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Holger Kunz*, Christian Löchte*, Franz Dietrich, Annika Raatz, Fabian Fischer, Klaus Dröder and Klaus Dilger

Novel form-flexible handling and joining tool for automated preforming

Abstract: The production rates of carbon fiber reinforced plastic (CFRP) parts are rising constantly which in turn drives research to bring a higher level of automation to the manufacturing processes of CFRP. Resin transfer molding (RTM), which is seen as a production method for high volumes, has been accelerated to a high degree. However, complex net-shape preforms are necessary for this process, which are widely manually manufactured. To face these challenges a new concept for the manufacturing of carbon fiber preforms with a form-flexible gripping, draping and joining end-effector is presented and discussed. Furthermore, this paper investigates the application of this concept, describes the initial build-up of a demonstrator, focusing on material selection and heating technology, and discusses test results with the prototype. This prototype already validates the feasibility of the proposed concept on the basis of a generic preform geometry. After a summary, this paper discusses future in-depth research concerning the concept and its application in more complex geometries.

Keywords: automated preforming; draping; form-flexible; handling; joining.

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***Corresponding authors: Holger Kunz,** Institute of Joining and Welding, Technische Universität Braunschweig, Langer Kamp 8, 38106 Braunschweig, Germany, e-mail: h.kunz@tu-braunschweig.de; and **Christian Löchte,** Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany, e-mail: c.loechte@tu-braunscheig.de
Franz Dietrich and Klaus Dröder: Institute of Machine Tools and Production Technology, Technische Universität Braunschweig, Langer Kamp 19b, 38106 Braunschweig, Germany
Fabian Fischer and Klaus Dilger: Institute of Joining and Welding, Technische Universität Braunschweig, Langer Kamp 8, 38106 Braunschweig, Germany
Annika Raatz: Institute of Assembly Technology, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

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. For vehicles with high production rates new metal alloys and designs were introduced, whereas vehicles with lower production rates, e.g., luxury and sports cars, fiber-reinforced plastics (FRP) led to a huge weight decrease. In recent times, the car manufacturers tried to take advantage of the lightweight potential of FRP for higher production rates.

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 molding process (RTM) is one approach for high volume manufacturing. Figure 1 illustrates the RTM production process in the upper (blue) process chain. After cutting textile plies into their desired shapes, these cut-outs are transported to a preforming unit. In the process step of preforming, textile cut-outs are draped into a near-net shape and joined to form the preform. This process step is carried out manually or automatically, depending on the complexity of the desired form. This preform has to be handled and placed within the RTM tool, where it is impregnated with resin and cured. After cooling down the RTM tool, the composite is withdrawn from the tool and is passed on to the finishing process step, e.g., machining, painting or polishing.

Although research on the RTM process has constantly led to decreasing cycle times, they are still too high for larger production rates, 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 Figure 2).

This situation is the motivation for the presented work in which a new approach for the automated manufacturing of preforms is presented. It aims at the reduction of production costs and time. The approach is based on a form-flexible, low-pressure textile gripping and draping

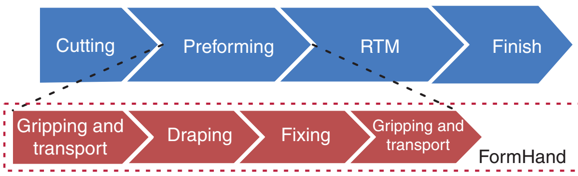

Figure 1 Process chain of a RTM production process and integration of FormHand.

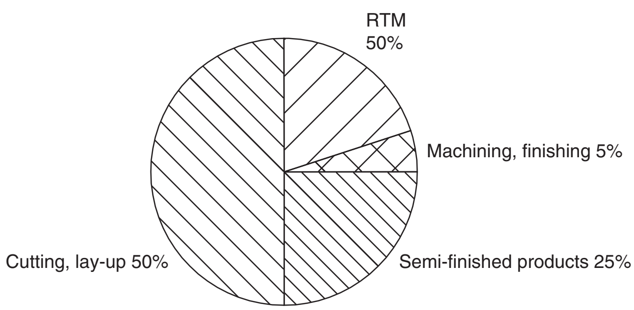

Figure 2 High process time for preforming process (cutting and lay-up) [4].

device with integrated heating technology for binder activation. It is developed in cooperation with the Institute of Joining and Welding and the Institute of Machine Tools and Production Technology, both at Technische Universität Braunschweig, Germany.

2 Challenges for high volume binder-based preform manufacturing

Two important properties of a composite part manufactured by RTM processes are established during the preforming step. The stacking sequence or fiber orientation and the net-shape geometry is given to the preform. A large amount of the complexity of reinforced plastics is thus handled during this process step. This explains the huge challenges for an automated preforming process, which 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,..) and
- geometry (two or three dimensional, tubular,..).

Furthermore, two different manufacturing approaches compete: direct preforming [e.g., weaving, braiding, knitting, Tailored Fiber Placement (TFP) and Fiber Patch Placement (FPP)] and sequential preforming [6]. Looking at the binder-based processes, all have to implement three process steps. Besides the transport of the textile raw material from the stock to the mold, the most challenging are:
- gripping of textiles,
- draping and
- fixing.

