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Simultaneous Grasping and Heating Technology for Automated Handling and Preforming of Continuous Fiber Reinforced Thermoplastics

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Abstract

Nowadays large-scale production systems for lightweight car-bodies made of composite materials become increasingly important. Especially, the use of thermoplastic matrix materials makes these composites worthwhile for large quantities. However, these so-called organo-sheets must be heated above melting temperature before manufacturing. In this state, the composite becomes form unstable, which complicates the handling in an automated process. To simplify the handling, this paper presents an approach, which allows the handling, heating and preforming of organo-sheets. This includes the introduction of a robot-tool, which is composed of heatable vortex-grippers and a folding mechanism, as well as a analysis of its automation potential.

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Keywords: robot; gripper; organo sheet; thermoforming; preform; woven fiber

1. Introduction

Modern lightweight design of car bodies in automotive industry and the increasing product varieties lead to suitable manufacturing and handling systems for fiber composite materials. Especially the processing of thermoplastic continuous fiber reinforced plastics (hereafter referred to as organo sheet) poses major challenges for robot grippers as well as production technologies. A completely heated flat organo sheet must have been processed within approximately ten seconds after heating. If this time is exceeded, the manufacturing could result in fiber failures and destruction of the polymer matrix during the forming process. The idea of producing a preform, as is the case with dry fibers, is hardly possible due to this short processing time. However, current developments in processing techniques focus on near-net shaping and over-all manufacturing costs [1]. For this reason, existing forming technologies, which were originally developed for metal forming, were transferred to composite materials in order to achieve higher quantities. Among other manufacturing processes, thermoforming is one of the frequently used stamp forming technologies for the manufacture of thermoplastic organo sheet components. During thermoforming, the thermoplastic matrix of the composite must initially be melted in a heating technique to accomplish a deformation of the flat fabric. The formability of organo sheet into given geometries depends strongly on the type of fiber reinforcement [1,2]. Since corners and edges with small radius on the stamp forming tool causes wrinkles or local fiber failures on the composite, high requirements on a process adapted material-feeding-system are necessary. For this reason, a simple robot gripper can barely handle this task. It is necessary to implement an active draping support into the gripper system. In a general production process, on the one hand, the entire organo sheet can be heated e.g. within an infra-red-radiator for preforming. On the other hand temperature elevation can be realized only in areas where large fiber deflection is required. A practicable approach which also maintains form-stability could be to partially heat the organo sheet only in those areas. Thereby, less energy for temperature elevation for the preform step is needed. Another advantage is the simplified transportation of the solid preform from a preform station to the actual stamp forming step. By the means of a purposeful preforming of organo sheet, a folding before thermoforming could avoid large fiber deflection while forming and therefore lead to a minimization of fiber wrinkling. In this paper, a function-integrated robot gripper to fold woven organo sheet in a preform process is presented. Since the handling and heating of thermoplastic fabrics are separate processes in a sequence, this gripper combines these two processes into a combined one using vortex levitation. The gripping principle of a vortex nozzle is a pneumatic non-contacting handling approach that uses a swirling air flow. This is similar to the Bernoulli-effect which shows a decrease in pressure, if air flows along an edge with high speed. If the flowing air gets heated by a special air heater, an organo sheet can be preformed at melting temperature easily.

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2. State of the Art

2.1. Thermoplast preforming

Many investigations regarding the drapeability of different dry fiber and prepreg fabrics started in the last few years [1]-[4]. Rozant et al.[1] and Mohammed et. al.[3] analysed different dry textile fabrics for stampable thermoplastic preforms. Therefore, tensile and sheer properties of woven fabrics at various fiber-orientations and the locking angle (Trellis effect) were determined. Drapeablity tests were performed in order to detect the necessary forming energy and the maximum sheer-deformation to predict the wrinkling of the fiber fabric after reaching its locking angle. As a result, Rozant et al. show that the deformation energy of woven fabrics is significantly higher than of knitted fabrics [1]. The maximum strain at different fiber orientations is thereby lower using woven fabrics. For this reason knitted fabrics can be draped in more complex geometries. Additionally, Mohammed et. al. studied four types of woven fabrics and presented different drapeability in terms of wrinkling as well [3]. The fabrics were draped over a hemispherical dome whereby it was shown that the use of tight plane weave provides the worst results compared to satin and a twill weave. Another interesting aspect are different material properties by manufacturing dry or fully impregnated fabrics. Chen et. al. [4] indicate that the applied deformation-force depends on the deformation-speed and the shear angle of the fabric itself. While dry textiles need less forming energy and according to this a lower forming force, pre impregnated fibers (prepregs) such as organo sheets require high environmental temperature for softening the polymer matrix. Related to this, Chen et. al. analysed a carbon woven fabric and Polyphenylene Sulfin matrix with a melting point at 280 °C [4]. It could be observed when the impregnated fiber was sheared, that more force would have to be applied compared to dry fiber preforming. However, an increase of the temperature gives weak influence to the sheer behaviour.

