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Integrated Gripping-system for Heating and Preforming of Thermoplastic Unidirectional Tape Laminates

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Abstract

Forming and overmolding of thermoplastic multi-layer UD-tape laminates has become increasingly important due to its potential for large-scale production. In the process the tape laminates have to be heated above melting temperature of the polymer in an infrared heater and then transported into the mold. To guarantee the formability of the laminate the temperature has to be maintained above the melting temperature during handling. To improve part quality a preforming of the tape laminate prior to overmolding is preferable. Integration of the preforming step in the handling process allows the shortening of the process route. In this work a gripping-system which allows further heating and preforming of the laminate during the handling process is presented. The temperature losses during transport have been modelled using the Stefan-Boltzmann law. By means of temperature measurements it is shown, that the integrated infrared-heaters allow a compensation of the cooling during handling, resulting in lower maximum heating temperature in the upstream infrared heating field and therefore a reduction of heating time and degradation of the polymer. The repeatability of the handling-integrated preforming has been evaluated using three-dimensional overlays of the resulting 3D-shaped laminates acquired by a laser scanning arm.

Keywords: Composite; Fiber reinforced plastic, Forming, Handling

1. Introduction

With increasing importance new products in the automotive sector require weight-savings for improvement technical efficiency due to ecological and economic reasons. Therefore fiber reinforced polymers (FRPs) more and more replace traditional materials as of their superior specific mechanical properties and other benefits like corrosion resistance. For assuring a high volume production at high quality the manufacture of FRP parts has to be automated which still poses considerable challenges in production technology [1].

Especially gripping of the semi-finished products in a FRP process chain is very demanding due to the anisotropy, air-permeability and limp nature of the textiles [2]. But there are several grippers available on the market which are basically suitable [3, 4]. Another major challenge in FRP parts manufacture is the preforming process step which is the shaping of a 3D semi-finished product [1]. This paper investigates the integration of heating and a preforming operation during the handling of unidirectional tape laminates. After presenting the state of the art, the investigated process chain and the design of the developed gripping system is presented. This is followed by an investigation of the thermal behavior of the laminates during handling and the evaluation of repeatability of the preforming process.

2. State of the art

Various scientific works showed the integration of preforming of dry fiber textiles in the handling process which is quicker and cheaper as sequential process steps. Brecher et al. proposed a gripping system for preforming called Octopus gripper using the finray effect which allows the adaptation to convex and concave shaped surfaces [5]. Ehinger developed a modular preforming end-effector with several draping units with elastic layers and an integrated

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heating wire for melting of the binder. The end-effector picks up and releases the textiles with a rolling motion activating and deactivating the draping units in a defined sequence [6]. Löchte et al. presented the handling and joining device FormHand with a form-flexible gripper cushion filled with granular material adapting to various surface geometries [7]. Another concept for a draping gripper is based on hexagonal pixels including a Coanda gripper with sensors each. The integrated sensors allow to actively influence the contact pressing force on each gripper pixel [8].

The trend towards thermoplastic FRPs using organo-sheets and unidirectional (UD) tape laminates as semi-finished products leads to new challenges for gripping. The grippers have to withstand the high temperature of the laminate heated above melting temperature. As the heated semi-finished products have to maintain their molten state during handling until deposition in the forming mold large contact areas have to be avoided to prevent heat losses. First research with heatable needle grippers show a possible prolongation of the handling time, but no solution is available commercially yet [9]. Another approach is the use of vortex grippers with heated air for simultaneous heating and handling of organo-sheets [10].