The lower part of Figure 1 depicts these process steps. Each process step has its particular challenges for handling, as described in the following:
1. The gripping of the textile patches and the transfer to the preform table. Textile raw materials are both limp materials and permeable to air. Their structure can easily be damaged by the gripper. These circumstances are very challenging for a handling device.
2. At the preform table the draping of the textile takes place. During the transformation from a two-dimensional plane into a near net shape the textiles have the tendency of forming cuttings or wrinkles which have to be avoided by a selective and guided draping. All contours have to be formed, from small details to the larger geometry of the part.
3. Once the textile is placed in its final position in the preform tool, it is fixed and joined to other layers of textiles. Two contradicting requirements make this process complex. On the one hand, the textiles need to be pushed into their final position by the draping tool, which can be achieved by preferably a large coverage of the draping tool on the textile and preform mold. On the other hand the joining technology, whether it is sewing or binder activation, needs access to the preform. This challenge needs to be considered for a function-integrated handling technology.

The state of art shows solutions for each of these process steps, individually. But the challenges listed above indicate that the interaction of the process steps and their challenges necessitate an integrated handling tool to realize a continuous automated preform process.

3 State of research

The challenges described in the previous section have been addressed from different perspectives by several research groups. All preforming concepts described in the following chapter have different combinations of the process steps gripping, draping and fixing in mind. From the perspective of process time both faster heating technologies for binder activation and an automated lay-up, comprising gripping and draping, have been addressed. These contributions to the state of research are detailed in the following sections.

3.1 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, focusing on heating technologies. Many concepts evolved from the manual preforming process typical of the early RTM parts with comparably low production rates. However, manual layup of textile cut-outs is still a typical and widely used process, especially for prototypes and low production rates. The binder activation is realized manually with a hot iron or under a diaphragm in an oven. The heating and cooling of the preform in order to activate the binder in an oven takes a long time due to the heat capacity of the molds and the low heat transfer in an oven [7]. This adds to the high processing times of the manual layup.

Especially the long heating and cooling cycles were addressed by the implementation of new heating technologies and successfully led to shorter process cycles [8]. Heated CFRP molds is one approach that has been proposed. The low thermal capacity of CFRP (compared with traditional mold 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 fibers, heated by electrical resistance heating, leading to similar benefits [9]. Furthermore, infrared heating technology can be used [10]. Besides a better heating performance compared with an oven, it can be used with an existing diaphragm vacuum press and for different part geometries.

However, all these approaches have in common that the lay-up of the textile fabrics is still carried out manually, which is only acceptable up to certain production rates. Automated binder-based preform concepts were only found for parts with certain geometries, such as the mainly flat geometry of a roof top or a cylindrical pressure vessel [11], that can be manufactured rapidly by compression molding or winding processes. Continuous preforming was thoroughly investigated in [2]. Carbon fiber 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 were investigated for the binder activation for this concept [2]. Preforming technology was also developed for very large parts like fuselage, helicopter or wind turbine rotor blades where, especially, the handling of high volumes of textiles rather than geometrical complexity, is decisive in order to achieve 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 Fiber Placement (ADFP) can also be attributed to these characteristics. Similar to Automated Fiber Placement (AFP) for prepregs, a set of binder-impregnated rovings is continuously placed on a mold and bonded using infrared heating by a fiber placement head, typically connected to a portal or industrial robot. ADFP allows high quality, high flexibility and precision of fiber placement and orientation as well as 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 essential for utilizing the lightweight potential of fiber reinforced plastics. The complexity comprises both stacking of patches varying in size throughout the preform and geometrical curvatures with different directions and radii.

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

The FPP concept was 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 supersedes 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 number of transport and placement operations of the robot, which leads to low fiber output [4].

Preforming processes based on function-integrated textile grippers are investigated by many research groups

[12, 16–19], and have gained a certain focus in the research lately. The advantage is that a high output can be realized since textile cut-outs are used as raw material. In comparison with FPP and ADFP, one whole layer can thus be handled in one step. Furthermore a standard industrial robot can be utilized. However, the concepts need to implement a high form-flexibility to allow for the draping of textiles into the mold. The concepts address these challenges and the integration of heating technologies differently, which is discussed in detail in the following section.

3.2 Form-flexible and function-integrated handling tools

During the investigation on form-flexible handling tools for an automated preform process it quickly turned out that at this time there are no market-ready technologies. But there are designs and prototypes of different concepts being researched. All of them are currently in development. These designs introduce form-flexible grippers for limp material to transform or drape textiles from the plane shape into a three-dimensional one.

The device described in [20, 21] was designed at IWB, Munich, Germany. The gripper is constructed cylindrically and can be rotated around its principal axis. The surface is composed of elastic foam material and is made of several identical modules. Each module is individually equipped with valve actuators and heating elements and can be controlled separately. A connected vacuum generator creates an airflow, which generates a negative pressure inside the gripper and thus the holding force at the gripper surface. Gripping and releasing of fabrics is carried out by a rolling motion. During this movement the modules are activated and deactivated sequentially. Dependent on the geometry of the work piece, the design of the end-effector can lead to limitations in applicability. There might be the need for additional support tools for draping. The form-flexibility is only realized by the foam material at the surface. In this way, the surface can adapt the contour of the preform tool with limited molding depth. The flexible surface returns to its original state as soon as outer forces, applied by the preform tool, are withdrawn. This is due to the fact that the surface of the gripper cannot memorize its shape. In this way temporary shaping and reusing a molded contour into the gripper's surface is not possible.

There is a prototype designed at Fraunhofer IPT, Aachen, Germany, which uses the fin-ray principle to adapt different contours passively [22]. The end-effector consists of four fin-ray elements. These elements are equipped with standard grasping modules such as cryo or needle grippers. These modules form discrete grasping positions. Its molding ability is limited to uniaxial curved surfaces.

