is reached. In the next step the considered pressure is applied and is held until the core material has reached room temperature and the composite part is extracted.

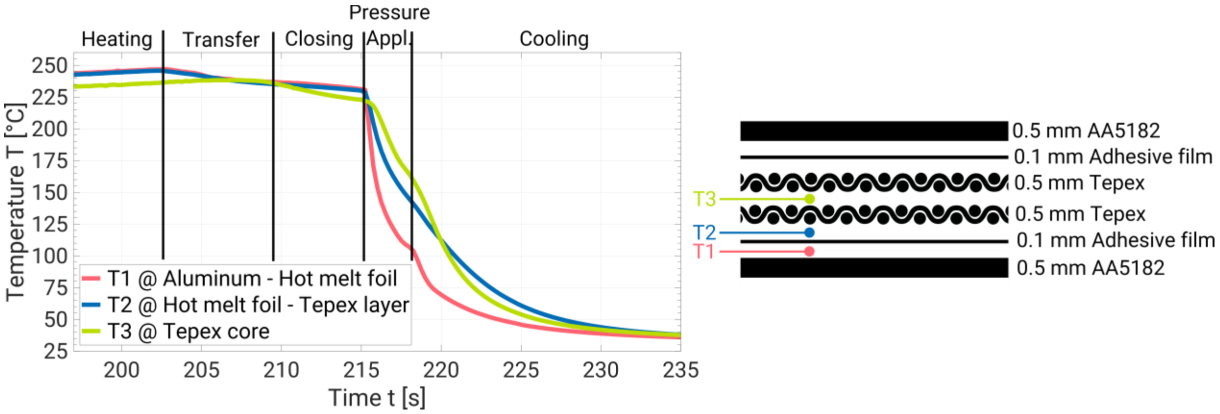

Figure 4: Temperature profile during the thermoforming process at different locations in the blank.

For all the combinations of process parameters, a qualitatively good adhesion can be observed. To quantify and compare the various specifications, three-point bending tests following standard ASTM D790 and lap shear tests according DIN EN 1465 are performed. Three-point bending tests are chosen to compare the flexural properties of the material combination whereas the lap shear tests allow a comparison of adhesive strength of the single layers.

4.1 Three-point bending validation

The setup of the three-point bending tests is shown in Figure 5. The radii of the loading nose and supports are 12.5 mm and the support span was set to be 80 mm. This dimension gives a span-to-depth ratio of 40:1 which is recommended for composite laminates with relatively high tensile strength and fairly low shear strength in the plane of the laminate [8]. The displacement speed of the loading nose is 6 mm/min.

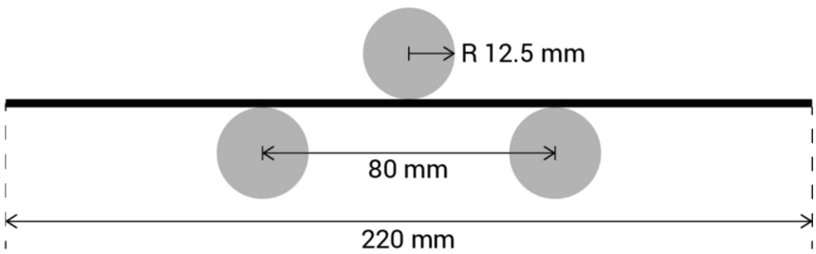

Figure 5: Three-point bending setup.

All configurations of the full factorial design are tested. The maximum force is observed for all specimens between a displacement of 17 mm and 20 mm. Except the combination of the temperature 230 °C and pressure 0.1 MPa, all combinations show an averaged flexural modulus of 52.87 GPa in comparison to the flexural modulus of 69 GPa of a pure aluminum alloy and 19 GPa of the organosheet. The specific flexural modulus is given by the division of the flexural modulus by the considered density of the tested material. The density, specific flexural modulus and the lightweight potential are shown in Table 1. In the case of the hybrid blank, a similar stiffness to weight ratio can be reached whereas the blank is 21 % lighter than the pure aluminum blank with the same thickness.

