HYBRID THERMOPLASTIC COMPOSITES FOR AUTOMOTIVE APPLICATIONS – DEVELOPMENT AND MANUFACTURE OF A LIGHTWEIGHT REAR FLOOR STRUCTURE IN MULTI-MATERIAL DESIGN

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Abstract

In a holistic lightweight approach a new vehicle concept, including a structural hybrid thermoplastic rear floor part, has been developed within the publicly funded research project “SMiLE - System-integrated multi-material lightweight design for e-mobility”. The properties of the individual materials are combined to achieve a high degree of functional integration. For this purpose a novel compression molding process was developed: the so-called “local advanced tailored D-LFT process”. In this process continuous-fiber-reinforced structures are overmolded only at specific sites to integrate load application elements and to generate higher stiffness in the areas where it is needed. Advanced simulation models are applied to optimize the manufacturing and to validate the technical feasibility of this innovative part. Based on these simulation models an advanced process chain was developed and set up at the Fraunhofer Institute for Chemical Technology, to enable the manufacturing of the lightweight rear floor structure in multi-material design.

1. Introduction

The application of fiber-reinforced polymers (FRPs) in automotive series production enables extensive weight reduction. However, some effort is needed to create economically feasible lightweight solutions with these kinds of materials. A holistic lightweight approach focusing on a whole system is the key for an economical implementation of FRPs in automotive applications. Such an approach was pursued within the research project “SMiLE - System-integrated multi-material lightweight design for e-mobility” for developing a new vehicle concept, including a structural hybrid thermoplastic rear floor part.

On the basis of unidirectional continuous-fiber-reinforced thermoplastic tapes (UD tapes) and long-fiber-reinforced thermoplastics (LFTs) a high degree of functional integration was achieved. The innovative part design was iteratively developed using advanced simulation models to optimize the manufacturing and to validate the technical feasibility. Furthermore, a specially adapted process chain was developed and set up at the Fraunhofer Institute for Chemical Technology ICT to enable manufacturing of the rear floor structure.

2. State of the art and fundamentals

2.1. Processing of thermoplastic fiber-reinforced polymers

Continuous-fiber-reinforced thermoplastics (cFRTPs) have an outstanding specific mechanical performance in terms of stiffness and strength due to their high load-bearing capacity in the fiber direction. Common cFRTP semi-finished products are UD tapes that are processed in tape laying and consolidation to manufacture so-called tailored blanks. This process technology with subsequent thermoforming offers many advantages for cFRTP processing [1]. Within the project SMiLE, UD tapes were processed with the Fiberforge tape laying system. In a subsequent step the tailored blanks are consolidated to join the individual courses and to reduce the amount of voids within the individual layers and inside the monolithic structure. However, due to material characteristics such as the drapeability and flowability, the design freedom of cFRTPs is limited [2]. The direct processing of LFTs (D-LFTs) in compression molding is an economical approach for high-volume production and offers various benefits such as reduced thermal degradation and reduced expenses for logistics and storage. As the fiber length determines material characteristics such as strength or stiffness, the mechanical performance decreases for shorter fibers [3, 4]. The D-LFT process at Fraunhofer ICT uses a two machine technology where the continuous reinforcing fibers are added to the polymer melt in a second extruder which enables optimized fiber incorporation without affecting compounding in the first extruder. Due to the bulk material flow capability, LFTs offer a high design freedom.

2.2. Hybridization with UD tape and LFT

To achieve an optimal design freedom with high stiffness and strength for structural applications, LFTs and cFRTPs must be combined. Current approaches often focus on the use of cFRTPs in the form of tailored blanks as local reinforcements along the main load paths. Here, the consolidated UD tapes are placed inside the mold and overmolded entirely. This increases stiffness and strength but also poses new challenges, for example controlling the position of tape reinforcements [2]. An example of local reinforcements is given in the MAI qfast project within the MAI carbon cluster [5]. In contrast to this approach, the project SMiLE developed a new process of combining LFTs and cFRTPs - the so-called local advanced tailored D-LFT process. By only using LFTs locally to reinforce the cFRTP structure and to avoid buckling, it was possible to reduce the wall thickness and thus the overall weight.