Another adaptive multifunctional end-effector, designed at IGM, Aachen, Germany, is described in [16]. Like the previously described gripper, this end-effector has discrete grasping points with mounted cryo grippers. The form-flexibility is realized by a parallelogram mechanism, which is actuated by a drive unit at the center of the gripper. Due to its kinematic structure the molding ability of this design is also limited to uniaxial curved surfaces. In order to improve the draping results, this end-effector is supported by an additional draping tool that is similar to a pressure roller.

A similar prototype for draping textiles into a three-dimensional preform mold was designed at ITA, Aachen, Germany [23]. This system can be equipped with needle, cryo or vacuum grippers. In contrast to the end-effectors described above, this one has no actuated kinematic structure. The gripper's surface is not form-flexible. The reshaping is realized with a rolling movement performed by the robot arm. Therefore, this end-effector is not as flexible as the others.

Other designs [24–26] realize a passive form-flexible end-effector that is based on jamming of granular material. In the simplest form the end-effector consists of an elastic air-impermeable membrane such as a latex balloon, which is filled with granular material, e.g., ground coffee. In the interior of the membrane, positive and negative pressure may be created by an external pump. If the pressure inside is negative, the granular material is slightly compressed and solidifies. This change of state is used to grip objects. The balloon-like body of the gripper is pushed around the work piece in soft state. Then it is hardened. With such a device, objects are handled by form closure only. The range of items to grip is wide, because of the high level of form-flexibility. In the preforming process this concept is not applicable. A combination with working principles from the other grippers might lead to competitive preforming tools.

This overview shows that the related technologies are still in an early stage of development. The majority of the grippers are considerably restricted in form-flexibility due to the used kinematics. Additionally, these grippers are equipped with discrete grasping points. Although standard components can be used, this limits the functionality when draping textiles into a three-dimensional shape. Only one end-effector applies a grasping mechanism that is situated homogenously on the surface of the gripper, which improves the draping performance. This concept, however, is limited in its molding depth. Due to the low form-flexibility of all the presented concepts, form-flexible heating devices have not been considered. Hot stamps that can be moved uniaxial onto the preform are used by

[18]. Conductive heating is utilized by [20]. Binder activation by hot air is investigated by [16].

4 Motivation and aim of research

The technological gap of automated preform processes for high volume production lines as well as the described challenges for handling and joining technologies during preforming triggered the present work at the Institute of Machine Tools and Production Technology (IWF) and Institute of Joining and Welding (IFS) of Technische Universität Braunschweig, Germany. The cooperation of these two institutes concerns the process chain of preforming. To improve the level of automation during preforming, the following research approach was chosen:

A handling and joining end-effector that integrates gripping, draping and fixing and that considers a high form-flexibility can solve the gap of an automated preforming. The combination of a form-flexible, low pressure textile gripper relying on the air-permeability of a cushion filled with granules, a draping device based on the sliding and jamming of granules, respectively, and integrated heating technology for binder activation addresses the key challenges during preform manufacturing.

This approach leads to questions concerning the basic design elements for the realization of such a handling technology, which are addressed in the presented work:

- Which design concept for a preform manufacturing tool can implement the described approach?
- Can adequate components be found to realize this concept design in a prototype?
- Is the prototype able to show the feasibility of the presented concept for the manufacturing of a demonstration preform?

In order to find answers to these questions, this paper discusses a new design concept (FormHand) and its components. Finally, initial experimental results obtained during automated preform manufacturing on a lab scale are presented.

5 Concept of a novel form-flexible handling and joining technology (FormHand)

The given overview on the state of research shows that there are a noticeable number of experimental set-ups to meet the challenges of preforming as described in Section 3. There are still limitations to the proposed approaches. Therefore, a new design concept, called FormHand, is developed with a focus on gripping air permeable material, a maximal form-flexibility to realize a draping of limp material and the possibility of integrating heating technology for binder activation. The design of FormHand extends the design of the prototypes described in Section 3 and recombines most promising features according to the approach defined in the previous section. The following sections describe the design of the new handling and joining end-effector and its process in detail.

5.1 Design of FormHand end-effector

The conceptual design of FormHand with its main parts is depicted in Figure 3. The form-flexible preforming device consists mainly of a base frame (1) and a cushion (3). The base frame has three main functions:

- supply the interface with a robot and the vacuum generator via a connection tube (2),
- give stability to the cushion (transmission of process force while draping) and
- integrate further components such as sensors, actuators or heating elements.

The gripper cushion (3) is filled with granulate material (4). Similar to a pillow, this gripper cushion is very form-flexible in a range that is allowed by the mobility of the granulate particles and the size of the cover. This cushion distinguishes FormHand from other concepts that are described in Section 3. The bottom of the gripper cushion can be heated by a form-flexible heating textile (5).

The stiffness of the cushion can be changed with an adjustable airstream by vacuum suction via a connector

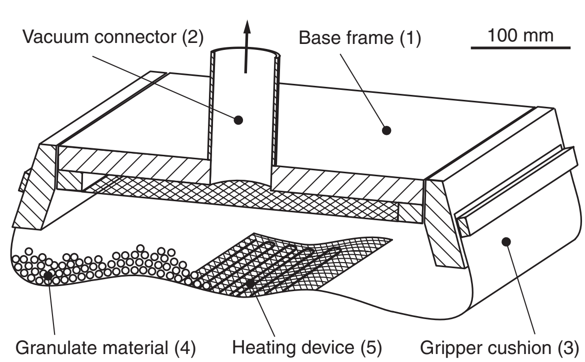

Figure 3 A conceptual design of FormHand with its main design parts.

in the base frame. The change in stiffness is due to the jamming of the granulate particles within the cushion. At the bottom, the cushion has a porous area, the gripping area. Here, the handled textile is ingested by the airstream through the gripper cushion. The airstream through the gripper cushion determines whether the granules within the cushion can freely move or is jammed and solidifies, which allows a specific forming or draping of the textile into a mold. Figure 4 shows the realization of this concept in hardware for testing the idea of FormHand in an industrial environment.

