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Modelling and Evaluating the Heat Transfer of Molten Thermoplastic Fabrics in Automated Handling Processes

Christopher Bruns[a,*], Jan-Christoph Tielking[a], Harald Kuolt[b], Annika Raatz[a]

[a]*Leibniz Univerität Hannover, Institute of Assembly Technology, An Universität 2, Garbsen 30823, Germany*
[b]*J. Schmalz GmbH, Johannes-Schmalz-Str. 1, Glatten 72293, Germany*

* Corresponding author. Tel.: +49-511-762-18247; fax: +49-511-762-18251. *E-mail address:* bruns@match.uni-hannover.de

Abstract

Modern manufacturing processes for lightweight parts and products have to face new challenges regarding the changed material properties. For instance, one of the upcoming new lightweight materials, which focusses on a large scale production, is the so called organo-sheet. An Organo-sheet is a continuous fiber reinforced thermoplastic which has to be processed above melting temperature. At this temperature, the organo-sheet loses its stiffness and changes into a limp state. In this state, it is possible to form the flat organo-sheet into three dimensional shapes. However, the heat transfer to the environment, such as the air, the forming-tool or the robot gripper, causes a fast cooling. To identify the thermal properties, this paper focuses on the analysis and characterisation of common robot grippers for handling heated organo-sheets in fully automated manufacturing processes. The paper presents the results of handling experiments using conventional suction-, needle- and clampgripper as well as a heated needlegripper. In addition, a heat transfer modelling approach is introduced.

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Keywords: robot gripper; handling; organo-sheet; heat transfer

1. Introduction

Nowadays the increasing importance of developing new products and processes for automotive lightweight design leads to new challenges regarding automated manufacturing. Beside modern lightweight metal materials, fiber reinforced thermoplastics (hereafter referred as to: organo-sheets) are used to build structural parts, such as bumper bars and car body attachment parts. However, organo-sheets in the current production are mainly restricted to applications in aerospace, sports cars or the high-price segment. The reason for manufacturing only small quantities is situated in the different manufacturing of organo-sheet, e.g. automated handling and stamp forming compared to sheet metal [1]. Therefore, suitable processes for large scale manufacturing which can be adapted to existing plant technologies are required to enable the usage of organo-sheets for a larger variety of products. In general, the handling process of organo-sheet consists of a tempering step, the subsequent gripping and handling, followed by the forming. Essential for a successful manufacture, however, is a sufficient processing temperature. As a result, two main challenging aspects which restrain automated handling and forming of organo-sheets are high temperatures and rapid cooling which occur as fiber failures and wrinkles inside the finished part [2]. Important for a successful forming on the one hand is the initial temperature elevation to processing temperature depending on the melting point of the used composite. On the other hand, the gripper design and the associated temperature insulation determine whether a component can be formed without imperfections. In this case, the used thermoplastic polyamide 6 (PA6) in this paper, changes from a rigid into a limp and deformable state above $220°C$. Therefore, it is essential in handling processes to remove the composite from an infra-red (IR) radiator at processing temperature (e.g. $260°C$) and to maintain temperature until forming. Since the entire process must be finished before reaching the melting point, temperature insulation within handling is to be identified. For this reason, this paper examines the potential of standard and heated grippers for large scale processes.

2. Robot gripper for handling non rigid materials

For a holistic view on automated large scale suited organo-sheet manufacturing, automated handling processes must be considered, since the forming of heated organo-sheet is time crucial. However, industrial handling processes require the gripping, followed by the handling and positioning step and end with releasing the composite inside the forming machine. By means of a rigid and form-stable object, conventional robot grippers have proved to be successful for industrial applications

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[3]. However, a dimensionally stable and temperature sensitive gripping, handling and releasing of limp and hot materials is still challenging [3–5].

