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Influence of gripper positions on the formation of wrinkles during the thermoforming process of thermoplastic UD-tape laminates

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Abstract. Thermoforming multiaxial UD fiber-reinforced thermoplastic tape laminates into complex geometries can lead to undesirable forming defects, such as out-of-plane wrinkles. These are detrimental to the performance of the resulting part and cannot be prevented by optimizing conventional process parameters alone. Other studies have therefore identified the introduction of membrane tension into the laminate during the forming stroke as an additional manipulation option to reduce wrinkling. The implementation of these membrane tensions is facilitated by the utilization of tension grippers, which can be positioned at various locations. To investigate the extent to which the position of the grippers affects the forming result, a forming study was carried out. Three different gripper positioning configurations were defined and applied to the forming of the UD tape laminates. Using an industrial scale automated process, the laminates were both fully and partially formed into a complex geometry using each gripper configuration. To evaluate the influence of gripper positioning on the forming result, the components were 3D scanned and compared and evaluated in terms of their external contour, surface curvature and thickness distribution. The influence of the gripper configuration was demonstrated for all three variables investigated. Concurrently, the analysis revealed discernible correlations between the three variables examined. Areas with locally high surface curvature also showed local thickening at identical locations, and more uniform material feed resulted in lower surface curvature.

Introduction

Thermoplastic tape laminates with continuous UD fiber reinforcement offer exceptional lightweighting potential and can be formed highly automated into 3D parts in low cycle times using comparable equipment to sheet metal forming. Combined with the possibility of additional functionalization through large-scale production processes such as injection- or compression-overmolding and their recyclability, they offer ideal prerequisites for use in large-scale automotive series production [1]. However, thermoforming of tape laminates may result in the occurrence of unfavorable forming effects, including voids, gapping and out-of-plane wrinkles. Latter one leading to consequences such as fiber buckling up to fiber breakage, significantly decreasing the mechanical properties and therefore being a major issue in thermoforming [2, 3, 4].

The formation of wrinkles is closely associated with the geometry of the formed structure and the layer composition of the laminate. In the case of double-curved parts, the formation of wrinkles is particularly pronounced [5]. Multiaxial laminates exhibit a higher tendency to wrinkling compared to biaxial laminates [6, 7, 8]. Both factors are usually predetermined by the part requirements and cannot be adjusted without significant modification. The optimization of conventional process parameters such as tool temperature, laminate temperature and forming speed alone is not sufficient to achieve a satisfactory forming result with minimal wrinkling. It is therefore essential to explore alternative methods for manipulating the three relevant forming mechanisms (inter-ply friction, in-plane shearing and out-of-plane bending) [3, 9, 10].

Several authors have investigated the application of tensile membrane forces during the forming process, either through a blank holder or tension grippers, consistently finding that it significantly impacts wrinkle formation in both forming fabrics and laminates [2, 11, 12, 13, 14, 15]. Using a blank holder, a higher clamping force has been shown to improve the forming result. In contrast, using tension grippers, a lower tension force combined with an increased number of grippers has been reported to reduce wrinkling [14]. Although gripper-induced membrane forces led to increased wrinkling, they had the most significant influence among the studied forming parameters. The authors propose a high potential for the reduction of wrinkle formation through the optimization of position, direction, number and operating principle of the tension grippers [2, 15]. Since grippers offer advantages over blank holders during heating and transfer of the laminate and do not cause additional friction and cooling during forming [1, 13], the influence of tension grippers is to be further studied. In order to optimize the forming result using tension grippers and to be able to establish guidelines for the correct use of grippers for different geometries, it is first necessary to understand the influence of the individual parameters in more detail. Among the previously mentioned parameters, namely tension force, number, direction, position and operating principle, research has been conducted on the influence of the number of grippers and their tension force. However, there remains a paucity of knowledge regarding the optimal gripper positioning. To enhance comprehension of the influence of tension grippers, a forming study was conducted to analyze the effect of gripper positioning in isolation.

