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Numerical and Experimental Investigation of GMT Compression Molding and Fiber Displacement of UD-Tape Inserts

Bernd-Arno Behrens[a], Florian Bohne[a], Ralf Lorenz[a], Hendrik Arndt, Sven Hübner[a], Moritz Micke-Camuz[a,]*

[a]*Institut für Umformtechnik und Umformmaschinen (IFUM), An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49 511 762 4102; fax: +49-511-762-3007. *E-mail address:* micke@ifum.uni-hannover.de

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Abstract

This publication deals with finite element based modelling and the experimental validation of the flow characteristics of glass mat reinforced thermoplastic composite (GMT). Furthermore, the interaction of GMT and UD-Tape inserts is examined. The simulation model is set up in LS-Dyna. In order to model the high degree of deformation of the GMT the smooth particle hydrodynamics (SPH) method is used. A viscoplastic material model is applied in order to take into account the strain rate as well as strain hardening flow behavior. For the experimental validation of the numerical investigations, a heated plate tool with a surface area of 300 x 300 mm was built. This tool contains two internal pressure sensors as well as a temperature sensor. With the help of this test setup, it is possible to investigate the pressure build-up, pressure differences and surface temperatures of the GMT as well as the time-dependent position of the flow front. In addition, to pressure differences over the contact area between tool and GMT, there are differences in wall thickness, fiber orientation and fiber matrix separation depending on the flow path. The forming tests were carried out at a tool temperature of 115 °C. After the validation of the simulation model the fiber displacement of UD-Tapes insert is discussed.

Keywords: GMT compression molding; material flow analysis; FE-simulation; UD-fibers

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1. Introduction

The importance of fiber-reinforced plastics (FRP) in automotive lightweight design is steadily increasing. In addition to traditional application areas in the interior or components such as under body parts and fronts ends, more and more structural and semi-structural parts are made of FRP. The increasing use of multi-material constructions in lightweight applications raises questions in design as well as production technology. A potential manufacturing approach is the combination of different forming processes for the production of new hybrid components. The implementation of such processes requires a sophisticated and sufficiently validated simulation model.

1.1. GMT compression molding

Compression molding of glass mat reinforced thermoplastics (GMT) and long fiber reinforced thermoplastics (LFT) is already widely used in the automotive industry [1]. The short and long fibers of the GMT can flow under sufficient pressure and elevated temperatures to form a complex fiber-reinforced part. The floor area of the semi-finished product is usually considerably smaller than the intended final part. In order to fill the contour, the mold must be designed flow-oriented so that the ductile GMT compound can be distributed to all cavities in the mold. The process essentially consists of four steps: Heating, transfer, forming and consolidation. Firstly, the thermoplastic must be heated to its processing temperature

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and afterwards inserted into the mold. The transfer time in commercial processes is 15 - 90 s. A shorter transfer time reduces unintentional cooling [2]. Tools for GMT/LFT compression molding have a vertical flash face which prevents the material from escaping from the mold. The stamp dips into the die towards the end of the pressing process. The vertical flash face closes off the cavity [3]. In the forming step, the fibers flow within the matrix along the cavities until they have filled the entire mold. The outer polymer-containing layers functions as lubricant additionally, while the inner material, which is rich in fibers, is deformed and follows the material flow [4]. In the subsequent consolidation and cooling process, a time of 5 s per mm-thickness of the part is recommended [5]. Longer consolidation times increase the mechanical properties and reduce the void content due to air inclusions. Higher tool temperatures improve the surface quality with the disadvantage of longer process times [5]. In the last step, the finished part can be removed from the mold and, if necessary, sent to post-processing.

Compared to injection molding, compression molding allows longer fiber lengths in the part after the manufacturing process. In LFT extrusion, fiber lengths of up to 10 mm in components have already been demonstrated [6]. As the fiber length increases, the component strength and impact strength increase.

1.2. Combined process GMT/UD-Tape

The combination of continuous fiber reinforced plastics (FRP) and GMT/LFT promises a high lightweight construction potential. On the one hand, the wall thickness of LFT components can be reduced by introducing endless fibres [7]. On the other hand, shell structures of high performance continuous fibers with the addition of 3D-elements out of GMT/LFT can become functionally integrated structural parts [8]. Impregnated, unidirectional fibres (UD) can be used to produce near-contour laminates, which are then pressed with the LFT hard pressing compound [7]. An increased fatigue strength can be achieved with constant wall thickness. In addition, this combination is characterized by an improved impact strength compared to pure LFT components [7]. However, there it is a major challenge to avoid fiber displacement caused by the interaction between the GMT and the loose UD-fibers. Fig. 1 shows this effect by means of a scaled down battery tray [9] made of GMT and UD-fibers in which the test part was manufactured in a combined forming step.