Since the importance of handling non rigid materials increases, gripper technologies especially for handling dry fiber fabrics with additional preforming functionalities have experienced great interest in industrial production [6,7]. Nevertheless, disadvantageous in the processing of dry fibres is an additional step for impregnating though. The RTM-process for impregnating dry fibers is time consuming and therefore less suitable for large scale production. Therefore, dry fibres are increasingly replaced by fully impregnated semi-finished products such as organo-sheets.

In order to develop automated handling processes of organo-sheets, a selection of suitable standard grippers is carried out. According to the physical principle grippers can be divided into form fit, force fit and material closure. Form fit grippers are e.g. grippers with flexible fingers, needle- and velcro grippers. Clampgrippers and suctiongrippers, as well as Bernoulli- and magneticgrippers operate according to force fit. Grippers that pick a part by molecular forces, such as adhesive tapes, glue mediums or freezing mediums, are typically used for objects which are less sensitive to heat transfer. In terms of organo-sheet handling, frequently used conventional grippers are needle-, suction- and clamping grippers [4]. Fig. 1 shows a comparison of the grippers with respect to the material and gripper criteria.

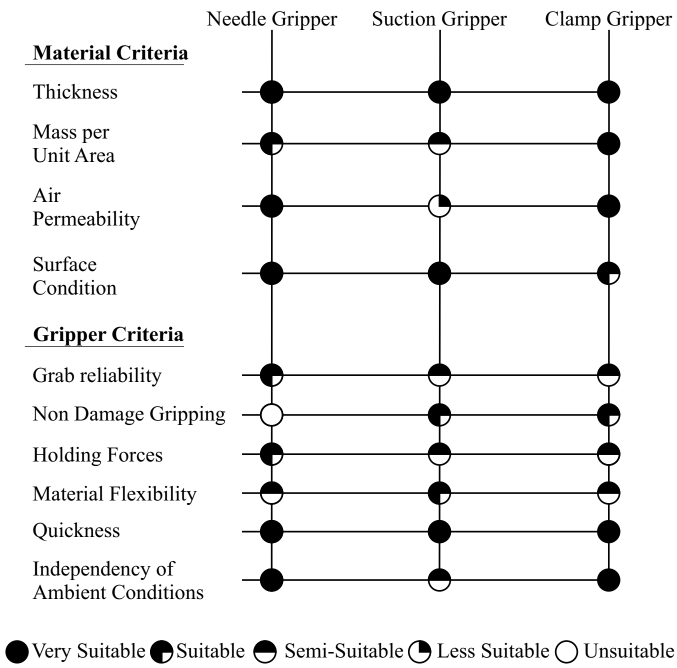

Fig. 1: Gripper selection matrix with the corresponding material and gripper criteria, adapted from [4]

Needlegrippers are capable to lift thick and heavy components even with poor surface conditions. However, there is always damage to the fabric as the needles perforate the material. Suction pads, on the other hand, do not penetrate and thus do not damage the material as fabrics are gripped by vacuum. Since there is just force fit due to low pressure, heavy objects or permeable surfaces makes a secure fit and handling difficult. For handling flat fabrics, there is also a possibility to pick it sideways [10]. Clampgrippers are suitable for this purpose. Depending on the stroke and design of the gripper jaws, handling large and thick parts is also possible. The load capacity of these grippers is sufficient even for large composites. Only the decrease of gripping force in terms of slippery surfaces with low adhesive friction aggravates a secure handling. Since these grippers have been used in many handling processes [3,4], this paper analyses weather these grippers are suitable for thermally sensitive handling processes. The experimental setup in Fig. 2 shows the simplified handling scenario to which the results of this study refer. At the beginning, the organo-sheet is placed into an IR-radiator by the robot and heated to processing temperature of $260°C$. The robot removes the heated organo-sheet and moves it into a forming machine. During this process, 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. In order to ensure that the organo-sheet is sufficiently tempered during forming, it is necessary to determine the cooling through convection, conduction and radiation.

