TIMESAVING QUALITY ASSURANCE FOR PREFORMING IN THE AUTOMOTIVE SERIAL PRODUCTION OF CFRP

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1 Introduction and motivation

Vehicles impact on the climate is getting increasingly important. To guarantee individual mobility also in the future the greenhouse gas emissions of passenger cars, such as CO₂, have to be reduced significantly. These emissions are known to be directly linked to the fuel consumption of cars. To meet the future CO₂ targets the primary goal of sustainable mobility must be the reduction of fuel consumption [1] (Figure 1). From the original equipment manufacturers’ (OEM) point of view the reduction of emission is not only important because of environmental reasons but also because of monetary factors. It is planned to establish harsh penalties against the manufacturers if the considered targets for the reduction of CO₂ emissions are not reached [2]. Against this background, the OEMs face the challenge of reducing fuel consumption and hence CO₂ emissions by using different options. First of all improvements on the combustion engine can be mentioned [3]. The second trend can be seen in the electrification of cars through hybrid technologies and full electrical drive concepts. The combination of highly efficient power train solutions and lightweight design in the long-term offers the potential for saving up to 70 % energy for cars [4]. So in addition to the mentioned improvements in the power train the reduction of the moving mass through lightweight design has more and more emerged as a key variable on the way to reduce fuel consumption.

To exploit the entire potential of lightweight design, also the material group of fiber-reinforced plastics (FRP) has to be considered by the automotive industry in addition to the traditional lightweight materials such as aluminum or magnesium. With respect to their material properties the group of carbon-fiber-reinforced plastics (CFRP) provides high potential, which makes them suitable for crash relevant and highly stressed structural components [2]. In order to reduce vehicle mass it must be the aim to establish the group of CFRP as a construction material for the volume car market. However, due to the current low automation rate and high production costs caused by the manual processes especially CFRP are not widely used yet. Consequently, the objective must be to develop automation technology to produce high quantities with a competitive price [5]. On the way to an automated production of CFRP one key variable is the quality assurance in the geometry generating preforming process. Because of the short cycle times in the automotive production also the quality assurance systems have to meet these time targets.

2 Challenges in the automated production

2.1 The RTM-process chain

To establish CFRP as a construction material for automotive volume production, the development of improved and automated production processes is of utmost importance. McKinsey & Company [2] assumes that further industrialization of carbon fiber production can lead to a cost reduction of up to 70%.

Because of its low cycle times currently the press based resin transfer molding process (RTM) offers the highest potential for realizing a volume production of continuous fiber-reinforced components like CFRP (Figure 2). The basic raw materials used are semi-finished textiles. In a first process step these textiles have to be cut according to the surface of the future part. After a handling process the semi-finished textiles are converted into a three-dimensional structure in the so called preforming process. Next follows the infiltration of the textile with a mostly thermosetting matrix in the
press. The curing process takes place under high pressure and high temperature for several minutes.

2.2 The preforming process

To enable the use of CFRP in the serial production of cars especially the automation of the forming operation of semi-finished textiles - the preforming-process - and the aligned quality assurance has to be developed.

The forming operation can be conducted in different ways depending on the chosen draping strategy. The draping strategy thereby also significantly influences the sensitivity of the preform against damages occurring in the preforming process. The preforming process consists of the sub-processes draping, fixation and layering process [6]. The structure of the preform is derived mainly from the part geometry but also from the intended part performance and form. It varies in the number of textile layers and in their orientation due to the anisotropic fiber properties. Depending on the requirements of the precast component and on the quality to be achieved, different preforming strategies can be used. Thereby three different main strategies can be distinct.

In the “local sequential approach” (Strategy 1), one huge continuous layer of semi-finished textile, called full-ply, is formed through several process steps. To facilitate this shaping, a few cuts in the semi-finished textile have to be made [7].

The “global patch-wise approach” (Strategy 2) is based on a decomposition of the component geometry in so-called patches. The blank of the patches is selected in a way that they can be adapted to the contour without huge deformations of the textile. This reduces the formation of folds and cuts can be omitted. So as not to reduce the performance of the entire component, patches are deposited with a stepwise offset over each other or overlapping of the patches with a stepwise offset is used. In these regions of the preform local thickening can occur. In both cases the accuracy of the patch positioning is crucial.

