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Novel Robot-Based Process Chain for the Flexible Production of Thermoplastic Components with CFRP Tape Reinforcement Structures

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Abstract

A process for flexible preforming of thermoplastic CFRP tapes strips has been implemented at wbk Institute of Production Science. An overview of the preforming process and the approach for the further processing of the preformed strips by additive manufacturing (AM) are presented in this paper. The combination of the novel preforming process and the future AM processing results in a fully flexible process chain for fiber reinforced components.
The novel, robot-bending based process is used to manufacture near-net shape preforms for reinforcement structures with a high accuracy. First, possible angles, the bending parameter selection and the obtainable accuracy are described. Afterwards, a toolbox for deriving a process compliant reinforcements shape from the target geometry is presented. Required parameters, such as bending angles, are automatically derived using shape analysis and evolutionary optimization.
The second step after preforming the strips is their assembly to a reinforcement structure and subsequently a component. To maintain the flexibility, molding shall be replaced or complemented by AM techniques. In this paper, a projected overall process chain is presented as well as results of the processing of the strips in AM. AM and a local consolidation unit are used to join the strips. The first step of joining consists of aligning the strips to each other and to the components. The AM process is used to apply additional layers and to join structures to the strips and components. For the production of a tough material bond, the printed layers and strips are selectively heated and pressed together with a local consolidation unit. Various strategies and suitable process parameters for joining are experimentally identified. In combination with a second collaborating robot, this opens up new approaches for joining preforms to reinforcement structures and for fiber reinforcement in AM. Furthermore, possible applications of this process are presented.

Keywords: Process Control; Fiber Reinforced Plastic; Multi-Robot concepts and systems;

1. Introduction

Fiber Reinforced Plastics (FRP) offer unique weight specific strength and stiffness especially with carbon fibers. In large scale production, FRP components can be manufactured using molding processes. However, metal designs often still offer a price advantage compared to FRPs due to material cost and long cycle time. Cost-wise, FRP can have an advantage over metals if small lot sizes are made thanks to the lower installation cost. Hand lay-up is one example for a process which is suitable for manufacturing small lot-sizes. It is used both in prototypical applications as well as serial production (e.g. small aircraft). Additive manufacturing is already widely used for prototypical application or individualization of purely plastic components. Research is focussed on the integration of reinforcement fibers into additive manufacturing processes,

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e.g. Arburg Plastic Freeforming [1], Fused Layer Modeling (FLM) [2] and Selective Laser Sintering (SLS) [3]. In these approaches, single fibers or rovings are used to reinforce the components, which limits the process speed. Due to the poor impregnation of the fibers in some of these processes, the adhesion between fibers and matrix is comparatively weak [4]. Furthermore, fibers can only be placed within the planar layers [5]. Additionally, there are other deficiencies in fiber reinforcement in 3D printing that need to be investigated like the influence of high void content as failure initiators [6]. In this paper, an approach for the integration of unidirectional (UD) tape strips into large additively manufactured (FLM) parts is presented as a proposed solution to the deficiencies mentioned.

2. Process Chain

FLM parts are made by layer-wise placement of molten thermoplastic beads. Although the layers are usually flat and parallel, segmented parts with tilted layer orientations (aka non-planar 3D printing) have also been manufactured [7]. In the process chain developed at wbk Institute of Production Science, preformed UD tape strips are integrated into such parts. The main steps for this are:

- Digital process chain for individual process planning
- Manufacturing of the UD tape preforms
- Printing of the base components using purely thermoplastic or fiber filled material
- Handling and joining of the preforms onto the base components
- Consolidation and overprinting of the preforms

A process for the flexible preforming of UD tapes using robotic swing-folding was developed at wbk [8, 9]. The process can be used to manufacture preforms consisting of flat regions in the orientation of the FLM layers which are connected with bends. The process and its advantages are briefly introduced in section 3.1. The process accuracy evaluation to ensure compatibility to the process chain is presented in section 3.2. In section 3.3., an approach for the semi-automatic derivation of preform geometries regarding the process chain restrictions is presented.

