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Heated gripper concept to optimize heat transfer of fiber-reinforced-thermoplastics in automated thermoforming processes

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Abstract

Today composite materials become increasingly more common to use for lightweight applications. This paper introduces a simulation approach for a handling and forming process. This process focusses on the robot based gripping, handling and forming of continuous-fiber-reinforced-thermoplastics, such as organo-sheet. The results of this paper show a manufacturing study of the heat transfer of a temperature-elevated organo-sheet during handling using heated needlegripper. Beside the fabric deformation, this research focuses on the temperature distribution during forming. Fast temperature drops lead to an increasing stiffness of the thermoplastic. Therefore, it is necessary to consider changing material parameters due to the temperature change.

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Keywords: organo-sheet, finte-element-analysis, heat transfer, forming, robot gripper

1. Introduction

Fabric-reinforced thermoplastic composites have aroused great interest in recent years due to their faster and therefore more cost-effective processing, good storage properties and better recyclability compared to thermoset composites [1]. Textiles pre-impregnated with thermoplastic resins can be heated above polymer matrix melting temperature with infrared radiators (IR) and formed into a three-dimensional (3D) geometries within seconds, which poses significantly shorter cycle times than in autoclave processing or the resin transfer molding (RTM) [2]. Advanced manufacturing techniques such as tape placement [3] are also facilitated by the welding feasibility of the thermoplastic matrix. Therefore, improved performance, shorter cycle times and low density have made fully impregnated woven glass thermoplastic composites (hereafter referred as to: organo-sheet) attractive to automotive industries. However, the low heat capacity causes the thin organo-sheet to cool down quickly after heating. The advantage of rapid heating of the organo-sheet within seconds is therefore disadvantageous for large and very thin component geometries. Once the melting temperature is reached, the thermoplastic recrystallizes, causing it to solidify and thereby reducing the formability. For this reason, an automated handling of the organo-sheet combined with a fast forming process in which heat transfer is kept to a minimum is essential.

The main objective of this paper is to characterize the influence of heated gripping technology on the cooling rate and temperature of a glass-fiber polyamide composite material. Due to the viscous nature of the thermoplastic matrix, stresses in the material depend on the load rate [4]. A precise constitutive description should consider this fact. In addition, the temperature dependence should be classified, since the temperature distribution in the component may not be uniform during forming. Very low forming speeds can lead to a fast heat transfer, which alters the mechanical behavior e.g. increasing the stiffness of the material. For a holistic view on automated manufacturing of complex shell geometries made of organo-sheets a powerful simulation model is essential for a proper process design. Finite element analysis

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is used to evaluate the process design in order to minimize heat transfer and the formation of wrinkles in the component.

2. Thermoforming of fiber reinforced thermoplastics

2.1 Stamp forming

Fiber-reinforced thermoplastics can be formed under elevated thermal conditions. The recommended forming temperature according to the manufacturer is approximately 40°C above melting temperature and below the decomposition temperature of the respective thermoplastic matrix material. Restraining forces to avoid wrinkling of the organo-sheet can be applied by using heated blank holder systems [5] or locally installed grippers [4]. At the end of the forming step the material has to be re-consolidated under pressure. After cooling in the mold, the finished part can be removed. An inhomogeneous temperature distribution during the forming and the consolidation step can influence the dimensional stability [6].

2.2 Forming simulation

The structure of the organo-sheet consists in general of a thermoplastic matrix and a glass fiber fabric. Both constituents affect the overall forming behavior.

A simulation model for analyzing the draping of a double dome geometry has been set up in [2]. The fibers are modelled as truss elements and the matrix has been modelled with help of membrane elements. The authors have concluded that the temperature evolution during the forming process has to be taken into account. Additionally the influence on the mechanical field has to be modelled for a precise simulation of the forming process. In [4] the authors couple the temperature field and the mechanical field in order to consider the physical interaction. The organo-sheet is discretized with shell elements and an explicit dynamic approach has been applied for time integration.