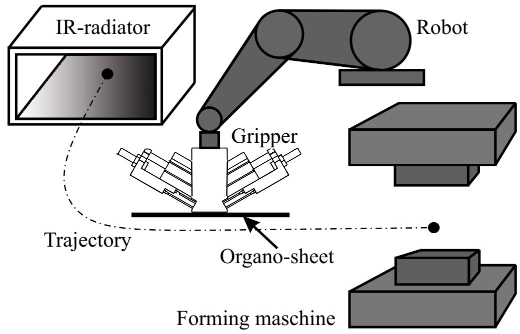

Fig. 2: Handling and processing scenario of organo-sheet for mass production applications

3. Heat transfer of conventional robot gripper

The experimental results will show whether conventional grippers are suitable for temperature crucial handling processes or not. In doing so, the focus is not the temperature resistance, but the thermal insulation to maintain the temperature of the organo-sheet. Additionally, a heat transfer model is introduced to predict the temperature decrease. Within the next sections, a comparison of two suction-gripper, two needle-gripper and four clamping jaw materials is carried out, with regard to the cooling rate of a three layer organo-sheet. Therefore, the experimental setup in Fig. 2 is used to identify the heat transfer. In order to minimize environmental effects, such as a heat transfer to the surrounding air, the organo-sheet is removed from the IR-radiator and positioned in front of a thermographic camera. Additionally, two thermocouples are placed between upper and lower layer to measure the temperature of the core layer inside and outside of the gripping area.

3.1. Modelling the heat transfer with temperature-dependent properties

In thermal systems, a regular interface implies that the heat loss by a system must pass integrally to another system. In thermodynamics, heat transfer in an isothermal process, which is limited by small gradients and large periods. Here, heat transfer by means of the heat-flux $\dot{Q} = \frac{dQ}{dt}$ describes the energy flow rate through an impermeable interface, see Eq. 1.

$$\dot{Q} \equiv \frac{dQ}{dt} = mc_v \frac{dT}{dt} \tag{1}$$

The heat flux depends on the mass m, the heat capacity c_v and the initial temperature T of the organo-sheet. In most heat-transfer problems, the inaccurate description of a system by a single average temperature can be improved using the heat-flux density $\dot{q} = \frac{d\dot{Q}}{dA}$. Now the heat transfer can be described through infinitesimal small volumes inside an organo sheet with a surface of A. The heat flux is related to the local temperature gradient or to the temperature difference between the system (temperature T) and the environment (temperature T_G), such as the gripper. When considering heat transfer, three modes, such as conduction, convection, and radiation are usually taken into account. The following models are used:

$$\text{Heat transfer } \dot{q}_i \begin{cases} \text{Convection:} \\ \dot{q}_c = \alpha(T - T_G) \\ \text{Radiation:} \\ \dot{q}_r = \epsilon\sigma(T^4 - T_G^4) \\ \text{Conduction:} \\ \dot{q}_\lambda = \lambda(T - T_G) \end{cases}$$

For simulating the heat transfer, thermal material properties, such as the thermal conductivity λ, the heat capacity c_v, the material density ρ and the heat emission coefficient ϵ must be taken into account. The following heat transfer model is to be considered as the energy balance for heat conduction through an infinitesimal non-moving volume. To describe the thermal effects of the system, the model (Eq. 2) is solved by using finite differences, according to the dimensions of the gripper and organo-sheet.

$$\rho c_v \frac{\partial T}{\partial t} - \nabla(\lambda \nabla T) = \sum_{i=0}^{N} \dot{q}_i \tag{2}$$

The thermal model, which describes the heat transfer from a heated organo-sheet (260°C) to the cold contact area of the gripper (25°C) is shown in Fig. 3. Here, a three layer composite model which includes heat transfer from layer to layer, to the environment and the gripper is used to predict the temperature loss inside the organo-sheet during handling.