Corbridge et al. already identified this problem in investigations with SMC and UD-tape. As a solution, an additional layer of UD-tape was placed orthogonally to the layer influenced by the material flow [10]. Another approach is to adjust the tool path by using a multi-axis forming process, to control the direction of flow along the fibres [11]. However, further basic investigations are required to model this effect in forming simulations.

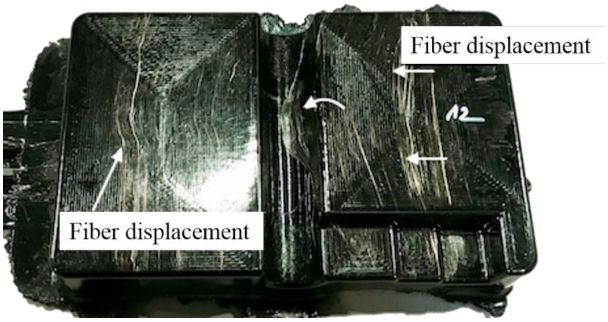

Fig. 1. Battery tray GMT and UD-fibers

1.3. Simulation

In literature GMT is mainly considered to be a smeared continuum and is described as a non-Newtonian fluid in FE-simulations. The flow behavior is characterized by the extensional as well as the shear viscosity and strongly depends on the boundary conditions. During the compression molding process shear flow as well as extensional flow can be observed [12]. In order to consider both flow conditions within one model, complex tensor based or weighting approaches can be used [13]. In the context of continuums mechanics a fluid with a degenerating viscosity function can be described through an idealized plastic material model [14]. This approach allows a plastic model to be derived from viscosity data. [15]. Hereby the use of a Lagrangian frame is enabled which facilitates the consideration of complex contact conditions, which arise within the description of the processing of hybrid parts. In order to deal with large deformation the smooth particle hydrodynamics method SPH is used, which is numerically robust and does not require a mesh for discretization [16].

2. Experimental setup

To analyze the material flow and to validate the numerical simulations a plate tool was designed and manufactured (see Fig. 2). The tool has an active area of 300 mm x 300 mm and can be heated by six electric heating elements. Two pressure sensors (Kistler, 6157CA) in the lower left and upper right corner as well as a centrally positioned temperature sensor (Kistler, 6192BG), which are in contact with the work piece during the pressing process, are integrated in the active surface of the die. The evaluation of the cavity pressures and the surface temperature was carried out during the tests with the process monitoring system "ComoNeo" (Kistler). The tool die also has an adjustable vertical flash face consisting of four edges. The vertical flash face prevents the material from escaping from the tool mold. The gap between the stamp and the vertical flash face is 0.02 - 0.03 mm. In order to avoid air inclusions in the cavity, four vent holes are provided in the bottom side of the tool. Sintering inserts prevent material from escaping through the vent holes.

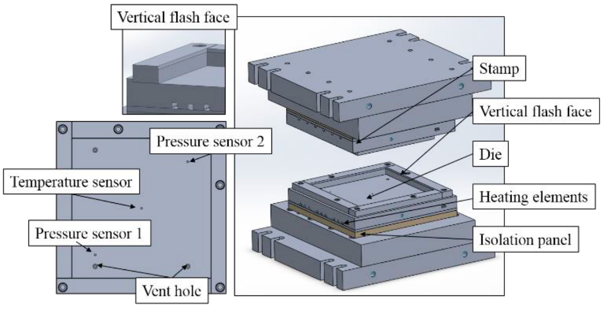

Fig. 2. Forming tool including sensor set-up

The validation tests were carried out on a hydraulic press (Hydrap HPDZb 63) at a forming speed of 40 mm/s and a pressing force of 600 kN. The GMT material was based on a PA6 matrix and the material thickness was 4.5 mm. The GMT was heated in a convection oven to a processing temperature of 280 °C in the core. The temperature of the plate tool during the series of tests was 115 °C. Further variations were made in the selection of the insertion position and the quantity of GMT.

3. FE-simulation model

In order to analyze the temperature distribution over time within the mold base, a one dimensional heat flow model with help of the finite volume method is created (Fig. 3). To facilitate the modeling a constant thickness h of the sample is assumed. A height of 1 mm is selected.