2.3. Process simulation

LFTs. To ensure the filling process of the LFT area, commercial software like Moldflow can be used. The new local advanced tailored D-LFT process meant that further developments were necessary to enable the use of commercial software. The advanced ribs, which are filled as in an injection molding process within the compression molding process, required a special focus. Furthermore, material parameters for D-LFTs are not readily available.

cFRTPs. For process simulation of cFRTPs, finite element (FE) forming simulation is usually applied. This enables the prediction of manufacturing defects and fiber orientation after forming, considering material behavior and process conditions by means of constitutive equations and boundary conditions. As expected given the current interest in the forming of cFRTPs, several approaches for FE forming simulation are found in literature. In addition, some of the codes are also commercially available, notably PAM-FORM [6] and AniForm [7]. Beyond these, so-called multi-purpose FE solvers offer material models for forming simulation.

Since the strengths and weaknesses of available approaches for FE forming simulation of cFRTPs were unknown at the beginning of the project SMiLE, a benchmark study based on a generic geometry was conducted [8]. In this study, in summary four different approaches for FE forming simulation are investigated. This includes PAM-FORM and AniForm as commercial codes on the one hand, and the multi-purpose solvers LS-Dyna and Abaqus on the other. For LS-Dyna, only built-in approaches were considered, whereas for Abaqus an advanced approach implemented in several user-subroutines was considered [9]. The benchmark study showed that each of the investigated FE codes offer the capability to be used as engineering tools for process design, since for example critical forming behavior with respect to the evolution of wrinkles is predicted by each of the investigated codes. However, there is a difference in prediction accuracy for the different FE codes. It could be shown that very good results are obtained with the user-defined modeling approaches, which are only available in literature. Finally, the approach implemented in user-subroutines of the commercially available FE solver Abaqus is applied to process design of the demonstrator part.

3. Lightweight rear floor structure

3.1. Development of part design

The development in processing LFTs and cFRTPs was essential for the rear floor structure. This includes the local advanced tailored D-LFT process for manufacturing of weight- and performance-optimized thermoplastic-fiber-reinforced structures with high function integration enables an innovative part design. The local overmolding with LFT was achieved with specially designed displaceable mold cavities that allow the forming of local geometric reinforcements like ribs instead of overmolding the whole continuous-fiber-reinforcement. At the beginning of the process development, the focus was on identifying the parameters which mainly influence the interface strength, and which determine the mechanical performance of the manufactured part. The underlying mold concept for this investigation is shown in Figure 1. The temperature of the UD tape, squeeze flow and form filling behavior of LFT were investigated. Using shear edge tests, the achieved interface strength was assessed. The results showed that a high interface strength can already be achieved with a UD tape temperature of 130°C, which is an important information for the processing [10].

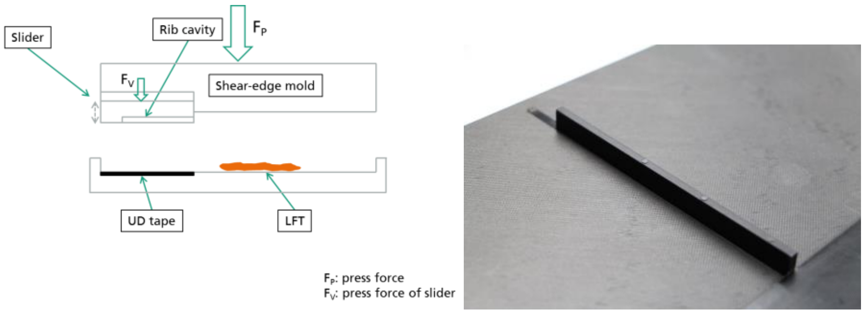

Figure 1. Mold concept for local advanced tailored D-LFT process (left) and UD tape specimen with local overmolded LFT rib (right).

In a subsequent development step, the process was transferred to a more complex geometry with diagonal ribs and ribs with varying heights and thicknesses. In an experimental study following a DoE, process settings were varied. Based on the experimental results, the process simulation model for LFTs was further developed with respect to material modelling and boundary conditions[11]. The parameters varied were mold temperature, UD tape temperature, maximum compression force and the initial charge position. With the final parameter settings, all compression molding filling stages showed a good match with the experiments. The improved simulation model was used in a next step to design the lightweight rear floor structure. The final part design is shown in Figure 2. A thin light shell made from a UD-tape-based tailored blank (grey) forms the main geometry. Large beads in the tailored blank in the direction of the vehicle’s longitudinal axis, combined with local advanced LFT ribs (green), generate a high moment of inertia of area and thus increase the part’s stiffness. The residual LFT areas at the rear of the structure form a crushing zone that will absorb energy in the event of a rear-end collision. Aluminum profiles (blue) at the side that bond to the LFT and to the UD tape are integrated into the one-shot manufacturing process as well. They increase the stiffness and help to transfer the forces into the LFT crushing zone. Additionally metallic inserts are integrated into the LFT for the direct mounting of parts which will be joined, e.g. the belt buckle.