A material model for modelling fiber reinforced thermoplastic sheets is implemented in the simulation code LS-Dyna for explicit integration. The material model MAT_249 of LS-Dyna was applied in [7], [8] and [12] for modelling reinforced thermoplastic sheet materials. It incorporates the influence of the fabric and the thermoplastic matrix. In [8] the material model was used in order to simulate an organo-sheet in a draping process. The mechanical as well as the thermal field were coupled and it could be shown that the strong stiffness differences between the matrix and the fibers lead to numerical problems regarding element deformation. In order to reduce the strong element deformations and to enhance the numerical stability, the matrix stiffness was artificially increased. The obtained results were in good accordance with the experimental results.

2.3 Automated handling

In order to achieve the required cycle times mentioned above, the dimensionally stable handling of the heated and formally unstable organo-sheet is an important aspect. Therefore, quite complex gripper systems based on needlegripper, suctiongripper and clampgripper have been developed and were successfully used in many fields of composite handling [9]. To avoid fiber failures and wrinkles in the formed part, end-effector systems with preform functionalities to enable larger forming degrees enable further improvements in production. Reinhard et. al. [10] introduced a barrel-shaped preforming end-effector. This end-effector works with vacuum and has an elastic drape element. This gripper provides good shape stability, but has poor properties when it comes to temperature insulation. Particularly the direct contact of the organo-sheet with the robot gripper leads to a fast cooling in the gripping area. This can lead to misalignments in the later formed part in these areas. For this reason, we developed heatable needle grippers together with project partners from the industry. In [11] we demonstrated that with a nonmoving needlegripper heated to 170°C, the time to reach the melting temperature could be extended by 18 seconds compared to an unheated needlegripper.

3. Experimental setup and numerical concept

The experimental setup in Figure 1 shows the simplified handling scenario, which is the subject of these investigations. In the beginning, the organo-sheet is placed into an IR-radiator by the robot and heated to processing temperature of 280°C. The robot removes the heated organo-sheet off the IR-radiator and moves it into a forming machine. During the handling, the temperature of the organo-sheet decreases on the trajectory from the IR-radiator to the forming machine due to the cold gripper and surrounding air. Due to the risk of fiber failure this preceding analysis focuses on the effects of the grippers on the forming behavior of the organic sheet. The objective is to determine a proper heating strategy for the needle grippers in order to prevent failure in the subsequent forming phase.

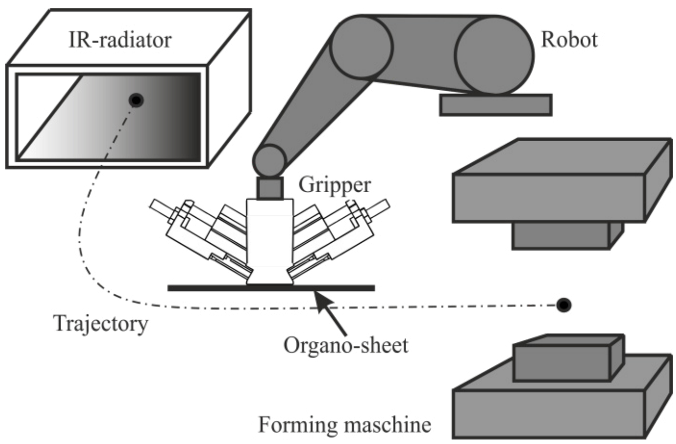

Fig. 1. Handling and manufacturing scenario of organo-sheet

3.1 Process steps for automated organo-sheet manufacturing

Behrens et al. [12] have demonstrated in preceding forming experiments that applying local restraining forces can induce local fiber shear and yarn straightening to draw surplus material out of a wrinkling area, such as the tunnel geometry of a battery tray.

Based on these forming experiments we developed a two-stage handling scenario to automate the forming process. This process begins with the pickup of the flat, trimmed organo-sheet off an infra-red radiator. A robot gripper consisting of 12 heatable needle grippers provides good shape stability and temperature insulation for the temperature-elevated organo-sheet (see Fig. 2). Eight needle grippers are arranged along the edges of the organo-sheet and four needle grippers are arranged in the middle to maintain the initial form. However, the process is particularly time crucial, since the organo-sheet thickness is just 1 mm, which favors rapid cooling. Therefore, when handling organo sheet, it is difficult to grip the entire surface of the blank. Either the organo sheet would cool down particularly quickly at low gripper temperatures or it could happen that the organo sheet adheres to the gripper at high gripper temperatures.