The “global stack wise approach” (Strategy 3) is a modification of the “global patch-wise approach”. With this strategy all layers of the preform are draped simultaneously. Again, a geometry decomposition may be required so that sub-preforms are produced which have to be joined with an overlapping. Also here the positioning of the sub-preforms for the joining is important.

In general not only the manufacturing method but also the preforming strategies are significantly depending on several influencing factors: The dimensions of the part, the geometrical complexity that can be achieved, the quality of the part and the characteristics of the part [8].

2.3 Potential defects occurring in preforming

Defects, which occur in the preforming process, can influence the performance of the part in a significant way. These defects occur in the semi-finished textile itself or through a wrong positioning and fixation.

The fibres in the textile are basically responsible for the high strength and the formidable characteristics of the parts [9]. Due to its pliable characteristics damages can be introduced by the handling as well as in the preforming process. This is critical because defects of the semi-finished textiles can lead to a loss in strength.

Geometry deviations such as folds, displacement, angular deviations of the fiber orientation, gapping as well as the gap width between two patches are the most commonly imperfections occurring in preforming (Figure 3). The dimensions of the defects occur mostly in the millimeter range.

In addition to the defects of the semi-finished textiles the correct fiber orientation and the correct positioning of patches and sub-preforms is of great importance. An offset leads to a deviation of the precast component’s material properties.

The importance of the correct positioning of patches and sub-preforms can be derived from the explained preforming strategies. In one case the patches have to be aligned with a defined overlapping or with a defined offset to each other. If this is not guaranteed the mechanical performance of the precast component can be reduced significantly [10]. Also a too long overlapping can lead to a weak spot in the precast component because of a local thickening which must be considered in the cavity.

The positioning of objects is even getting more important if joining elements like inserts have to be positioned. Here not only lateral deviations in the positioning are critical. Also vertical angel deviations have to be measured because they can lead to tensions after the joining process or the part even cannot be jointed.
All these influences and defects have in common that they have to be detected already in the preforming process. Otherwise they can lead to high scrap rates or component failure. So apart from the fiber orientation the geometrical 3D reproducibility in the component manufacturing was identified as a main target [11]. To reduce the mentioned scrap rates it is necessary to detect these defects at an early stage.

As a consequence the aim must be to integrate quality assurance methods and metrology systems already in the preforming step with the premise to meet the cycle times.

3 Approach for quality assurance in preforming

3.1 Measurement time reduction through ROI

In order to realize quality assurance within the preforming process the measurement operation has to be adjusted to the cycle times. Because of this an appropriate measurement strategy has to be used. Considering the time aspect it is not possible to measure the entire surface of a preform. It’s rather necessary to measure only the critical areas where defects may occur due to geometric factors. As a consequence the critical zone of the component, the region of interest (ROI), has to be identified [12] (Figure 4).

One possibility to identify these regions is to analyze the local bending gradient index or principals used in the draping simulation like the shearing angle of the semi-finished textile. This information can be used based on CAD-data. Apart from this critical regions also can be identified by manual draping tests.

This procedure can lead to a link between specific defects and a geometric feature so that ROIs can be identified on the preform surface. The matching of the measurement system and the specific defect completes the procedure.

3.2 Quality assurance for 3D geometries

The overview of the defects occurring in the preforming process has shown that most of them lead to 3D form deviations. So in assessing the reproducibility of geometry and dimensional accuracy the focus is on capturing 3D properties.

Because of the sensitivity of the carbon semi-finished textiles against damage only a non-contact measurement principle can be used. A potential non-contact measurement method for generating 3D data is the laser stripe sensor system. It is based on the principle of triangulation.

By projecting a laser line on the component surface, the topology of the surface is detected by the image of the reflected laser line on an area scan camera. For generating 3D information the laser stripe sensor system has to be moved over the surface under constant and known conditions. To get metric information a precise geometric arrangement between laser and camera is necessary [13].

Despite the fact that this technique has some limitations, due to the reflective surface of the carbon fibers, tests have shown the potential for measuring the surface of carbon preforms by means of the laser strip sensor system [11] (Figure 5). Nevertheless due to the sequential scanning process of the metrology system it is not possible to measure the whole surface of each layer in the preforming process in a reasonable time.