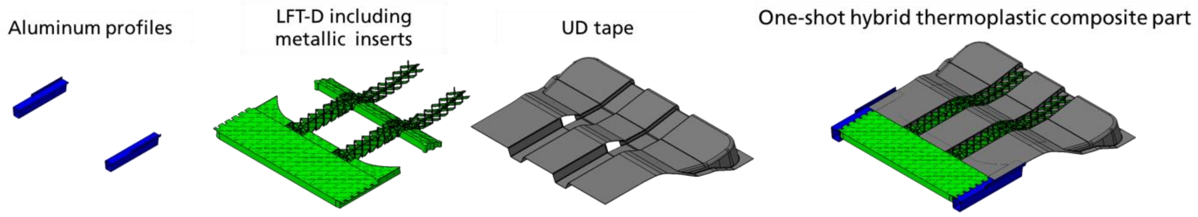

Figure 2. Part design of the lightweight rear floor structure.

The forming of the UD tapes and the compression molding process of the D-LFT is conducted within the same press closing cycle. Nonetheless, process simulation decouples these two elements of the manufacturing [12]. This approach is reasonable, since the forming of the UD tape part is completed by the time the compression molding of the LFT part begins.

Forming stage. Initially, the sequence of the displaceable cavities and the distance between the individual cavities was investigated via FE forming simulation. On this basis, it could be shown that a minimum distance of the bead height is necessary to prevent excessive fiber tension and thus fiber breakage and mold wear. This leads to a forming from the inside to the outside and thus to an imitation of the hand-draping processes. Nonetheless, critical spots regarding forming behavior could be identified by means of forming. On this basis, the design was adapted to avoid these critical spots.

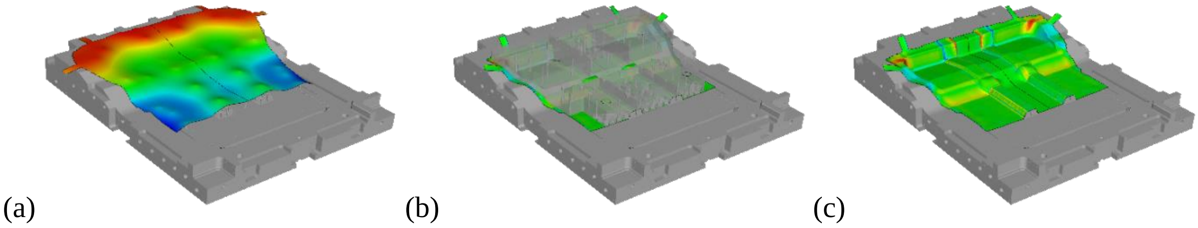

Figure 3. Forming simulation results for the tailored UD-tape part: Deposition of the laminate on the ejector pins (displacement in forming direction) (a), final forming simulation result (shear strain) with transparent tools (b) and hidden tools (c).

Based on the identified forming sequence and adapted design, a so-called tailored blank was manufactured using the approach presented by Dörr et al. [13] to enable a near-net shape forming of the UD tape part. This tailored blank is applied to forming simulation including the modelling of the deposition of the UD tape and LFT on the lower male tool (cf. Figure 3). On this basis, the position of the ejector pins - which were applied prior to the forming stage to minimize the tool-laminate contact - was optimized. By this method, premature cooling prior to the forming stage could be significantly decreased. Beyond that, the design adjustments as well as the tailored blank were virtually verified.

Compression molding stage. After the forming simulation, the mold filling simulation was carried out. The main focus was to ensure complete filling. Due to the long flow length needed, with the thin advanced ribs, this could not be achieved with the initial design by solely changing the LFT strand position or the process parameters. A detailed study was therefore carried out to improve the geometry in the area of the advanced ribs with the long flow path. By adding a rib foot to the center rib in the area of the advanced ribs, a complete filling could be achieved. In the second step, the LFT strand position and the maximum press force were varied to reduce the maximum pressure within the tool.

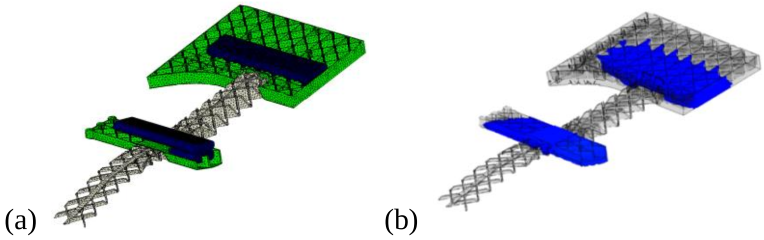
(a) (b)

Figure 4: Compression molding simulation; a: initial model with 2 LFT position with 2 strands each (blue), the compression area (green) and the advanced ribs (grey); b: intermediate mold filling process result (right).

