FORM-FLEXIBLE HEATING DEVICES FOR INTEGRATION IN A PREFORM GRIPPER

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Abstract

The lot sizes of carbon fibre reinforced plastic (CFRP) parts are rising constantly which drives research to bring a higher level of automation to the manufacturing processes of CFRP. Resin transfer moulding (RTM), which is seen as production method for high volumes, has been accelerated to a high degree. However, three-dimensional preforms are necessary for this process, which are widely manufactured manually. A new concept for the manufacturing of carbon fibre preforms with a form-flexible gripper with integrated heating technology is presented and discussed. Different heating technologies are investigated and evaluated. Heating rates under different process conditions are assessed. The concept is proven by the manufacturing of a prototype preform. Further research is motivated in the closing summary.

Keywords: preforming, induction, form-flexible, heating textile, binder, RTM

1 Introduction

The high pressure on car manufacturers to build more energy-efficient vehicles generates a high and enduring demand for lightweight parts and structures. In vehicles with high lot sizes new metal materials and designs were introduced, while in small lot sizes, e.g. luxury and sports cars, fibre-reinforced plastics (FRP) led to a huge weight decrease. In recent times, the car manufacturers have tried to take advantage of the lightweight potential of FRP for higher lot sizes.

High material and process costs have so far prevented the wide use of FRP. Thus, automated high-volume manufacturing processes for complex FRP parts are necessary [1].

The resin transfer moulding process (RTM) is one approach for high volume manufacturing. But the cycle time is still too high, mainly due to the long injection and curing times as well as the complex preform manufacturing process. According to [2] the preforming process is responsible for up to 60\% of the production cost mainly due to manual work [3] (see Fig. 1).

This situation motivates the current paper in which a new approach for the automated manufacturing of preforms is presented. It aims at the reduction of production cost and time. The approach is based on a form-flexible, low pressure textile gripping and draping device with integrated heating technology for binder activation. It is developed in cooperation of the Institute of Joining and Welding and the Institute of Machine Tools and Production Technology, both Technische Universität Braunschweig, Germany [4].

This paper focuses on the heating technology and the preform process linked to the new handling and draping device. Heating results are presented for induction heating and conductive heating textiles. The integration into the preform device is discussed. A prototype setup as well as a demo process is shown. Details on the form-flexible handling device are presented in the paper “Form-Flexible Handling Technology for Automated Preforming” submitted to ICCM 19 by Löchte et.al. [4].

2 State of the Art

2.1 Challenges for High Volume Preform Manufacturing

Two important properties of a composite part manufactured in RTM processes are established during the preforming step. The stacking sequence or fibre orientation and the net-shape geometry are given to the preform. A large amount of the complexity of
reinforced plastics is thus handled during this process step. This explains the high challenges for an automated preforming process. The demand and requirements for such a process are described in the literature as follows:

- “Manufacturing of complex, loadpath-optimized net-shape preforms with local variation of thickness in medium and high volumes” is necessary [1].
- “Automation technology for preforming and handling of preform and parts” is required for “reduced manufacturing time through preforming” [5].
- “Reproducible and automated preforming process” is demanded [1].

A huge number of different concepts and technologies have been developed to fulfill these requirements. The preforming technologies have been developed with various combinations of the following characteristics in mind, which explains the large number of technologies that have evolved:

- Application (Aerospace, Automotive, ..)
- Size of preform/part (bicycle saddle, pressure bulk, wind turbine rotor, ..)
- Raw material (Roving, Fabric, ..)
- Geometry (2D, 3D, tubular, ..)

Furthermore, two different manufacturing approaches are competing: direct preforming (e.g. weaving, braiding, knitting, Tailored Fibre Placement (TFP) and Fibre Patch Placement (FPP)) and sequential preforming [6]. For the latter, the fixing of the preform textiles can be realized using an adhesive, often called binder for preforming, or sewing. Sewing allows for high process rates and a reinforcement in z-direction, but is limited in the complexity of the geometry and can lead to reduced mechanical properties due to misaligned fibres. This can be overcome by bonding the textiles which also allows for more complex preforms. Challenges are the right choice of adhesive and a fast curing or activation process. A false choice of binder may influence the injection process and the mechanical properties. Hot-melt adhesives are often used as binders. A short heating process to melt and activate the binder is necessary to achieve sufficiently high cycle times. Several binder-based preforming processes have successfully been implemented and new manufacturing concepts have been presented lately, which aim at increasing the automation of the preforming processes.