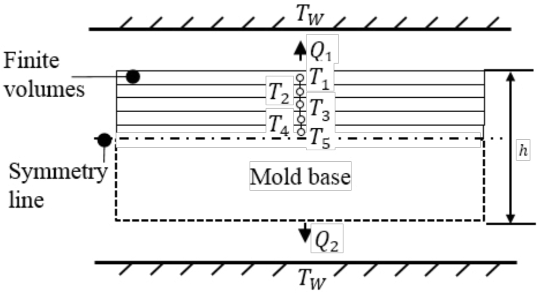

Fig. 3. Finite volume heat flow model

The simulation model of the compression phase was set up in LS-Dyna (Fig. 4). The model comprises the mold base, the upper tool as well as the lower tool. Aside from the upper tool the walls of the mold are modelled with help of rigid walls. The inhomogeneous material structure of GMT is considered as a smeared continuum. The viscous plastic material model *MAT_VISCOPLASTIC_MIXED_HARDENING is used. This material model allows the definition of the flow stress as a function of the effective plastic strain as well as the effective plastic strain rate.

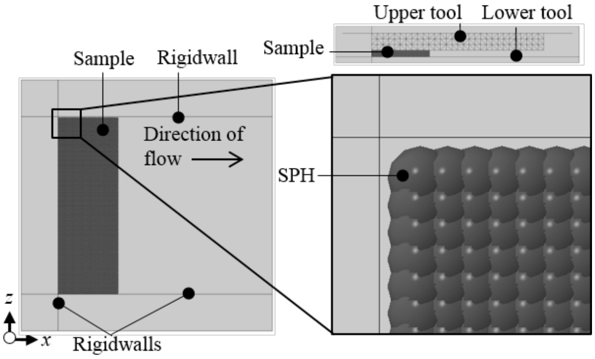

Fig. 4. Simulation model

The influence of plastic strain and plastic strain rate on resulting flow stress used function was determined in compression tests and is illustrated in Fig. 5. In order to improve the extrapolation for high strain rates data of preceding forming tests were taken into consideration. Surface friction is neglected and an ideal elongational flow is assumed. To avoid numerical instabilities due to large deformation, the smooth particle hydrodynamics (SPH) method in combination with explicit time integration is applied. For reducing the simulation time scaling is used.

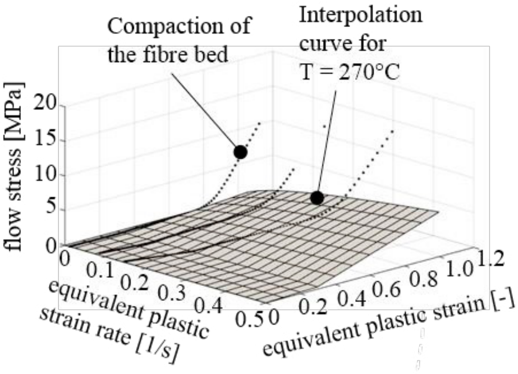

Fig. 5. Flow stress as a function of the equivalent plastic strain and strain rate

4. Results and Discussion

4.1. Experimental results

Fig. 6 shows the curves of the mold cavity pressures and the surface temperature at a mold temperature of 115 °C, the same amount of GMT (165 x 165 x 4.5 mm) and different positioning of the GMT as well as two flow directions. First, the GMT was positioned in the lower right corner of the lower tool. The time at which the GMT arrives at the sensors can be evaluated on the basis of the pressure curves and the temperature curve. With manual positioning and lower measuring accuracy in the lower pressure range, cavity pressures in the range of 50 bar are measured after 1.1 s and 1.8 s after the start of the forming process and a flow path of 85 mm.