3.2. Process development

To enable manufacturing of the lightweight rear floor structure in multi-material design, an adapted process was developed. The process steps in this adapted process can be divided into the following: heating of cFRTP semi-finished products, handling and transfer of cFRTPs and LFTs and forming by compression molding.

For the first process step of heating the UD tape material a customized heating device was developed and constructed that uses infrared (IR) heaters. The biggest challenge was the size of the tailored blank with 1.6m in width and 1.2m in length. In order to heat the material homogeneously to a processing temperature of 280 °C, the main influencing parameters had to be adapted. During initial operation the position of the tape and its effect on the temperature distribution was therefore analyzed. The control parameters of the heating device were also varied to find an optimum configuration to achieve a homogeneous temperature distribution and short heating time. Figure 5 shows the IR heating device within the process chain and during operation with an organosheet.

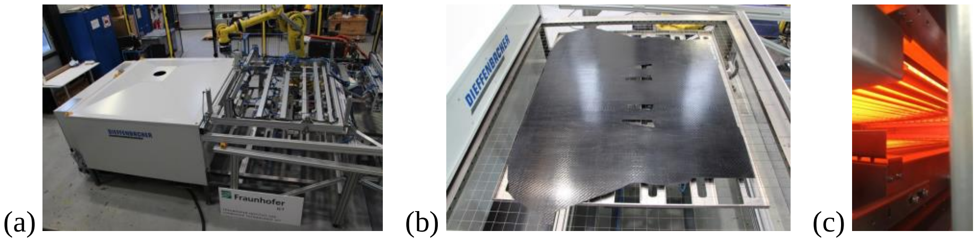
(a) (b) (c)

Figure 5. IR heating device (a) and in operation (b) with a PA6 glass fiber organosheet (c).

After heating the tailored blank and providing the LFT on a heated transfer station, the material had to be handled and transported into the mold. For this purpose an automated handling system was designed that uses pneumatic needle gripper modules to handle the tailored blank and LFT material. These grippers have only a small contact surface to the material, minimizing the cooling during handling. The individual grippers were positioned so that the tailored blank was under constant tension without being deformed through gravitational force. The needle grippers for handling the LFT material have longer needles to enable a safe and repeatable handling. Based on the amount of LFT material needed for a complete form filling, two LFT strands had to be transferred. Both gripper modules are mounted on a gantry system moved by an industrial robot. The programming for the material transfer was realized by using the industrial robot's software. Figure 6 shows the automated handling system.

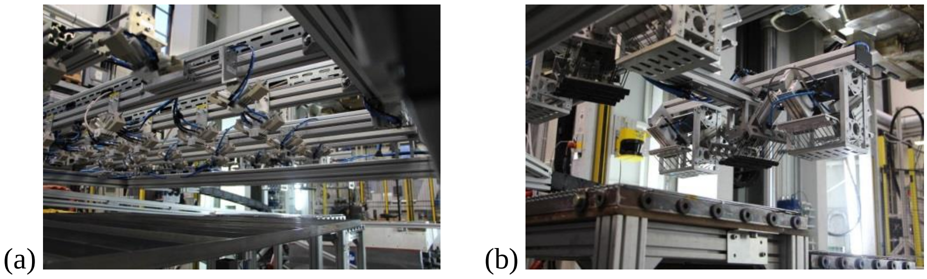

Figure 6. Handling system with needle grippers for the tailored blank (a) and LFT (b).

The last process step is forming and compression molding of the tailored blank and LFT material. In total there were six displaceable mold cavities that were also used to drape the tailored blank in order to reduce defects such as wrinkles. The sequence for moving the cavities was derived from the process simulation and was realized by using the auxiliary functions of the hydraulic press. The pressure can be applied until the mold is completely closed. Because the tailored blank has to be formed by the mold a surrounding shear edge was not possible. The mold was therefore sealed against LFT material by reducing the flow path cross section, by adapting the mold geometry so that the aluminum profiles compressed the tailored blank. Figure 7 shows the displaceable cavities and the sealing concept between aluminum profiles and cFRTPs.