2.2 Binder-based Preforming Processes and their Integration of Heating Technology

In the following a comprehensive overview of chosen concepts for binder-based preforming is given and discussed. Many concepts have evolved from the manual preforming process typical for the early RTM parts with comparably low lot sizes. However, manual layup of textile cut-outs is still a typical and widely used process especially for prototypes and small lot sizes. The binder activation is realized manually with a hot iron or under a diaphragma in an oven. The heating and cooling of the preform to activate the binder in an oven takes a long time due to the heat capacity of the moulds and the low heat transfer in an oven [7]. This causes high process times.

Especially the long heating and cooling cycles have been addressed by the implementation of new heating technologies and successfully led to shorter process cycles [8]. Heated CFRP moulds are one approach that has been proposed. The low thermal capacity of CFRP (in comparison to traditional mould materials) and the high heat transfer by thermal conduction allows for high heating rates and low energy consumption [8]. Alternatively the diaphragm can also be heated by the integration of carbon fibres, heated by electrical resistance heating, leading to likewise benefits [9]. Furthermore, infrared heating technology can be used [10]. Besides a better heating performance compared to an oven, it can be used with an existing diaphragma vacuum press and for different part geometries.

However, all these approaches have in common that the lay-up of the textile fabrics is still manual which is only acceptable up to certain lot sizes. Automated binder-based preform concepts have only been found for parts with certain geometries like the mainly flat geometry of a roof top or a cylindrical pressure vessel [11], that can be manufactured rapidly by compression moulding or winding processes, respectively. Continuous preforming was thoroughly investigated in [2]. Carbon fibre fabrics are gradually formed and fixed in a process similar to pultrusion to produce preform profiles even with slightly varying cross sections along the profile. Inductive heating and hot air have been investigated for the binder activation for this concept [2]. Preforming technolo-
gy was also developed for very large parts like fuselage, helicopter or wind turbine rotor blades, where especially the handling of high volumes of textiles is decisive for high lay-up rates. The authors of [12] propose a handling system to roll out textiles for this purpose. Heating technology has not been integrated into the described prototype. Automated Dry Fibre Placement (ADFP) can also be attributed to these characteristics. Similar to Automated Fibre Placement (AFP) for prepregs, a set of binder-impregnated rovings is continuously placed on a mould and bonded using infrared heating by a fibre placement head, typically connected to a portal or industrial robot. ADFP allows high quality, high flexibility and precision of fibre placement and orientation and reducing material wastage [13][14]. However, the described automated processes cannot be used for more complex, flat geometries. Particularly in the automotive industry, rather small and complex preforms are demanded to utilize the lightweight potential of fibre reinforced plastics. The complexity comprises both stacking of patches varying in size through-out the preform and geometrical curvatures with different directions and radii.

Two promising preforming concepts can be named, which address these category of parts: Fiber Patch Placement (FPP) and function-integrated textile grippers.

The FPP concept has been proposed by [15]. Small fiber patches are placed and fixed on a mold by a fast parallel robot step by step. The small size of the patch superseded a draping process, which allows for the simple setup of this concept. Its advantages are the high flexibility of local fiber orientations and part geometry, low waste and simple tooling. The small fiber length of the patches necessitates a very high transport and placement operation of the robot, which leads to low fiber output [16].

Preforming processes based on function-integrated textile grippers are investigated by many research groups [18][12][19][20][21]. They differ in the draping kinematic, standard gripper components and integration of heating technologies. The authors of [4] extensively discuss the kinematics as well as the draping and gripping performance of these concepts and come to the conclusion that the chosen kinematics limit the draping performance and the flexibility for different part geometries. Due to the low form-flexibility of the concepts, form-flexible heating devices have not been considered. Hot stamps that can be moved uniaxial onto the preform are used by [20]. Conductive heating is utilized by [17]. Binder activation by hot air is investigated by [18].

In summary, this overview shows that automated concepts have been found for certain geometries and conditions. Although a huge number of concepts have been presented for more complex flat parts, new or improved methods for an automated preforming have to be found, since either the draping, gripping or binder activation capability limits the extensive, automated and flexible use in high volume production.

3 Concept of Form-Flexible Handling Device with Integrated Heating Technology

Concluding the state of the art three key aspects have been identified for the automated binder based manufacturing of textile preforms: Gripping, draping and bonding. Especially draping and fixing depend on each other since the draped textile will spring back if it is not fixed in the final form. Together with the form-flexibility, necessary for draping, this makes up the complexity of the manufacturing technology.

