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Development of a Combined Process of Organic Sheet forming and GMT Compression Molding

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Abstract

This research describes the development of a combined one-step process of complex organic sheet forming and GMT (Glass Mat Thermoplastics) compression molding which can be integrated in processes using conventional stamping technology. Hence, no additional injection molding step is required. Compression molding allows adding a third dimension to the two-dimensional organic sheet. Thus, reinforcements or screw connection points can be produced out of complex 3D-structures with fiber lengths up to 40 mm. While forming simulations for both separate processes already exist to a certain degree of maturity, the coupling of organic sheet forming and GMT compression molding in one software tool involves major challenges. This paper presents a solution approach that depicts the combined process in a single FE-based forming simulation carried out with LS Dyna. The investigation was mainly focused on the interaction between the two materials and the temperature distribution which largely influences the forming effects and the bonding of the materials to one another.

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1. Introduction

The importance of fiber-reinforced plastics in automotive lightweight design and the associated substitution of metallic materials are steadily increasing. In addition to traditional application areas in the interior or components

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such as under body parts and fronts ends, more and more structural and semi-structural parts are made of fiber-reinforced plastics. The increasing use of multi-material constructions in light-weight applications raises questions in design and production technology which entail considerable research requirements. Currently, the use of fiber-reinforced plastics (FRP) is mainly restricted to applications in the upper price segment and to small numbers. In order to qualify FRP structural components for large scale series in the automobile industry, it is necessary to develop large-scale processes. Stamp forming processes are suitable for large scale production and recognized as the main manufacturing process for automotive body parts. The Institute of Forming Technology and Machines (IFUM) develops forming processes which can be integrated into conventional press technology, as it is available in the pressing plants of the forming industry.

1.1. Stamp forming of fiber reinforced thermoplastics

To conduct forming processes on conventional stamping presses, thermoplastic based semi-finished products should be used, because of their advantages due to their re-melting capability compared to thermoset-based materials. Fiber-reinforced thermoplastics can be formed under elevated thermal conditions [1]. The recommended forming temperature according to the manufacturer is approximately 40 °C above melting temperature and below the decomposition temperature of the respective thermoplastic matrix material. Compression molding of GMT (glass mat reinforced thermoplastics) and LFT (long fiber reinforced thermoplastics) are widely spread in the automotive industry [2]. Mechanical part properties can be improved by using continuous fibers. Impregnated and consolidated fiber sheets are called organic sheets. Latest researches focus on organic sheet thermoforming or hybrid processes of organic sheet thermoforming and LFT-injection/compression molding [3,4]. Forming and joining can be integrated in one process step which reduces cycle times [5]. Restraining forces to avoid wrinkling of the organic sheet can be applied by using heated blank holder systems [6] or locally installed grippers [7,8]. At the end of the forming step the material has to be re-consolidated under pressure. After cooling in the mold, the finished part can be removed. Longer re-consolidation times and increased pressure and compression velocity increase mechanical properties and reduce void content [9].

Due to the contact with the relatively cold tool, the material cools down rapidly during the forming phase. The re-consolidation of the organic sheet must be avoided before completing the forming process, since forming is prevented by premature solidification of the matrix. As a result, fiber deflection at internal radii and fiber fractures at external radii can occur [10]. In order to prevent the rapid cooling, the forming tools are heated to a temperature of 50 to 150 °C below the processing temperature of the respective matrix material.

1.2. Material characterization and FE-simulation

Despite various minor forming effects such as fiber elongation and yarn straightening (tensile stress along the fiber) or inter ply slip, the forming behavior of an organic sheet mainly dependents on the intra ply shear and bending properties. The bending is strongly influenced by the stiffness of the thermoplastic matrix. The shearing of the fabric is caused by shearing stresses and can be characterized by the picture frame or bias extension test. Both characterizing methods have quite different setups but lead to comparable results [11, 12]. The bending stiffness is usually determined with help of the cantilever test [13]. For the simulation of a draping process, different methods are presented in literature. The kinematic model assumes a constant fiber length and that the wrinkling of the fabric occurs after reaching a critical angle [14]. The use of the basic balance equations of momentum and energy in order to calculate the draping enables the consideration of mechanical and thermodynamic material properties of fibers as well as thermoplastic matrix. The FEM is usually applied to solve the arising set of differential equations.