For the thermoplastic process chain with forming of a organo-sheet or UD tape and additional overmolding in the same mold, a preforming is very favorable for the forming result i.e. reducing fiber failures [11]. For compression molding with a long-fiber reinforced thermoplastic (LFT) strand a preforming is essential to avoid the LFT to flow on the wrong side of the reinforcement laminate or the displacement of the laminate by the LFT [12]. Existing handling-integrated preforming approaches for thermoplastic reinforces laminates are working with an additional die. The gripping-systems feature a mechanically actuated kinematic to drape the laminate over the die [10, 13]. Other handling-systems for organo-sheets include a pneumatic stamp for preforming directly on the forming tool [11]. A different approach shows the near-net-shape preforming of cold cut-out UD tape pieces with a gripping-system featuring suction grippers and ultrasonic welding for fixation [14].

The presented approaches in the literature for the preforming of thermoplastic laminates are limited to draping over a die or in a mold. Investigations of the cooling and its prevention during handling focus only on the contact areas between gripper and laminate. In the following a new gripping-system is presented which features heating of the whole laminate to prevent heat losses during handling and a kinematic for preforming without additional tool.

3. Investigated process chain

The reference part for the research is a generic geometry inspired by a car underbody with the door sill, the center tunnel and two cross beams for the mounting of the seats, which was conceived in the research project MAIqfast [15]. The part is manufactured in a compression molding process with endless fiber reinforcements made of unidirectional tapes and long-fiber-reinforced thermoplastics from a direct extrusion line. Fig. 1 shows the final part and the preforming step of the UD tape patches.

The UD tape patches for the investigations in this paper were fabricated as rectangular plates on a tape placement machine and consolidated on a double belt press. Afterwards the stripes were cut out and thermally bonded for the tape laminate no. 1. The tape is a Celstran CFR-TP PA6 CF60-03 with a polyamide 6 (PA6) matrix. According to its datasheet it possesses a melting temperature of about 220°C and 60 wt-% of unidirectional carbon fiber reinforcement. The laminate architecture of the plates is 0/90° with 16 layers overall resulting in a thickness of 1.5 mm.

4. Design of Gripping System

4.1. Gripper selection

For the handling of heated tape laminates and organic sheets suitable grippers have to be selected. According to Bruns et al. needle grippers, suction grippers and clamp grippers can be used with different advantages and disadvantages [9]. Additionally own preliminary experiments for the selection with a needle gripper, suction grippers with a diameter of 22 mm and 40 mm and Coanda grippers have been carried out in a similar processing and handling scenario like Bruns et al. with tape laminates heated in an infrared radiator and subsequent handling. The cooling

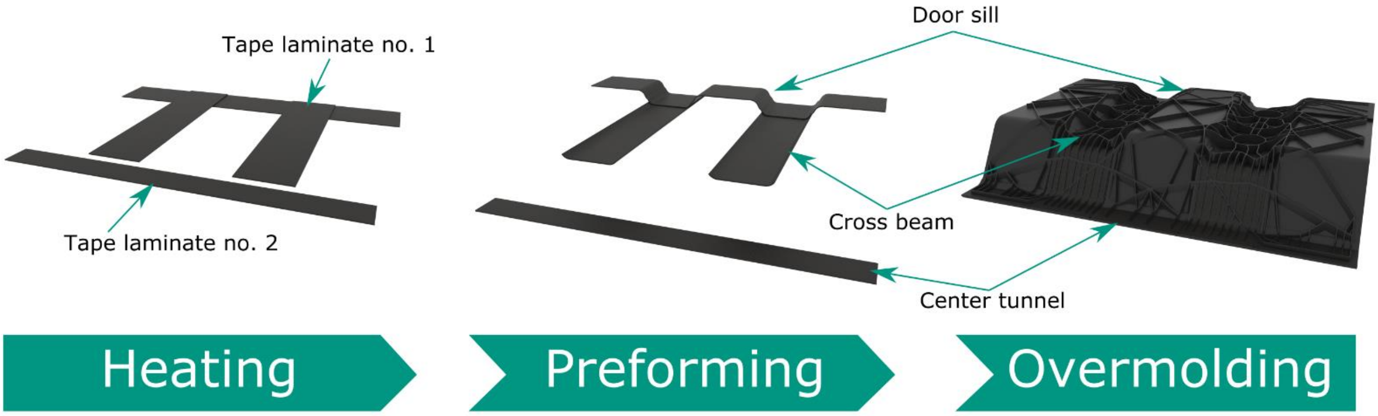


Fig. 1 Processing steps of unidirectional tape laminates

of the laminate has been recorded with an infrared camera. Fig. shows the qualitative results of the experiments. Due to the minor fiber damage and temperature loss combined with good holding force the suction grippers with a diameter of 22 mm were selected for the gripping-system.