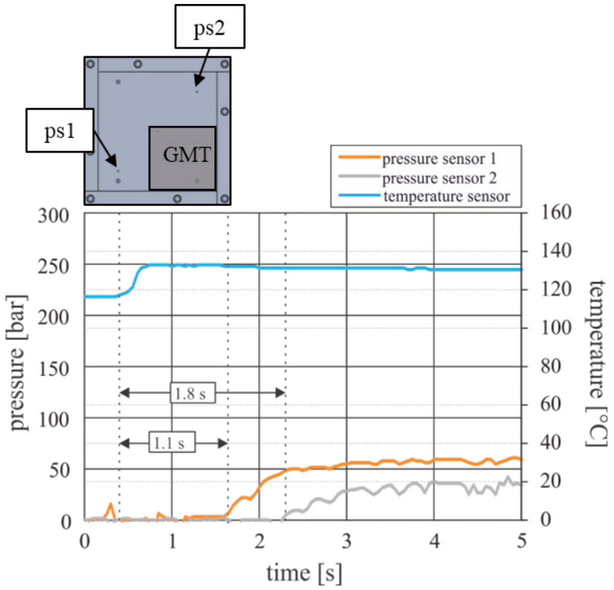

Fig. 6. Pressure and temperature curves with off-centre positioning of the GMT without initial pressure sensor contact

The temperature sensor records a surface temperature of 135 °C, although the initial material temperature is well above the melting point of the polyamide 6 matrix of about 220 °C. The measured value suggests the solidification of a thin film on the tool surface immediately after the forming pressure is applied.

When the GMT is positioned in the lower left corner in contact with the temperature sensor and pressure sensor 1 (ps1) (Fig. 7), the cavity pressure rises to 260 bar within one second.

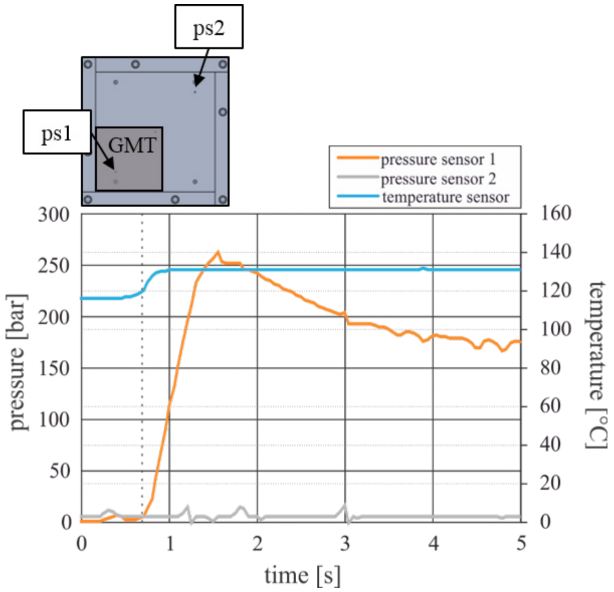

Fig. 7. Pressure and temperature curves with off-centre positioning of the GMT in contact with pressure sensor 1

Pressure sensor 2 (ps2) is not reached during the flow process. The difference between the measured pressures quantifies the pressure gradient between the insertion point and the flow front end of about 200 bar after a flow path of 150 mm.

To investigate the flow behavior with almost complete die filling and only one global flow direction, two layers of GMT (300 mm x 100 mm) were placed over the full width of the plate tool at the height of pressure sensor 1 (see Fig. 8, right, white line).

When the tool is closed, a pressure builds up continuously at measuring point 1 until the maximum of 100 - 110 bar is reached. The pressing force presses the GMT in the direction of the temperature sensor and the second pressure sensor. Two flow fronts are formed. While the flow front is braked laterally by the increased friction on the tool walls, the separation of the flow front in the middle is probably due to the integration introduction of the temperature sensor into the tool surface.

After a flow path of 50 mm and a time of 0.3 s, the material reached the temperature sensor. As in the prior tests, a surface temperature of 134 °C is recorded on contact between the sensor and the extrusion compound. In pressure sensor 2, a cavity pressure of 10 bar is measured after 2.25 s pressing time. The thickness of the pressed plate decreases from the insertion point of the GMT to the end of the flow path by 0.06 to 0.09 mm due to fiber-matrix separation.