In summary, woven fabrics are highly prone to wrinkling and the forming energy even increases with the use of prepregs. In addition, there is a rapid cooling after a previous heating, which makes handling more difficult. A possible solution is to heat the composite partially and to form it only in areas where high fiber deflection is desired. This would also preserve shape stability of the organo sheet and thus facilitate handling. A worthwhile approach in order to combine a pick up operation and partial temperature elevation is the use of vortex levitation. The difference to conventional handling tasks e.g. wafer manufacturing, where vortex grippers are used is hot instead of cold air to lift up the work piece.

2.2. Vortex levitation

Using vortex levitation to grasp and lift work pieces originally comes from e.g. wafer and food handling. In both cases a contact with the work piece must be avoided to protect the touch sensitive surface or to prevent the work piece from being contaminated. Xin et. al.[7] analysed the potential of a vortex gripper for a wafer pick and place process. Therefore, a work piece placed under a vortex nozzle, as shown in figure 1, can be picked up and held in an equilibrium position. The reason is, the lifting force depends on the gab thickness h between the vortex nozzle and the work piece at a fixed air flow rate. Inside this narrow gab, the lifting force decreases if the work piece moves from the equilibrium position in direction of the vortex nozzle and increases if the work piece deviates away.

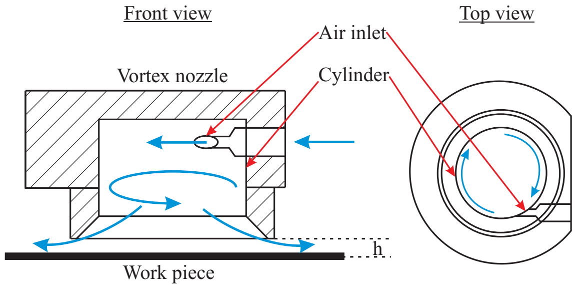

Fig. 1. Design of the vortex nozzle

According to the dimensions of the nozzle, a maximum gripping force of approximately $0.55N$ was detected with an air flow rate of $24.2 \cdot 10^{-5} m^3/s$. However, there are many other approaches to realize vortex levitation in a handling scenario [5]-[10]. Wu et al. [9,10] analysed a similar vortex nozzle with a diversion body. Contrary to [7,8] the conical tapering diversion body in the center of the nozzle causes a decrease of flow velocity in the middle and an increase in the outer areas of the gripper. As a result, the gripping force was slightly increased. Another approach presents Xin et al. [8] with the introduction of a non contact gripper using swirl vanes. The gripper mainly consist of a motor and a set of blades, that take air in and causes it to swirl inside a chamber. Therefore, the centrifugal force pulls the air from the center to the edge of the gripper and creates negative pressure underneath. Since moving parts produce negative pressure as a rotating system using swirl vanes, the seals or bearings of the gripper could be damaged by high air temperatures.

In summary, a hot air stream flowing through a vortex gripper can perform both a vacuum to lift the work pieces as well as the heating of the organo sheet. Compared to the swirl vane or a conventional Bernoulli-gripper, a vortex gripper has certain advantages like no moving parts or seals. The cup-shaped and entirely aluminium-made body of the nozzle provides good resistance against high temperatures.

Vortex levitation in conjunction with hot air can be a worthwhile approach for the preforming of organo sheet. The next section introduces the mechanical design of a robot gripper for picking up and preforming a flat organo sheet in a fully automated process. During the handling operation, the organo sheet is partially softened in order to fold it onto a die.