A robot extrusion system [10] as shown in section 4 is used for printing the base component which is a special form of FLM due to the direct processing of granules and therefore called Fused Granular Fabrication (FGF). In the single screw extruder up to 900 g/h of material can be plasticized and heated to 450 °C. It is able to process various thermoplastic unfilled and short fiber filled granules (e.g. Polyamide (PA)). Using fiber filled material, the base performance of the part can be improved compared to the performance of pure thermoplastics.

To further improve the mechanical properties, the UD tapes are joined to the base part. First, they are placed on the component by a robot. Afterward they are consolidated and overprinted. This poses two challenges: For high flexibility, manual programming must be avoided which requires automatic code generation for all hardware devices in the cell. To conduct the forces into the reinforcement strip, a good bond is needed requiring suitable methods and parameters for the consolidation and overprinting.

The experimental cell used for this project consists of two robots and a tilting heated print bed (as shown in Fig. 1). The two robots allow parallel production of the preforms and printing of the base component, which reduces process times. The two robots collaborate to position and join the preforms and the base component. The tilting heated print bed is synchronized with the robots and ensures that the extruder is aligned as vertically as possible during the entire production process to avoid problems during non-planar printing.

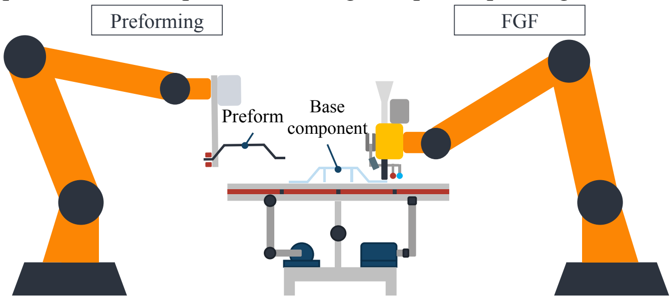

Fig. 1. Experimental cell with tilting print bed

3. Flexible Preforming by Robotic Swing-Folding

During preforming, the raw material is brought into a shape which enables the following process steps. In large scale production, preforming is needed to insert the material into the mold and mold it without damaging it. In the process chain defined in this paper, it is used to adapt the shape of the reinforcement tape to the parts shape prior to assembly.

3.1. Process Description

A novel robot based swing folding process was developed for the preforming of the strip at wbk. The process consists of four main process steps (Fig. 2.):

1. The UD tape is unreeled and gripped by a jaw gripper
2. The tape is heated using infrared (IR) radiation
3. The tape is bent by the robot movement
4. After several iterations of step 1 to 3, the tape is cut from the spool and handled further by the robot end effector