Accordingly, this paper and [4] propose a form-flexible handling device that integrates an under-pressure textile gripping system and heating technology for binder activation. A draping of textiles is possible during gripping and heating due to the form-flexibility of this device. This gripper is called “FormHand” in the following descriptions. It can be attached to a robot and integrated into an automated production process.

The essential build-up of the gripper can be seen in Fig. 2. It consists of a flexible cushion with an air-permeable cover (3) and granulate material filling (4). The cushion is attached to a base frame (1), which stabilizes the cushion from one side and serves as a platform for the connection to the robot and the secondary equipment like vacuum blower, electrical heating generator, measurement and control instrumentation. With the build-up described so far, the steps gripping and draping of limb fabric can be realized. Further details on the concept and its abilities are given in [4]. The heating technology (5) needs to be integrated into this build-up without limiting the other functionalities, especially the form-flexibility.
4 Process Concept for Automated Preforming with a Form-Flexible Handling and Heating Device

The automated preforming process with the form-flexible handling device comprises the following steps for each ply (see Fig. 3):
- Pick-up of pre-cut ply or ply set in 2D
- Transport from cutting and binder application system to preform mould
- Draping of ply or ply set into preform mould
- Fixing by hot-melt bonding

These steps need to be repeated for each ply until the preform is finished. The process time for each step needs to be reduced as far as possible since it is multiplied by the number of plies. This requirement is especially important for the last step, in which the textiles need to be heated above the melting temperature of the hot-melt binder and cooled down afterwards to fix the textiles. High heating and cooling rates need to be realized by the heating technology, which can either be integrated into the mould or the handling device. In this paper the latter is discussed since the integration into the handling device offers several advantages. Such a handling device allows parallelising the draping and the heating steps during the preform layup. As shown in Fig. 3, the textiles can be preheated to a temperature below the melting point during pick-up, transport and draping into the mould. During the fixing step the textile and binder are heated above the melting temperature and cooled down. The cooling can be accelerated by the air stream from the vacuum gripper.

5 Aim of Research

The work presented in this paper is a feasibility study to show whether the presented concepts can be realized in a prototype setup and whether it is able to manufacture preforms. While [4] aimed for the identification of a suitable construction and materials for the prototype of a form-flexible handling and draping device, the aim of this paper is to identify appropriate heating technology to allow integration into the device and to pursue initial preforming experiments. Furthermore the influence of different parameters like air stream, heating rates and heating method are assessed by initial experiments.

6 Heating Technology for the Integration into the Form-Flexible Preform-Gripper

Two crucial requirements were defined for a heating technology which can be integrated into the form-flexible handling device. The heating technology needs to allow for
1.) a fast heating of the handled textile layer and
2.) a low disturbance of the handling process.

Especially the form-flexibility of the gripper cushion may not be disturbed since it is crucial for draping the textile into a complex three-dimensional geometry. Beside these requirements, the main challenge for the integration of heating technology into the form-flexible gripper concept FormHand is its distance and access to the preform to be heated. Due to the draping process access (e.g. direct contact or UV radiation) is prevented by the gripper, especially the gripper cushion textile and filling, on one side and by the mould on the other. Therefore, several heating technologies that have been mentioned in section 2 for binder activation in different preform setups were excluded early:
- Infrared heating is difficult to be integrated due to the missing direct access to the preform.
- Laser could only be used if laser transparent materials could be used for the gripper cushion and membrane or if optical fibres could transfer the energy to the gripper cushion, which would greatly increase the complexity of the gripper.
- Direct heating of the carbon fibre preform by contacting the carbon fibre through electrical contacts on the gripper cushion was excluded due to the difficult adaption to different cut-out geometries.
- Heated moulds could well be used together with the form-flexible handling technology and would reduce the complexity of the preform gripper by eliminating the necessity for integrated heating technology. However, heated moulds for preforming are comparatively expensive and are limited to a specific geometry.

Two remaining technologies were chosen for the initial assessment in this paper: Conductive heating textiles and inductive heating. The integration concepts are depicted in Fig. 4.