3. Mechanism and Design

In a conventional thermoforming process, the form-stable handling of a fully heated, flexible fabric as well as the cooling rate after the heating process are challenging in terms of limp material behaviour and the low sheet thickness. Therefore the main aspect is to develop a robot mounted handling system which fulfills the mentioned challenges sufficiently. After picking up the organo sheet, it is important to maintain form stability in order to achieve a near net shape preform of the flat composite on a certain preform tool. Using a simple handling technology without any draping functionalities for given geometries also causes wrinkles on the fabric during the stamp forming step. This effect often appears in areas with large deflections in locations with e.g. double curvatures of the woven fiber. After finishing the preforming step the robot performs the transfer into the stamp forming tool. In a subsequent heating step directly inside the tool a moveable heating technique melts the preform before the tool shuts and forms the final contour. Subsequently, a potential combination of a vortex gripper including a folding mechanism to preform organo sheet efficiently is introduced.

3.1. Experimental setup

The test setup for the function-integrated vortex gripper consists of an air-flow controller with an included flowsensor, two downstreamed air-heater and three rows of vortex nozzles (see figure 2). The air supply delivers an adjustable pressure of 10^{-5} to $6{\cdot}10^{-5}\,Pa$. Depending on the desired negative pressure underneath the vortex nozzle it is necessary to adjust the air pressure as well as the air flow via the controller. To minimize temperature losses both air-heaters are mounted to the gripper with macor ceramics for insulation. However, only the vortex nozzles in the middle row of the gripper are temperature-controlled, due to the temperature elevation only in the bending area of the composite. The nozzles placed in the left and right rows are essential for handling stability [5,6]. Otherwise the organo sheet starts to tilt or vibrate through the air flow within the handling process. In this case, neglecting these additional nozzles can interfere a secure handling and a fast heating.

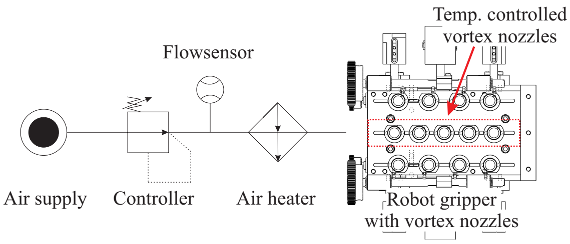

Fig. 2. Air-supply and heat circuit

3.2. Gripper mechanism

The mechanical structure of the gripper is shown in figure 3 on the left and presents the folding kinematic consisting of two electric motors with gears. To each gear a shaft with an arm for folding the organo sheet is attached. At the end of each arm a pivotable plate is mounted, which presses the composite against the die. However, before the air flows out of the vortex nozzles, it is passed through two air-heater which are fixed to the gripper with temperature insulating material (figure 3 right). These two heater are connected with metal pipes to the central row of vortex nozzles. The adjustable temperature on the controller has a range from ambient temperature to $T = 750\,°C$. Since a vortex-nozzle cannot transmit any transient forces, a mechanical stop at each corner of the fabric is required to keep it in position.

The actual preforming process is realized by the folding tool when the gripper is positioned above the die by the robot. In this case, the tool folds the partially heated organo sheet over a 90° die with a radius of 14mm (figure 4). While forming, the robot

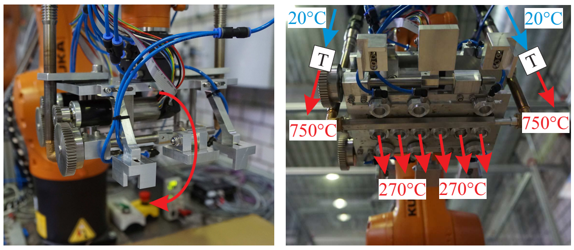

Fig. 3. Fold-mechanism and temperature controlled vortex nozzles

does not move at all. The folding onto the die is accomplished by the motors inside the gripper. However, other folding angles rotated along different axes with different amounts are also possible to preform other shaped parts by adjusting the gripper construction. Therefore the manufacturing of three dimensional shaped preforms within one handling step is provided. It would be conceivable for e.g. tub-shaped casings or wavy shapes. The bending radius can also be set by adjusting the radius of the die. However, this compared to the folding angle has no great influence on the quality of the folding edge in terms of fiber-wrinkling.
In general the preforming is divided into four sub-processes:

