OPTIMIZATION OF PROCESS CHAIN FOR CONTINUOUS-DISCONTINUOUS LONG FIBER REINFORCED POLYMER STRUCTURES

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Abstract

The integration of sheet molding compound (SMC) as discontinuous fiber reinforced plastics (DiCoFRP) and unidirectional fiber reinforced tapes (UD-Tape) as continuous fiber reinforced plastics (CoFRP) aims to provide a novel cost-effective hybrid material with better mechanical properties. For the handling of the combined CoDiCo-semi-finished part, the reliable gripping during the overall process chain is important. For complex 2.5D contours, the combination of preforming technology and handling technology is worthwhile. In order to combine both technologies, the separately consideration of handling and preforming technology is necessary. This study considers on one hand the necessity of the preform step for CoDiCo-semi-finished parts, on the other hand the possibility to integrate the UD-tape with SMC. Moreover, the quality of the preformed semi-finished parts effects directly on mechanical properties of final parts, the quality assurance system is therefore necessary, in order to ensure a defect free product during preforming step and to guarantee fast reaction, in case any defects are detected. One objective of this project is to generate methods for holistic quality assurance during manufacturing of 3D SMC parts with integrated unidirectional-fibers. Therefore, sensor systems, thermography, ultrasound and acoustic methods will be used.

1. Introduction

In times of global warming and increasing greenhouse gas emissions, lightweight design gains more and more importance. Lightweight design can be achieved in different ways, most commonly by using lightweight materials. Besides lightweight metals, plastics play a more and more important role [1]. Plastics feature good mechanical properties compared to their weight [2]. However, they are often not sufficient to be used in structural relevant components. Therefore, new approaches are examined to combine the low weight of plastics with better mechanical properties of other materials. The paper at hand concentrates on the process chain of sheet molding compound production, which aims at exactly this combination of materials. Especially two process steps will be investigated. On one hand, the handling process, which consists of the sub-steps: Arranging of individual layers, forming of layers in combination with unidirectional reinforced carbon fiber prepregs and subsequent transportation of the

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material into the press. On the other hand, the quality assurance system will be considered more closely. It is already employed during the handling process to detect defects early and make adjustments possible. The production process of the semi-finished material will not be analyzed closely.

Fiber reinforced plastics are increasingly used in automotive applications. Especially Sheet Molding Compound (SMC), which is reinforced with glass fibers, is used in applications like spoilers, underbody and trunk lids [3]. This material offers the opportunity to model complex geometries that are not subject to a large degree of mechanical stress. However, applications as structural components are not yet possible. During the production process of semi-finished SMC, the raw material is blended together with other additives and then conveyed and homogenized by a twin-screw extruder. Afterwards two doctor knifes apply the mixture to an upper and lower carrier film. Cut glass fiber rovings in lengths between 10 and 50 mm are spread out between the two resin-covered carrier films without specific alignment. The two carrier films are then compacted by rolling to press out air inclusions. The semi-finished material is then spooled onto coils and cured up to 4 weeks [4-5].

In case of unidirectional SMC (UD-SMC) semi-finished parts, the fibers are applied with a specific alignment onto the resin covered carrier films. The liquid resin impregnation is usually used for this technique. After curing period, the UD-SMC is formed into parts using extrusion techniques. Process temperatures vary between 125 °C and 170 °C and pressures up to 100 bar [4]. The process chain of part manufacturing of the combined SMC-UD-SMC is shown in Figure 1. After the SMC and UD-SMC have cured, they are gripped and preformed depending on the end contour requirements. Then, the sub-preform are joined together and brought in to the press. Under the press the combined SMC-UD-SMC is consolidated and cured. Finally, the combined SMC-plastics are ready for the post-machining step. Besides the material fabrication, handling and quality assurance are important aspects in the process chain, which also require new system approaches.

The investigated discontinuous thermoset (DiCoFRTS) in this study is SMC on vinyl ester basis with additives provided by the Fraunhofer ICT. It contains a fiber volume share of 23 vol.-%. The length of the glass fibers is ca. 2.5 cm. The continuous fiber material (CoFRTS) with carbon fiber reinforced labelled UDCarbon27CF60-12K from Polynt Composites features a semi-finish weight of 500 g/m² with a fiber volume share of 50 vol.-%. The material is produced on a hybrid resin system basis. This epoxy based UD-tape has continuous fibers with 60% nominal fiber weight content.