Configuration	Total thickness [mm]	Density [g/cm³]	Specific flexural modulus [10^6 m^2s^{-2}]
Pure aluminum blank	2.2	2.7	25.56
Hybrid blank	2.2	2.14	24.71

Table 1: Comparison of density and specific flexural modulus for pure aluminum and hybrid blank.

The comparison of the maximum force of each experiment is shown in Figure 6.

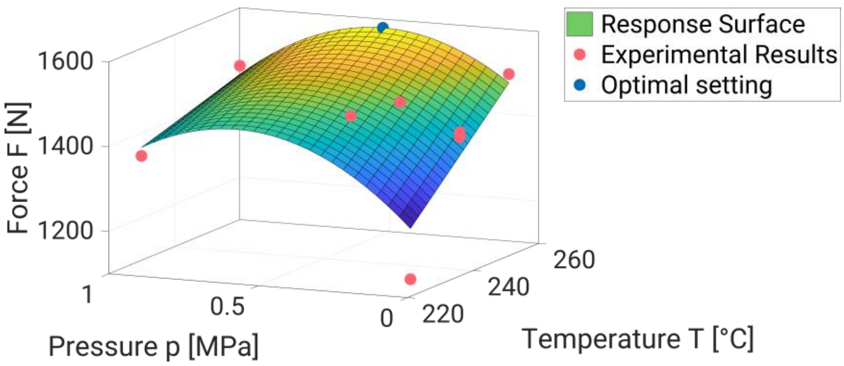

Figure 6: Maximum punch force in three-point bending test in dependence of pressure and temperature.

It can be seen that for all parameter combinations, excluding the combination of 230 °C and 0.1 MPa, the maximum force lies between 1300 MPa and 1500 MPa. In this range of temperature and pressure combinations, a response surface of the system is fitted. It can be noted that a linear interpolation of the temperature and a quadratic interpolation of the pressure fits the experimental data best. Therefore, the optimal setting is found to be a combination of 260 °C and applied pressure of 0.52 MPa.

4.2 Lap shear validation

To investigate the adhesion behaviour of the adhesive film, lap shear tests are performed. The test samples are prepared by cutting strips with a width of 25 mm along the short edge of the before pressed parts. To load the adhesive film between the organosheet and the aluminum layer, two layers on each side are removed. This leads to an overlapping length of 12.5 mm. The considered cross-section geometry is shown in Figure 7.

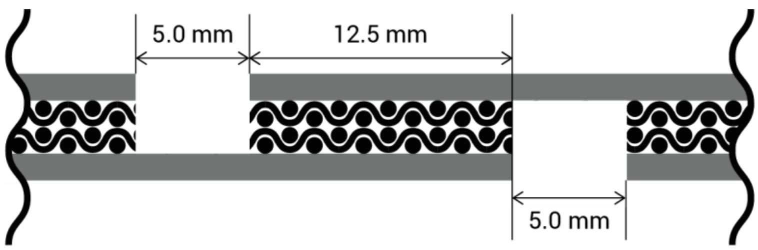

Figure 7: Set-up of lap shear test.

Again, the maximum bearable force is chosen to determine the characteristic maximum shear stress. To calculate the shear stress, the maximum measured force is divided by the width of 25 mm and the length of 12.5 mm of the overlapping area. In all experiments, the first failure is observed at the polymer film between the organosheet and the outer aluminum layer. Depending on the parameter combination, loss of adhesion occurred between 0.3 mm and 1.5 mm displacement. Figure 8 shows a comparison of the maximum shear stress for all process parameter combinations.

In the case of the lap shear test, the variation of temperature and applied pressure show an increased influence on the adhesion strength of the adhesive film. It can be stated that the adhesion strength is rising with increasing temperature and decreasing pressure. It must be considered that certain scattering in the measured maximum shear stress is observed. All lap shear specimens per configuration are manufactured from the same blank to guarantee same process boundaries for the lap shear experiments. Nevertheless changing conditions in the blank plane cannot be prevented entirely which may explain the observed scattering in the case 1.0 MPa pressure at 245 °C and 260 °C. To gain the best adhesion properties between AA5182 and the organosheet with the adhesive film for the chosen temperature and pressure range, a high temperature of 260 °C and low pressure of 0.1 MPa should be chosen.