- the grasping of organo sheet from a material supply station,
- the transportation and simultaneous heating of the material,
- the actual forming by the folding mechanism on a die
- and the cooling phase

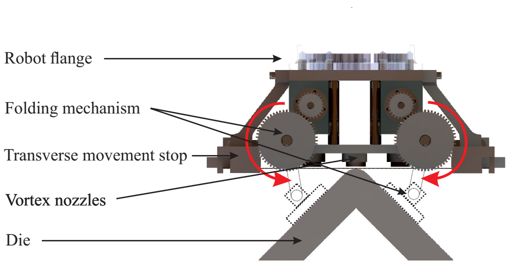

Fig. 4. Front view and functionality of the gripper mechanism

To improve the production of a composite and thereby the material flow, the preform can subsequently be inserted into a stamp forming machine and brought into its final shape. Within this process, the preform is placed in the forming-tool by an industrial robot and afterwards brought to processing temperature with e.g. an infra-red (IR) radiator. When the processing temperature is reached, the IR emitter moves out of position to initialize the stamp forming process.

4. Experimental Results

Important parameters for a secure preforming are the lifting force due to vortex levitation and the temperature distribution inside the thermoplastic polymer matrix of the woven fabric. For an efficient process, the time which is needed to elevate the fabric to processing temperature is relevant as well. The experimental results presented in this section based on an organo sheet with a thickness of $1mm$ and two layers of woven glass fiber impregnated with a Polyamid 6 (PA6) matrix.

4.1. Lifting force

For the acquisition of the gripping force at different air-flows as a function of the distance h of the vortex nozzles to the flat fabric is measured. The gripper is mounted on an adjustable support and a laser distance sensor is attached to the gripper, to measure the distance between the fabric and the vortex nozzles. The fabric has the outer dimensions of $150mmx250mm$ and is mounted on a force sensor, whereby the gripping force (pulling force) of the vortex gripper can be measured. The indicated characteristics of the gripper, like its maximum force at different flow rates, shows figure 5. The figure illustrates a non-linear characteristic, where the obtained gripping force first increases with a high gradient until the maximum. After the maximum, the composite is too close to the vortex nozzles, so the gripping force drops if the gap becomes smaller. On the other side a gab larger than $0.4mm$ causes a decreasing force as well. The reason is a slower air flow due to a lower flow resistance because of a larger gab. For example, with an air flow of about $33.3 \cdot 10^{-4} m^3/s$ the gripper is able to hold a work piece of about $750g$ in equilibrium position underneath the vortex nozzles. As a result, the gab-distance h of $0.4mm$ will be adjusted to the work piece automatically regarding the gripping-force characteristics and force maximum in figure 5.

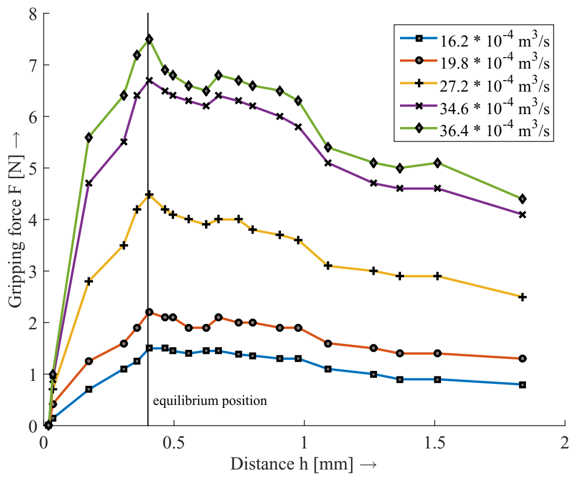

Fig. 5. Gripping-force-characteristics at different air flows

In order to determine the minimum necessary force to pick up and handle a fabric, the air flow is reduced until a secure gripping of the work pieces is no longer possible. The test scenario to measure the minimal lifting force involves the grasping from a material storage using maximum lift up velocity by the robot at $2m/s$. This movement is particularly critical since the vertical acceleration on the flat fabric causes the greatest air resistance opposite to the lifting direction. In this case, a minimal air flow of $15 \cdot 10^{-4} m^3/s$ is necessary to pick and lift up and an air flow of $16.6 \cdot 10^{-4} m^3/s$ to handle and manipulate the given work piece . This means, if the air flow drops below $16.6 \cdot 10^{-4} m^3/s$, it cannot be ensured that the work piece does not fall off the gripper.