In the second stage, the robot-gripper places the limp organo-sheet into the ACS (active clamping system). The ACS is used to apply controlled forces to the fabric during the press forming process. By controlling the forces in magnitude and direction, we can actively influence the shear behavior of the fabric in order to prevent wrinkle formation, which will finally result in an improved product quality. To achieve a short processing time, the ACS drapes the organo-sheet directly on the lower forming tool (Fig. 3).

The ACS, in this configuration, has four clamping units to fix the organo-sheet in a rectangular frame. The first step in Figure 3 consists of the clamping (i) of the fabric by the four clamping units after taking over from the gripper. The second step before press forming is the fabric draping (ii). Disadvantageously, the clamps and the forming tool, like the needle grippers, cannot be heated to the thermoplastic melting temperature, as otherwise the organo sheet will adhere to the clamps or the tool. In the next section, the process related challenges are derived in order to address the focus of this paper with regard to thermal optimal handling processes.

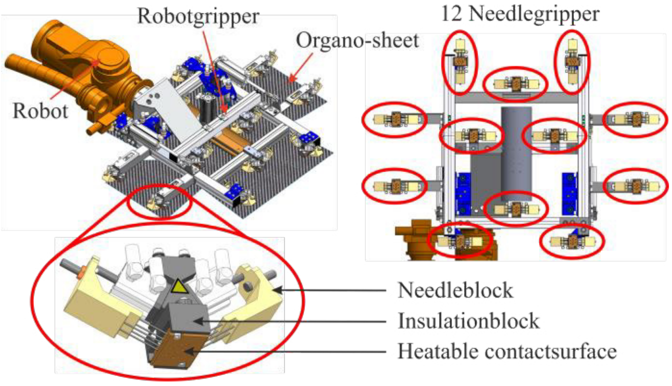

Fig. 2. Robot gripper with 12 heated needlegrippers arranged to the corresponding crosscut geometry of the organo-sheet

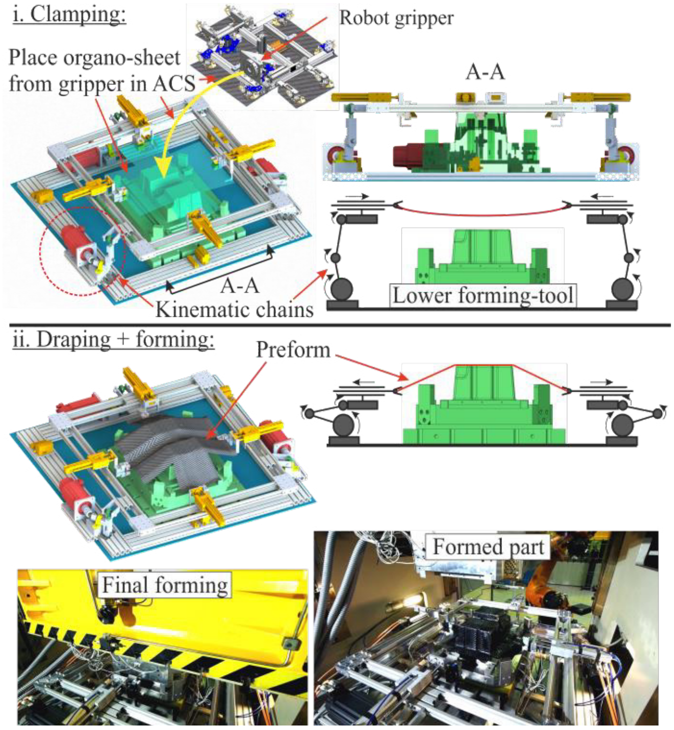

Fig. 3. ACS with four clamping units, the process steps and the final part with the use case geometry of a battery tray

3.2 Challenges in handling of hot and limp organo-sheets

In [11] the heat transfer behavior of different commonly used robot grippers were analyzed. Due to the permeability of organo-sheets, suction pads have proven to be poor, as the thermoplastic cools down quickly due to the suction of cold air through the fabric. Needlegrippers, however, are disadvantageous in terms of perforating the organo-sheet with cold metal needles. Therefore, the J. Schmalz GmbH developed a needlegripper, which can be heated to a certain temperature in the gripper contact area. Figure 4 shows a comparison of an unheated and a heated (170°C) needle gripper with 10 needles and a picked organo-sheet.