Induction heating was chosen due to its contactless heat transfer and high heating rates [7]. Fundamental condition is that electrically conductive textiles are
handled and that the fabric has different fibre orientations. Eddy currents can then be induced in the fibre fabrics, which results in a volumetric heating of the preform textiles by Joule losses. This causes very high heating rates in the binder which is in direct contact to the textiles. Approach for the integration of this technology in FormHand is to attach small inductors on the inside of the gripper cushion. The second integration concept is based on conductive heating textiles. Electrically conductive filaments or rovings (e.g. copper, steel, carbon fibre) are typically integrated in or on a supporting textile. A contacting at the edges of the textile allows the connection of an electric generator and the heating by Joule losses. The textiles can be integrated into FormHand by partly substituting the gripper cushion cover or by attaching it on the bottom of the cushion (see Fig. 2 and Fig. 4 (a)). The heating characteristics and integration concept of both technologies was evaluated in initial investigations, which are described in the following.

6.1 Preform Materials for Heating Experiments
Two carbon fibre textiles were used as preform materials. One carbon fibre twill weave (HTS 40) manufactured by C. Cramer GmbH & Co.KG and a bi-axial non-crimp fabric (0/90°) by Hexcel. A powder-binder EPIKOTE 05390 by Momentive was used for the investigations due to its low melting temperature. It is an Epoxy based binder activated in a temperature range between 80 – 90°C.

6.2 Inductive Heating
Four plies of a carbon fibre weave with binder between each ply were heated by induction. A generator EW 2 by the IFF GmbH, Germany was used for the inductive heating experiments. The frequency domain is 15-25 kHz. The equipment was chosen since air-cooled coils were available. The coil U7050, shaped like a horseshoe magnet and a solenoid coil were used (see Fig. 5). Vacuum was applied for as compaction pressure on the carbon fibre fabrics and the temperature was measured in the binder below the top carbon weave. The experimental setup is depicted in Fig. 5.

The heating patterns of the two coils can be seen in Fig. 6. The heated area is approx. 40 x 60 mm for the U7050 and almost double as large for the solenoid with a cold spot in the middle. It depicts that with inductive heating only small areas (points or lines) can be preformed if the inductor is not moved above the preform. However, a punctual fixation might be enough for some preforms. Beside the heating pattern, the distance of the inductor to the preform is the second crucial parameter that needed to be evaluated. Fig. 7 shows heating rates for typical distances used during induction heating for two frequencies and moderate power (500 W). High heating rates up to 10 K/s can be reached, which could even be increased by higher power. However, the sensitivity of the heating rates to the distance indicate, that it is important to ensure a constant distance within the heated area to prevent overheating. Since a curvature can be expected within the heated area, inductors with a smaller heating pattern are necessary. A smaller solenoid inductor was investigated, but did not provide enough power. Further investigations need to be performed with adapted induction equipment.

6.3 Conductive Heating by Heating Textiles
Two ways for the integration of heating textiles in the gripper cushion can be discussed. First the heating textile can take over the function of the outer shell of the gripper cushion. It has to fulfil both requirements from the handling and heating perspective. As an alternative the heating textile can be stitched to the outer shell of the gripper, which reduces the requirements and simplifies the integration. However, the decreased air permeability needs to be considered in the conceptual design of FormHand.

The major requirements for the selection of heating textiles can thus be summarized according to the sub-processes as:

A) Gripping and Draping
- Air permeable
- Drapable

B) Heating
- Temperature resistant to allow high temperature difference between cold preform textiles and heating textile which drives heating rates
- High heating power to allow for low process cycle times
- Resistance against electrical short circuits to prevent overheating while the textile is draped
- Electrical isolation against preform carbon textiles

Three different commercially available heating textiles were evaluated, which are shown in Fig. 8: a knitted fabric with a low percentage of steel fibres (A), isolated copper fibres bonded to a polyester fabric (B) and carbon fibre rovings stitched to a glass fibre fabric (C). All of them are based upon electrical resistance heating. Table 1 compares these textiles and assesses their properties according to the requirements defined above.

The heating textile A shows excellent properties in terms of drapability and a homogenous heating pattern (see Fig. 9 left). However the temperature stability of 90°C needs to be improved to reach the melting temperature of the hot-melt binder. Furthermore the conductive steel filaments are not electrically isolated. Thus if carbon fibre cut-outs are heated and the heating textile is in direct contact to the cut-out, both textiles act as parallel resistors, which leads to a lower temperature in the contacted area. Fig. 9 (right) shows this effect. Heating the carbon fibres directly is a good effect at first and if enough power is supplied, a sufficient temperature might be reached. However, the heating textile would be overheated in the region that is not connected to the carbon fibres. Furthermore, the whole carbon fibre stack would be heated and the temperature would thus strongly depend on the type of fabric, their resistance and the number of plies.

