Process development and tooling design for intrinsic hybrid composites

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Abstract. Hybrid parts, which combine the advantages of different material classes, are moving into the focus of lightweight applications. This development is amplified by their high potential for usage in the field of crash relevant structures. By the current state of the art, hybrid parts are mainly made in separate, subsequent forming and joining processes. By using the concept of an intrinsic hybrid, the shaping of the part and the joining of the different materials are performed in a single process step for shortening the overall processing time and thereby the manufacturing costs. The investigated hybrid part is made from continuous fibre reinforced plastic (FRP), in which a metallic reinforcement structure is integrated. The connection between these layered components is realized by a combination of adhesive bonding and a geometrical form fit. The form fit elements are intrinsically generated during the forming process. This contribution regards the development of the forming process and the design of the forming tool for the single step production of a hybrid part. To this end a forming tool, which combines the thermo-forming and the metal forming process, is developed. The main challenge by designing the tool is the temperature management of the tool elements for the variothermal forming process. The process parameters are determined in basic tests and finite element (FE) simulation studies. On the basis of these investigations a control concept for the steering of the motion axes and the tool temperature is developed. Forming tests are carried out with the developed tool and the manufactured parts are analysed by computer assisted tomography (CT) scans.

1. Introduction

Growing requirements regarding the product performance and the product costs are the key drivers for the development of new materials. The main product requirements in the field of the transportation industry are the lowering of the fuel consumption and the emissions of pollutants [1]. To reach these aims different lightweight concepts are widely used [2]. One concept is the use of hybrid materials. These materials are made of different material classes to combine the advantages of the used materials [3].

In the field of transportation industries the combination of metal sheets with fibre reinforced plastic (FRP) offers the fusion of good static mechanical properties of FRPs with the advantageous behaviour of metals under high dynamic loads [4]. Such materials are commonly known as hybrid metal composites. A drawback for the widely use of this material class is the sophisticated and expensive manufacturing process. To reduce the cycle times and therefore the manufacturing costs, the concept of intrinsic hybrid composites has been developed [5]. Within this approach the forming and the
joining, also known as hybridization, of the different material layers is carried out in a single step manufacturing process. The load carrying capacity of hybrid composites strongly depends on the strength of the interface between the materials. Concerning this matter various studies have shown that a combination between direct adhesion and mechanical interlocking can significantly improve the interface strength [6, 7]. In the scope of this paper the novel approach for producing an intrinsic hybrid composite is presented. Thereby the research work is focussed on the production process and the tooling technology.

2. Concept of the intrinsic manufacturing process

The investigated hybrid composite consists of a continuous FRP combined with an integrated metallic layer. The FRP is an unidirectional carbon fibre sheet composed of a thermoplastic PA6 Ultramid B40 (BASF) matrix and Toray’s T700S (50-K) carbon fibres. The use of a thermoplastic matrix system has the advantages of short cycle times, good formability and high recycling potential [2, 8]. Thermoplastic composites are available as sheets and could be processed by conventional thermoforming processes. The objectives for the forming process are the generation of the global part geometry, the creation of the local mechanical interlock elements and the hybridisation of the hybrid composite in one process step. For this purpose, the forming is applied on two geometric scales. One scale is the forming of the part geometry and the second scale is the forming of the mechanical interlock structures. Figure 1 shows the basic concept of the developed process. More detailed information can be found in [9]. The forming of the part geometry has the characteristic of a thermoforming process and the forming of the mechanical interlock elements can be classified as a sheet metal forming process. The challenge is the combination of these two different processes in one common process. At the beginning of the global forming process, the metallic insert is a plain structure without form fit elements. Thereby, the global forming process is not affected by the mechanical interlock elements and fibre shifting is not affected. Just before the lower dead centre of the global forming process the metallic insert is loaded with a tension force (local forming) to generate the form fit elements. The specific design of the metallic insert which creates form fit elements under tensional load is described in detail in [10]. The challenge for the tool development is the combination of the two different forming processes (local and global) in one forming tool.

![Figure 1. Concept of the intrinsic process chain with the forming on two scales](image)

3. Tool and process development

3.1. Process Design

During the forming process the movement of the die and the pulling unit must be controlled beside the tool temperature. The schematic interaction between these three process variables is shown in Figure 2.

For designing the process the whole procedure is divided into different sub-process steps. In the first step (until point (a)) the FRP is warmed up directly in the pre-heated forming tool until the forming temperature is reached. Thereby the optimal forming temperature of the FRP was investigated in separate forming tests [10]. At point (a) the global forming process is started by moving the punch downwards. Subsequently the global forming process is stopped at a predefined position and the local
forming process is started (point (b)). The time period between point (b) and point (c) depends on the velocity of the die and the pulling unit as well as the pulling length at which the local forming process is finished (form fit elements reach the maximum out of plane displacement). The maximal pulling length was determined in FE – simulations of the local forming process. The precision of the FE simulations is validated with tensile tests of the metallic insert. The local forming process is finished at point (c) and the global forming process is started again. Until point (d) the form fit elements are pressed into the molten matrix of the FRP by moving the die downwards. At point (d) the global forming process is finished and the consolidation phase is started by cooling the tool. The tool can be opened, if the removal temperature is reached (point (e)).

