FORM-Flexible Handling Technology for Automated Preforming

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Abstract
The production of composite components for automotive applications using the RTM (resin transfer molding) technology still faces challenges. This paper focuses challenges that occur during the preforming. With respect to the handling technology, the preforming is one of the remaining automation challenges in the RTM process chain. To face these challenges this paper suggests a concept for a form-flexible handling technology, in called FormHand in this article. Further, this paper describes the application of this concept, looks at key aspects of the realization phase for a first experimental setup and discusses test results with a first prototype. This prototype already validates the features of the proposed concept. After a summary, this paper discusses future research fields according to the concept of FormHand.

1 Introduction
The automated production of composite components for automotive applications in a large volume scale still faces unsolved challenges. Among the vast number of production technologies under discussion, numerous reports recommend resin transfer molding (RTM) for a high volume production especially in the automotive context. Though praised regularly for its potential to cut down cycle times in general, RTM requires the production of fiber preforms, which is time consuming and complex. Figure 1 illustrates the RTM production process in the upper (blue) process chain. After the cutting of textile plies into desired shapes is done, these cut-outs are transported to a preforming unit. In the process step of preforming, tailored fiber blanks are draped into a near net shape and joined to form the preform. This process step is carried out manually or automated, 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 After cooling down the RTM tool, the composite is withdrawn from the tool and goes to the finishing process step, e.g. machining, painting or polishing.

The above described production process is the basis for the research of the current paper. A focus of the described research is laid on the preforming. This production step shows the following challenges for a competitive handling technology.

1.1 Challenges for a handling technology in the preforming process
In the RTM production process, the preforming is in terms of handling technologies the most crucial production step. For this process step, there is still no mature automation technology available. Of particular interest is the handling (gripping and transporting) of fiber blanks and the transfer from a flat geometry into a three-dimensional preform, the draping. Besides this, there are unsolved issues during the fixing process of different textile layers in the preform mold. Currently, these steps still require considerable manual effort, the automotive industry is not willing to accept.

The lower part of figure 1 depicts the single process steps within the preforming. Each process step raises its peculiar challenges for the handling, as described in the following:

1. The process chain (in red) starts with the gripping of the textile patches and the transfer to the preform table. Fiber material (glass or carbon) are both limp materials and permeable to air. 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 to form cuttings or
wrinkles which have to be avoided by a selective and guided draping.

3. Once the textile is placed in its final position in the preform tool, it is fixed and connected to other layers of textiles. Usually for fixing different types of heating technologies are required.

4. After fixing, the final preform is transferred into the RTM tool. Due to the fact that even a preform of more than one layer still has a limp behavior it has to be handled with care. There, the challenge for the handling device occurs from the three-dimensional shape that should not be damaged during transporting. Also the exact positioning of the preform in the RTM tool has to be considered in the design of an appropriate handling device.

The number of challenges shows that there is the need of an enhanced and specialized handling technology for preforming. One main focus must be on gripping of air permeable material. Another focus lies on the required form-flexibility to be capable of draping limp material into the desired shape of the final preform. A third focus is determined by an appropriate fixing technology within the handling tool.

1.2 Development of an enhanced and specialized handling technology

The technological gap of manual preform processes for high volume production lines, as well as the described challenges for handling 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:

Encouraged by the availability of a very flexible and free programmable robot technology, there must be a way to find a flexible handling device that can meet the challenges of a complex preforming process. This handling device empowers an automated preforming with similar results as a manual process with less effort.

This approach leads to questions concerning the basic design elements for the realization of a handling technology as flexible and as capable of complex tasks as the human hand. Other questions concern the integration of functionalities into such a handling device, especially the required fixing technologies, so that the complex preforming becomes more competitive.

It is obvious that only the reconstruction of a human hand cannot empower a production process into a large volume scale process. Furthermore, a more process specific machine concept is required. Therefore, in the cooperation of IWF and ifs a novel form-variable handling technology (called FormHand) is investigated. The research topics in the new field of FormHand are as diverse as the main research fields of the cooperating institutes.

In order to find answers to the put questions, this paper discusses the concept and ideas behind FormHand and shows experimental results obtained during the preparation of RTM preforms. There is a second paper, also published at ICCM19, which treats “Form-Flexible Heating Devices for Integration in Preform Gripper”, [1]. It investigates important aspects of FormHand that empower the presented concept with further functions that are required for realizing a highly sophisticated performing for RTM production. Namely, the additional paper describes concepts for a heating or fixing technology that along with the here presented form-flexible handling technology aim at the automated production of RTM preforms.