In order to guarantee a secure gripping and handling of the heated laminates the gripping points are determined empirically as a draping simulation requires temperature dependent material data. The boundary conditions for the gripper positioning are on the one hand the sag of the heated laminate and on the other hand the fixation at the points to be formed. 18 gripping points at the locations shown in Fig. 3 have been found out to be suitable for the application.

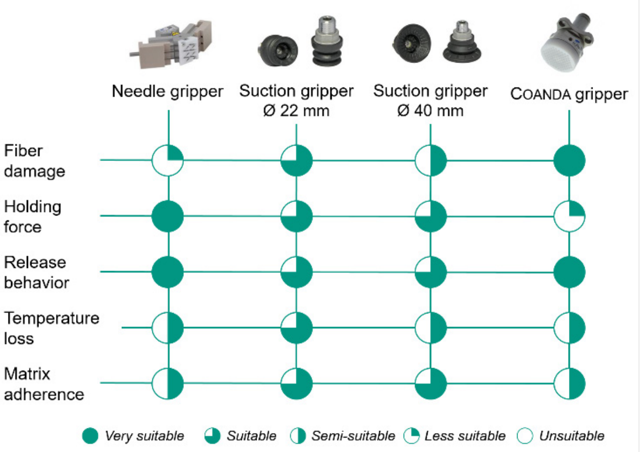


Fig. 2 Matrix for gripper selection with investigated criteria

4.2. Kinematic design

For the design of the kinematics of the gripping-system fulfilling the preforming, the required draping movement of the tape laminates have been determined from the three-dimensional CAD model of the part and the mold. In order to form the laminate from its initial two-dimensional geometry to the three-dimensional contour of the mold the movements depicted in Fig. 3 are required. The curvature of the tape patch at the door sill is realized by a combined movement of different magnitude of the cross beam patches and the outer parts of the door sill patch in positive and negative y-direction. Additionally the cross beam patches have to be moved in the z-direction.

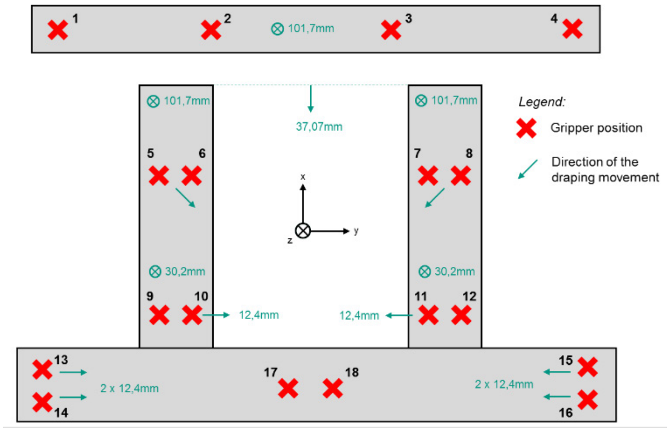


Fig. 3 Geometry and required movement of the tape laminates

Based on the required draping movements a concept for the kinematics of the grippers has been derived. For the preforming quality it is crucial no tension is applied to the tape laminates by the movements. In addition, the directions of the individual draping movements were taken into account in order to be able to combine movements in the same direction if possible.