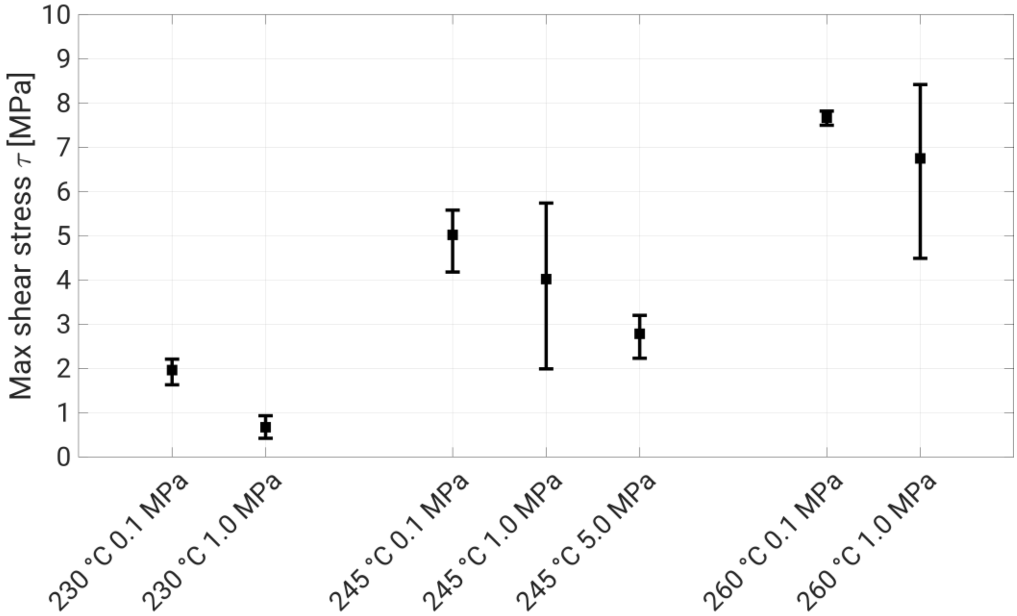

Figure 8: Comparison of maximum shear stress for all parameter combinations in the lap shear test.

5 V-SHAPED DEEP-DRAWING

The hybrid thermoforming process is now applied to a simple two-dimensional deep-drawing geometry. The final part geometry can be seen in Figure 9.

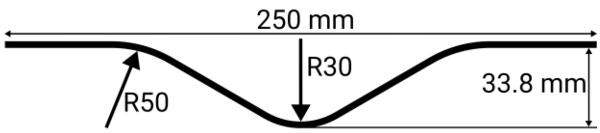

Figure 9: V-shape geometry.

The process boundary conditions are following the flat press experiments. In this case, a full factorial design with an extended temperature range of 230 °C to 280 °C and applied pressure of 1 MPa to 7 MPa is chosen. To compare the influence of the process parameters on the consolidation of the GFRP core layer, microscopic pictures of the cross-sections are manufactured. The quality of consolidation will ultimately determine the performance of the final component and is therefore a quality criterion of the forming process. The applied temperature and pressure causes compaction of the structure and therefore an increase of the fibre volume. Optimum consolidation conditions are necessary to guarantee reasonable bonding of all layers, high fibre volume fraction, and low content of air voids [9]. The results of the cross-sectional evaluation are shown in Figure 10.

It can be noticed that in the case of 230 °C and independent of pressure, the organosheet and the aluminum layers are only partially in contact which leads to a decreased overall stiffness of the component. The adhesive film is not able to close this gap therefore leading to air voids. An increase in pressure cannot compensate for this undesirable occurrence. This high fraction of air voids is noted in the whole component for this combination of parameters. Increasing the temperature to 280 °C, at which the blank is taken out of the oven, leads to an almost void-free structure. Independent of pressure, the adhesive film shows good adhesion of the aluminum layers and the organosheet. Only locally small air voids in the organosheet layer can be observed. These observations lead to the assumptions that the temperature influence is more important than the variation of the applied pressure whereas the latter cannot compensate void formation at lower temperatures.