Textile B has a higher in-plane shear stiffness, but a low bending stiffness and good flexibility due to the low thickness. The heating pattern is defined by the number and position of the embedded copper filaments. Each filament is isolated by a polyurethane layer. Thus a good electrical isolation towards the carbon fibre fabrics is guaranteed. The textile offers very high air permeability, which can be adapted to the gripping needs by the density of the PET-filaments. The textile could be used in exchange for the gripper cushion. However the current density of the copper filaments and the low temperature resistance of the PET-filaments only allow for a comparably low heating power.

The third heating textile (C) that was investigated is based on carbon fibres as heating elements, which are stitched to a glass fibre fabric (see Fig. 10). It is much thicker than both other textiles, but has a good draping and acceptably low bending stiffness. The glass fibre layer could be eliminated in future optimization loops to further improve the draping behaviour and decrease the thermal barrier between resistance-heated carbon rovings and preform. However, the electrical isolation against the carbon fibres of the preform is guaranteed by the glass fibre layer and the gripper cushion. The temperature stability of the heating textile up to 180°C is sufficient for the preforming process. Its heating pattern is shown in Fig. 10. The heated carbon rovings can well be identified in the thermal image. Although the heating pattern is not homogenous, a good preforming performance can be expected since more than 50% of the area is heated directly by resistance heating. Due to the best combination of temperature stability and heating power assessed in initial experiments, textile C was used for further investigations and in the prototype FormHand.

The experimental setup for these heating experiments with conductive heating textile C depicted in Fig. 11. Three layers of carbon fibre textile are positioned on a flat glass panel. The conductive heating textile is placed between the gripper cushion and the carbon textiles.

 Thermocouples are fixed on the heating textile (T1), the glass panel (T7), between the top and second textile layer (T5) as well as the second and third (T6) (see Fig. 11). The gripper is connected to a vacuum generator via the air connection (1). Both an low pressure and overpressure air stream can be regulated and measured (S1) by the vacuum generator and an attached flow meter. The self-weight of the gripper with cherry pits is approximately 7.5 kg and is used as compaction pressure.

The temperature distribution in the experimental setup comprising heating textile, preform and mould can be seen in Fig. 12. While the heating textile reached a temperature of 140°C within 4s, the temperature in the preform below the top layer increases delayed and with a lower heating rate. The melting temperature of the binder is reached after approx. 28s. Thermocouple T6 (one ply further away from the heating textile) does not reach the melting point. The influence of the gripper air stream on the heating performance was investigated in further experiments. As described in Section 4 the time for the transport of the textile cut-out from the batch to the
mould can be exploited for the pre-heating of the handled textile. During this phase a low pressure is applied to grip and hold the textile during transport. Experiments were conducted to assess the influence on the heating performance. Fig. 13 shows the temperature over time for different air stream flows. While the initial heating rates vary only slightly, the temperature increases slower with higher airstream flows. The maximum temperature reached after a 35s heating cycle with the same electrical power decreases as well. The loss in heating power depending on the air stream needs to be compensated by a higher power supply during heat-up.

While the airstream decreases the heating rates during heat-up, it might help to accelerate the process during the cooling phase. The gripper can be lifted from the preform as soon as the binder solidifies below its melting temperature. Both under- and overpressure air stream can be realized and measured by the vacuum blower with electro-pneumatic reversing. Fig. 14 shows that the cooling rate can almost be doubled by utilizing an airstream of approx. 200 m³/h. This helps to increase the layup rate of the preform gripper.

Furthermore, the influence of the heating textile temperature on the heating rates in the preform is investigated. Fig. 15 illustrates, that a higher temperature of the heating textile leads to increasing heating rates. A rise of the textile temperature from 125°C to 170°C leads to an almost doubled heating rate. Thus, the parameter is crucial for a fast preforming time and depicts the necessity for heating textiles, which are suitable for high temperatures.

6.4 Assessment of Investigated Heating Technologies

Both heating technologies are suitable to heat up the binder in the preform above the melting temperature of the binder. However, the results showed that the heating rates of 1-2 K/s in the binder layer are significantly lower in the case of the heating textiles in comparison to the induction heating results with 10-15 K/s. This can be explained by the different heat development. During induction, the heat is generated in the top carbon plies of the preform, and thus close to the binder. With the conductive textiles, the heat needs to be transferred through the carbon ply between the heating textile and binder powder. This leads to a delay of the temperature increase in the binder layer. However, induction heating is only applicable for electrically conductive fibres, like carbon fibres, and large inductors can limit the homogenous heating, drapability and air permeability of the gripper cushion. Both represent no problem if the heating textiles are used. Furthermore, induction heating is mainly limited to line- or punctual heating while heating textiles can achieve a more homogenous, planar temperature distribution. The prototype gripper was therefore realized with a conductive heating textile. Further development of specific inductive heating equipment could allow for a later integration into the gripper.