Material and experimental setup

The laminates used for this study were made from the carbon fiber reinforced PA6-Tape CELSTRAN® CFR-TP PA6 CF60-03 from Celanese with a fiber mass fraction of 60 %, a thickness of 0.16 mm and slitted to a width of 107 mm. Using Dieffenbachers automatic tape laying machine Fiberforge, the UD-Tape was processed into a spot-welded layup of twelve layers with a $(0/90/45/-45/0/90)_s$ stacking sequence. Prior to the subsequent consolidation step and before the final forming trials, the material has been dried in a convection oven for a period of 48 hours at a temperature of 80°C. For consolidation, each layup was placed in between two aluminum plates, pretreated with a release agent and heated to a temperature of 280 °C utilizing a Wickert contact heating table. The molten layup together with the aluminum plates was transferred to a hydraulic press and pressed on a flat steel die at a pressure of 2 MPa. The consolidated laminates were then cut to the required size of 400x400 mm.

The forming trials were conducted with industry scale equipment and fully automated transfer for high reproducibility (see Fig. 1 (a)). Using a gripper frame attached to an industrial robot the laminate was picked up at the loading station by eight pneumatic grippers and transported into a C-shaped Krelus infrared heating field with 2x75 kW heating power. Each gripper consists of a radial gripper and a linear cylinder and is mounted to be rotatable within the laminate plane. The radial grippers hold the laminate with a pin that engages in pre-drilled holes in the laminate at defined gripping points, while the linear cylinders are used to generate a membrane tension in the laminate by means of a constant tensile force. The grippers can be repositioned between the trials, ensuring that, depending on the defined points of application, each gripper is consistently aligned perpendicular to the laminate. After the culmination of the heating process, the laminate is positioned at a height of 5 mm above the die. The membrane tension is kept constant during the subsequent forming stroke of the hydraulic press. A heated, complex-shaped steel tool with a forming depth of 50 mm and differently pronounced double-curved areas is used for forming (see Fig. 1 (b)).

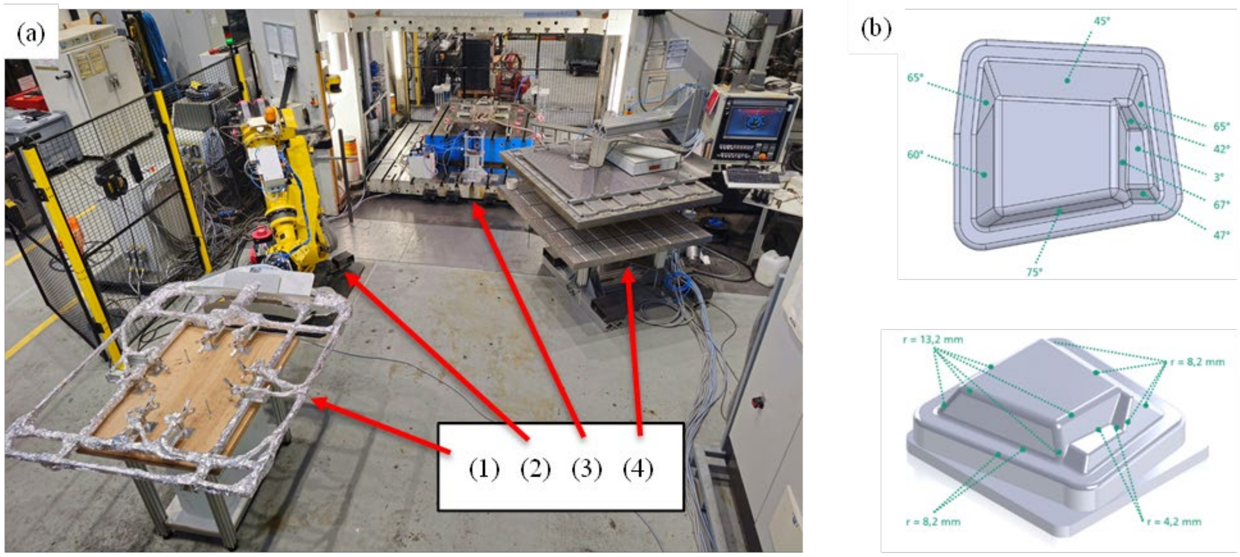

Figure 1 – (a) industry scale process with (1) the gripper frame at the loading station, (2) an industry robot for transfer (3) a hydraulic press with the tool mounted and (4) a c-shaped infrared heating field; (b) complex shaped tool stamp with different forming radii and forming angles