The organo-sheet is modelled as a three layer fabric with a lower layer, a core layer and an upper layer. Depending on the used gripper, a contact with the upper layer (e.g. suction and needlegripper) or the lower and upper layer (e.g. clampgripper) is established. Therefore, each layer has a time and area depended temperature level and temperature distribution at the beginning inside the oven and at the end after releasing on the forming tool. Table 1 shows the material properties used for modelling the organo-sheet.

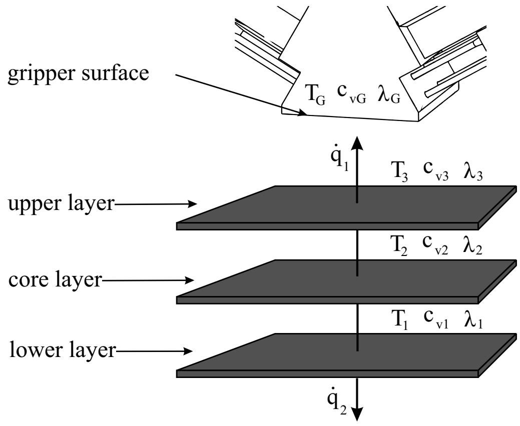

Fig. 3: Boundary conditions and discretization for heat transfer of a three layer organo-sheet

Table 1: Material properties of the used organo-sheet

Parameter	Variable	Value	Unit
Density	ρ	1814	kg/m^3
Heat capacity	c_v	1300	$J/(kgK)$
Coefficient conduction	λ	12	$W/(mK)$
Emission coefficient	ϵ	0.8	-
S. Boltzmann constant	σ	$5.67 \cdot e^{-8}$	$W/(m^2K^4)$
External temperature	T_G	25	$°C$

3.2. Suctiongripper

Due to the steadily increasing use of organo-sheet in production processes, the demand for high-temperature resistant suction pads is also increasing. Particularly, the sealing lip of a suction pad shall not melt and as a consequence deform plastically even at high temperatures (≥ 200°C). Otherwise, a secure gripping of organo-sheet is not possible and as a result the handling process can be interrupted. By means of heat transfer, another important parameter is the thermal insulation during handling.

Figure 4 shows the thermographic images of a silicon and a HT2 suction pad onto an organo-sheet which is heated to 260°C. After five seconds in contact with the gripper, there is no cooling down below melting temperature of both grippers. After 10s, however, the fabric temperature has dropped below the melting point. A subsequent forming is no longer possible. The temperature in the gripping center drops particularly strong. Since the laminate is a permeable woven-fibre-fabric, the gripper centre is cooled down by cold air streams through the fabric. Fig. 5 shows the corresponding temperature profiles for a duration of 20s. As already mentioned, two thermocouple measurements in ($TC\ gripper_i$) and next to ($TC\ exterior_i$) the gripping area and three thermographic images outside ($Cam\ exterior_i$) and inside ($Cam\ gripper_i$) the gripping area and in the gripper center ($Cam\ center_i$) are illustrated. For instance, compared to the HT2-gripper, the silicon-gripper drops below 220°C after 8s ($Cam\ center_1$) instead of