5.2 Application of FormHand in the RTM preform process

The automated preforming process with the form-flexible preforming device (FormHand) comprises the following steps for each ply (see Figure 5):
- pick-up of pre-cut ply or ply set in 2D,
- transport from cutting and binder application system to preform mold,
- draping of ply or ply set into preform mold and
- 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 mold or into the preforming device. In this paper the latter is discussed since the integration into the preforming device offers several advantages. Such a handling and joining device allows parallelizing the draping and the heating steps during the preform layup. As shown in Figure 5, the textiles can be preheated to a temperature below the melting point during pick-up, transport and draping into the mold. 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.

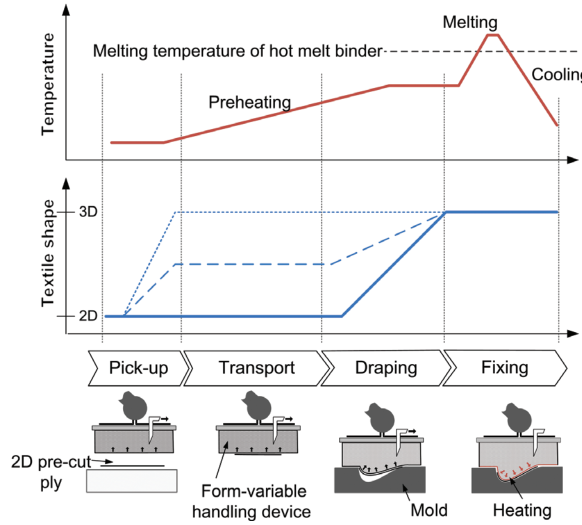

Figure 5 Process timeline with temperature profile.

Figure 4 FormHand mounted to a six DOF industrial robot with connected vacuum supply.

6 Selection of granular and textile material for FormHand

The description of the concept of FormHand in Section 5 illustrates that a suitable granulate material as filling for the gripper cushion, and a flexible textile for the cushion itself, are two key aspects for a successful realization of FormHand. This triggered an investigation with the aim of identifying material requirements for the filling and for the cushion of FormHand. This section focuses on fundamental experiments characterizing different granules and textiles for the gripper cushion, which are the basis for the material selection for the prototype and its gripping and draping performance in the demonstration process described in Section 8.

6.1 Selection of granulate material for the inside of the gripper cushion

The investigation included granules from three categories:
- synthetic materials such as expanded polystyrene (EPS), expanded polypropylene (EPP) and acrylonitrile butadiene styrene (ABS),
- recycled and expanded glass and
- biological materials such as cherry pits or rape seeds.

Table 1 Six granules under investigation for FormHand. Granules are required as a filler for the gripper cushion. Depending on the characteristics of theses granules a high form-flexibility of the FormHand cushion can be realized.

Granulate Material	Density [kg/m³]	Diameter [mm]	Form	Surface/ elasticity
EPS	15	4	Spherical	Slightly rough
EPP	18	6	cylindric	Slightly rough
Expanded glass	190	3	Spherical	Rough
ABS	720	6	Spherical	Plain
Cherry pits	578	7	Irregular	Rough
Rape seeds	722	2.5	Spherical	Plain

The investigated granules are different in material and, consequently, in their density, grain size, granular form and surface finish. Figure 6 and Table 1 give an overview on the investigated pellet materials.

EPP and EPS, due to their porosity, have a very low density (about 17 kg/m^3) and are elastically deformable. The surfaces of EPP and EPS are slightly rough. The grains of EPS granules are spherical in shape. The grain diameter is approximately 4 mm. The EPP granules have a slightly cylindrical shape and measure about 6 mm on their longest side. The ABS granules have a perfect spherical shape and have a diameter of 6 mm. They have a plain surface. Because they are solid, the density is nearly 50 times higher than that of the foamed plastic materials. Moreover, they are not elastically deformable. The granules of foam-glass are spherical, have a rough surface and

Figure 6 Selection of granules: from top left: EPP, EPS, expanded glass, ABS, rape seeds, cherry pits.

are fragile. Their diameter is about 3 mm. The density is 190 kg/m^3. The cherry pits have a very irregular shape with a slightly rough surface. The pits are inelastic. The rape seeds have the smallest grain diameter of about 2.5 mm. Their density is similar to that of ABS.

With the selection of these granules a wide range of different properties is covered. Low densities allow large volumes of cushion. High densities support the draping. Depending on the elasticity of the granules, the state of jamming at negative pressures can be reached or the cushion remains deformable. A good heat resistance of the granules supports the integration of heating technologies for the fixing step while preforming.

6.2 Selection of textile material for the gripper cushion

The investigation on potential materials for the gripper cushion identified two completely different fabrics, which are detailed in Table 2: a cotton fabric and a polyester fabric. Beside the difference in material, the fabrics are also distinctive in the weave. The single fibers of the cotton fabric are not firmly connected to each other. Therefore, this fabric has a good form-flexibility. The close weave makes it less air permeable, so the cotton fabric has a higher air drag. In contrast the polyester fabric is not woven as closely as the cotton. As a result, the air permeability is much higher. In addition, the single fibers are firmly connected to one another, which results in less form-flexibility. The different weaves and materials affect the area weight. The cotton fabric is about 14 times heavier than the polyester fabric. Moreover, the selected fabrics are distinguished by their heat resistance. Polyester can be exposed briefly to a temperature of 130°C. It melts at 225°C. Cotton, however, may be exposed for a longer period to temperatures of more than 200°C. The heat resistance of the materials might be important during preforming, when different textile layers are bonded to each other.