4.2. Temperature distribution

Another important factor is the temperature distribution inside the gripped composite. For this purpose, the organo sheet was analysed thermographically. During the heating, the temperature of the surface of the organo sheet opposite to the vortex nozzles is observed. Figure 7 shows the thermogram to the corresponding diagram in figure 6.

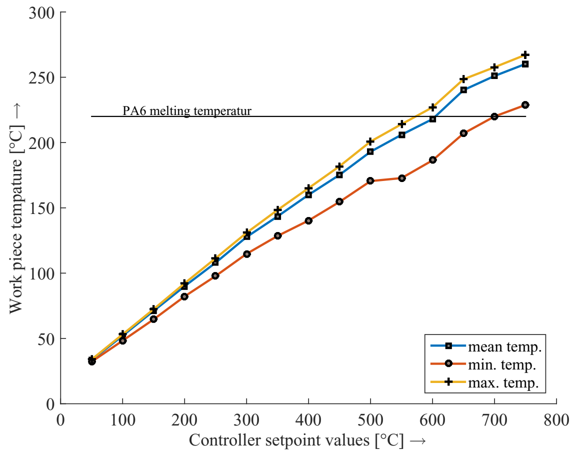

Fig. 6. Stationary characteristic of the temperature distribution

Figure 6 shows the stationary characteristics of the mean, minimal and maximal temperature of the bending zone. It shows the reached temperature of the work piece by a fixed controller temperature setting. Hereby, the mean temperature in the relevant controller setting range of 650 − 750 °C occurs with a deviation to the minimum measured temperature of 31 °C and to the maximum of 7 °C. Since the used material is an organo sheet with a Polyamid 6 matrix with a melting point at 220 °C, a temperature setting of about 650 − 750 °C is necessary to achieve a homogeneous softening of the material.

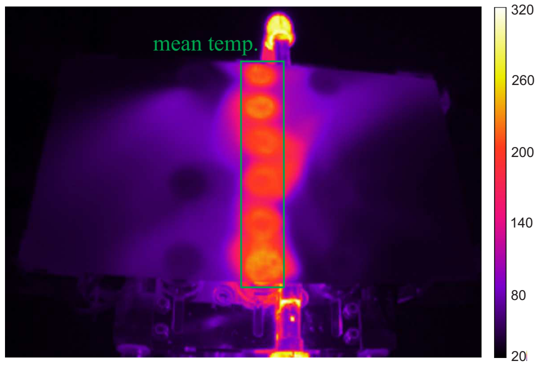

Fig. 7. Temperature distribution of the gripping area

4.3. Partial temperature elevation

For a successful implementation of this process it is evident that the melting temperature is reached only with a setting of at least 700 °C. However it takes about 70 seconds to reach 220 °C at a controller adjustment of 700 °C and about 63 seconds at 750 °C. Since there is no intermediate step of transporting, as is with conventional thermoforming processes with prior warming, there is no phase of cooling before the actual stamp forming. This is an advantage compared to other applications, since the material does not have to be heated higher than necessary to compensate the cooling. A lower heating performance has a material-saving effect as well. However, using the highest temperature setting of the heater of 750 °C in figure 8, an approximately stationary temperature distribution of the entire bending zone occurs after approximately 60 – 70 seconds. By optimizing the air heater system, for example by using shorter pipes, better insulation and less air circulations the efficiency of the system like saving energy and achieving higher temperatures can be improved.