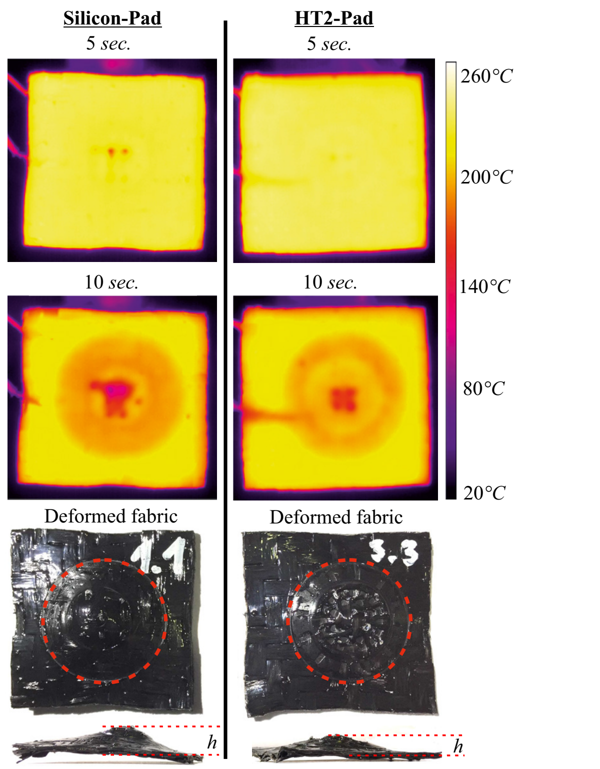

Fig. 4: Thermografic images of an organo-sheet with standard silicon and HT2 suction pads and fabric deformation after releasing off the gripper

10s (*Cam center*$_2$). As a result of the test series, a dent with a height of h occur in all fabrics (Fig. 4, bottom), depending on the geometry of the gripper. Due to the forming process, the deformations can lead to damage in the subsequent component.

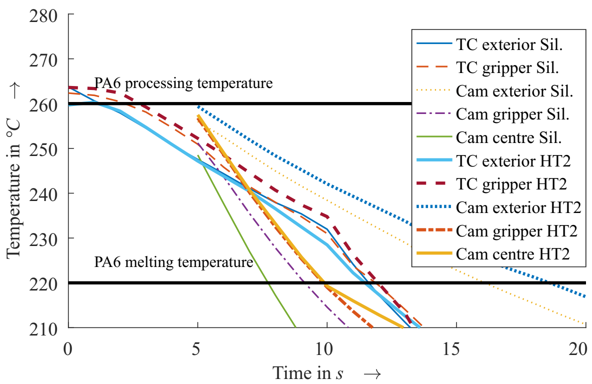

Fig. 5: Temperature profiles of organo-sheet with suction pads after removing off the IR-radiator

3.3. Needlegripper

The test procedure applied to the suction pads is the same for the experimental tests of the needlegrippers. Two needlegrippers, one with ten needles and a diameter of $\varnothing 1.2$ *mm* and a needle-gripper with six needles and a diameter of $\varnothing 2$ *mm* are examined within this study. Fig. 6 shows the temperature distribution after 5s, 10s and 13s of cooling. The punctures of the cold needles are clearly visible after a few seconds. Especially in these areas, the organic-sheets cooling rate is the highest because of rapid heat conduction through the metal needles. In contrast to the needles, both grippers have a PTFE-coated surface in the gripping area to slow down cooling. Similar to the suction gripper, the melting temperature is reached in less than 10s due to heat transfer (see Fig. 7). In the gripper center near the puncture points of the needles, the cooling rate is less than 8s for gripper $\varnothing 1.2mm$ and 5s for gripper $\varnothing 2mm$.

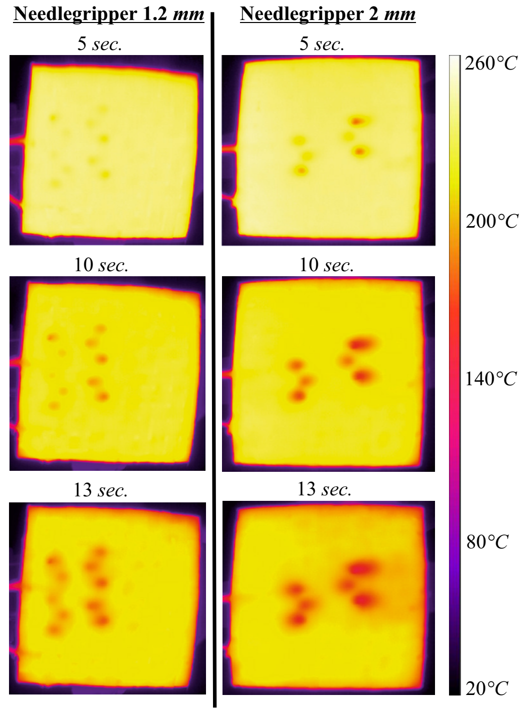

Fig. 6: Thermografic images of organo-sheet with needlegrippers with $\varnothing 1.2$ *mm* and $\varnothing 2$ *mm* needles