In order to describe the flow of a thermoplastic the balance equation of momentum, mass and energy are used in an Eulerian frame [15]. Different material models are used to capture the non-Newtonian flow behavior by describing the viscosity as a function of the shear rate (Power Law, Carrau and Cross Modell [11], [16]). In order to take the forming history into account, viscoelastic models can be applied [15]. In [17] an elastic plastic approach has been chosen for the simulation of a compression molding process of a SMC material. Determining the fiber orientation and the volumetric fiber content resulting from the compression molding as well as injection molding process is important for predicting the structural strength of the formed component. The first model describing the distribution of fibers, which was first applicable in simulation models, was developed by Folgar and Tucker [16]. This model or its adapted versions are used in commercial injection and compression molding codes, such as Moldflow and Moldex3d. A further simulation program used for the simulation of both processes is LS-Dyna [17, 18]. The simulation of a coupled fluid structure interaction of an injection molding and sheet forming process is described in [18] and served as basis for the simulations, which are described in this work.

2. Experimental setup

2.1. Objects of investigation

The reference part in this research was a downscaled battery tray for a plug-in hybrid automobile. The geometry consists of a shell featuring a step-geometry and a tunnel-geometry for an exhaust gas system across the rectangular tray. The organic sheet is formed by folding a cross-shaped blank and forming the step geometry and a tunnel-geometry. The GMT material is used to locally reinforce the organic sheet shell geometry with a rib structure. Fig. 1 depicts the CAD-model of forming tool and schematic figure of the clamping frame with the cross-shaped organic sheet.

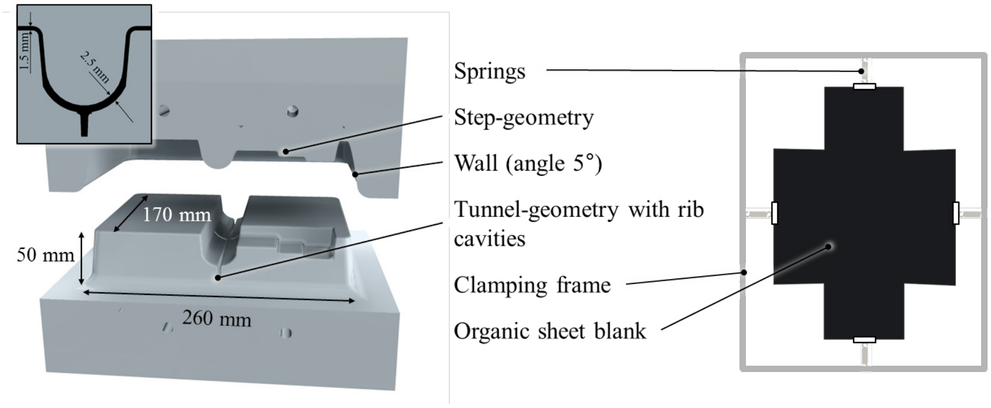

Fig. 1: Forming tool and clamping frame

The tool consists of an upper and lower die. Both can be electrically heated. Except for the radius in the tunnel, the tool offset is 1.5mm. The tunnel area of the lower die features cavities (1 mm additional offset and rib structures) for the GMT. A main goal is to limit the distribution of the GMT material to the tunnel geometry. The sealing is achieved by a defined contact between organic sheet and forming tool at the front face and flanks of the tunnel.

The organic sheets consist of 0/90° woven glass fiber sheets with a polyamide 6 (PA6) matrix. The melting temperature was about 220 °C. The material thickness was 1.5 mm. The GMT material was also based on a PA6 matrix and the thickness was 4.5 mm. The organic sheet is clamped centrally to all four sides by springs (k = 1.867 N/mm).

2.2. Process steps

Both, the GMT material and the organic sheet were heated in an external infra-red (IR) radiator to 260°C. By decoupling the heating from the forming process, the cycle time can be reduced. However, there is a higher risk off cooling while transferring the material. The process steps of the combined forming process are depicted in Fig. 2.

(1) The GMT material is placed into the tunnel pocket of the heated lower die (T_{tool} = 110 °C). (2) The clamping frame is positioned above the stamp without tool contact. (3) Subsequently, the tool closes with a velocity of 45 mm/s and the part is formed. In order to prevent wrinkling of the organic sheet, the clamping frame is used to restrain the material and locally induce fiber shear and yarn straightening (see Fig. 2, step 3). When the organic sheet comes into contact with the GMT material in the, the cavities are already sealed at the end faces by the

organic sheet. In addition, sealing occurs at the 5° steep flanks of the tunnel between the organic-sheet and the lower tool. (4) At the end of the process, the two components have to be joined and both materials have to be re-consolidated . (5) After a dwell time of 10 s with a pressing force of 160 t, the part can be removed.