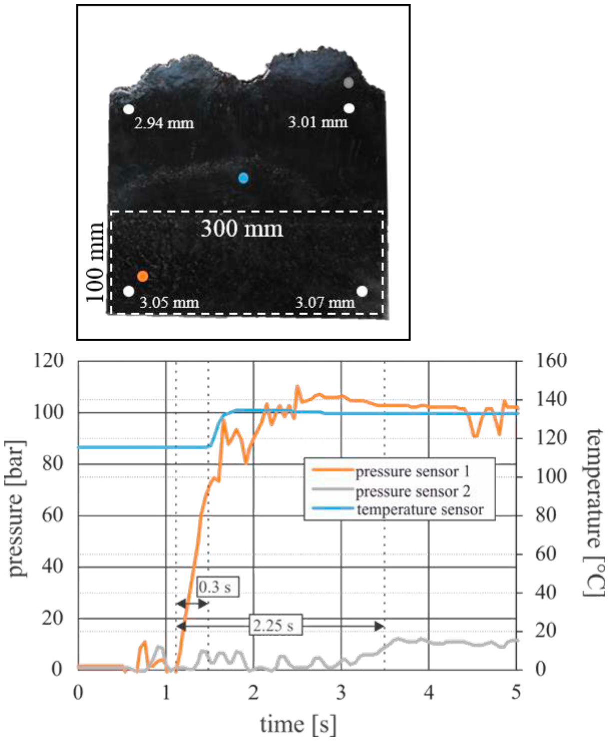

Fig. 8. Pressure and temperature curves with one-sided central positioning of the GMT and almost complete mold filling

4.2. Simulation results and validation

The forming phase of the compression molding process considered in this work takes place within 0.25 seconds. Thus, the computed temperature drop is stronger than in the experiments and represents an upper bound. Due to the symmetry of the heat flow problem a symmetric model is set up. The mold base is subdivided in five volumes (T1 – T5). Tool temperature TW is set constant to 115 °C. The Initial temperature of the mold base is 280 °C. The obtained system of equation is solved with MATLAB and results are displayed in Fig. 9.

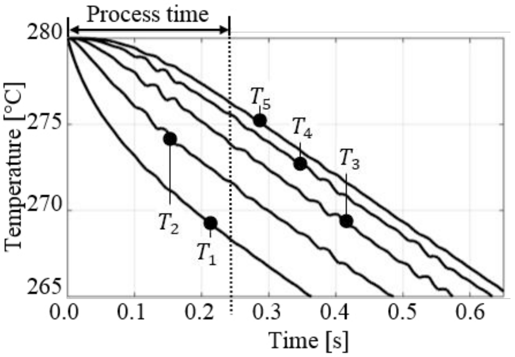

Fig. 9. Computed temperature time curves for the volume temperatures

Based on the maximum temperature change of 13 °C in the outer layer the temperature influence on the flow behavior during the forming phase will be neglected in further considerations and an isothermal approach is chosen for the forming simulation.

In order to analyze the compression molding process, the simulation results are examined and the experimental results are compared to the predicted results (Fig. 10). It can be observed that the geometry of the flow front deviates from the experimental results. This might be caused by a temperature sensor which is positioned in the center of the mold base during experimental tests and was not included in the numerical model. In the experimental tests, this sensor can affect the formation of the flow front and result in the geometry drawn in Fig. 10 (top). The experimentally recorded pressure values are compared to the stress acting normal to the surface. The numerically determined pressure field oscillates around a value of 100 bar. The oscillations are probably caused by the applied SPH method. Nevertheless, the averaged stress value as well as the predicted maximum force of 560 kN is close to the experimentally measured pressure of 110 bar and a maximum force of 600 kN. In further numerical analysis it was observed that the coefficient of friction influences the resulting maximum force. This is caused by the relative large contact surface in the process. The choice of the SPH method over the conventional FEM in combination with remeshing seemed to be advantageous due to smaller modelling effort. Compared to an Euler approach no time consuming coupling between the Lagrangiantool surfaces and the flow field is required. Nevertheless, the oscillations in the flow field, hinder a clear assessment of the stress field.