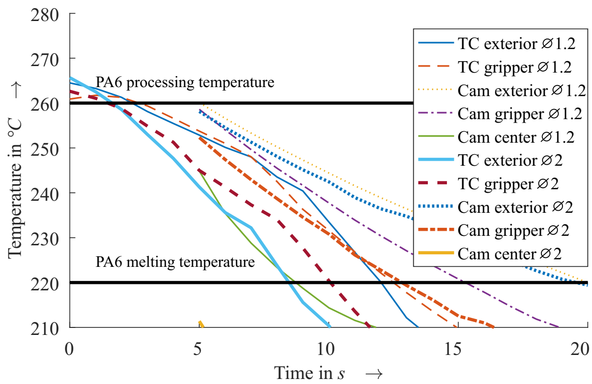

Fig. 7: Temperature profiles of organo-sheet with needlegrippers after removing off the IR-radiator

3.4. Clampgripper

Clampgrippers are not usually used for handling flat composites. However, if draping functionalities to preform the fabric are necessary, the application of tractive forces to drape the organo-sheet onto 3D preforming tools become important. Since a clampgripper grips an object on both sides instead of one side, higher holding forces can be achieved. As a result, the cooling rate due to heat transfer on each side of the fabric is higher though. According to this, the cooling rate is twice as high when using the same material for the gripper jaws. For this matter, the test scenario includes the analysis of four different gripper jaw materials. An uninsulated and uncoated aluminium gripper jaw was used as a reference. Subsequently, gripper jaws coated with macor glass ceramic, PTFE and a high-performance insulating material called BRA-GLA 3 were tested at same conditions. The temperature profile in Fig. 8 show, that only macor ceramic achieves an advantage in temperature insulation compared to the other materials of $4s$. While BRA-GLA 3 and PTFE reach the melting point similarly fast (after $\approx 7s$), macor maintains temperature for $\approx 11s$ seconds above melting temperature.

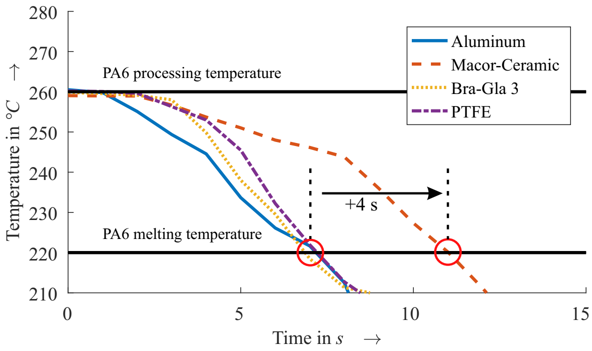

Fig. 8: Temperature profiles of organo-sheet with different clamping jaw materials

3.5. Conclusion

Regarding the results of this experiment, the use of standard grippers for composite handling can only satisfy the requirements for fast large scale production processes because of rapid cooling. Therefore, new approaches using heating technologies to decrease the temperature gradient are necessary to meet the requirements for larger handling cycle times.

4. Improving heat transfer using heatable grippers

The experimental results using unheated grippers have proved difficult handling, regarding viable processing times. The organo-sheet can solidify on the gripper during handling. Thus, a forming process tend to fail. For this reason it is necessary to minimize the temperature gradient as low as possible. One opportunity is to use temperature controlled grippers. The modified needle gripper in this study is equipped with a heater cartridge and a thermocouple at the gripper surface. Gripper temperatures of up to $400°C$ can be achieved via temperature control.