This paper presents in the following a more detailed description of the conceptual design of FormHand. After this, the selection of materials for a first experimental set-up is described. This prototype realizes experiences with FormHand which are illustrated in the second part of this paper. This part introduces also demo applications of FormHand. The final section discusses first results and gives an overview on the future work.

2 State of research

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 in research. All of them are currently in development. The following examples give an overview on concepts for preform grippers that cope with the same challenges as FormHand. These designs introduce form-flexible grippers for limp material to transform or drape textiles from the plane into a three-dimensional shape.
The device described in [2, 3] was designed at IWB, Munich, Germany. The gripper, shown in figure 2, 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 temporally 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, see figure 3 and [4]. 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 [5] and shown in figure 4. 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. Because of 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 depicts figure 5. It was designed at ITA, Aachen, Germany [6]. 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 re-shaping is realized with a rolling movement performed by the robot arm. Therefore, this end-effector is not as flexible as the others.

Other designs [7, 8, 9] realize a passive form-flexible end-effector that bases on jamming of granular material. In the most simple 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. The design of FormHand extends the design of the described prototypes and recombines most promising features. This design is described in the following.

3 Concept of a novel form-flexible handling technology

The given overview on the state of research shows that there is a noticeable number of experimental set-ups to meet the challenges of preforming as described in section 1.1. Still there are limitations to the proposed approaches. Therefore, FormHand is developed with a focus on gripping of air permeable material and a maximal form-flexibility to realize a draping of limp material. It is designed to realize an automated preforming with an integrated heating technology.
3.1 Design of FormHand

FormHand comprises a form-flexible vacuum tool that can be used in different configurations during the preform process: as a gripper, as a draper or as a form tool. A more detailed description of these applications follows in section 3.2. This innovative concept of FormHand is ready for the integration of further functionalities, such as heating (further described in [1]), actuation or sensor-based quality assurance.

Figure 6 shows a conceptual design of FormHand with its main parts. The form-flexible handling device consists mainly of a base frame (1) and a cushion (3). The base frame has three main functions:
1. Supply the interface with a robot and the vacuum generator via a connection tube (2),
2. Give stability to the cushion (transmission of process force while draping) and
3. 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. This cushion distinguishes FormHand from other concepts that are described in section 2. The stiffness of the cushion can be changed with an adjustable airstream by vacuum suction via 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 work piece is ingested by the airstream through the gripper cushion. If these objects are flexible or limp material, e.g. cut-outs of a textile, FormHand can change their shape. With an increased airstream the gripper cushion becomes solid which allows a direct forming or draping of the textile into a mold. Figure 7 shows the realization of this concept in hardware for testing the idea of FormHand in an industrial environment.

3.2 Application of FormHand in the RTM preform process

Section 3.1 already introduced different ways of using the form-flexibility of the FormHand concept. Figure 8 shows the application of FormHand during preforming. In the upper line, the piled cut-outs of a textile are gripped by the cushion of FormHand. The cut-out is flat at the bottom of the cushion. In this state, the cushion is hardened and inflexible. As an end-effector, FormHand can be placed over a preform mold. The preform mold is denoted in figure 8 with A. A lower airstream increases the mobility of the granulate material inside the cushion. A higher mobility of the granulates makes the cushion form-flexible again. This allows the gripped material to be draped, see second line of figure 8. After fixing the actual textile layer to others in the mold and repeating the process, FormHand transports the preform to the RTM tool, marked with B in figure 8. There, different preforms may be combined. After this assembly step, the RTM tool closes and resin is injected.

4 Selection of granular and textile material for FormHand

The description of the concept of FormHand in section 3 makes clear, that there are two key aspects for a successful realization of FormHand: A suitable granulate material as a filling for the gripper cushion and a flexible textile for the cushion itself.

This triggered an investigation with the aim to identify material requirements for the filling and for the cushion of FormHand. To achieve this aim, basic practical experiences with the behavior of candidate materials have to be gathered by the experimental use of these materials. These experiments will provide the basis for a later optimization or a specific design of required materials. The following sections describe materials that were chosen for these experiments. The selection process was determined by two aspects: availability and diversity of the materials.

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

The investigation included granulate pallets from three categories:
1. Synthetic materials such as expanded polystyrene (EPS), expanded polypropylene (EPP) and acrylonitrile butadiene styrene (ABS).
2. Recycled and expanded glass.
3. Biological materials such as cherry pits or rape seeds.