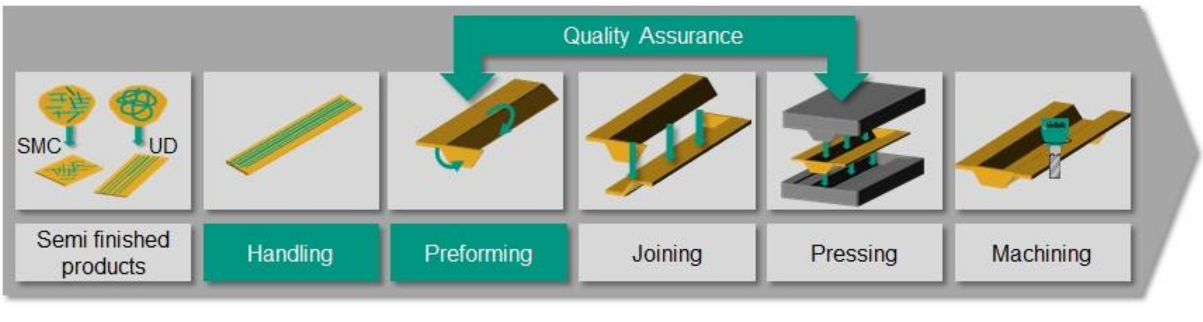

Figure 1. Process Chain of Part Manufacturing of the combined SMC-UD

2. Methods

The following sections outline the testing methods regarding handling, preforming and quality assurance. A detailed description of their application in the process chain is given.

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In this study, we firstly considered the necessity of the preforming step for the CoDiCo-SMC-UD-tape on final parts, whether the preforming step provides better quality in term of defect-free fiber and contour accuracy.

For preforming of dry fabric, the conventional preforming technologies in RTM process are used. They are divided in sequential preforming and global preforming [6]. By sequential preforming, the dry fabric is draped sequentially in a tool cavity. This provides an exact preformed product, but takes a high prefoming time. In contrast, the global prefoming technology offers a short preforming time, which is valuable in a serial production, but delivers a lower surface quality of the preform. In case of the hybrid SMC-UD-tape, the importance of the preforming step, therefore, needs to be proved.

Secondly, the possibility to integrate UD-Tape with SMC is investigated. In general, SMC is laid between 20% to 70% of mold cavity, in order to gain better surface quality thanks to SMC flow capacity. The SMC fills the mold cavity during pressing process under certain pressure and temperature. Combining UD-tape with SMC, the variation of SMC mold occupancy is restricted. We assumed that the SMC-UD cannot be produced with a low percentage of SMC mold occupancy. The longer the SMC flow path is, the more inaccurate is the UD-tape quality. In addition, we assumed that the UD-tape has to be laid around the area where SMC is. In order to prove these assumptions, in this study, the possible percentage of the SMC for integrated SMC-UD with different UD-positions is investigated.

Finally, a quality assurance step will be implemented in the process chain. Thereby, quality has an important role to detect defects on an early state of the process. By examining form and contour accuracy as well as fiber orientation of the prepregs before pressing, intervention is possible in a timely manner. Here, the combined semi-finished materials are checked after the handling process. At this stage it is still possible to correct errors and defects that occurred during the manufacturing and handling process. Therefore no further steps adding value are performed on a defect part. To allow for a holistic approach of quality control, fully cured parts will be checked for defects as well to define any correlation between semi-finished state and finished part.

2.1 Handling and Preforming System

To investigate the necessity of the preforming step for the combined material, a mold in hut profile form as a 2.5D example was used. The testing setup is shown in Figure 2(a).