In the developed concept, the desired draping movement is divided into two sections: First, two intermediate levels, to which the further kinematics are attached, are moved inwards by 12.4 mm in the y-direction with two pneumatic cylinders. The pneumatic cylinders installed on the intermediate level then move the gripping points 13 to 16 (compare Fig.) inward by a further 12.4 mm. This completes the movement in the y-direction. At the same time, pneumatic cylinders, to which the gripping points 5 to 12 are attached, perform a movement in the z direction of 30.2 mm. The movement of 71.5 mm in the z-direction and 37.5 mm in the x-direction from gripping points 5 to 8 by 71.5 mm and 37.5 mm respectively happens passively by gravity after the patch has been deposited. A sketch of the concept is shown in Fig. 4. The deposition of the tunnel patch in z-direction is carried out by additional pneumatic cylinders not displayed in Fig. 4 for reasons of clarity.

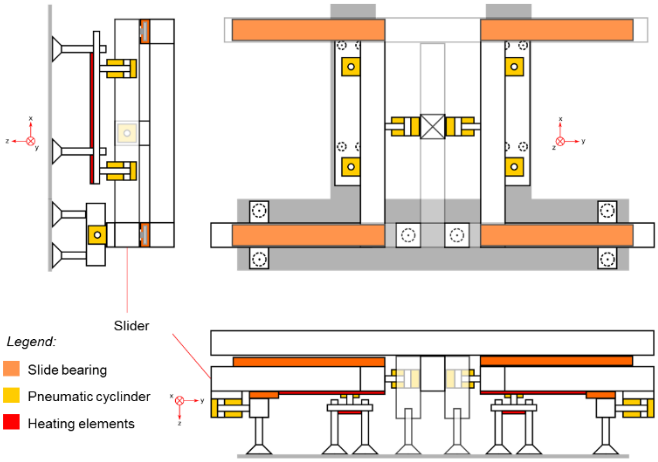


Fig. 4 Kinematic design of gripping-system

4.3. Dimensioning and selection of infrared heaters

In the first instance, the heat losses of the tape laminates are calculated in order to estimate the required power of the infrared radiators for maintaining the temperature. Then an estimation of the losses occurring during irradiation is made to determine the required electrical power of the infrared radiators.

For the calculation of the heat losses it is assumed that the heat dissipation of the laminates is limited to heat radiation and convection. Heat losses due to heat conduction via the contact surface between the laminates and the gripper are neglected. In addition, the geometry of the laminate is converted into a simpler, horizontal plane surface of the same surface size in order to simplify the calculation. Furthermore, it is assumed that the laminates are taken over from the upstream infrared heating field at a temperature of 250°C.

The thermal losses emitted by radiation $\dot{Q}_r$ are calculated using equation 1 and the values in Table 1. It is assumed a stationary state and that the laminates are located in an infinitely large white room at room temperature (20°C), so that no irradiation takes place.

$$\dot{Q}_r = \varepsilon * \sigma * A * (T_l - T_a) \tag{1}$$

For the calculation of the thermal losses $\dot{Q}_c$ by convection with equation (2), a maximum heat loss due to forced convection by a horizontal movement of the robot with a velocity *w* of 1.5 m/s is assumed.

$$\dot{Q}_c = \alpha * (T_l - T_a) \tag{2}$$

The heat transfer coefficient α is calculated by equation (3) based on the values in Table 1 with physical values taken from [16] and the Nusselt number Nu with equation (4) and (5).

$$\alpha = \frac{Nu * \lambda}{L} = 7.61 \; \frac{W}{m^2 K} \tag{3}$$

$$Nu = 0.664 * Re^{1/2} * Pr^{1/3} \tag{4}$$

$$Re = \frac{w * L}{\nu} \tag{5}$$

Table 1 Parameters and values for calculation of thermal losses

Parameter	Variable	Value	Unit
Emission coefficient	ε	0.8	-
S. Boltzmann constant	σ	$5.67 \cdot 10^{-8}$	$W/(m^2 \cdot K^4)$
Kinematic viscosity	ν	$280.1 \cdot 10^{-7}$	m²/s
Thermal conductivity	λ	$34.34 \cdot 10^{-3}$	W/(m•K)
Prandtl number	Pr	0.669	-
Characteristic length	L	0.5	m
Laminate surface	A	0.294	m²
Laminate temperature	T_l	523.15	K
Ambient temperature	T_a	293.15	K