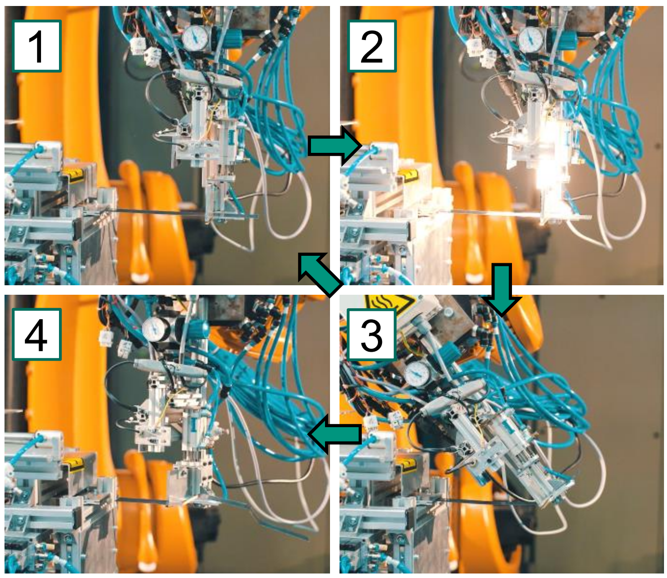

Fig. 2. Steps of the sequential swing folding process

In the representation in Fig. 2, the tape is supplied from the supply unit in the left. In the right of the figures, the end effector is visible. When inserting the gripper onto the tape, a gripper position close to the supply unit is desirable to minimize influences of the elastic deformation of the tape. After insertion, the gripper can be moved along the tape to the gripping position. The heating of the tape is realized with either a radiation heater (as shown in Fig. 2.2) or an additional pair of heated gripper jaws. Once the tape is preheated, the robot movement begins and the radiation heater is switched to a low power heating level. The heating is deactivated after the robot executed the bending movement. Simultaneously, a cooling nozzle is switched on. As soon as the tape is solidified, the gripper can be opened and removed from the tape. The process is repeated sequentially until the part is finished.

With the described process, reinforcement geometries consisting of plane section connected by bends can be made. The execution of the process takes approximately 10 seconds per bend. In experimentation, especially the angular accuracy of the bend proved to be challenging [11]. A description of the process kinematics and accuracy is given in section 3.2. In section 3.3, an approach to automatically adapt the bend parameters to approximate a given 3D input shape is presented.

3.2. Experimental Analysis

The preforms made with the bending process can be described as straight segments connected with bends. Parameters are the length of each segment l_i, the rotation of the bending line α_i and the amount of bending β_i. In Fig. 3, parameters for a sample specimen are described. The most critical factors for the overall quality of the preform is the accuracy of the β angles as their error adds up along the tape length [11].

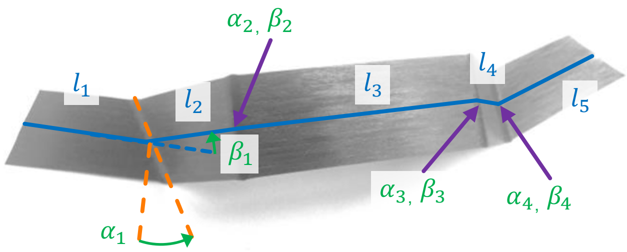

Fig. 3: Parameters for the description of the preforms

Two heat sources (as mentioned in section 3.1) are available for softening the bending zone: a contact heater and a radiation heater. For the selection of the final heater, the angular accuracy of the process using the two heaters was evaluated and compared.

For each heater the robot movement, amount of heating and cooling time determine the angular accuracy of the bending process. The parameters are listed in Table 1. To identify significant parameters (>95%) and to determine their optimal value to ensure the angular accuracy, series of experiments were conducted. As a result, optimal parameter values for the movement, heating and cooling were proposed and the overall accuracy of the two different heating principles is compared.

To be able to investigate a nonlinear factor effect of the parameters on the angular accuracy of the bending process, a Latin Hypercube Sampling (LHS) experimental design was selected. It tests many different setting values per factor, allowing the investigation of a nonlinear factor effect. Using this design, 19 series of experiments with a total of 1177 experiments were conducted. Quadratic regression was used as the method for evaluating the test series. The created regression model then provides information on the significance of each parameter on the angular accuracy. To better determine the significant parameters in subsequent series of tests, the principle of stepwise regression was applied. After each evaluation, the least significant factor was set to a constant value and excluded from the next series of experiments and the regression model. This constant factor value was derived from the preceding quadratic regression model. If necessary, fine tuning was executed in a single factor variation. For the significant parameters, the values with the best predicted angular accuracy were selected as optimal. In this paper, concrete values are omitted due to space reasons as they strongly depend on the conditions like tape thickness, ambient temperature and are complex to put into context.