Table 2 Overview on selected textile materials for the gripper cushion. This selection contains textiles with different properties and is the basis for first practical experiences with the performance in the interaction with different granulates, Table 1.

Cushion material	Air permeability	Area density [kg/m^2]	Heat resistance [°C]
Cotton	Low	0.279	200
Polyester fabric	High	0.20	130 (briefly)

6.3 Experimental evaluation of material combinations

All materials mentioned were investigated in an experimental set-up, as described in the following section. The aim of the experiments was to determine the behavior of the selected materials while interacting in the gripper cushion. In the early state of the development of FormHand a general understanding of the working principles of the FormHand concept is important. Being interested in these fundamental practical experiments, the authors selected a candidate set of material combinations, which underwent basic testing procedures. These test procedures were carried out with a simplified test set-up of FormHand. The intention of these experiments is to obtain a general understanding of relevant performance measures and the influence of the design parameters involved. These results will guide the choice of more sophisticated elaboration methods to obtain sophisticated design principles and characterization procedures.

The following set-up was designed to conduct the experiment of interest, Figure 7: a simplified functional model of the gripper cushion is attached to a vertical linear axis. The simplified cushion is box shaped and consists of a soft but impermeable foam material. The inside of it is hollowed out. In the experiments it will be used as a clamping device for different materials. Samples of textile material are mounted to the foam material by small pins. The textile samples are exchangeable by removing the pins. At the same time the clamping device can be filled with different granules. In this way any combination of granules and textiles can be tested. The axis can move the clamping device up and down. A storage area under the clamping device provides space to place fiber cut-outs. A vacuum generator is connected to the clamping device, so that fiber cut-outs can be grasped, lifted and put down

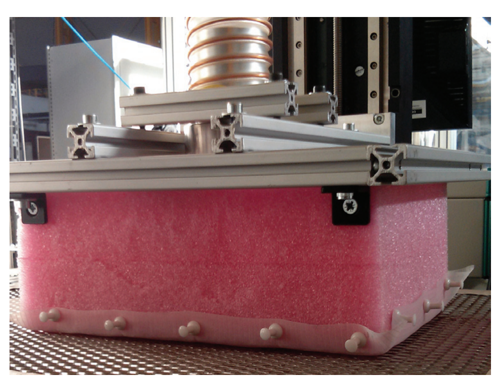

Figure 7 Experimental set-up for testing granulate-textile combinations for FormHand.

again. A sensor in the vacuum tube from the generator to the functional model of FormHand measures the airflow volume.

The following experimental runs were carried out to determine the minimal required airflow to lift carbon fiber blanks from a plane surface. Different sized carbon fiber cut-outs (100%, 50% and 25% of the surface size of the clamping device) were placed onto the storage area. From there they were grasped and raised by the clamping device. In each experimental run different combinations of textiles and granules were tested. In each experiment the air drag was measured, as Figure 8 depicts. In each case the air flow of the vacuum generator was adjusted, so that the textiles were held against gravity force. Each experimental run was repeated 30 times.

The data recorded in these experiments show a strong influence of the material combination on the performance of the gripper. It turned out that granules with low densities have a positive influence on the functional behavior of the gripper. If the weight of the filling is too high, sufficiently large differential pressure cannot be generated. In this case a grasping of the textile cut-out is not possible. Due to the air permeability of the entire system, the jamming of heavy granules cannot be achieved. As a result, the weight of the filling cannot be held against gravity force and the gripper surface cannot be reinforced. Therefore, lifting of textiles from the plane is difficult. The low density of EPS and EPP met this criterion in terms of low density and showed a good performance in combination with the tested cushion material.

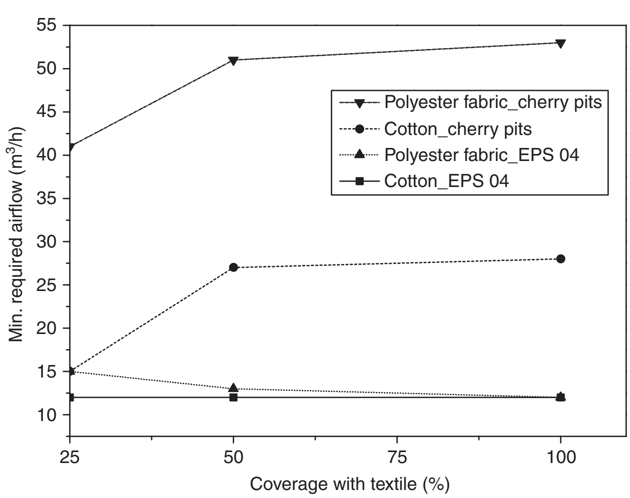

Figure 8 Required airflow for grasping fiber cut-outs depending on the combination of textiles and granules, but also the coverage of the gripper surface. The lower the airflow, the better the performance of material combination in the gripper.

During the selection of the cushion material the following has to be considered: low air permeability is advantageous for producing sufficient differential pressure inside the cushion. This has an effect on the required airflow rate when the gripper surface is covered only partially by a fabric, because a cushion with lower air permeability has less leakage at the uncovered parts of the gripper surface. The low air permeability of cotton fabric proved to be practical, whereas the permeability of the grid-like polyester fabric was too high.