Forming study and evaluation

In the scope of the forming study, three distinct gripper configurations for the positioning of the eight grippers (G1 to G8) at the edges of the laminate were examined. To facilitate a comprehensive assessment of the wrinkling, six parts were partially formed for all three configurations. In addition to three fully formed parts (s = 0 mm), three parts each with a remaining tool gap of 5 mm (s = 5 mm) and three parts each with a remaining tool gap of 10 mm (s = 10 mm) were molded.

The configuration of the eight grippers was determined using a coordinate system positioned at the center of the laminate (see Fig. 2 (a)). The distance from the pre-drilled gripper hole to the edge of the laminate was constant at 10 mm. As indicated by the nomenclature, the distance is therefore specified exclusively to the x-axis or the y-axis.

Table 1 presents an overview of the three gripper positioning configurations (GC1, GC2 and GC3). In the configuration referred to as “Gripper configuration 1”, the grippers were arranged symmetrically with respect to both the x-axis and the y-axis. The distance to the x-axis was set at 75 mm, while the distance to the y-axis was set at 110 mm. With gripper configuration 2, the distance to the y-axis was maintained at 110 mm, while the distance to the x-axis was adjusted to 110 mm. This resulted in all grippers being positioned at a consistent distance from the center of the laminate. Gripper configuration 3 exhibits no symmetries in comparison to the aforementioned configurations.

In order to assess the isolated influence of the gripper positioning on the wrinkle formation, all process parameters except the gripper positioning were kept constant throughout the test campaign.

The laminates were heated in the infrared heating field to a target temperature of $T_{laminate}$ = 280 °C, measured using two pyrometers, and held at this temperature for a holding time of $t_{holding}$ = 5 s to ensure thorough heating of the laminate.

The duration between the cessation of the holding phase in the heating field and the initial contact of the tool stamp with the laminate was measured to be $t_{contact}$ = 10.7 s, with a standard deviation of 0.5 s.

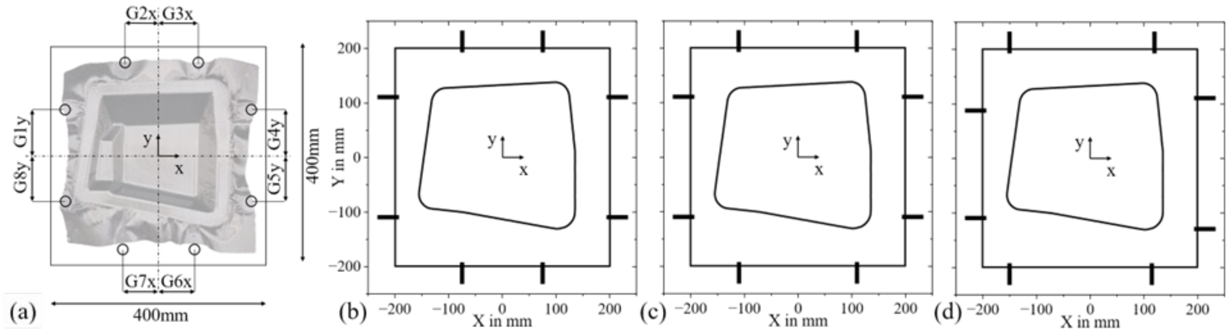

Figure 2 – (a) Gripper distances to the center point; (b) Gripper configuration 1; (c) Gripper configuration 2; (d) Gripper configuration 3