4.1. Temperature adjustable needlegripper

Due to the fact that this gripper also has needles with $\varnothing 1.2mm$, a direct comparison with the non heated needlegripper can be conducted. The corresponding thermographic images in Fig. 9 show obviously a lower drop in temperature. To analyse which gripper temperature, in terms of fabric cooling, is suitable for larger industrial cycle-times a total of three measurements are carried out. The gripper temperature, therefore, is set to $150°C$, $170°C$ and $190°C$.

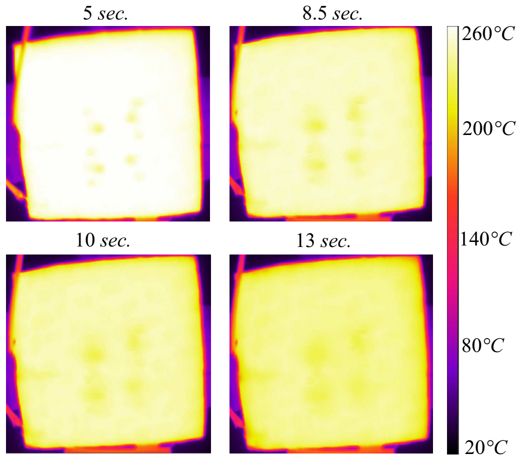

Fig. 9: Thermografic images of organo-sheet with heatable needlegrippers with $\varnothing 1.2\ mm$ needles at $170°C$

The cooling rate can continuously be reduced with increasing gripper temperatures, see Fig. 10. While $220°C$ is reached within $12s$ at a controller temperature of $150°C$, the temperature at $170°C$ is maintaining $20s$ longer. Only at a gripper temperature of $190°C$ a increasing cooling rate occur again. This is due to the fact that polyamide adheres to the gripper at such high temperatures. In this way, heat transfer is increased due to thermal bridges. Additionally, the gripper is permanently contaminated with the remaining thermoplastic. In comparison to the non heated needlegripper, the heated needlegripper maintains the fabric temperature for 22 seconds longer (Fig. 10, $170°C$). Due to this low cooling rate, handling time can be increased significantly from $16s$ to $37s$.

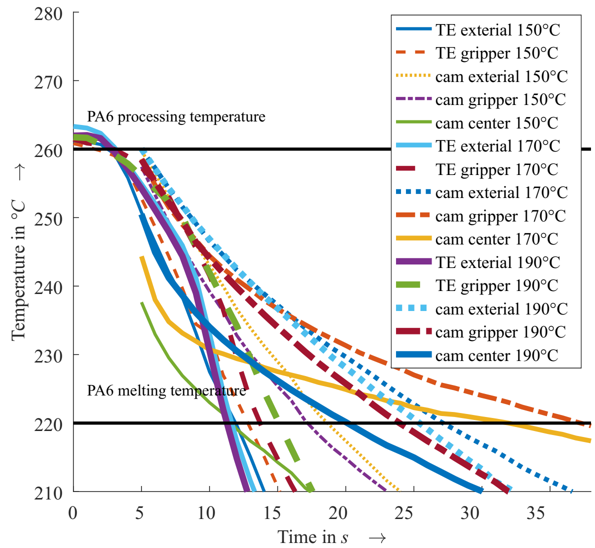

Fig. 10: Temperature profile of organo-sheet with heatable needle-gripper after removing off the IR-radiator

4.2. Evaluation of the heat transfer model with the experimental results of the $\varnothing 1.2mm$ needlegrippers

Following the analysis of standard-grippers, the model of heat conduction with material dependent properties shown in Table 1, is important to predict the cooling rate for automated handling processes. Therefore, the heat transfer model in Eq. 2 is used to calculate the layer dependent cooling rate. The initial processing temperature of each layer is set to 260°C. The temperature of the contacting gripper surface, however, is set to the ambient temperature of 25°C. Fig. 11 shows the heat transfer and corresponding temperature profiles of the three layer organo-sheet and the needlegripper in the unheated and heatable version.