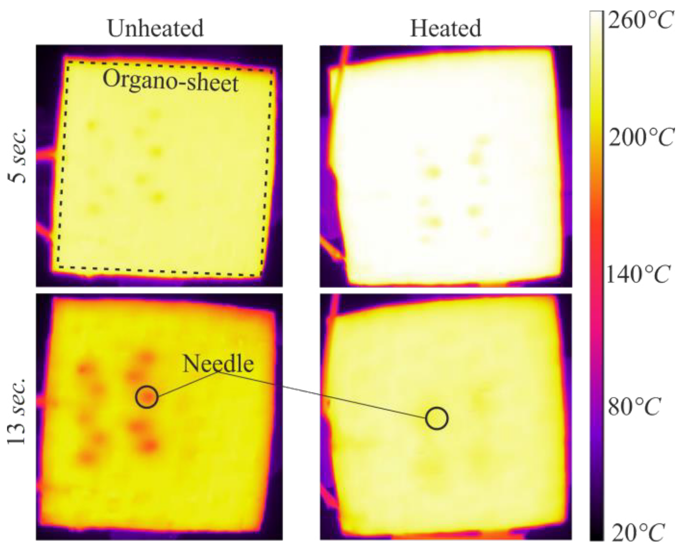

Fig. 4. Thermographic images of organo-sheets, left: unheated needlegripper, right: heated needlegripper (170°C)

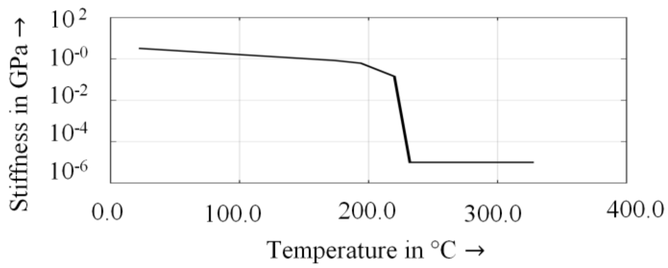

Fig. 5. Stiffness of the thermoplastic depending on the temperature

After 13 seconds of cooling, the cold needles become clearly visible compared to the heated needles. The resulting problem is the already solidified polymer matrix in the cold needles' regions. If these areas have to form small radii in the subsequent forming process, material damage may occur, due to strong stiffness gradients induced by the temperature difference between the gripped area and the surrounding organo-sheet.

Figure 5 illustrates the stiffness of thermoplastic matrix. The stiffness of the thermoplastic matrix decreases considerably when the melting temperature is reached. In the subsequent temperature range, the forming is optimal. If the temperature in the process drops locally below the melting point, a steep increase in stiffness occurs. For that reason, it is essential to identify an optimal gripper temperature to the corresponding handling time. Since the gripper covers only small areas of the organo-sheet, the majority of the organo-sheet cools by means of convection and radiation at the surrounding atmosphere.

In order to demonstrate the different cooling rates in these two areas, Figure 6 shows the temperature profiles at the five process phases (I-V). In the first phase, the organo-sheet is heated to processing temperature (in this case 290°C). The organo-sheet is then removed from the IR radiator by the robot gripper and fed to the forming machine (phase II). Inside the forming machine, the organo-sheet is placed in the ACS in phase III. At this point, the organo-sheet has already cooled down to approx. T_{diff}= 255°C. Since the forming tool is closed during forming, there is no temperature measurement at the forming phase IV. The temperature can only be measured after the mold has been opened again (phase V). The forming tool is heated to 110°C, which confirms the residual heat of approx. 120°C in the organo-sheet after tool opening.