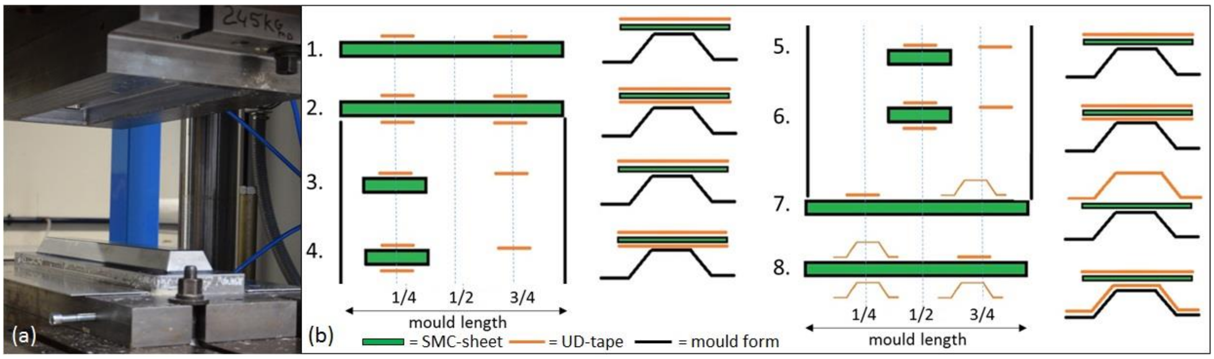

Figure 2. (a) Upper and under mold of a hut profile mounted on a press machine; (b) Testing variation in SMC mold occupancies, SMC-UD-stacked position and preformed UD

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The dimensions of the form are 130 mm width, 500 mm long. The hut profile cross section has an isosceles trapezoid form with the parallel length of 48 mm and 70 mm and 30 mm height. Several hut profiles with different conditions have been produced as shown in Figure 2(b). We used a pressing process with a 40 Ton-press. The pressing parameters were set as followed; 150ºC mold temperature, 90 seconds pressing time and 50 bar pressing pressure. The cut SMC semi-finished sheet have a dimension of 140 x 510 mm^2 with 5 mm thickness, whereas UD-tapes have 140 x 60 mm^2 with 0.5 mm thickness. Test number 7 and 8 were considered, which were pressed at a full SMC mold occupancy with preformed UD-tapes. The position of the preformed UD-tapes was varied in upper and lower side of SMC sheet along the mold cavity. They were heated to 36ºC for 5 minutes and then preformed. The UD-tapes and the SMC sheet were subsequently stacked together and laid on the press.

As shown in Figure 2, the test number 1 to 6 were conducted in order to investigate the influence of different SMC mold occupancies on final parts with varied positions of UD-tape. The SMC mold occupancy was varied between quarter (25%) and full (100%). In case of quarter SMC mold occupancy (test number 3 to 6), the SMC sheets were cut in 4 pieces, which were stacked together with UD-tapes and placed in the mold. The position of SMC-UD stacks was varied between quarter and half of mold length. In case of a full SMC mold occupancy (test number 1 and 2), SMC sheets were stacked with UD-tapes at certain position. The SMC-UD stacks were then placed in the mold.

2.2 Quality Assurance

In the first step, all relevant defects are defined which impact part quality. Already at this point, a distinction has to be made between semi-finished material and fully cured parts. Table 1 shows an overview of possible defects, first in semi-finishes and later in cured parts followed by a short description.

Table 1. Defects in semi-finished material and fully cured part

Semi-finished material	
Folds	Folds occur especially at the edges during the forming process
Fiber or resin accumulation	Inhomogeneous fiber distribution due to defects in the cutting unit during production of semi-finished materials
Air inclusions	Imperfect blending of raw material components or missing additives can cause formation of air inclusions
Fully cured part	
Bubble formation	Bubbles may form due to trapped gas. This is caused by closing the press too fast or too high humidity of raw material
Delamination	Caused for example by weak bonding between fibers and matrix resin
Wrong positioning	Prepregs may shift around due to high pressing forces and insufficient fixation

The effects of the defect categories folds, fiber accumulation, resin accumulation and air inclusions on the semi-finished material are looked into more closely. This will allow to make statements about the

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effects of those defects on the cured part afterwards. To examine the impact on the prepreg as well, all defects will be introduced beneath the prepreg. The fully cured part will be checked for delamination and bubble formation using thermography and ultrasound.

3 Results and Discussion

3.1 Handling and Preforming System

From the test to investigate the necessity of the preforming step, two effects can be observed: The first effect is that the UD-tapes that were preformed before stacking with SMC sheet result in lower width than the one which were not preformed. Figure 3 shows the results from testing number 7 and 8 (full mold occupancy with preformed tape) comparing with the testing number 2 (full mold occupancy without preformed tape). The width of each tape on the position 1A, 1B, 2A and 2B of pressed hut profiles was measured.