The investigated pallets are different in material and, consequently, in their density, grain size, granular form and surface finish. Figure 9 and table 1 give an overview on the investigated pallet materials. EPP and EPS, due to their porosity, have a very low density (about 0.017 kg/l) and are elastically deformable. Its surface is slightly rough. The grains of EPS pallets are spherical in shape. The grain diameter is approximately 4 mm. The EPP beads have a slight cylindrical shape and measure about 6 mm at its longest side. The ABS beads 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 granulates of foam-glass are spherical, have a rough surface and are fragile. Their diameter is about 3 mm. The density is 0.19 kg/l. The cherry pits have a very irregular shape with a slightly rough surface. The pits are inelastic. The rape seeds have the slightest grain diameter. It is about 2.5 mm. Their density is similar to that of ABS.

With the selection of these granulates 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 granulates, the state of jamming at negative pressures can be reached or the cushion remains deformable. A good heat resistance of the granulates supports the integration of heating technologies for the fixing step while preforming. Experiments with these granulates, as described in the following, have the aim to form a better understanding of their behavior. This understanding leads to a specific application of certain granulates for special purposes.

4.2 Selection of textile material for the gripper cushion

The investigation on potential materials for the gripper cushion identified two completely different fabrics: a cotton fabric and a polyester fabric. Beside their difference in material, the fabrics are also distinct in their weave. The single fibers of the cotton fabric are not firmly connected with 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 with each other, which results in less form-flexibility. The different weaves and materials effect on the area weight. The cotton fabric is about 14 times heavier than the polyester fabric. Moreover, the selected fabrics distinguish in 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 layer are bonded to each other.

The fabrics were chosen to compare the different properties of the materials in practice and find out which effects they have on the functionality of FormHand. Table 2 gives an overview on the selection of textiles for the gripper cushion. On the basis of these practical experiences further experiments will be carried out.

4.3 Experimental evaluation of material combinations

All mentioned materials 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 they are 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 experiences, 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, see figure 10: 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. At the inside it is hollowed out. In the experiments it will be used as 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 granulates. In this way any combination of granulates and textile 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 again. A sensor in the vacuum tube from the generator to the functional model of FormHand measures the volume airflow.

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 size of the surface 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 granulates were tested. In each experiment the air drag was measured, as figure 11 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 thirty times.

The data recorded in these experiments shows a strong influence of the material combination on the performance of the gripper. It turned out that granulates with low density have positive influence on the functional behavior of the gripper. If the weight of the filling is too high, no sufficient large differential pressure can 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 granulates cannot be achieved. As a result, the weight of the filling cannot be held against gravity force and the gripper surface cannot be reinforced. Lifting of textiles from the plane is then 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.

During the selection of the cushion material the following has to be considered: low air permeability is advantageous in order to produce 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.

The best performing material combination is determined by a low airflow with a reliable grasping of the fiber cut-outs. Figure 11 shows that EPS pallets in combination with the tested cotton material perform best in each test case.

5 Validation of the FormHand concept
With the practical experiences from the above sections a first functional model of FormHand was realized, see figure 12.

The blue surface represents the gripping cushion. It is filled with small polystyrene pallets, see section 4.1 and table 1, row 1. In the figure 12 the module holds a cut fiber blank in the middle of the cushion via an airstream provided by a vacuum generator. The figure shows the state after forming the cushion on a 50 mm deep mock-up (at the right) of a part that might be produced in carbon fiber reinforced plastic (CFRP).

In summary these practical tests validated a gripping, holding while transport and forming of textile materials with FormHand. Figure 13 depicts the infrastructure for carrying out the first experiments with a FormHand module. There is a vacuum generator with control at the right which is attached to a FormHand module (left) via a flexible hose. With this set-up, it was possible to carry out further tests for validating the concept of FormHand.

5.1 Set-up for the validation of FormHand
For rebuilding the application of FormHand from section 3.2 and figure 8, the prototype from figure 7 was used. In this reconstruction the FormHand device is mounted to an industrial 6-dof robot arm. Figure 7 also shows the connected vacuum hose, coming from the vacuum generator, see figure 13. A series of tests showed, that in a semi automated process the concept of FormHand is performing well. Figure 14 shows the steps of the application of FormHand (at the top) with equivalent shots from the test series (at the bottom).

5.2 Results of the validation of FormHand
One layer of cut-out fiber material could be 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 shows no disarrangement of the textile. After positioning the gripper cushion with the textile over a generic mold, see figure 14 middle, the cushion is pressed into the mold. At the same moment the airstream is reduced. In the tests the cushion could be easily inserted into the mold. A draping of the textile cut-out was performed without any drawbacks, see figure 14 right. Another test series of a simple preform process demonstrated the preforming ability of FormHand with an integrated heating device, see figure 15. In the demo process two layers of carbon fiber are placed manually on a s-shaped preform mold. Hot melt adhesive is distributed between the single layers, see figure 15 at the left. By placing a FormHand module on to the preform mold the carbon layers are draped into it. The FormHand module is equipped with a heating device. The heating device activates the hot melt, see figure 15 in the middle. More de-
tails of the heating and activation process describes [1]. The result of this demo process is shown in figure 9 at the right. With the help of FormHand it was possible to produce a demo preform that is ready for the following RTM injection process. No preconfiguration of the tool or complex control units are required. Only by the design of the FormHand module and its form-flexibility the demonstration of this simple preform process could be carried out in such an easy way.