Table 1 – Distance of each gripper to the center point for the three gripper configurations

Gripper configuration	G1y	G2x	G3x	G4y	G5y	G6x	G7x	G8y
[-]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
GC1	110	-75	75	110	-110	75	-75	-110
GC2	110	-110	110	110	-110	110	-110	-110
GC3	87	-150	120	125	-130	115	-130	-110

The tool temperature was set at T_{tool} = 110 °C, and the press force for the fully formed parts was set at F_{press} = 1.000 kN. During the forming process, the linear cylinders of the grippers were subjected to a pressure of p_{pull} = 1.6 bar, which, according to [2], results in a tensile force of approximately F_{pull} = 75 N per gripper for multiaxial laminates.

For evaluation the 27 formed parts were 3D scanned with a GOM ATOS 5 system to evaluate the forming result and to assess the effects of gripper positioning on the wrinkle formation. The resulting point clouds were preprocessed and initially meshed with the GOM-Inspect software to improve further postprocessing [16].

As one of the comparison criteria, the outer contour of the corresponding part in the forming direction was determined from each of the resulting meshes. All nodes of the mesh were therefore projected into the x-y plane and the α-shape, describing the outer surrounding contour of a set of points, was determined. Since this process has an intrinsic smoothing effect, the selection of an appropriate α-value, in this case α = 0.1, achieved a reduction of small unwanted scan errors [17].

In addition to the outer contour, the thickness distribution of the fully formed parts was also determined from the 3D scans. The scans were virtually trimmed to the outer contour of the CAD part, as the material extending beyond the tool edge is not relevant in this approach. GOM-Inspect software was then used to generate a thickness distribution plot from the trimmed scans.

For wrinkling quantification, the surface curvature of the partially formed parts was determined. The 3D scans were similarly trimmed to focus on the area relevant to the final part. To reduce small scale effects, the trimmed meshes were remeshed with a coarser target edge length of 1.9 mm. This was done using the Isotropic Explicit Remeshing filter inspired by [18] of the PyMeshLab Python library [19] with ten iterations. To determine the surface curvature, the procedure originally proposed by [7] and described in [2, 15] and the Python script created as part of these works were used. This script first estimates the two main curvatures κ_i^I and κ_i^{II} at each mesh node i using the algorithm developed by [16], and then computes the modified mean curvature $\bar{\kappa}_i$ as an equivalent scalar as described by Eq. 1 [7]:

$$\bar{\kappa}_i = \frac{1}{2}\left(\left|\kappa_i^I\right| + \left|\kappa_i^{II}\right|\right). \qquad (1)$$

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The distribution of the surface curvature determined in this way was visualized in the ParaView software as a distribution over the part surface. For joint observation of the triple repeat tests performed for each combination of gripper configuration and remaining tool gap, a joint heat map of the average modified mean curvature was generated from the three measurements.

Results and discussion

Due to the material's minimal elongation capacity in fiber direction, the external contour of the formed components provides insight into the material's deformation during the forming process, facilitating a comprehensive understanding of its behavior. Fig. 3 shows the outer contours of the nine fully formed parts depending on the gripper configuration. The contours are plotted in the same coordinate system at the center of the laminate that was used to define the gripper positions. The outer contours of the parts formed with gripper configuration 1 (GC1) are shown in three shades of red, those of the parts formed with GC2 in three shades of blue and those of the parts formed with GC3 in three shades of green.