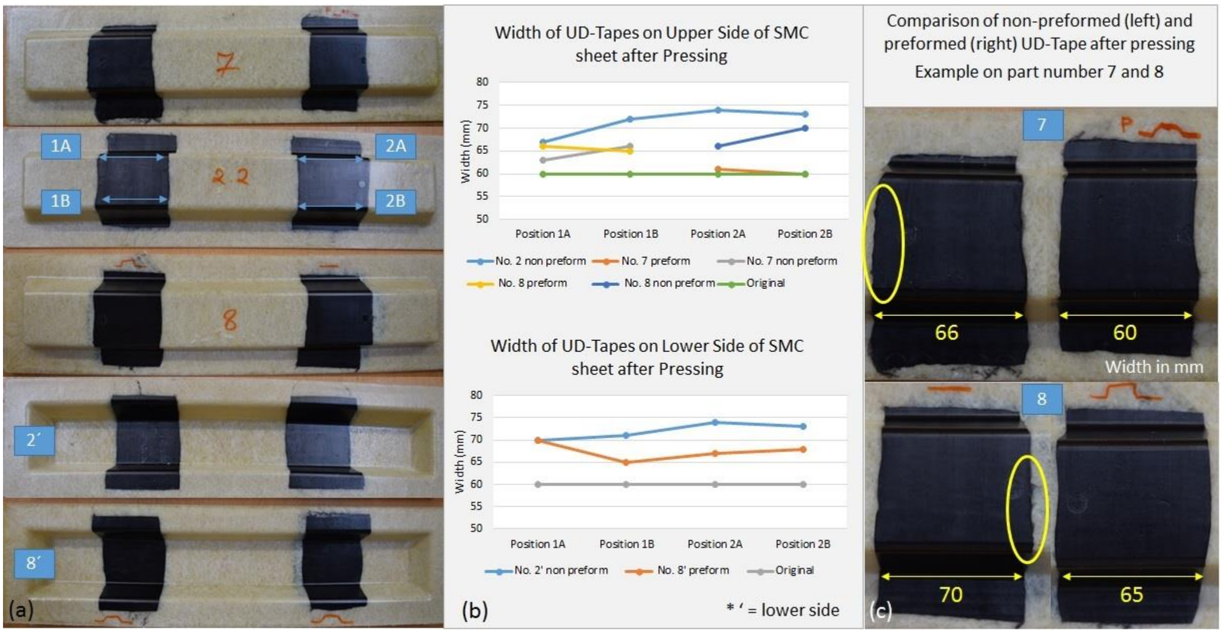

Figure 3. (a) Pressed hut profiles of test no. 2 (non-preform), 7 and 8 (preform and non-preform); (b) Comparison of UD-tape width after pressing on upper side and lower side; (c) Deformation of non-preformed UD-tapes regarding fiber flow and tape width as example

In order to exploit the load transmission capability of carbon fibers on combined SMC-UD-structure, the form of UD-tape has to maintain constant with less or without deformation, e.g. fiber flow, fiber gapping or fiber expansion. After pressing, the width of UD-tapes tends to expand due to flow property of SMC sheet from the original width of 60 mm. The width of preformed parts on both upper and lower side is less than the width of non-preformed part as shown in Figure 3(b). The average width of non-preformed and preformed UD-tapes on upper side are 70.13 (5% expansion) mm and 63 mm (16.8% expansion) respectively. The other effect is the fiber flow effect on non-preformed UD-tapes. Figure 3(c) shows the comparison of tapes between non-preformed (left) and preformed (right) tapes from testing number 7 and 8 as an example. Yellow circles illustrate the fiber flow effect occurring on the edge of UD-tapes. It is obvious that the UD-tapes, which were preformed before stacking, provide a higher form stability. The preforming step obviously influences the form stability of UD-tape in term of fiber flow and fiber expansion.