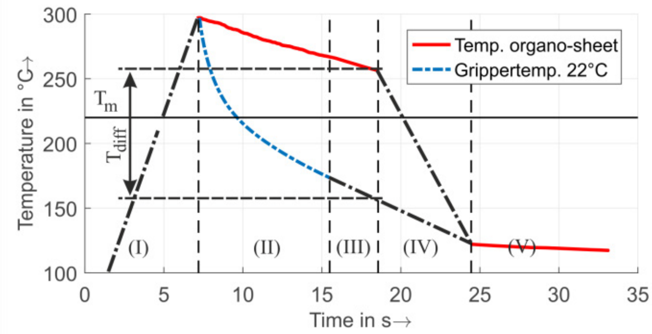

Fig. 6. Cooling rates of organo-sheets (red) at atmosphere and with unheated needlegripper 22°C (blue)

However, if the areas in which handling took place (phase II) are considered, it can be observed that the temperature has dropped to 180°C. Since the melting temperature of polyamide is T_m = 220°C, it can be assumed that forming difficulties in those areas can be expected.

In order to analyze the heat transfer during forming we employ a finite element model to analyze the temperature distribution during the forming process. In particular, it is to be investigated whether the areas, in which the gripping took place, are located in component areas with a critical forming history.

3.3 FE model of the forming process

In order to analyze the forming history of the gripped spots the forming phase is simulated. The model of the forming process is shown in Figure 7. It comprises the upper as well as the lower tool and the organo-sheet, which is positioned between both tool units.

The clamping and connection to the ACS is modeled by stiff regions, which are subjected to a downwards movement w and pulling forces F_1 and F_2.

The corresponding translation of the tool and the ACS are shown in Figure 8. The forming tool starts to close as the ACS has finished the preforming after 1 second.

The geometries are discretized by shell elements. In order to model the mechanical behavior of the organo-sheet the material model MAT_249 of LS-Dyna is used. The material parameters for the matrix and the fabric are numerically

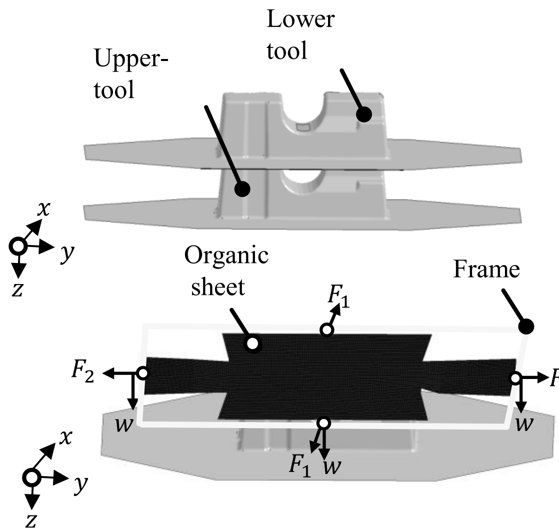

Fig. 7. Simulation model of the draping and forming process in Figure 3

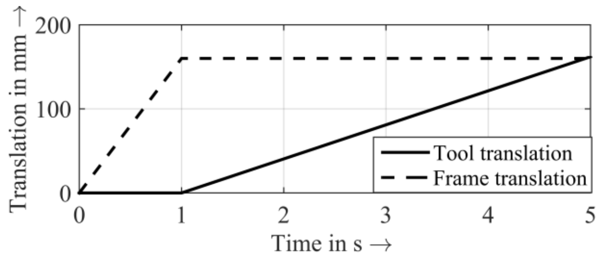

Fig. 8. Tool and frame translation as in the process in Figure 3

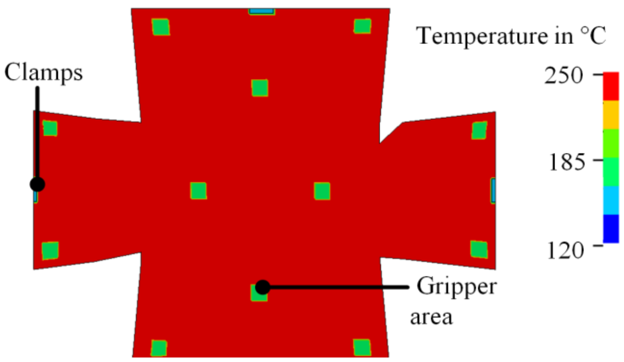

Fig. 9. Initial temperature distribution of the organo-sheet. The cool areas were in contact with the grippers during the handling phase