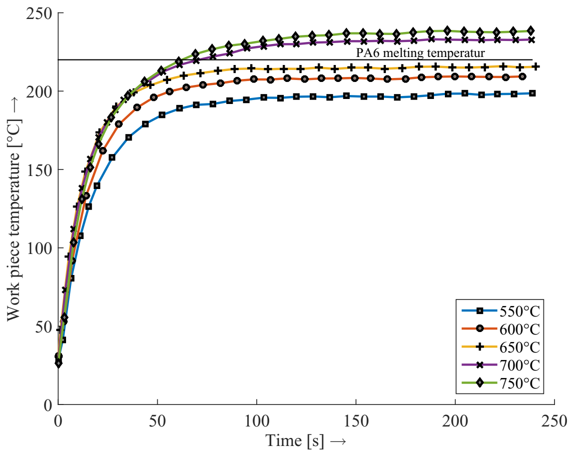

Fig. 8. Temperature profile of the gripping area

Other heating technologies can perform a faster temperature elevation. Nevertheless, for the use of a conventional IR radiator, the robot must perform an insert and remove operation before the composite can be placed inside the forming machine. This requires an additional pick and place operation. In this case, temperature elevation using circulating hot air takes longer in comparison to other heating methods, such as contact heating or IR radiation. The process of heating up during transportation can be shortened by integrating a prior continuous heating station by means of IR radiators. In this case, the organo sheet in a continuous heating station is brought to a temperature near matrix melting temperature. In addition, the organo sheet will be heated only locally at the bending zone through the gripper. Therefore, the composite must only be brought to processing temperature locally, during the transportation.

As one result, figure 9 shows the bottom side of the reshaped composite. In this case, as an example the angular deviations are shown at four different points in the 3D-Scan. The desired 90 ° angle of the die is reached only at one edge of the preform. These deviations can be compensated by adjusting the gripper positioning and / or an adaptation of the folding kinematics. This can be done, e.g. by increasing the contact surface of the forming kinematics transversely with respect to the composite. The wrinkling in figure 9 is also clearly visible, which in this sample has a maximum height of two millimetres.

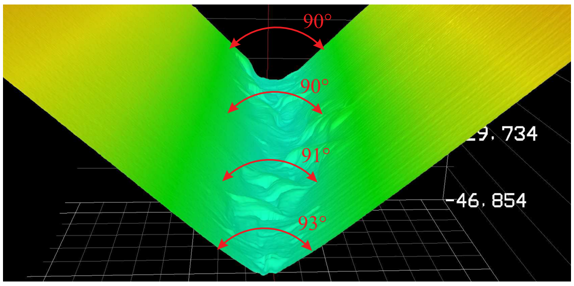

Fig. 9. 3D-scan of the bottom side of the folded preform

A sufficient manufacturing of lightweight components for modern car design was thus demonstrated on basis of the listed results. The fiber wrinkling in figure 9 on the bottom side of the bending zone is challenging in terms of a successful stamp forming. However, by heating the entire surface of the preform, inner stresses of the organo sheet are minimized due to the liquid polymer matrix. After shutting the tool, a smooth surface of the component can be expected. At least, it is necessary to identify process limits if a preforming failed with for example fiber failures.

4.4. Process limitation

In general, the folded preform is heated for 70 seconds to ensure an over all softening of the polymer matrix in order to achieve the desired 90 ° angle. Here, a cooling time of 40 seconds is set to prevent a rebounding of the woven fibers on the die. In this case, the duration of a controlled cooling and reheating of the air that streams out of the vortex nozzles is longer. Therefore, the heat must be dissipated through the die. By installing e.g. an active water cooling of the die, this time might be shortened. However, if the composite is heated too short or too long, material damage may occur. Specific limitations are important for an implementation into an industrial process and have to be taken into account for a successful production, respectively. For some samples, a wrinkling of the fiber rovings occur of the bottom side of the bending edge. This is more or less distinguishable depending on the heating time and temperature. Correspondingly, the fibers on the upper side of the bending edge (figure 10, left) are stretched. This is affected by the local heating. Due to a interlayer sliding of the stacked woven fabrics cannot occur and the additional strong deformation of the preform result in these effects (figure 10, right). In a further study, it has to be investigated if these wrinkling and fiber stretching affects a stamp forming negatively.