7 Manufacturing of a Generic Preform using FormHand

The hardware prototype of the FormHand concept has been tested and validated for the manufacturing of a generic s-shaped preform. The binder powder EPIKOTE 05390 was used and applied one-sided on three plies of non-crimp fabric (0°/90°) consecutively, see Fig. 16 (a). Afterwards the textile was draped into the mould by FormHand, see Fig. 16 (b). The preform shape was fixed by heating the binder to approximately 100°C through the heating textile on the gripper cushion. Fig. 16 (c) depicts that FormHand could completely drape the textiles into the shape. The final preform shows that the binder activation was successful, Fig. 16 (d). These experiments validated the concept of FormHand.

8 Conclusions

The concept of a form-flexible handling device with integrated heating technology and the corresponding process is discussed. Induction and conductive heating are initially assessed as possible technologies for the integration into a preform handling device. The results show that very high heating rates can be achieved by induction and high heating rates for the heating textiles. The initial assessment of the preforming concept with a form-flexible handling prototype with integrated heating technology has shown that preforms can be manufactured. Heating textiles could successfully be integrated without constraining the gripping and draping performance. The crucial temperature of at least 80°C has been reached between the top layers of the prototype preform to
melt the binder and fix the carbon fibre textiles of the preform.

The conductive heating textiles investigated in this paper show that form-flexible heating technology is available and can be integrated into the handling concept. Further investigation is necessary to enhance the interaction of the heating textile with the gripping and draping while increasing the heating power. The results indicate that the heating textile temperature is one crucial parameter for high heating rates. The possible preform process time has to be determined during the further research.

References


Fig. 1: High process time for preforming process (Cutting and lay-up) [8]

Fig. 2: Concept of the form-flexible, low pressure handling device FormHand with integrated heating technology, see [4]

Fig. 3: Process timeline with temperature profile

Fig. 4: Form-flexible handling device with a heating textile (a) and with inductors on the gripper cushion (b)

Fig. 5: Experimental setup for inductive heating
Fig. 6: Thermal image and schematic build-up of inductor U7050 (left) and solenoid (right); Two colder rectangles can be attributed to spacers

Fig. 7: Heating using induction with different coil distance and frequency

Fig. 8: Heating textiles; Knitted fabric with a low percentage of steel fibres (A), isolated copper fibres bonded to a polyester fabric (B) and Carbon fibre rovings stitched to a glass fibre fabric (C)

Table 1: Comparison of heating textiles

<table>
<thead>
<tr>
<th>Textile</th>
<th>Supplier</th>
<th>Maximal Temperature</th>
<th>Draping</th>
<th>Aerial weight</th>
<th>Material</th>
<th>Heating power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knitted fabric</td>
<td>ITP GmbH, Germany</td>
<td>90 °C</td>
<td>Very good</td>
<td>180 g/m²</td>
<td>Trevira CS + 16% Stainless steel</td>
<td>1250 W/m²</td>
</tr>
<tr>
<td>Polymerweave with isolated copper filaments</td>
<td>Sefar AG, Switzerland</td>
<td>180°C</td>
<td>Good</td>
<td>90g/m²</td>
<td>PET Monofilament + Copper filament</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>Carbon fibre rovings on glasfibre</td>
<td>Gerster TechTex GmbH &amp; Co. KG, Germany</td>
<td>230 °C</td>
<td>Ok</td>
<td>Approx. 300 g/m²</td>
<td>PES + Carbon fibre rovings</td>
<td>&gt; 3000 W/m²</td>
</tr>
</tbody>
</table>
Fig. 9: Thermal image of knitted fabric (A) without isolation (left) and with silicon liner (right)

Fig. 10: Heating textile by Gerster TechTex (left) and thermal image (right)

Fig. 11: Experimental setup for conductive heating

Fig. 12: Temperature on heating textile (T1) and in preform (T5/T6) over time during conductive heating

Fig. 13: Influence of the gripping air stream on the heating performance

Fig. 14: Cooling rates in the top binder layer against air flow

Fig. 15: Influence of the temperature of the heating textile on the heating rates in the top binder layer
Fig. 16: Preforming with the prototype of FormHand