Summing up and with regard to the build-up of the FormHand-prototype, EPS in combination with cotton showed the best performance in terms of a low airflow necessary for a reliable gripping and jamming process. However, this combination lacks the high temperature resistance necessary for the integration of heating technology into the prototype. The only material combination investigated that fulfills all requirements is the combination of cherry pits and cotton with the drawback of a lower gripping and draping performance. The performance of these material combinations in the overall preforming process is investigated and assessed in detail in Section 8.

7 Heating technology for the integration into the FormHand concept

The integration of heating technology within the FormHand concept is necessary for the activation of the binder which fixes the plies of the preform in its final shape. Section 2 indicated the high challenges that result from the function-integration of draping, gripping and heating into one preforming device. In this section, concepts are derived and assessed. The implementation of one concept in the FormHand prototype is described in detail.

7.1 Challenges and concepts for the integration of heating technology

Two crucial requirements were defined for a heating technology which can be integrated into the form-flexible preforming device described in the previous sections. The heating technology needs to allow for:
- a fast heating of the handled textile layer and
- a low negative influence on the handling process.

Especially the form-flexibility of the gripper cushion must 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 ultraviolet radiation) is prevented by the gripper, especially the gripper cushion textile and filling on one side, and by the mold on the other. Therefore, several heating technologies mentioned in Section 3 for binder activation in different preform setups were excluded at an early stage:

- Infrared heating is difficult to integrate 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 fibers could transfer the energy to the gripper cushion, which would greatly increase the complexity of the gripper.
- Direct heating of the carbon fiber preform by contact with the carbon fiber through electrical contacts on the gripper cushion was excluded due to the difficult adaption to different cut-out geometries.
- Heated molds 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 molds 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 Figure 9.

Induction heating was chosen because of its contactless heat transfer and high heating rates [7]. A fundamental condition is that electrically conductive textiles are handled and that the fabric has different fiber orientations.

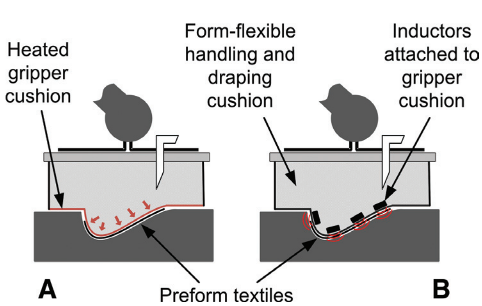

Figure 9 Form-flexible handling device with a heating textile (A) and with inductors on the gripper cushion (B).

Eddy currents can then be induced in the fiber 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 with the textiles. An approach for the integration of this technology into 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 fiber) are typically integrated in or on a supporting textile. A contact 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 (Figures 3 and 9).

The heating characteristics and integration concepts of both technologies were evaluated in initial investigations. The results for induction heating showed that the heating power of available and adequately small inductors was not enough to reach the melting temperature of the binder. Thus, the second concept was pursued in this paper and described in detail in as follows.

7.2 Conductive heating by heating textiles

Two ways for the integration of heating textiles into 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 fulfill both requirements from the handling and heating perspectives. Alternatively, 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 gripping and draping:

- air permeable and
- drapable

and heating:

- temperature resistance to allow high temperature differences between cold preform textiles and heating textiles 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 and
- electrical isolation against preform carbon textiles.

Table 3 Comparison of heating textiles.

Textile	Supplier	Maximal temperature	Draping	Aerial weight	Material	Heating power
Polymerweave with isolated copper filaments	Sefar AG, Switzerland	180°C	Good	0.090 kg/m²	PET Monofilament+ Copper filament	1000 W/m²
Carbon fiber rovings on glass fiber	Gerster TechTex GmbH and Company. KG, Germany	230°C	Ok	Approx. 0.300 kg/m²	PES+Carbon fiber rovings	>3000 W/m²

Two different commercially available heating textiles were evaluated, Table 3: A textile made of isolated copper fibers bonded to a polyethylene terephthalate (PET) fabric (A) and carbon fiber rovings stitched to a glass fiber fabric (B). Both are based upon electrical resistance heating. Table 3 compares these textiles and assesses their properties according to the requirements defined above.

The heating textile A has a very 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 fiber 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 second heating textile B that was investigated is based on carbon fibers as heating elements, which are stitched to a glass fiber fabric, Figure 10. It is much thicker than the other textile, but has a good draping and acceptably low bending stiffness. The glass fiber layer could be eliminated in future optimization loops to further improve the draping behavior and decrease the thermal barrier between resistance-heated carbon rovings and preform. However, the electrical isolation against the carbon fibers of the preform is guaranteed by the glass fiber 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 Figure 10. The heated carbon fiber 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 B was used for further heating investigations and in the prototype FormHand.

The experimental set-up for these heating experiments with conductive heating textile B is depicted in Figure 11. Three layers of carbon fiber 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 layers (T5) as well as the second and third (T6),Figure 11.

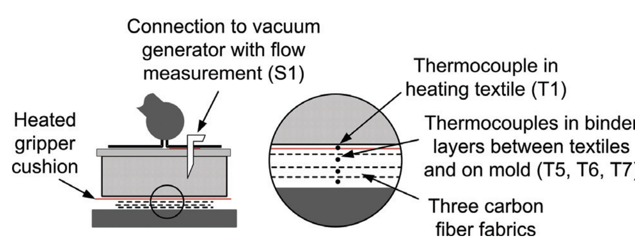

Figure 11 Experimental setup for conductive heating.