The heat loss by the laminates heated to 250°C is shown in Table 2, taking into account the simplifications shown. To maintain this temperature during the handling process, the IR emitters must deliver this power to the laminates.

Table 2 Results of heat loss calculation

Tape designation	No. of tapes	Required power [W]
Center tunnel	1	300
Cross beam	2	237
Door sill	1	649

Based on the dimensioning of the required heating power and the infrared emitters available on the market to cover the geometry, four infrared round tube emitters with 1000 watts and a length of 430 mm have been chosen. Two of them are positioned along the door sill patch and one along each of the cross beam patches. An additional twin-tube infrared emitter with a nominal power of 3600 watts is placed over the gripping position of the tunnel patch. The IR emitters can be controlled with a PID controller to adjust their power. Fig. 5 shows the gripping-system with activated infrared emitters and a heated laminate.

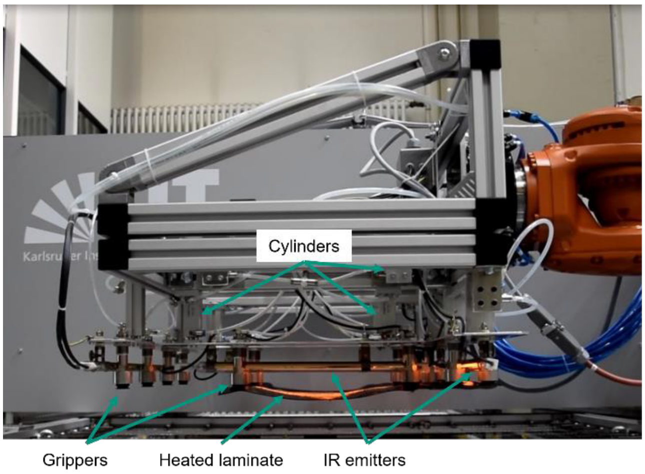


Fig. 5 Gripping-system during handling test with laminate and activated infrared emitters

5. Evaluation of thermal behavior during handling

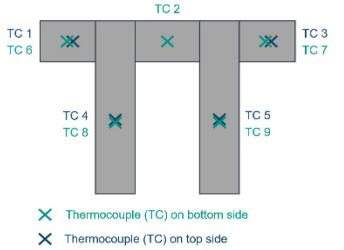
To investigate the thermal behavior of the tape laminate several experiments have been conducted to validate the advantages of the handling integrated heating.

5.1. Experimental approach

For the acquisition of the temperature during heating and handling, the tape laminate no. 1 has been fitted with five thermocouples on the upper side and four thermocouples on the lower side (cf. Fig. 6) which have been fixed to the tape surface with a polyimide film. These type K thermocouple have a deviation of ±2.5°C. Preliminary investigations with an IR camera showed a temperature distribution within a range of 5°C. During the experiments the laminate is heated from both sides in a temperature-controlled infrared oven to different preset temperatures well above the melting point of polyamide (~220°C) and subsequent holding at the preset temperature for 30 s. After exiting the oven, which takes about 5 s, the laminate is picked by the gripping system.

The first test series involves heating the tape laminate in an infrared oven and subsequent transport at the gripper without heating by the built-in IR emitters. The aim is to determine the target temperature of the IR oven necessary to ensure a temperature level above the melting temperature after the transfer to the mold. In order to achieve the melting temperature of 220°C after handling, which is required for forming, the four different target temperature levels 250, 275, 300 and 325°C are set on the IR oven.