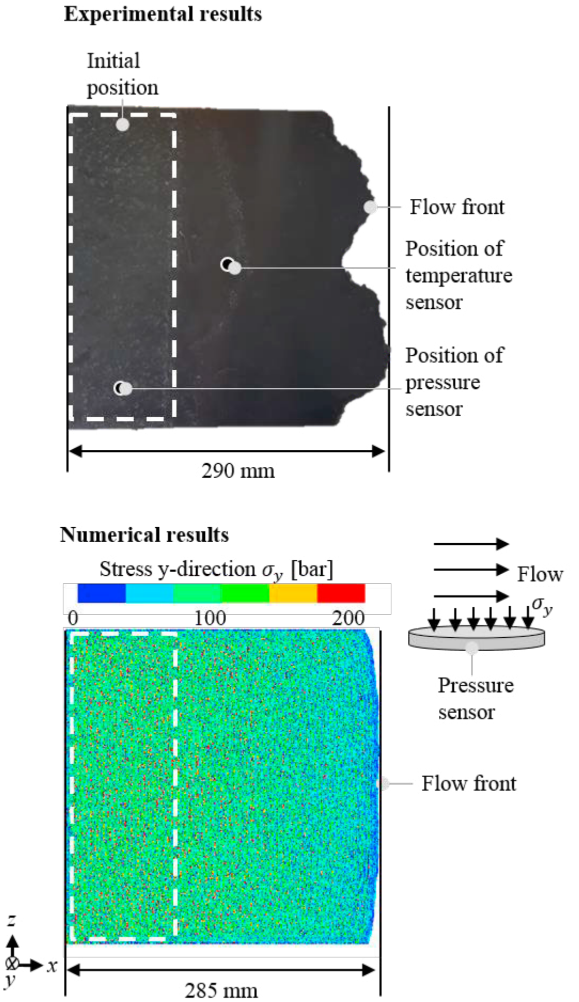

Fig. 10. Comparison of experimental (top) and numerical results (bottom)

4.3. Interaction between GMT and UD-tape

In a combined process of draping flat continuous fiber-reinforced thermoplastic semi-finished products and forming flowable masses, there is interaction between the semi-finished products and, as a result, unwanted fiber displacements. In the case of fabrics and laminates with different orientations of the fiber layers, the effect is insignificant. In the case of unidirectional fabrics, this effect must be taken into account. In order to illustrate and investigate the problems of the interaction between GMT and UD fiber structures during forming with linear tool movement, a GMT strip was placed on one side of a larger fully impregnated and carbon fiber UD-tape structure consisting of six layers. When closing the plate tool, the GMT should flow over the UD-tapes. The results of these investigations are shown in Fig. 11.

The layer structures can be seen on the left side of the Figure. The size of the UD-tape blanks (165 x 165 mm) and the GMT (35 x 165 mm) were kept constant during the tests. The stacked semi-finished products were positioned on two sides in contact with the tool wall to limit the flow direction. The UD-tape structure consisting of six layers was aligned along the preferred flow direction (Fig. 11a) and transverse to the preferred flow direction (Fig. 11b). The results of this test are shown on the right-hand side. Here, the pressed plates are shown after forming and subsequent reheating to demonstrate the effect of the UD-fibers.

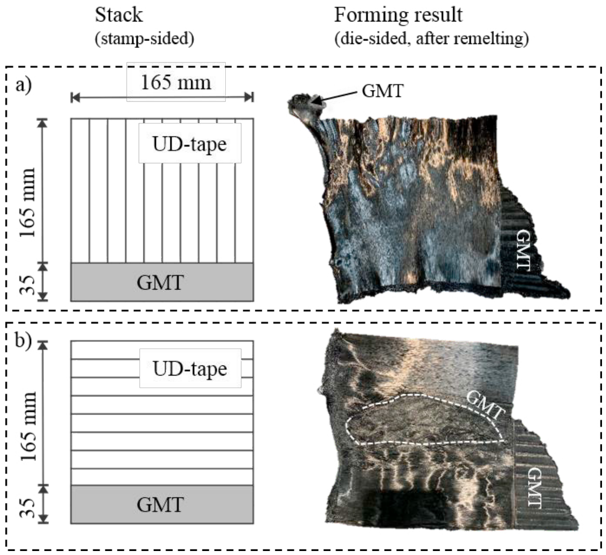

Fig. 11. Interaction GMT/UD-tape, test setup and forming results

In test setup Fig. 11a), the GMT flows largely along the UD-fibers. There are only slight deviations from the initial alignment. The GMT emerges to the side less than in stack setup Fig. 11b. With an orientation transverse to the preferred flow direction (Fig. 11b), the fibers are entrained by the GMT and accumulate until the six fiber layers are penetrated and the GMT continues to flow on the other side of the tool. Furthermore, the resistance to the lateral exit of the GMT mass is lower.

5. Conclusion and outlook

This publication focuses firstly on investigating the flow characteristics by analyzing the pressure and temperature on the tool surface, which was in contact with the GMT. Secondly, input data for material flow simulations was generated, a numerical model was build and first validations were conducted. The predicted material flow and the pressure distribution shows good accordance with the experimental results. The deviations can be explained by the integration of the temperature sensor in the middle of the forming tool.

A combined forming test using GMT and fully impregnated UD-fibers illustrates the differences in GMT-UD fiber interaction depending on the fiber orientation of the UD-fibers.

Further research will focus on the validation of the forming simulation regarding the interaction between materials for molding (GMT/LFT) and continuous fibers.

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