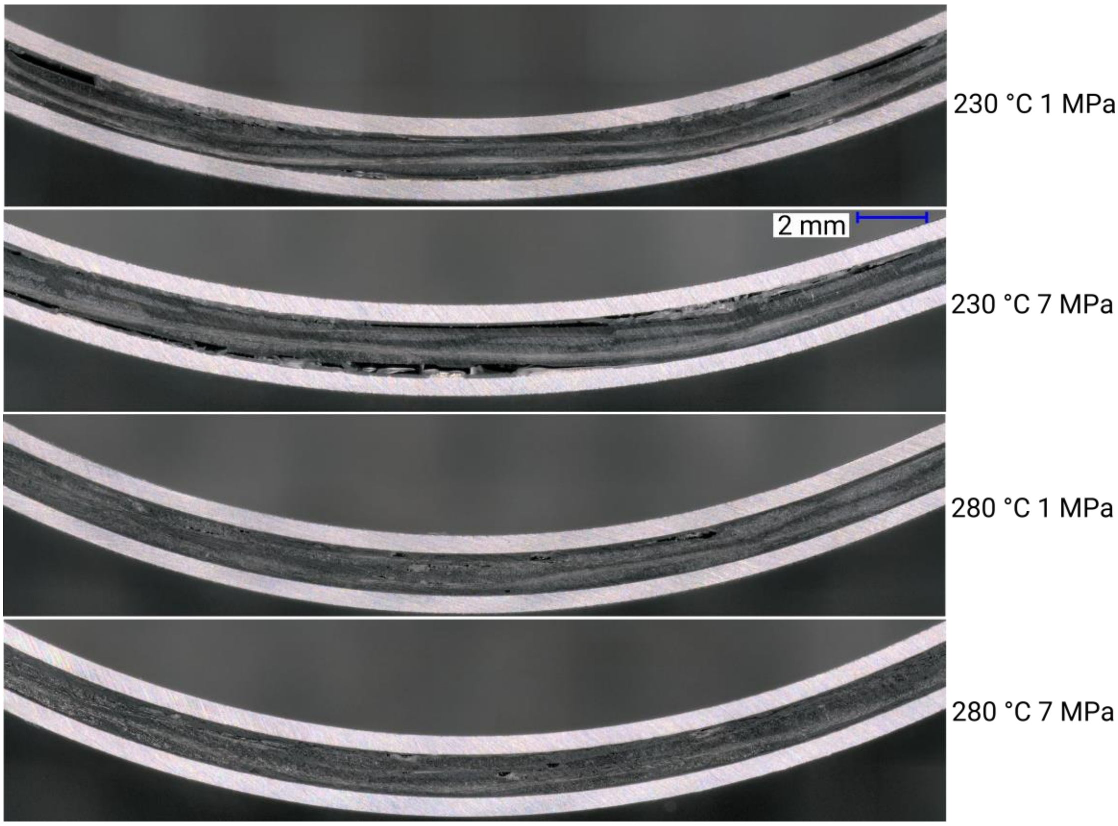

Figure 10: Cross-sectional evaluation of V-shape profile.

7 CONCLUSIONS AND OUTLOOK

Maunfacturing fibre metal laminates in a hybrid thermoforming process allow components with high strength, low density and high energy absorbing capacity. The applied pressure at the consolidation phase and the temperature at which the hybrid blank is formed have significant influence on the final performance of the component. With a flat tool compression test and a two-dimensional V-shaped geometry, a feasible process with optimum process parameters are determined. The optimization of the process parameters is done by performing validation experiments based on a three-point bending test, lap shear tests and microscopic evaluation of the cross-section area. These observations are translated into a virtual model allowing the determination of optimum process parameters on a more complex deep-drawing component. Work on the virtual validation of the presented experimental results is ongoing. Preliminary comparisons between the numerical simulation and the herein made observations show promising agreement and must be confirmed with further investigations.

ACKNOWLEDGEMENTS

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