![Figure 2. Schematic interaction of the process variables during the intrinsic forming process](image)

3.2. Thermal Tool Design

As seen in Figure 2 a variothermal tooling concept is necessary. The requirements are a fast as possible cooling and heating time and a homogenous temperature spread on the tool surface. The thermal behaviour of the tool was investigated by FE simulations. Different heating strategies were compared in [11]. The simulations show, that the best concept is the combination of electric heating by cartridges and the cooling by a thermal fluid. In further FE simulations, the temperature regulation concept is investigated. This comprises the number of regulation zones for each tool part and the location for the measurement of the actual temperature. In the scope of this paper only the results for the die are shown, because this is the geometrically most complex part of the tool. The used FE-model is developed with LS Dyna and is depicted in Figure 3. The loss of heat by convection and radiation is considered by the concept of the “effective” heat transfer coefficient [12]. The quantity and power of the heating cartridges were dimensioned analytically.
For modelling the heating cartridge the LS-Dyna keyword LOAD_HEAT_CONTROLLER is used [13]. This function controls the heat generation by monitoring a remote nodal temperature (thermocouple). The controller can be specified as on-off, proportional, integral or combined proportional/integral. For the pre-design of the tool the on-off controller was used [14]. In the first step a “one zone” controller is investigated. For this purpose the heating cartridges 1 to 7 are controlled by the use of the thermocouple 2. In Figure 4 the temperature over time curves for the heating and cooling of the die are plotted. The first heating phase is finished after 1000 seconds. Afterwards, the die is cooled for 60 second until the temperature drops to a value of 180°C for consolidation and then the reheating is started. The measuring points “d” and “e” show a large overshooting effect. Because of that, the tool temperature is homogenised not until 1400 seconds. This leads to a long thermic cycle time for the process of 400 seconds. To avoid the overshooting a “three zone” controlling concept was investigated. To this end, the heating cartridges 1 and 2 are controlled by thermocouple 1, the heating cartridges 3, 4 and 5 are controlled by thermocouple 2 and the heating cartridges 6 and 7 are controlled by the thermocouple 3 (cf. figure 3). Figure 5 shows the measured temperature over time curves for the “three zone” concept. With this concept the first heating time is reduced to 600 seconds. The cooling time amounts also 60 seconds. The overshooting effect after the reheating is significantly minimised and therefore the thermic cycle time is reduced to 250 seconds.

3.3. Forming Tool

Based on the results of the investigations concerning the heating strategies, the forming tool was developed in detail. The tool consists of three parts which are pillar guided. The pulling unit is realised with hydraulic actuators, which are controlled by the press controller. The required displacement and
tension force is determined in FE simulations of the metallic insert [11]. The developed forming tool is shown in Figure 6.

![Forming tool for the intrinsic manufacturing process](image)

**Figure 6. Forming tool for the intrinsic manufacturing process**

4. **Concept for process controlling**

Regarding the results of the FE-simulations and process requirements a concept for the process controlling is developed. To fulfill the requirements a coupled control system for the two independent motion axes and the tool temperature is developed. Figure 9 shows the schematic process control. For starting the global forming the tool temperature must be higher than the determined minimal forming temperature. The global forming process is controlled by the stroke of the punch. At a predefined position the motion of the punch stops and the local forming process will be started if the tool temperature is higher than the melting temperature of the matrix material. During the local forming process, the force displacement curves are logged and analysed. The local forming process is finished when a defined force value is reached. This force value must be investigated in tension tests of the metallic insert for each insert material and specific geometry. Afterwards the punch is moved to the lower dead centre point and the global forming process is finished. The force controlled motion of the hydraulic actuators, realized the complete forming of the form fit elements and provides the mechanical interlock.

![Process control schema](image)

**Figure 7. Process control schema**

5. **Experimental results**

The experiments were performed on a hydraulic press with a punch force of 15000 kN (Dunkes HS 3-1500). As a generic demonstration part a hat shaped profile is manufactured. The temperature spread on the die surface is measured with a thermographic camera. The results are depicted in Figure 7. The die surface temperature is as homogenous as predicted from the FE simulations. During the forming process, the tool temperature is monitored with six thermocouples. The motion axes for global forming process is displacement controlled and the hydraulic actuators for the local forming process are force controlled. At the beginning of the forming process the tool is heated up to the forming temperature. Afterwards the punch is moved downwards to initialize the global forming process. At a predefined die position, the local forming process is initiated and the hydraulic actuators realise the predefined
tension stroke. If the set value for the tension force is reached, the motion of the hydraulic actuators is stopped and the die is moved to the lower dead centre point.

To evaluate the part quality, CT scans were realised (Figure 8). The CT scans show the metallic insert between the FRP layers. No fibre shifting could be detected, however some minor dry spots and cavities could be seen. To avoid these imperfections, foils of pure PA6 matrix material are placed between the FRP and the metallic insert. Thus fibre content ratio is decreased. The cross section view shows the “out-of-plane” deformation of the metallic interlock element. The out-of-plane deformation is much smaller than expected. To increase the out-of-plane deformation the synchronization between the local and the global forming process as well as the tool temperature must be improved. This is subject to current work.

6. Conclusion
In the scope of this paper a new process design for the manufacturing of an intrinsic hybrid is presented. Thereby the innovative approach is based on a forming process on two geometric scales. For this process the tool development with focus on the thermal tool design and the process controlling is presented. The intrinsic production process needs a variothermal tool concept. The investigations show that the thermal cycle time and the temperature spread on the tool surface are strongly depending on the temperature control concept. For the examined tool the results for the die are shown. For the investigated tool component, the concept with three heating zones fits very well to the experiments. In the first experiments, the developed control concept was tested. The manufactured part was analysed via CT scan and a mechanical interlock were detected.

Further investigations will address optimization of the control concept to improve the mechanical interlock.

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