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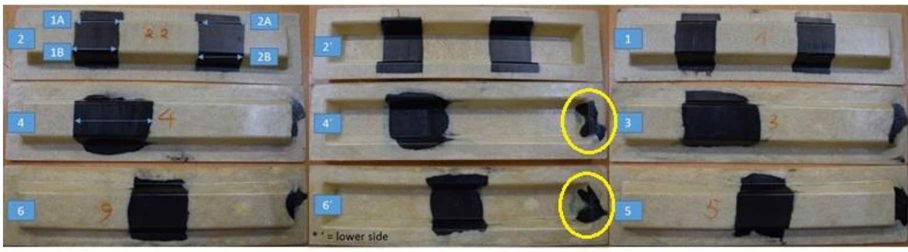
Looking at Figure 4, the results from tests investigating influence of different SMC mold occupancies with varied positions of UD-tape are shown. It demonstrates final hut parts from test module of no. 2, 4 and 6 and of no. 1, 3 and 5 that represent pressed hut profiles with combined UD-tapes on the upper side and on both upper and lower side of the hut respectively. On test no. 1 and 2 (SMC full mold occupancy), the width of each tape was measured at position 1A, 1B, 2A and 2B. On parts with quarter mold occupancy (no. 3-5), the longest width was measured. As seen on Figure 4, in case of non-full mold occupancies, the stability of UD-tapes cannot be maintained. The UD-tapes performed either fully expansion or flow off. Looking at part no. 3, 4 (quarter mold, tape on upper side, right laying position) and 5, 6 (quarter mold, tape on upper and lower side, middle laying position), the single tapes that were not stacked with SMC sheet flowed off due to the long SMC flow path. The flow off effect is illustrated in yellow circles. The tapes stacked on the left end of the cavity resulted a higher width up to 120 mm (200% expansion) from initial size of 60 mm than the tapes stacked in the middle of the cavity, which exhibited less flow off with 88 mm final width (46.7% expansion). It is obvious that the single tapes (non-stacked with SMC) do not maintain required form. As shown in Figure 4, the single tapes were surged by SMC to the end of the mold (yellow circle marks). The results show that hut profiles with full SMC occupancy (no. 1 and 2) deliver the best form stability and provide less fiber deformation with average width of 61.67 mm and 74 mm. Their expansion percentage in perpendicular direction to fiber orientation are 23% and 3.28% accordingly. Moreover, the tape has to be stacked in the area of SMC to avoid the fiber flow off effect.



Width of UD-tapes after pressing (mm)					
No.	1A	1B	2A	2B	Average
2	67	72	74	73	74
4	120		Flowed off		-
6	89		Flowed off		-
2´	69	71	74	73	71.75
4´	103		Flowed off		-
6´	88		Flowed off		-
1	64	64	61	60	61.67
3	118		Flowed off		-
5	83		Flowed off		-

Figure 4. Comparison of pressed hut profiles of test no. 1 to 6 with quarter and full SMC mold occupancy and their width in mm

3.2 Quality Assurance

The examinations show that some of the introduced defects have distinct impacts on the cured part. A fold in the semi-finish part leads to a local orientation of fibers as well as a decrease in fiber count. This is illustrated in Figure 5. Furthermore, enlargement of the prepregs occurs due to being stretched out by the material accumulation within the fold. Additionally, the accumulation of resin has significant structural impacts on the prepreg. As shown in Figure 6, the local positioning and contour of the prepreg is altered. Minor fiber accumulations on top of the semi-finished material did not impact it in any way. Although suspected, impaired bonding of fibers with resin could not be confirmed. Intentionally introduced air inclusions show no effect.

In summary, first investigations show that especially folds and resin accumulation can produce severe defects in the fully cured part. Small amounts of air inclusions do not seem to impair bonding between the two semi-finishes parts but have to be considered for further examinations. This means that sensor systems need to be found which are able to detect form deviations caused by the formations of folds and resin accumulations.

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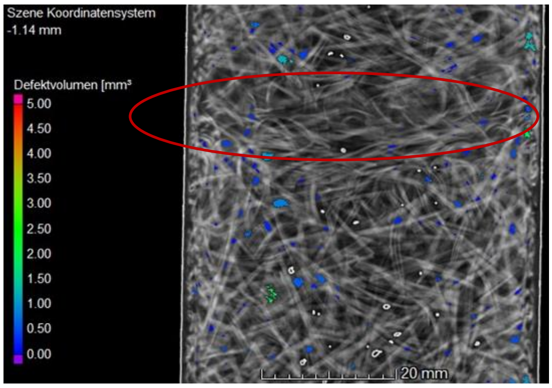

Figure 5. CT image of fold

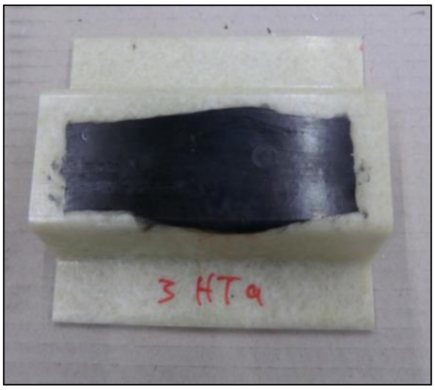

Figure 6. Effects on the fully cured part

Examinations of the cured part using thermography clearly show the tape orientation and individual glass fibers. Carbon fibers are not visible in the image, which was taken 1 second after the flash. This is due to the difference in thermal conductivity. Thermal conductivity is two to four times higher in carbon fibers than in glass fibers [7]. The contour of the carbon fiber tapes is yet visible, so that fiber orientation can be deduced. Also individual glass fibers are distinguishable as shown in Figure 7 and Figure 8 showing defects that are embedded deeper. This includes air inclusions between carbon fiber tape and SMC as well as inhomogeneous bonding between SMC prepreg and glass fiber SMC.