6 Summary and outlook

This paper introduced a novel form-flexible gripping and handling technology. The development of this concept was triggered by the technological gap of manual preforming and a desired high volume production of composite. Particularly, the presented work aims at providing automation equipment to handle and drape limp material into a near net shape. This paper describes the developed concept, the selection of the needed materials for a first prototype realization and the results of tests with this prototype. All test procedures showed very promising results.

Further work will concern the integration of other functionalities than gripping into FormHand. This integration will increase the parallelization of processes and therefore speed up the production of fiber preforms. Before integrating FormHand into production processes a deeper evaluation of the discussed materials for the prototype realization is required. This paper only described a first approach for finding a good combination of granulates and cushion textiles. A development of custom made granulates will start with the simulation of the granular behavior inside the cushion. A next step for a better process control is the integration of a force torque sensor system into the FormHand module. With the generated data a better knowledge of the process forces is expected. This also supports the simulation of the granular behavior. The evaluation of energetic aspects is also focused in the future.

References

Figures and Tables

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

Fig. 2: IWB, Munich – handling and preforming with an elastic vacuum gripper. The draping process is realized by a rolling movement of the tube shaped end-effector.

Fig. 3: Fraunhofer, IPT Aachen: handling and preforming of limp material with a fin-ray like gripper. Grasping and draping is supported by the movement of the gripper structure.

Fig. 4: IGM, Aachen – handling and preforming with a parallelogram structure and discrete grasping elements (cryo or needle gripper).

Fig. 5: ITA, Aachen – end-effector for handling and preforming limp material. Cryo or needle grasping modules are mounted on a convex draping element. Grasping and draping is supported by the movement of the robot arm.

Fig. 6: A conceptual design of FormHand with its main design parts.
Fig. 7: FormHand mounted to a six DOF industrial robot with connected vacuum supply.

Fig. 8: Application of FormHand in the RTM process.

Fig. 9: Selection of granulates: from top left: EPP, EPS, expanded glass, ABS, rape seeds, cherry pits. For further details see table 1.

Fig. 10: Experimental set-up for testing granulate-textile combinations for FormHand.
Fig. 11: Required airflow for grasping fiber cut-outs depending on the combination of textiles and granulates, but also the coverage of the gripper surface. The lower the airflow, the better is the performance of material combination in the gripper.

Fig. 12: Functional model of FormHand for the validation of gripping and forming (approx. 50 mm deep) of a textile material.

Fig. 13: Set-up for testing the handling device. A FormHand module (left) connected to a vacuum generator, at the right.
Fig. 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.

Fig. 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
Tab. 1: Six granulates under investigation for FormHand. Granulates are required as a filler for the gripper cushion. Depending on the characteristics of these granulates a high form-flexibility of the FormHand cushion can be realized.

<table>
<thead>
<tr>
<th>Granulate Material</th>
<th>Density [kg/l]</th>
<th>Diameter [mm]</th>
<th>Form</th>
<th>Surface/Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>0.015</td>
<td>4</td>
<td>spherical</td>
<td>slight rough</td>
</tr>
<tr>
<td>EPP</td>
<td>0.018</td>
<td>6</td>
<td>cylindric</td>
<td>slight rough</td>
</tr>
<tr>
<td>Expanded glass</td>
<td>0.190</td>
<td>3</td>
<td>spherical</td>
<td>rough</td>
</tr>
<tr>
<td>ABS</td>
<td>0.720</td>
<td>6</td>
<td>spherical</td>
<td>plain</td>
</tr>
<tr>
<td>Cherry pits</td>
<td>0.578</td>
<td>7</td>
<td>irregular</td>
<td>rough</td>
</tr>
<tr>
<td>Rape seeds</td>
<td>0.722</td>
<td>2.5</td>
<td>spherical</td>
<td>plain</td>
</tr>
</tbody>
</table>

Tab. 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.

<table>
<thead>
<tr>
<th>Cushion material</th>
<th>Air permeability</th>
<th>Area density [g/m²]</th>
<th>Heat resistance [°C]</th>
</tr>
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<tbody>
<tr>
<td>Cotton</td>
<td>low</td>
<td>279</td>
<td>200</td>
</tr>
<tr>
<td>Polyester fabric</td>
<td>high</td>
<td>20</td>
<td>130 (briefly)</td>
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