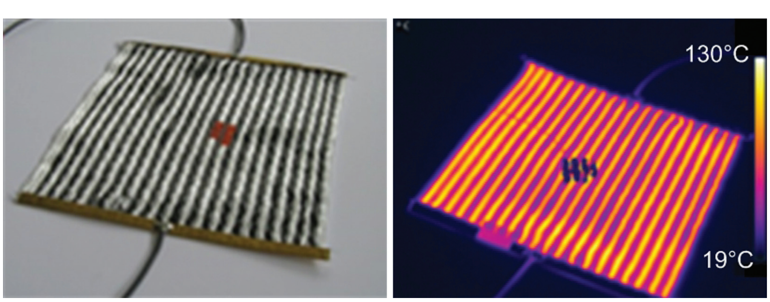

Figure 10 Heating textile (B) by Gerster TechTex (left) and thermal image (right).

The gripper is connected to a vacuum generator via the air connection (1). Both a 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 mold can be seen in Figure 12. While the heating textile reached a temperature of 140°C within 4 s, the temperature in the preform below the top layer increased late and with a lower heating rate. The melting temperature of the binder was reached after approximately 28 s. 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 mold can be exploited for the pre-heating of the handled textile. During this phase a low pressure wass applied to grip and hold the textile during transport. Experiments were conducted to assess the influence on the heating performance. Figure 13 shows the temperature over time for different air streams. While the initial heating rates vary only slightly, the temperature increased more slowly at higher temperatures with higher airstream flows. The maximum temperature reached after a 35 s heating cycle with the same electrical power decreased accordingly. The loss in heating power depending on the air stream needed to be compensated by a higher power supply during heat-up.

When the air stream decreases the heating rates during heat-up, it might help to accelerate the process during the

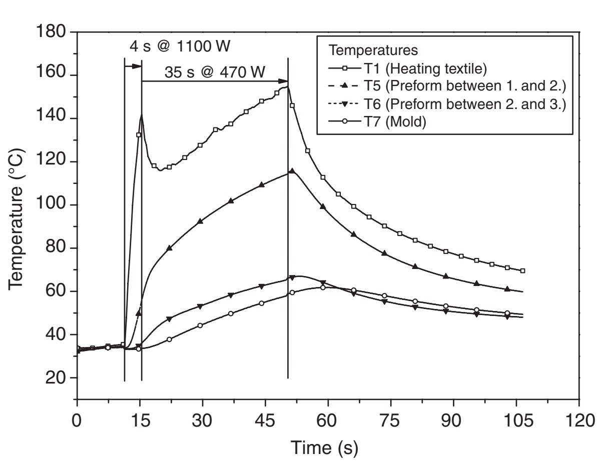

Figure 12 Temperature on heating textile (T1) and in preform (T5/T6) over time during conductive heating.

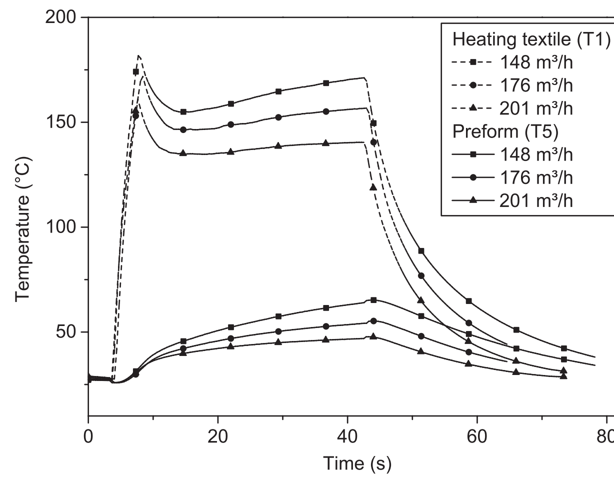

Figure 13 Influence of the gripping air stream on the heating performance.

cooling phase. The gripper can be lifted from the preform as soon as the binder solidifies below its melting temperature. Therefore, if the cooling rate can be increased by the air stream, a shorter cooling phase can be realized. The cool down for different air streams is shown in Figure 13. It depicts that the time to cool down the preform decreases with an increasing airstream up to 200 m^3/h. This helps to increase the layup rate of the preform gripper.

Altogether, the results show that a heating textile could be identified, which will allow for enough heat energy to be transferred into the binder layer of the preform so that the melting point is reached. Furthermore, the experiments with the airflow showed that the heating textile offers a good air-permeability. However, the interdependence between the three process steps, gripping, draping and fixing, need to be investigated in detail. The investigated heating textile was chosen for the prototype which is described in the following section.

8 Validation of FormHand concept by manufacturing of a generic preform

The characterization of materials and the heating technology described in the previous sections showed that components could be found which successfully allow for the realization of each process step individually. Furthermore, the tests showed that an acceptable interdependency can be expected between the heating technology and the gripping and draping components. For the validation of the whole FormHand system the components of the isolated tests were combined in a demonstration prototype and utilized in an automated preforming process.

8.1 Validation of gripping and draping

For the validation of the functionalities *gripping* and *draping* of the described tool a first prototype was built-up. For the realization of the considered process chain this prototype was not equipped with heating technology. This simplification was done to transfer the fundamental results from Section 6 to the complex challenges of the gripping and draping during the preform manufacturing. The prototype is depicted in Figure 4. The best material combination from Section 6 was chosen for the validation of gripping and draping. Furthermore, the surrounding system needed to be built-up, which comprised: Form-Hand-prototype; an industrial 6-dof robot arm; a force-torque-sensor; a vacuum supply and a control unit. In this system the FormHand device was mounted to the industrial 6-dof robot arm and was connected to the vacuum generator via a vacuum hose (see Figure 4).