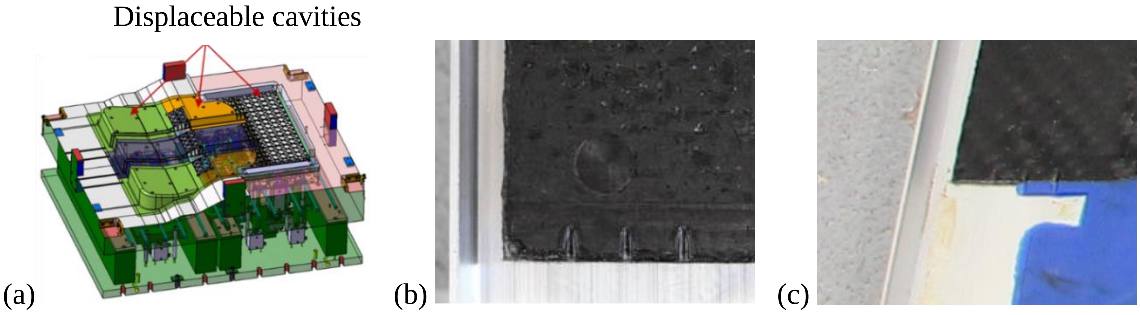

Figure 7. Mold with displaceable cavities (a), sealing concept with reduction of cross section (b, c).

4. Process chain and part manufacturing

The main focus during initial operation of the developed process chain was to validate the tool concept and functionality. In this context, a forming study was carried out, at first only with a tailored blank. The residual travel of the mold for each forming step was chosen so that initially only the first displaceable cavity touched the tailored blank, followed stepwise by the others until the blank was formed to its final shape. The results showed a good conformity with the results from simulation models. Figure 8 shows the formed parts for different residual mold travel.


(a) (b) (c)

Figure 8. Forming study results for residual mold travel of 70mm (a), 40mm (b) and 25mm (c).

After integrating the aluminum profiles successfully into the process chain, the form filling behavior was analyzed to validate the simulation results and to ensure a complete form filling of the local LFT ribs. As in the forming study, the material was transferred into the mold and the residual mold travel was varied in different steps. The material flow inside the cavity could be studied until a complete filling was achieved. The results given in Figure 9 show that the LFT reaches the rib intersections with larger dimensions first, before the material flows into the smaller ribs. At the end of the form filling process the ribs along the beads are filled with LFT from both LFT strand positions. All form filling behavior was in good conformity with the simulation results. As a last step of the initial operation, the metallic inserts were integrated into the process. They were placed manually inside the lower mold and overmolded with LFT.

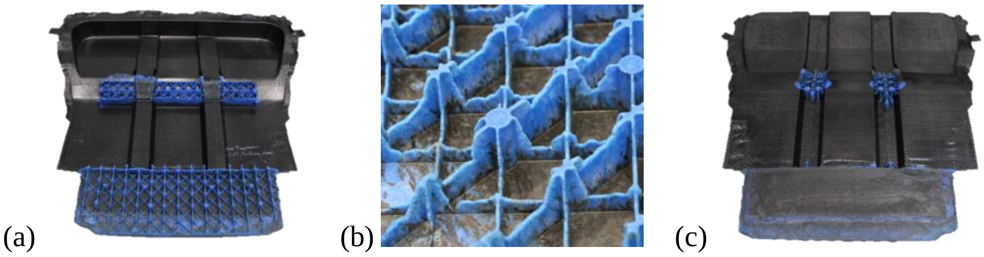
(a) (b) (c)

Figure 9. Results from the form filling study: top (a), rib intersection (b) and bottom (c).

The final process chain for manufacturing the lightweight rear floor structure includes the following steps: Insertion of aluminum profiles into the upper mold – placing the metallic insert inside the lower mold – heating the tailored blank and providing the LFT material – transfer of the material inside the mold – forming and compression molding – demolding. It was successfully put into operation, enabling the manufacture of the structural hybrid thermoplastic rear floor part.

5. Conclusion

The project’s aim was to develop a new vehicle concept for e-mobility in multi-material lightweight design following a holistic approach. The challenges, especially for the structural hybrid thermoplastic rear floor part, were in designing such a large scale FRP part and developing the required process technology for manufacturing. Together with the project partners it was possible to develop a structure that fulfills mechanical requirements. Additionally a prototypal process chain could be put into operation for successful manufacture of the thermoplastic rear floor structure. In further investigations the mechanical performance was tested and a life cycle analysis was carried out, thus showing a holistic pathway for the application of FRPs in future e-mobility concepts.

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