In the second and third test series, the tape laminate has first been heated in the IR oven with a target temperature of 250°C and 275°C respectively. Then they are picked by the gripping system with the IR emitters set to four different power levels to maintain the heat. The power levels indicate the used power in % of the maximum power of 4000 watts of the four round tube emitters placed above the gripping points for tape laminate no. 1. The parameters for the three test series are shown in Fig. 6.



Parameters for investigation of thermal behavior

Test series	Preset temperature of IR oven [°C]	Power level of IR emitters [%]
#1	250, 275, 300, 325	-
#2	250	40, 50, 60, 70
#3	275	40, 50, 60, 70

Fig. 6 Position of the thermocouples on the laminate and parameters of test series

5.2. Results of investigation of thermal behavior

The temperature measurement during heating in the infrared oven shows an asymptotic increase of the temperature to the target temperature and the almost constant holding phase for 30 s. Fig. 7 shows the temperature profiles as mean of all thermocouples for test series #1 without heating during handling. When exiting the IR oven the laminates cool down at the gripping-system. The possible handling time from the start of the handling to the laminate dropping below the melting temperature is 7 s, 19 s, 23 s and 32 s for the different preset temperature ranging from 250°C to 325°C.

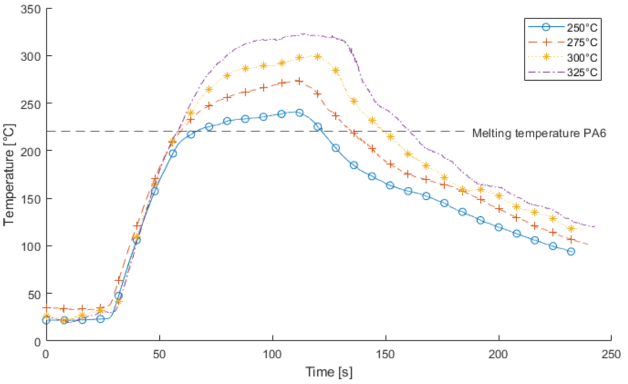
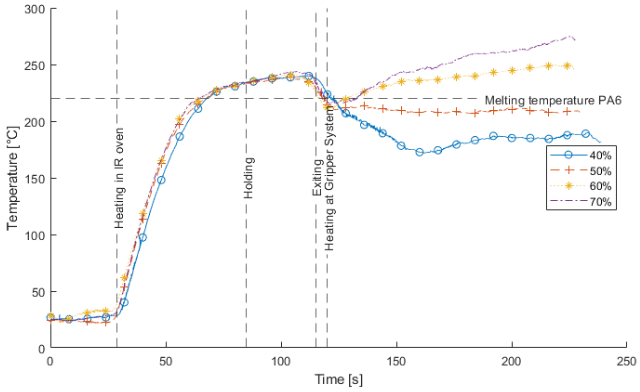


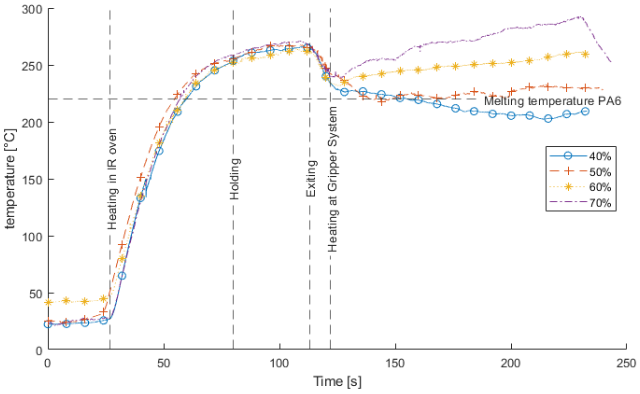
Fig. 7 Temperature profiles for heating in infrared oven to different target temperatures and subsequent handling without heating (test series #1)

Fig. 8 shows the temperature profiles for test series #2 and #3 with heating to a target temperature of 250°C resp. 275°C and subsequent heating by the infrared emitters on the gripping-system with different power levels. In all four experiments of series #2 (Fig. (a)) the temperature drops below the melting temperature of the matrix polymer before the start of the heating at the gripping-system. The infrared emitters compensate the heat loss during handling at a power level of 50 % to maintain a constant temperature. With power levels above 60 % the temperature of the laminate increases again over the melting temperature.