Table 1. Influencing parameters on the bending accuracy

Parameter	Affects	Relevant for
Preheating time	Molten area	Both
Heating temperature	Molten area	Contact
Cooling time	Springback	Both
Distance gripper to molten area	Movement	Both
Molten area size	Movement	Both

The experiments on the heating showed a high significance of the preheating time for the radiation heater and the high significance of the preheating time and the heating temperature for the contact heater on the angular accuracy. The cooling time has no significant influence on the angular accuracy if it is longer than a critical threshold. Using the optimized heating parameter values, further series of experiments were conducted to optimize the kinematic description parameters of the bending motion of the robot arm in the same experimental manner. The two adjustable parameters were the distance between gripper and molten area and the width of the molten area as described in the kinematic model [11]. As a result, optimal parameter values are determined for each heating principle.

For the final comparison, the angular accuracy of the two heaters was evaluated by conducting two times 90 experiments varying α and β in an LHS design. The result is presented in Fig. 4 (contact heater) and Fig. 5 (radiation heater).

The figures show the predicted angular accuracy error of the quadratic regression analysis in form of a heat map plotted over the angles. The green regions show angle combinations with the best accuracy. In the red regions, too little bending angle (red) is predicted. The two different scales are presented in the right of the figures.

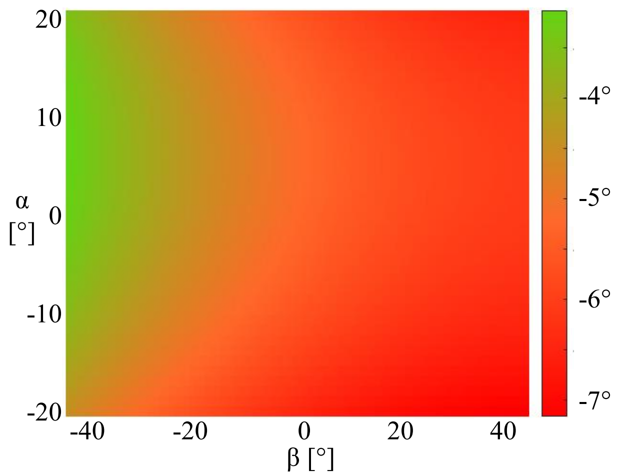

Fig. 4. Angular accuracy error - contact heater

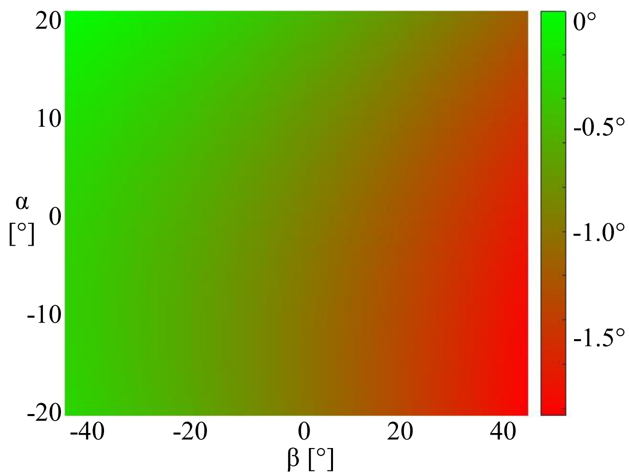

Fig. 5. Angular accuracy error - radiation heater

From the comparison of the two figures, it is obvious that the contact heater has a lower angular accuracy than the radiation heater. Thus, the radiation heater proves to be the more angle-accurate technology for the robot-assisted swing folding process. The reason for the asymmetric distribution of the error are minor asymmetries in the test rig which the heating principles are differently sensitive for. In a test series where five specific angle combinations were manufactured ten times, the average standard deviation in β was 0.63° for the radiation heating and 1.15° for the contact heating indicating that a partial correction by constant offsets can be obtained.

Furthermore, the radiation heater seemed less difficult in use during experimentation as it is not necessary to fine tune the two gripper positions relative to each other and no contamination of the heating gripper can occur. Therefore, the radiation heater is selected for future work.