3.3 Approach for measurement time reduction through 2D measurement

3.3.1 Concept for a measurement strategy

To meet the target variable of short cycle times alternative approaches have to be found. When thinking about car production, a sequential scanning measurement process can result in a bottleneck depending on the scanning speed. So in addition to speeding up the laser stripe scanning process it seems to be a suitable attempt to use measurement processes that cope without a sequential scanning like a 2D area scan camera. So this kind of measurement would use some kind of 3D information generated out of 2D measurements. The advantage of a 2D area scan camera measurement is that in one shot a whole ROI of the preform can be captured.

For evaluating the quality of a ROI a template-based approach could offer a solution with the aim to generate a decision whether a 3D geometry is alright or not by analyzing 2D data [11].

The concept can be divided into 3 steps (Figure 6):

The starting point is a preselected ROI which has to be checked on 3D form deviations. First this zone will be measured by a laser stripe sensor to generate 3D information of this preform region. At the same time an area scan camera system will take a 2D picture of the same ROI. By performing a set-actual
comparison the data offered by the laser stripe sensor gives the information if the preforming process was successful and the desired geometry was achieved. In combining the 3D and the 2D images the information is generated, how a 2D picture of an area scan camera looks like if the draping was successful. If this process is successful the image can be converted into some kind of template for the next step (Phase 2).

If the tests have shown that the template-matching system works reliable for this specific ROI the laser stripe sensor can be replaced by an area scan camera to measure the known 3D ROI in the serial production process [11].

3.3.2 Hardware requirements for a vision system
The main output generated by a vision system is in most cases the decision if a part is OK or not. To get towards this information not only the evaluation algorithms have to work properly. A main source for a good evaluation is the data quality of the generated picture. Thereby the lighting has a significant influence on the data quality, especially if reflecting materials as carbon fibers have to be detected. Depending on the feature which should be detected and how the evaluation will work a suitable light source has to be selected [14].

The main kinds of light sources to be mentioned are diffuse lights as dome lights or lights for bright field and dark field situations. Figure 7 shows the different influences light sources can have onto the information in the captured image. In addition the wavelength of the light can influence the image. Depending on the specific defect which has to be detected the raw data quality of images can be further improved by functions as High Dynamic Range (HDR) and strategies like Shape from Shading.

3.3.3 Shape from Shading – 3D information in 2D
The shape from shading method is used to derive 3D information out of several 2D images. These images can e.g. differ in the direction from which they are lighted [15]. The method offers the possibility to get 3D information out of these different pictures by the generated shading. Another advantage is its ability to inspect reflecting surfaces [16]. Due to this ability Shape from Shading theoretically also could be an option to inspect imperfections like folds on the reflecting preform surface.

To evaluate the potential of this method a commercial shape from shading system was used for testing. The used system uses a special dome light with several light sources for lighting. Based on four images with different light settings the outputs of the system are different calculated images.

The slope images in x and y direction are based on the first derivation. Here the direction of the form deviation can be seen by the different grey values. Bright values represent a rising, black a decline of the slope. The curvature image based on the second deviation contains all topographic information adapted from the two slope images. The texture image shows the differences in brightness and can be compared to an image generated by using a dome light [17].

To demonstrate a form deviation in a preform, a small fold was formed into a semi-finished textile for the test (Fig. 8). The gained images show that especially in the slope image in x direction the fold can be seen. Further the edges of the woven fabric can be seen well like all short wave form deviations. The tests carried out have shown that the shape from shading system in the tested configuration only can be used in a limited way for measuring preforms. This is especially due to the low detection range in z-direction as well as because of shadowing effects occurring with big folds.

3.3.4 Conceptual implementation of 3D defect recognition in a 2D area scan camera image
All 3D defects of preforms have in common that they are deviations from the target geometry. To detect this form deviation in a 2D image the deviation has to be made visible by highlighting it in any way. This forms the basis for an approach using template matching as mentioned in 3.3.1.