At a target temperature of 275°C additional heating during handling at a power level of 40 % extends the handling time to 38 s which is significantly longer than without handling-integrated heating (cf Fig. 8 (b)). As in test series #2 heating at 50 % is sufficient to maintain the temperature at a constant level.



(a)



(b)

Fig. 8 Temperature profiles for heating in infrared oven to 250°C (a) and 275°C (b) with subsequent handling-integrated heating

The experiments show that a power level of 50 %, which corresponds to 2000 watts, is required for the compensation of the heat loss during handling. Compared to the calculated heat loss of 1137 watts this is significantly higher due to beam angle of the round tube infrared emitters not focusing the available power only on the surface of the laminates and their starting behavior.

6. Evaluation of handling-integrated preforming

6.1. Experimental approach

For the evaluation of the repeatability of the handling-integrated preforming five test laminates no. 1 have been heated and preformed at the gripping-system. Based on the results of the thermal behavior investigation, the tapes were first heated in the infrared oven to a target temperature of 275

°C with a holding time of 30 seconds and subsequent heating at a power level of 60 % at the gripper.

The acquisition of the geometry of the preformed tape laminates was done with a laser scanning arm of the company FARO (Lake Mary, USA). For the scans the laminates were placed at an identical position on a table and treated with a developer agent to enhance surface details for the scan head. The acquired geometry information was processed with the software Geomagic Qualify 12. First the point cloud of a measurement was reduced to 25 % with curvature priority to improve data handling efficiency but maintain accuracy in the deformed regions. After suppressing noisy points of the cloud, the point data was converted to polygon objects to allow further operations like filling of missing regions.

After preprocessing of the scan data of all five laminates, the repeatability was evaluated by overlaying the scan data. For the evaluation of the deviation of the different laminates a 3D comparison was carried out with the software. Therefore the software projects the geometry data of one laminate onto the surface of the second laminate and displays the deviation in color on the reference object (cf Fig. 9). To evaluate the repeatability every laminate has been compared to all others.

6.2. Results of preforming investigation

Fig. 9 exemplifies the deviation of two of the investigated laminates as result of the 3D comparison. The deviation in the region of the most complex geometry changes with the double curvature along the door sill patch is around ± 1.5 mm. The maximum deviation can be detected in the region of the cross beam patches where the laminate sags due to the big distance between gripping points 5/6 and 9/10, resp. 7/8 and 11/12 (cf. Fig.). The differences can be attributed to a different sag behavior of the laminates. The differences in this area can be neglected for the further processing of the tape as it is placed on a flat surface inside the compression mold.

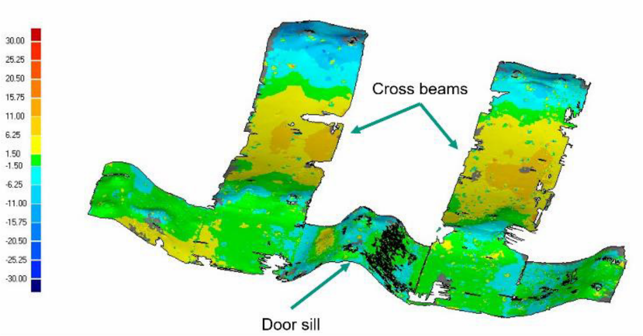


Fig. 9 Deviation of two laminates preformed during handling

7. Summary and outlook

The paper addresses the lack of gripping solutions for the handling of thermoplastic laminates integrating preforming and heating to compensate temperature loss. The temperature loss of the heated laminates has been calculated analytically and the handling-integrated heating validated experimentally. The results show that the handling time can be enhanced significantly allowing lower temperatures for the initial heating in the infrared oven. At lower heating temperatures the matrix materials is less prone to degradation of mechanical properties.