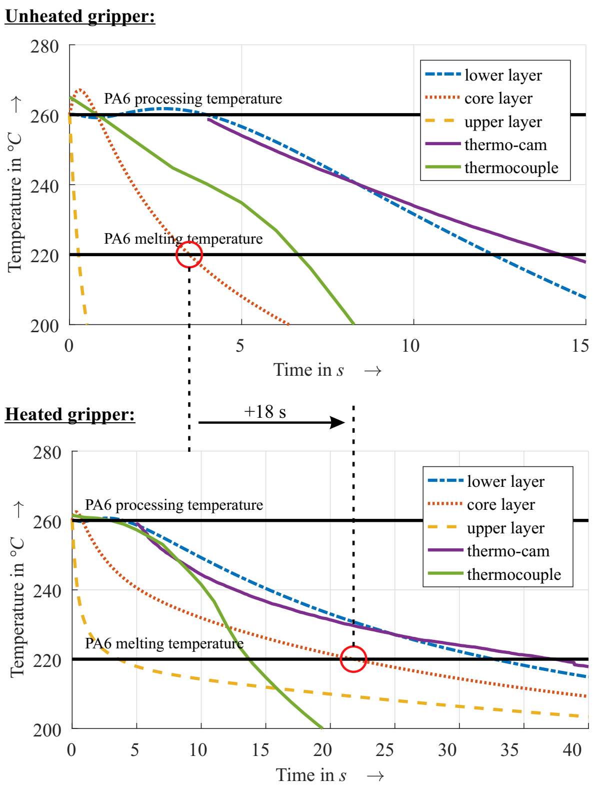

Fig. 11: Comparison of the measured and simulated heat transfer of unheated and heated grippers by using the example of the needlegrippers

The temperature profile of the lower layer, opposite to the gripper, is similar to the measured temperature with the thermographic camera (thermo-cam). Compared to the thermocouple placed inside the laminate, the core layer temperature, however, shows a difference, which is caused by ”lofting”. Lofting is a result of the decrease of residual stresses in the material. This creates cavities, which means that the thermocouple is no longer in contact with the material. As expected, the layer which is in contact with the gripper surface shows the fastest temperature loss. The temperature drops below the melting point after less than 1s for the unheated needlegripper. Due to the use of a heated gripper, the heat flux is reduced due to the lower temperature gradients. Modifying the heat transfer model with a larger gripper temperature, a decreased cooling rate is achieved. Figure 11 shows the temperature profile of the model in comparison with the measurement at 170°C gripper temperature. The model includes the contact area between gripper and the organo-sheet, but not a damping air layer in between. Accordingly, the upper layer is cooling down to melting temperature in less than 5s. On the other hand the organo-sheet stores heat due to its heat capacity. This can facilitate the upper layer to remelt because of heat flux from layer to layer.

5. Conclusion

The thermal characteristics of thermoplastic fabrics in automated handling processes were specified. Commercially available standard grippers and a heatable needlegripper were investigated with regard to heat conduction. In addition, a model to calculate the heat flux from organo-sheet into the gripper was presented. For this purpose, the thermal parameters, such as the heat capacity, the conduction coefficient or the emission coefficient, must be identified and integrated into the model. Using the energy-balance and corresponding initial temperatures of the gripper and the organo-sheet, a prediction of heat transfer can be achieved. It was shown that heated grippers are beneficial because they prevent rapid cooling. The processing time can thus be extended by up to 18s, depending on the gripper temperature. The presented results motivates us to investigate the efficiency of heatable suction pads and heatable clampgrippers in future works. The design of automated handling processes and therefore the limits for processing times can be determined and incorporated into production planning.

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