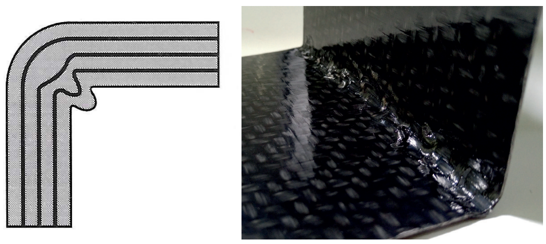

Fig. 10. Folded organo sheet (70 sec. heating, 40 sec. cooling)

To allow the sliding of intermediate layers, at least one half of the organo sheet must be heated entirely from the bending zone to one edge. This corresponds to the sliding width. However, before thermoforming, it is necessary to meld the entire polymer matrix and therefore a high pressure stamp forming can undo the fiber wrinkling of the preform. Other composites defects are worse and have to be avoided. Starting from a heating time of 40 seconds, which corresponds to a mean temperature of the bending zone of 200 °C, fiber cracks (figure 11, left) occur at the outer folding edge. This happens because the matrix material is not completely melted and the fibers cannot move sufficiently. By a further homogenization of the temperature inside the bending zone, the appearance of fiber cracks can be minimized, since this effect happens first at the coldest points between the nozzles. As a result, a shorter process time can be realized. However, a further homogenization of the temperature would be possible by means of a new nozzle design, for example by reducing the distance between the vortex nozzles.

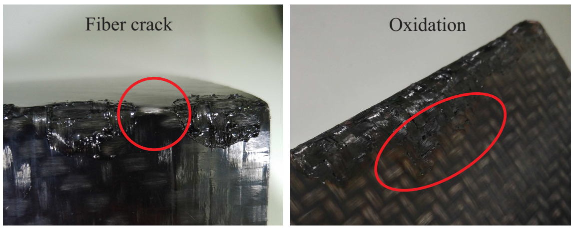

Fig. 11. Fiber failures (left: fiber cracks, right: matrix oxidation)

Nevertheless, a too long heating time or a too high composite temperature can weaken the organo sheet by oxidation. This effect decreases the mechanical properties of the polymer matrix and has to be avoided. Figure 11 on the right shows an example of discoloration of a preform. The illustrated organo sheet was heated at a set temperature of 750 °C for about 300 seconds. If a polymer is processed for a long time at high temperatures, the environmental oxygen reduces its strength.

5. Conclusion

After presenting an approach to design a function-integrated robot gripper for preforming organo sheet, this study analysed the automation potential for the integration into an industrial stamp forming process. Using vortex levitation the investigations on simultaneous grasping and heating have shown that a handling of locally heated, limp organo sheet is well suited. The idea to combine existing vortex nozzles [7,8] with air heaters enables new possibilities to preform composites. On the one hand, the lifting force of the vortex nozzles act directly on the form-unstable, locally heated areas and thus prevents the organic sheet from being deflected. On the other hand, it was shown that the material is not damaged by the non-contacting gripper, as is by using e.g. needle gripper. At a controller temperature of the air heaters of 750 °C a minimum heating time of 63 seconds could be observed. For the realization of a shorter processing time a prior heating of the entire organo sheet to a temperature below melting temperature would be sensible. As mentioned, a heating only by convection takes a correspondingly long time in contrast to other heating methods. Nevertheless, the successful preforming of the desired bending angle of 90 ° was shown. The subsequent positioning of the preform into a stamp forming machine is simplified, since the preform is heated entirely direct inside the forming tool after releasing from the gripper.

The gripper technology presented in this paper is also capable to pick and preform thinner or thicker organo sheets. In case of a thicker composite with more than to layers, on the one hand it might be necessary to include more vortex nozzles into the gripper system, since the weight of the work piece increases above the mentioned 750g. On the other hand, the temperature elevation time increases as well, since the provided air heaters can only heat a specific amount of air regarding their fixed diameter and air pressure. Another possibility is the usage of more or larger heater to accelerate the heating process to a faster level.

The quality of a finished component after stamp forming has to be investigated in a further study. With the presented preform process, simple geometries can be produced in serial production, as is necessary for e.g. a folding process of an organo sheet for a car body. In order to optimize the process, an external prior heating step before folding as well as a faster cooling by means of an actively cooled die could provide more improvements.

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