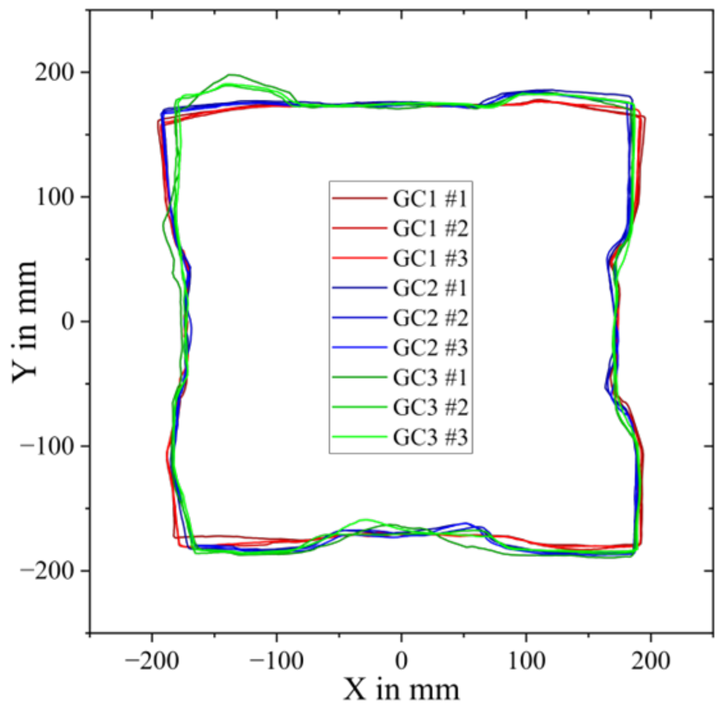

Figure 3 – outer contour of the nine fully formed parts depending on the gripper configuration

The three replicate trials with each gripper configuration demonstrate a remarkably similar outer contour. However, a clear deviation is evident for GC3 between the first repeat (in dark green) and the other two samples, which has been attributed to a minor disturbance in the heating field. The clear consistency of the replicate tests is an indicator of the high reproducibility that could be ensured by the automated process. Depending on the gripper configuration used, the outer contours of the components can be distinguished. For the two gripper configurations, GC1 and GC2, the contour exhibits significant variations along the upper and lower edges of the part. Due to the identical positioning of the grippers on the left and right sides of the laminate, the material feed on these two sides behaves almost identically. It deviates only slightly towards the corners, suggesting that the influence of a gripper primarily affects the material feed on the gripped edge and has minor interaction with the material feed on the neighboring edges. The top and bottom edges of the GC1 samples showed the most uniform material feed. On these two edges the grippers had the smallest distance from the centre of the laminate and were positioned in the almost straight section of the tool between the tool corners. Comparable uniform material feed can also be seen in the upper half of the left edge for GC3, where the same applies to the corresponding gripper position. On edges with grippers positioned further outwards, either in or already outside the area of the tool corners, and therefore further apart, a significantly more ununiform material feed can be seen. Here, the material is pulled more toward the center of the tool, which has the greatest forming depth.

The surface curvature distribution over the part surface is shown in Fig. 4 as a joint heat map of the average modified mean curvature of the three replicate trials for each of the three gripper configurations GC1, GC2, and GC3 for both the two remaining tool gaps s = 10 mm and s = 5 mm. The initial square dimension of the laminate with the initial gripper positions is also shown around the heat map. In the heat maps, a stronger shade of red combined represents a higher frequency of occurrence and a higher intensity of the modified mean curvature.

All heat maps clearly show the inherent curvature of the formed geometry, especially noticeable in the base of the part. For all partially formed parts, additional surface curvatures of varying intensity can be seen almost along the entire part contour. This confirms the observations of [6, 7, 8] that wrinkling is a forming defect challenging to control in the forming of multiaxial laminates. Accumulations of strongly pronounced surface curvature can be seen mainly around the double-curved part corners, as also observed by [5]. While the positions of the areas of particularly high intensity differ moderately for the three gripper configurations, they are recognizable at the same position for a progressive forming stroke from s = 10 mm to s = 5 mm with a constant gripper configuration but tend to become smaller and increase in intensity.