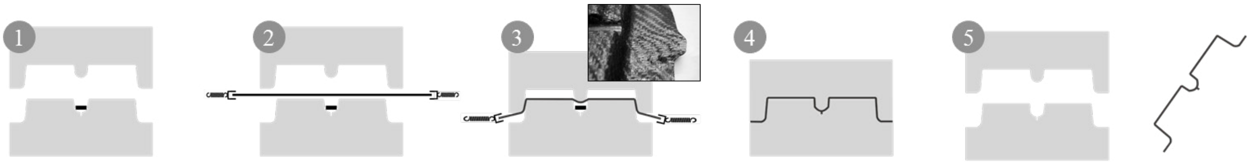

Fig. 2. Process steps, combined stamp forming (organic sheet – GMT)

3. FE-simulation model

A major challenge was the consideration of the interaction between the organic-sheet and the thermoplastic extrusion mass. For describing the organic sheet a material frame was selected and for describing the GMT a spatial frame was deployed. The combination of both descriptions in a fluid-structure interaction leads to a complex mechanic as well as thermodynamic model. Since few production-related processes involve the simultaneous forming of an organic sheet and a GMT closed commercial forming programs rarely provide the option to model the sophisticated fluid structure interaction, which is encountered in this process.

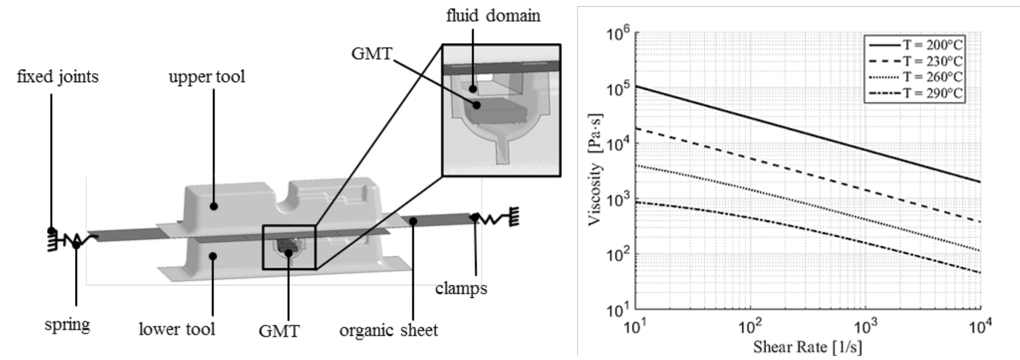

Fig. 3. (a) Model of the coupled organic sheet and compression molding process, (b) Viscosity as a function of the shear rate

Therefore the simulation model, which is shown in (Fig. 3), is set up in LS-Dyna. It consists of an organic sheet, which is clamped between four springs. The springs are connected to fixed bearings. The upper tool drapes the organic sheet into the lower tool, which presses the extrusion mass into the cavity of the lower tool. The material model MAT_249 was used for modelling the organic sheet, which was discretized by using shell elements. In order to reduce the calculation time during the coupling calculation between the GMT and the organic sheet, the sheet was divided into three regions and only the middle region was directly coupled to the GMT. The battery tray comprises different local geometries. For the bottom area of the upper and lower tool a coarse mesh was used. However, a much finer mesh was used in the tunnel area of the lower tool in order to resolve the rib structure. The mesh of the tunnel area was adapted to the element size of the surrounding fluid mesh. The GMT is described in a spatial frame as a non-Newtonian fluid, having a shear rate-dependent viscosity shown in Fig. 3 b. In several simulations the fluid domain and the local element size were iteratively adapted to the observed displacement of the mold base. Particularly in the lateral region as well as in the rib region, a fine mesh was selected. The formability of the organic-sheet and mold base is strongly related to the temperature. An isotropic thermal conductivity was assumed for both materials. The viscous thermoplastic mold base and the organic sheet are mechanically and thermodynamically coupled. The mechanical coupling has been carried out by using a penalty method. Explicit time integration scheme with variable time stepping was selected for time integration.

4. Results

The results of the experimental test are depicted in Fig. 4. A firm bond is formed between the GMT and the organic sheet. The extrusion process has been successfully limited at both the flanks of the tunnel and the front face of the tunnel area. The sealing works for the GMT material, but the air in the cavities could be evacuated and the cavities in the tunnel area have been entirely filled. The 5° wall angle is sufficient to apply enough re-consolidation pressure on the organic sheet. Throughout the forming process, the edges of the cross-cut were fluidly joined in the corners of the tray.