defined on basis of experimental results in [8]. The model takes into account the temperature-dependent stiffness shown in Figure 5. Instead of artificially increasing the matrix stiffness as performed in [8] the model is numerically enhanced to withstand the strong element deformations.

For the thermal analysis, an isotropic material model is applied. An explicit solver is used for the time integration. The process time of five seconds is scaled down to 0.1s to avoid large simulation times. The focus of the analysis is put on the temperature field and therefore, the influence of the inertia on the forming result is neglected. The energy balance is scaled by the factor 50 to properly map the heat flow.

The initial temperature distribution is shown in Figure 9. The start temperature of the organo-sheet is 250 °C, which corresponds to the temperature in Figure 6. In the areas that have been subjected to the grippers during the transport phase an initial temperature of 180 °C is applied.

4. Heat transfer of organo-sheet in automated forming processes

4.1 Temperature field during forming using cold needlegrippers during handling

At the beginning, the ACS drapes the organo-sheet over the lower tool. The temperature in the contact regions starts to decrease immediately. Figure 10 shows the temperature distribution before tool closure. A steep temperature gradient in the gripper contact areas can be observed. The temperature of the cooled areas is below the melting point and a preliminary consolidation can be expected.

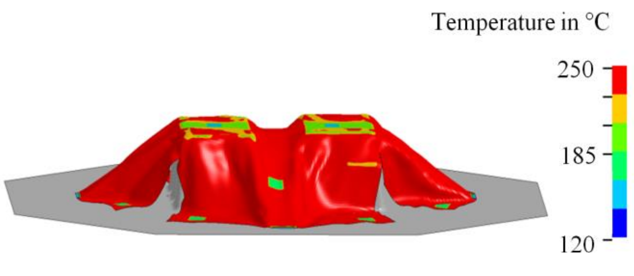

Fig. 10. Temperature distribution after the organic sheet is draped over the lower forming tool

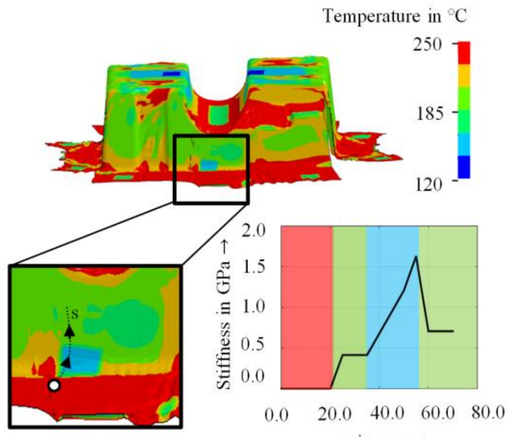

Fig. 11. Temperature at the end of the forming process. The cooled area is moved to the edge and is bent

The tool closes and the temperature in the contact regions decreases. Meanwhile the organo-sheet slides over the lower tool and a strong inhomogeneous temperature distribution arises. The cool regions on top of the tool are dragged into the tunnel region and undergo bending.

The influence of the grippers on the temperature field can be observed in Figure 11. One grip spot, which cooled down during the handling phase moves into the edge area and is bent accommodating the edge curvature. The cooling can lead to a preliminary solidification of the matrix, which increases the matrix stiffness and inhibits a further deformation. In the worst case fiber failure can be the consequence.
The aim of obtaining the most homogeneous temperature distribution possible is now achieved by heating the needle grippers. In the following section, the cooling behavior in the handling phase is examined with different gripper temperatures.