Compared to GC2 and GC3, GC1 shows a less pronounced concentration and intensity of surface curvature along the upper and lower part edges. The grippers exhibited a closer proximity at these two edges, and a uniform material feed was observed for GC1, based on the outer contours. The same correlation is also observed for GC3 at s = 5 mm in the upper half of the left edge of the component, where an accumulation of strongly pronounced surface curvature occurs at GC1 and GC2, but clearly reduced surface curvature is recognizable at GC3. In this area, the outer contour of the components formed with GC3 shows a very uniform material feed, presumably due to the gripper being positioned closer to the center of the laminate. An accumulation of pronounced surface curvature in the center of a part edge is only seen on the top edge of the part in GC3, which is the edge where the grippers are farthest out and away from each other.

Fig. 4 also shows the thickness distribution for one fully formed part per gripper configuration. Green represents the average of the scale for a part thickness of 1.85 mm, with increasing thickness from yellow to red and decreasing thickness from turquoise to blue. For all three gripper configurations, the presence of thin spots is evident in the corners at the base of the part, exhibiting uniform dimensions irrespective of the gripper configuration. The thin spots are more pronounced along the lower, steeper edge of the part compared to the upper, less steep edge. Another thin spot can be seen in the upper area of the interference contour on the left flank.

Contrary to the thin spots in the part corners, this one shows an influence of the gripper configuration. The thin spot for GC1 and GC2 is almost identical and very small, whereas for GC3 it is significantly larger and extends over almost the entire sloped edge of the interference contour. This thin spot is in the area where an improvement in material feed and surface curvature was observed, with the gripper being significantly closer to the centerline for GC3 compared to GC1 and GC2.