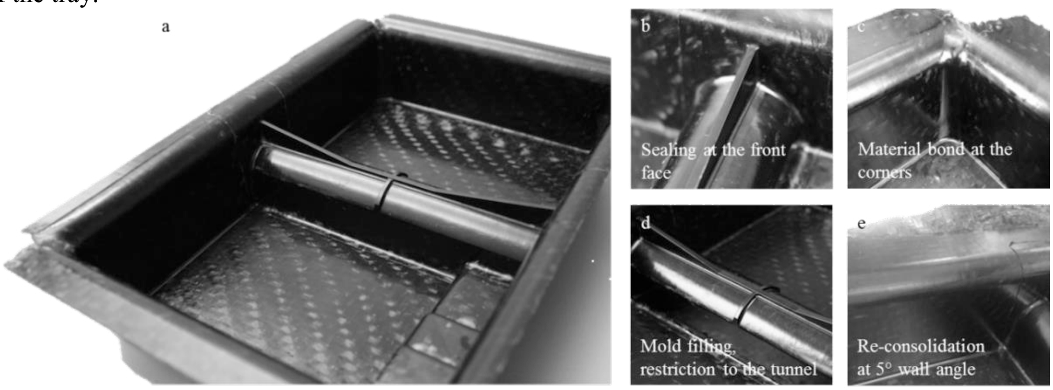

Fig. 4. Experimental results: (a) Battery tray overview, (b) front face tunnel, (c) corner, (d) tunnel geometry with rib structure, (e) wall

Furthermore, a dimensional analysis of the formed part was carried out using the measurement system ATOS by GOM. The results in z-direction are depicted in Fig. 5 (a). The tool temperature was 110°C and the dwell time was 10 s at 160 t pressing force. Shape distortions of composite parts can be divided into warpage and spring–forward. Warpage is defined as the curvature and twist of initially flat parts, and is mainly caused by a non–balanced stress distribution. Spring–forward is defined as the decrease of a wall angle [19]. Due to the cross shaped blank and the joining of the corners of the part, there is no detectable spring-forward regarding the formed part. However, the distortion by warpage in the bottom area is significant. On the right side of the tunnel area (+x-direction), the warpage effect (+1.02 mm) is reduced by the additional stiffness provided by the step geometry. On the left side (-x-direction) a deviation between the tool and the part geometry with a maximum value of 1.72 mm with a shift towards positive y-direction was measured. This unsymmetrical distortion causes an additional torsion of the whole part as detected by measuring the deviation of the corner points.

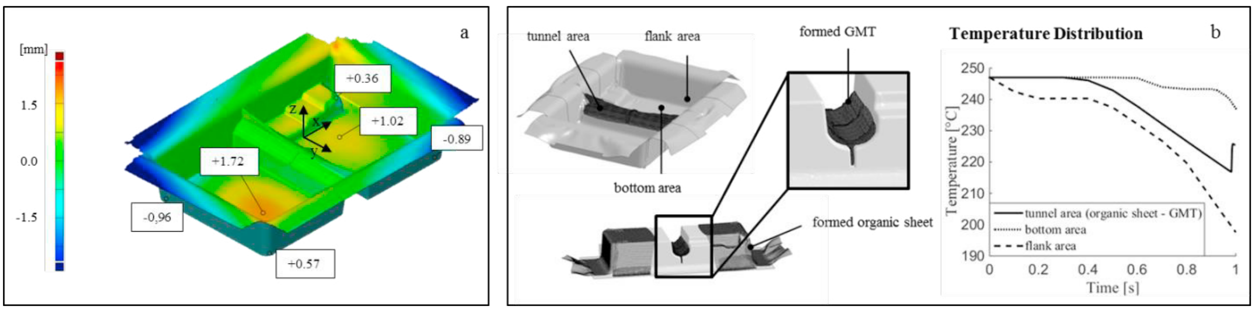

Fig. 5. (a) Dimensional analysis, (b) FE simulation results

The results of the forming simulation depicting a process with a process time of one second are shown in Fig. 5 (b). In the end phase of the organic sheet forming the sheet presses the mold base in the cavity of the lower tool. The simulation model predicts the forming of both constituents quite well. The temperature distribution shows that the cooling during the process is locally heterogeneous. The tunnel area of the organic sheet cools down under melting temperature due to tool contact. After contact the intersection area between the organic sheet and the GMT is heated up over melting temperature, which is required for a strong bond between both constituents.

5. Conclusion

Due to the usage of conventional, commercially available semi-finished products and the cycle times below 20 s, a combined process of organic sheet forming and GMT compression molding qualifies for large scale manufacturing on conventional stamp forming technology. Shell structures of high performance continuous fibers and 3D-elements formed in a one-step process, allows manufacturing of high performance functionally integrated structural parts. The concept of folding a cross-shaped blank enables any forming depths.

The simulation of the process requires taking the complicated fluid structure interaction into account. Within this work it was possible to predict the forming of the battery tray adequately, giving an insight in the basic process aspects.

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