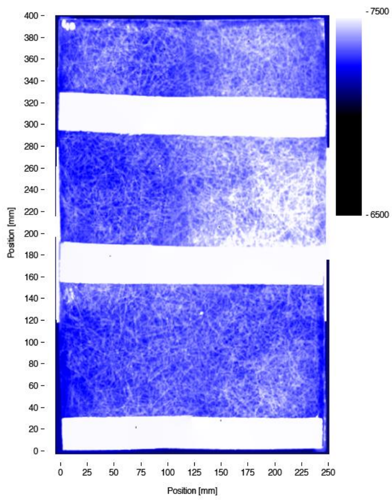

Figure 7. Thermogram, taken 1 sec after flash

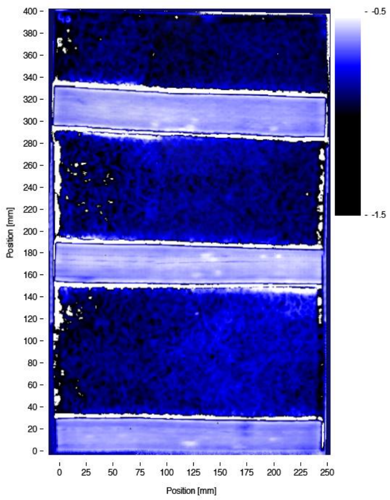

Figure 8. Thermogram with deeper defects

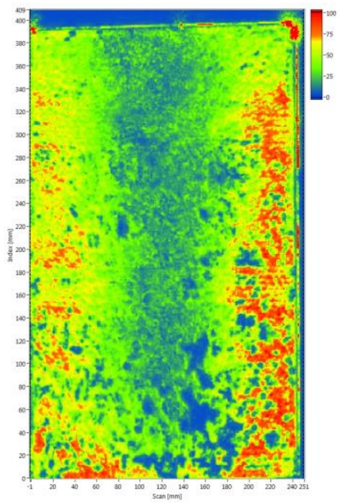

Figure 9. C-Scan of Air coupled ultrasound

The result of the examination with ultrasound shown in Figure 9 exhibits the same defects, but here the depths of the defects cannot be determined. Furthermore the carbon fiber tapes are not visible so that a clear distinction between SMC prepreg and the glass fiber SMC is not possible. Another issue is that mostly the curvature of the cured part is visible but not the underlying defects. Early test measurements of sensor systems have shown that methods like laser light section and laser triangulation are suitable for form and contour measuring of semi-finished materials. Nevertheless, additional image processing systems will be analyzed to ensure that a holistic statement is possible. A combination of different systems is likely, since a single system probably will not meet all requirements.

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3 Conclusion and Outlook

The growing importance of lightweight materials demands new material combinations. Those new combinations in turn demand an adaptation of the process chain and its further development. This study shows the need of a preforming step to manufacture combined SMC-UD plastics. The preformed UD-tapes before stacking provided a higher form stability in term of fiber expansion and fiber flow. It can be concluded that the preforming of UD-tape before pressing is necessary. Moreover, this study shows the influence of different SMC mold occupancies on UD-tape quality on final parts. It concludes that the 2.5D combined SMC-UD materials can be produced only with the SMC full mold occupancy, so that less deformation that are fiber expansion and fiber flow occurs. The lower the SMC mould occupancy has, the more instability has the UD-Tape on pressed products. In addition, the UD-tapes have to be stacked on the area of SMC sheet to avoid tape flow off effect. Regarding the quality assurance aspect, new quality assurance concepts need to be developed and applied to guaranty a high and sustainable quality level. Testing of the material before pressing, in its semi-finished state, enables a timely prediction about the state of the finished part. Adjustments are still possible at this stage of the process chain, so that defective parts can be fixed before pressing. Based on existing examinations it is suitable to use non-destructive testing methods such as thermography for checking finished parts. However, additional sensor systems need to be identified which are able to detect not only form and contour accuracy but also fiber orientation within the semi-finished material.

Acknowledgments

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