The principle of template matching is based on algorithms that search after a known pattern in a picture. Hereby, a similarity measure is derived out of a reference image in a teach-in process. Therefore, it can only be used for localizing already known objects [18]. After the template is generated it can be used in the matching process e.g. in the production line. There the images first are preprocessed before the similarity measure is derived and an evaluation is made.

When thinking about form deviations of preforms it is much more difficult. This is the fact because not
an object has to be searched but a form deviation. Because of this the method to highlight the deformation is quite important. This highlighting can be done by using a special lighting strategy adjusted to the specific geometric ROI which has to be detected.

As stated the lighting strategy can have a significant influence onto the evaluation algorithm. For the detection of defects occurring at a convex structure an evaluation strategy based on using dark field lighting seems possible. The idea is that through using dark field lighting, deviations on the surface can be highlighted and detected because of the reflections they cause.

By using a template it is possible to separate the reflections which always occur from the reflections caused by the defect. This template does not search for a similarity in the image that has to be evaluated. It is used to erase the “normal” reflections so that the “abnormal” reflections caused by defects can be localized. So the approach can be divided into two steps.

In step one, we have a learning phase at an ideal preform. Here the always reflecting areas are marked. These areas are then saved as a template. The template represents the areas that have to be erased in the image that has to be evaluated. In step two, the generated template is then adopted onto an image made of the ROI in the preforming process so that only the reflections of the form deviations are left.

Figure 9 shows schematically the principle laboratory setting. The light of the dark field lighting impinges under a flat angel onto the surface of the preform. The plain surface appears dark without reflections. Only edges and form deviations are highlighted because of their reflections.

For the investigations a defect was produced at the transition between the flat surface and the convex zone (Fig. 10). By using an area scan camera an image of the ROI is made. Based on the grey scale image the information in the image is reduced only to the bright reflecting regions. Then for further processing the image is converted into a binary image (Fig. 11).

As mentioned dark field lighting also leads to regular reflections. Because of the fact that they always occur at the same region they have to be marked in the template (Fig. 12).

Now in step two an image of the same setting can be evaluated. After the same preprocessing of the image the areas saved in the template can be subtracted from the image to be evaluated (Fig. 13). After this only the reflections of the defects are left, so that they can be evaluated. To enlarge the defects for the evaluation a dilatation and segmentation of the defects in the image can be done (Fig. 14).

4 Conclusion and outlook

The development of production technologies for new lightweight materials as FRP is getting more and more important. This is the case because weight reduction of passenger cars can be seen as the enabler for a sustainable mobility in the future. Because of their extraordinary mechanical properties CFRP offer the highest potential for highly stressed components in the automotive industry. To bring this material group into mass production especially the preforming process and the aligned quality assurance have to be further automated. Here the short cycle times pose a challenge.

The presented approach shows a possibility to reduce the measurement time by evaluating 2D area scan camera images with the aim to detect 3D form deviations. By this, sequential scanning operations e.g. through laser stripe sensors can be reduced in the application.

The investigations have shown the principle potential of using dark field lighting to make form deviations visible in a 2D image which builds the basis for the evaluation algorithms. The approach is strongly depending on the orientation of the preform, the orientation of the lighting and the orientation of the area scan camera. As a consequence this leads to a high complexity in adopting this principle onto individual geometrical features.

Further investigations will cope with this challenge. It has to be the aim to find criteria how an optimal measurement setting has to look like in relation to the geometry to be evaluated.

5
Fig. 1. CO₂ targets for the car fleet emissions in different world regions (g/km) [1]

Fig. 2. RTM process chain

Fig. 3. Typical imperfections in preforming [11]

Fig. 4. The way to a measurement strategy for preforms [12]

Fig. 5. Laser stripe sensor scans - convex specimen covered with carbon semi-finished textile [11]

Fig. 6. Concept for a time reducing measuring strategy by using template-matching [11]
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Fig. 7. Images of semi-finished textile with different lighting situation

Fig. 8. Shape from Shading images of carbon semi-finished textile

Fig. 9. Dark-field illumination of the region to be measured

Fig. 10. grey value picture of the preform ROI

Fig. 11. Binary B/W image showing the reflecting areas due to dark field lighting

Fig. 12. Areas which are allowed to reflect for generating the template
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References