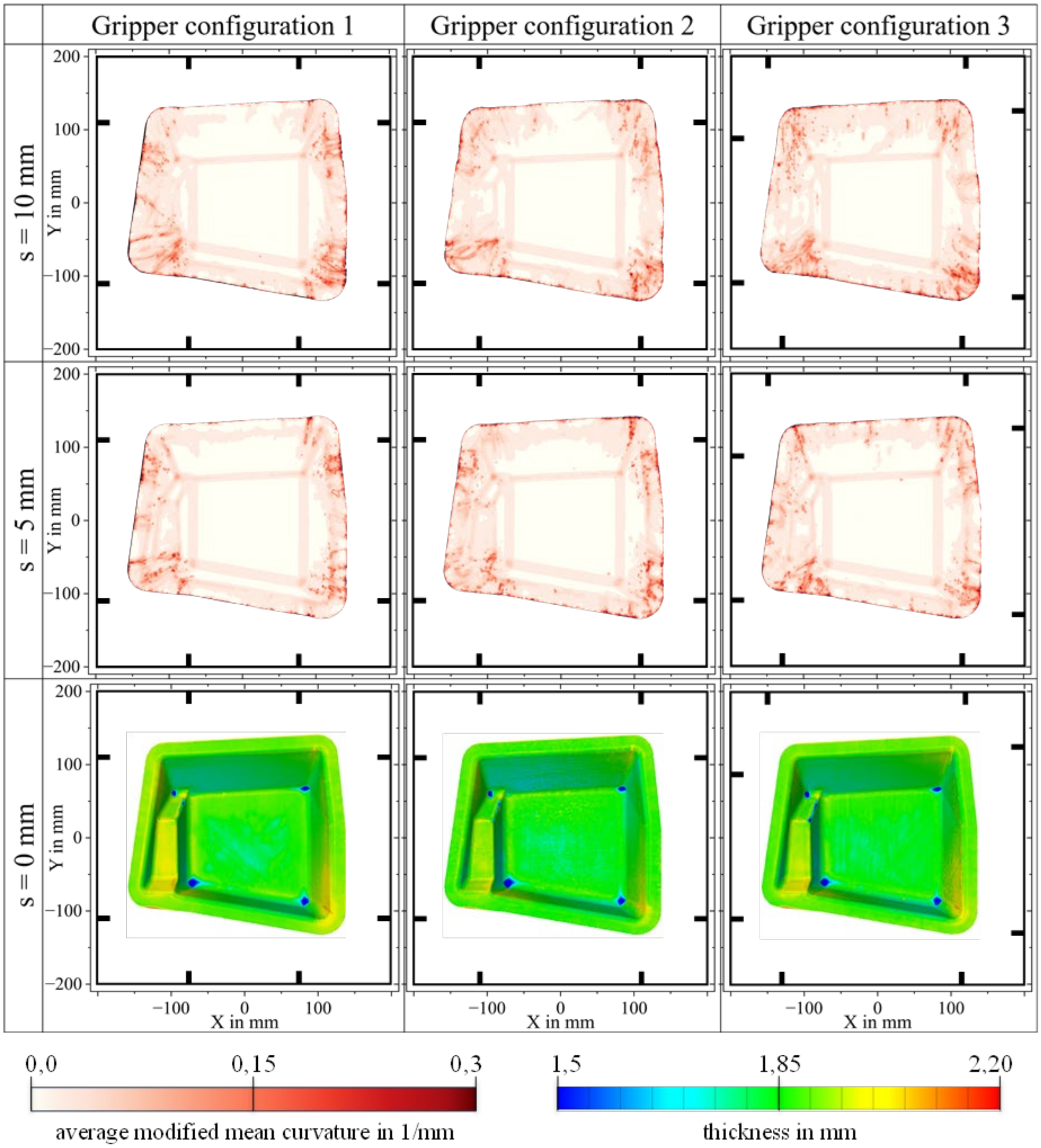

Figure 4 – Forming results for the three gripper configurations studied, shown within the initial laminate size and with the initial gripper positions. For the partially formed parts with remaining tool gap s = 10 mm and s = 5 mm as a joint heat map of the average modified mean curvature of the three replicate trials and for the fully formed parts with s = 0 mm as thickness distribution plots of a representative part.

For all three parts, local thickening of varying intensity can be seen in the upper half of the flanks in the area of the part corners. The positions of the thickenings can be clearly correlated with the positions of more pronounced surface curvature. Wrinkling and the resulting folds lead to local material accumulation and are probably the reason for the locally higher component thickness. This observation is consistent with the findings of [2, 8]. The local thickening is most pronounced for all gripper configurations in the lower right corner, whereby it is most pronounced for GC1 and least pronounced for GC2. The intensity of the second larger spot of increased part thickness, located in the intermediate plane of the interference contour, is also sorted in the same order. The most pronounced local thickening can be seen for GC1. In contrast, the most homogeneous thickness distribution is found for GC2, where all grippers have the same distance to the center point.

Conclusion

In this study, the influence of different positionings of tension grippers at a UD fiber-reinforced laminate on the thermoforming result was investigated with the aim of reducing the forming defect of out-of-plane wrinkles. Three gripper configurations with different positionings of eight pneumatic grippers along the laminate edges were defined and varied with otherwise identical test parameters. To evaluate the influence, for each gripper configuration parts were fully formed and partially formed with a remaining tool gap of s = 10 mm and s = 5 mm. The parts were evaluated with respect to their outer contour, surface curvature and thickness distribution using 3D scans.

A correlation was observed between a uniform material feed along an edge and low surface curvature at the corresponding edge. Both were achieved by moving the grippers closer together so that the tensile force is applied to the edge of the part rather than the corners. The correlation between pronounced surface curvature as a measure of wrinkling and local thickening, which is also described in the literature, was confirmed. Despite the reduced surface curvature for gripper configuration 1 along the upper and lower part edges, the greatest thickness variations in the part were observed for this configuration. In contrast, the equidistantly positioned grippers in GC2 resulted in the most uniform thickness.

It was demonstrated that appropriate gripper positioning can reduce the surface curvature and shrink and move the areas where wrinkles occur. Therefore, when considering a wider range of variation, it can be assumed that gripper positioning can be further optimized to reduce wrinkling. However, in addition to positioning, the tensile force of each gripper should also be included in the optimization so as not to reduce wrinkles in favor of other forming defects, as was seen in GC3 in the upper area of the left edge, where wrinkles were locally reduced but local thinning increased as a result.

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