The described system was used to validate the steps of gripping and draping of textiles first, which is shown in Figure 14. One layer of cut-out fiber material was carried with the even and hardened gripper cushion, Figure 14 left. The carbon fiber stays firmly at the bottom of the cushion. Carrying and moving the cut-out at the gripper with moderate speed showed no disarrangement of the textile. After positioning the gripper cushion with the textile over a generic mold, see Figure 14 middle, the cushion was pressed into the mold. At the same moment the airstream was reduced. In the tests the cushion could be easily inserted into the mold while the textile could still be gripped. This showed that a simultaneous gripping and draping was possible. A draping of the textile cut-out was performed without any visible drawbacks, Figure 14 right. Furthermore, the shape of the cushion can be kept after forming in the mold while gripping of the now-draped textile was still possible.

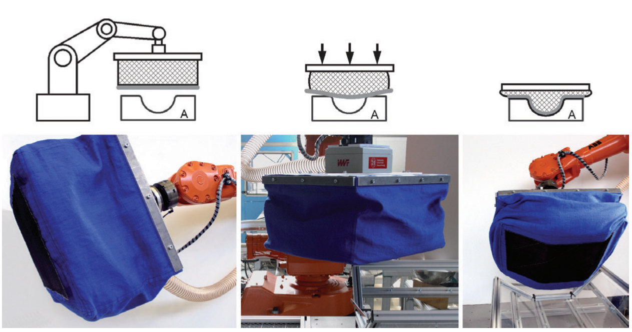

Figure 14 Application of FormHand in a demo process for proving the concept of a form-flexible handling technology. Left: grasping a cut-out of carbon fiber material at the even gripper, middle: placing the FormHand module over a transparent preform mold, right: FormHand lifted out of the preform mold with a molded carbon fiber cut-out.

All experiments described can be carried out automatically, which showed the high potential of the Form-Hand-concept for complex draping processes. However, built-up preforms with several layers and their fixed shape binder and its activation was necessary. As pointed out in the summary of Section 6, a high temperature resistant material combination was required. Therefore, the filling EPS was replaced by cherry pits. Nevertheless, further experiments showed that draping and gripping was still possible, so manufacturing of preform can be assessed, which is described in detail in the following subsection.

8.2 Validation of preform manufacturing

A second hardware prototype of the FormHand-Concept with temperature resistant filling and an integrated heating textile has been tested and validated for the manufacturing of a generic s-shaped preform. The gripper was on a lab scale and had dimensions of approximately 300×200 mm. It allowed for a forming depth of 150 mm.

The binder powder EPIKOTE 05390 was used and applied one-sided on three plies of non-crimp fabric (0°/90°) consecutively, Figure 15 (A). Afterwards the textiles were draped into the mold by FormHand, Figure 15 (B). The preform shape was fixed by heating the binder to approximately 100°C through the heating textile on the gripper cushion. Figure 15 (C) depicts that FormHand could completely drape the textiles into the shape. The final preform showed that the binder activation was successful. All three process steps could be realized with one integrated tool. These experiments validate the concept of FormHand for an automated preforming process.

9 Summary, conclusions and outlook

This article introduces a novel form-flexible gripping and handling tool and the design and validation of the required process for this tool. The development of this

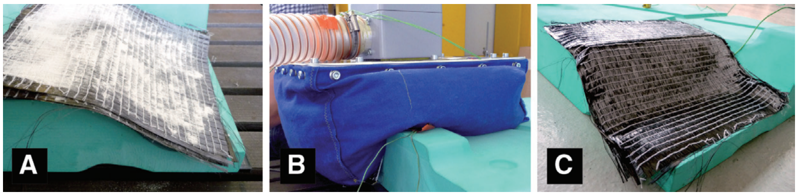

Figure 15 First preforming with a prototype of FormHand. Two layers of carbon fiber textile are preformed with hotmelt adhesive. Left: application of hotmelt adhesive, middle: draping and fixing of textile layer, right: preformed textile layers.

concept was triggered by the technological gap of manual preforming and a desired high volume production of composites. Particularly, the presented work aims at providing automation equipment and processes to handle, drape and fix limp material into a near net shape. The developed concept, the selection of the required materials for a first prototype realization and the results of tests with this prototype are described. Induction and conductive heating are initially assessed as possible technologies for the integration into a preform handling device.

From the experiments to characterize the granules and textiles for the gripper two main parameters were identified: the density of granules and the air-permeability of the gripper cushion. It was concluded that contradicting requirements are imposed by the gripping and draping. While higher air permeability allows for a better gripping on the bottom of the tool, lower air permeability improved the jamming effect supporting higher forming forces. It turned out that the requirements of the granules with high temperature resistance, low density and a mechanical stability are difficult to meet. However, with the selection of a cotton gripper cushion and cherry pits as granules, a combination of materials could be identified which enabled a temperature resistant tool that was able to grip and drape textiles.

The evaluation of heating concepts revealed that heating textiles are most adequate for the integration into the preforming tool. A heating textile could successfully be integrated without constraining the gripping and draping performance. The results showed that the heating textile was suitable for the binder activation within the handled preform. The crucial temperature of at least 100°C has been reached between the top layers of the prototype preform to melt the binder and fix the carbon fiber textiles of the preform.

The prototype of the form-flexible handling and joining tool was used to manufacture a generic preform. It can be deduced that the presented tool concept was basically able to implement the necessary process steps during preforming.

Further work will concern deeper understanding of the materials and design and their influence on the abilities of FormHand in the preforming process. The aim is to find methods to build-up FormHand devices for specific parts within automated industrial processes. Furthermore, the lab-scale prototype needs to be resized to allow for the manufacturing of larger and more complex preforms.

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