The evaluation of the preforming shows a good repeatability of the obtained geometry, which is suitable for further processing. Further investigation have to be performed on possible defects like deconsolidation or fiber wrinkling induced during the preforming step.

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References

[1] Fleischer, J., Teti, R., Lanza, G., Mativenga, P. et al., 2018. Composite materials parts manufacturing 67, p. 603.
[2] Fantoni, G., Santochi, M., Dini, G., Tracht, K. et al., 2014. Grasping devices and methods in automated production processes 63, p. 679.
[3] Seliger, G., Szimmat, F., Niemeier, J., Stephan, J., 2003. Automated Handling of Non-Rigid Parts 52, p. 21.
[4] Fleischer, J., Ochs, A., Förster, F., 2013. Gripping Technology for Carbon Fibre Material, in CIRP International Conference on Competitive Manufacturing, Universität Stellenbosch, Stellenbosch, 65-71.
[5] Brecher, C., Emonts, M., Ozolin, B., Schares, R., 2013. Handling of Preforms and Prepregs for Mass Production of Composites, in International Conference on Composite Materials 2013: (ICCM-19); Montreal, Quebec, Canada, 28 July - 2 August 2013, Curran, Red Hook, NY.
[6] Ehinger, C., Reinhart, G., 2014. Robot-based automation system for the flexible preforming of single-layer cut-outs in composite industry 8, p. 559.
[7] Löchte, C., Kunz, H., Schnurr, R., Langhorst, S. et al., 2014. Form-Flexible Handling and Joining Technology (FormHand) for the Forming and Assembly of Limp Materials 23, p. 206.
[8] Förster, F., Ballier, F., Coutandin, S., Defranceski, A. et al., 2017. Manufacturing of Textile Preforms with an Intelligent Draping and Gripping System 66, p. 39.
[9] Bruns, C., Tielking, J.-C., Kuolt, H., Raatz, A., 2018. Modelling and Evaluating the Heat Transfer of Molten Thermoplastic Fabrics in Automated Handling Processes 76, p. 79.
[10] Bruns, C., Raatz, A., 2017. Simultaneous Grasping and Heating Technology for Automated Handling and Preforming of Continuous Fiber Reinforced Thermoplastics 66, p. 119.
[11] Behrens, B.-A., Raatz, A., Hübner, S., Bonk, C. et al., 2017. Automated Stamp Forming of Continuous Fiber Reinforced Thermoplastics for Complex Shell Geometries 66, p. 113.
[12] Rietmann, G., Boxus, E., Muhammad, K.S., Verghese, N., 2016. Manufacturing Solutions for Hybrid Overmolded Thermoplastic UD Composites, in Proceedings of SPE Automotive Composites Conference & Exhibition.
[13] Löhler, G., Ochs, A., Schneider, M., 2009. Automatisieurng in der Leichtbauproduktion: Handhabung heißer, biegeschlaffer Verstärkungseinleger zur Herstellung von FKV-Bauteilen 99, p. 615.
[14] Kühnel, M., Schuster, A., Buchheim, A., Gerngroß, T. et al., 2014. Automated near-net-shape preforming of carbon fiber reinforced thermoplastics (CFRTP), in I.C.S. Conference Journal, Paris.
[15] AG, A., 2015. MAI qfast Abschlussbericht für alle Projektpartner Berichtszeitraum: 01.11.2012-30.04.2015. [Audi AG], Neckarsulm.
[16] N.N., 2013. VDI-Wärmeatlas. Springer Berlin Heidelberg, Berlin, Heidelberg.