4.2 Heat transfer during handling using elevated needlegripper temperatures

The heatable needlegripper system presented in chapter 3 consists of a hot cartridge and a thermocouple embedded in the gripper contact surface. An integrated temperature controller is used to set and control the desired temperature. However, the heat transfer from the organo-sheet into the gripper, like the heat transfer into the forming tool (Fig. 10 and 11) depends on the chosen material combinations. Therefore, it is necessary to determine the cooling rates for different gripper temperatures. The aim is to set the temperature so that the gripping areas have at least the same temperature as the areas, which are subjected to the air environment. The fabric layer dependent heat exchange model presented in [11] is applied to identify the respective gripper temperatures (see Fig. 12). In this case, four gripper temperatures are used to determine the organo-sheet's temperature decrease. Three temperature profiles show possible cooling scenarios if elevated temperature grippers are

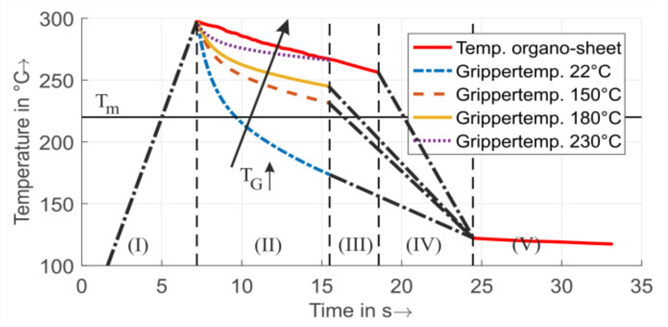

Fig. 12. Temperature profiles with four different gripper temperatures during handling

used. The temperature profile of the unheated gripper (22°C gripper temperature) serves as reference. An increase in the gripper temperature T_G results in a smaller temperature gradient and thus leads to a minor heat loss of the respective organo-sheet areas.

On basis of these results, it can be concluded that at a gripper temperature of approx. 230 °C a cooling of the organo-sheet areas can be reduced.

4.3 Temperature field during forming using temperature elevated grippers during handling

In order to reduce the risk of fiber failure the needle grippers are heated to 230°C. In the simulation model a homogenous start temperature is defined and the process is simulated again.

The respective result is shown in Figure 13. It can be observed that the main temperature distribution is similar to the temperature distribution shown in Figure 11 except for the gripper regions. Here, the temperature is higher. With regard to the cold spots obsevered in Figure 11, the risk of fiber failure can be minimized using heated gripper.

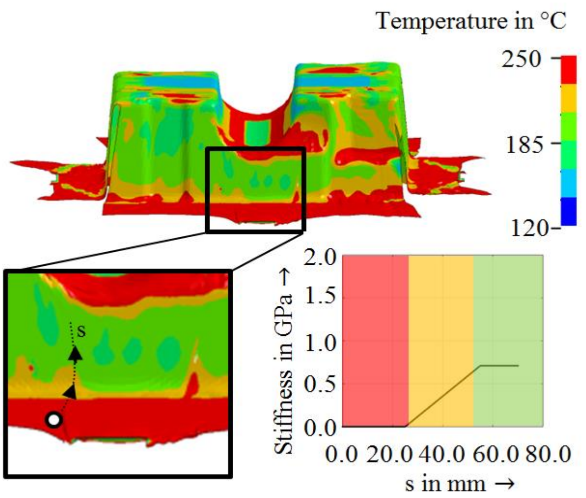

Fig. 13. Temperature distribution of the organo-sheet at the end of the forming process, in case of a homogenous start temperature

5. Conclusion

The lack of automated process designs and powerful simulation models is currently a major challenge for the production of complex organo-sheet components. This paper deals with the development of a process design for the large-scale production of organo-sheets by automated gripping, handling and forming. The objective of this contribution is to investigate the performance of heated needlegrippers to improve product quality. Therefore, a sophisticated thermal analysis has been performed in order to show the effects of applying unheated grippers on the risk of fiber failure during forming. A suitable temperature was determined with help of a thermal model describing the temperature evolution in the gripped areas during handling phase. The temperature decrease could be reduced using a gripper temperature close to the thermoplastic melting temperature.

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