3.3. Shape Derivation

All manufacturing processes influence the shape of parts made with them. The limitations of the swing folding preforming process are based on the kinematic of the process (see section 3.2). To overcome limitations of the possible geometries, the shape can be adjusted to fit both manufacturing process as well as product requirements. For space reasons, details on the optimization are given in [12]. The overall workflow is presented in Fig. 6.

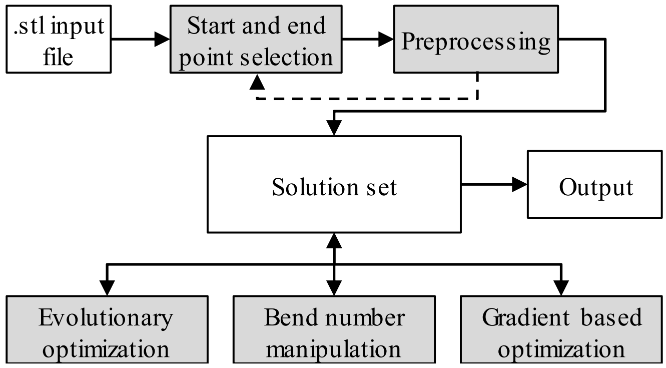

Fig. 6. Overall workflow for shape derivation

First, a .stl CAD file is loaded into the toolbox and Start and end point of the tape are selected. In the preprocessing step, a solution is analytically derived. Afterwards, evolutionary optimization, gradient based optimization and manual bend number manipulation can be used to improve the shape until it can be saved as output. All functions of the shape derivation can be accessed via a GUI. For the results, both optimization settings and the preform geometry coded as genome or machine code for the manufacturing cell can be exported. Suitable geometries could be obtained for most parts, using the described approach.

4. Additive Assembly - Handling, Joining and Consolidation of the Reinforcement Preforms onto Base Components

As described in section 2, the printing of the basic components takes place during the preforming process using the robotic extrusion system as shown in Fig. 7. In addition to the fast production of individual large thermoplastic components, the system offers more freedom due to the 6 axes, which is particularly beneficial when printing non-planar layers. Initial prototype extensions have been developed and tested for the extruder to integrate the UD tape preforms. Fig. 9 shows the conceptual design of the required extensions. In addition to different heat sources, movable pressing units are also required for flexible welding and consolidation of the preforms onto the base components.

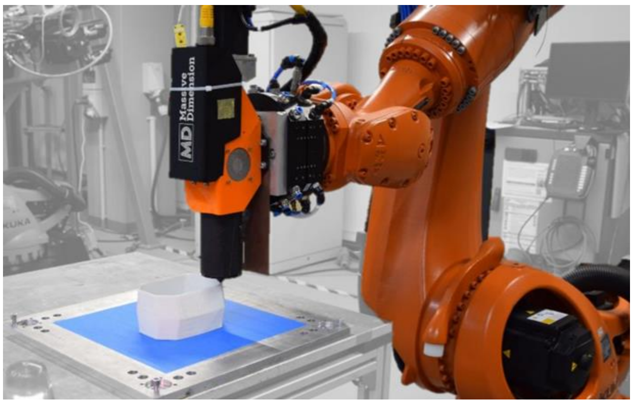

Fig. 7. Robotic extrusion system – Additive manufacturing of large thermoplastic components

4.1. Handling and Joining of the Preforms onto the Base Components

After the base component is printed to a specified layer, the end effector for flexible preforming (as shown in Fig. 2) acts as an ordinary gripper and positions the preform. The layer on which the preform is placed is printed non-planar (see Fig. 9) for a tight fit without voids. As can be seen in Fig. 8, it is not sufficient to simply lay down the preform, since the preform would be displaced during subsequent overprinting and consolidation. Therefore, the heated compressing unit on the extruder is used for local welding of the preform to the base component at defined points. The exact positioning of the joints is highly dependent on the shape of the preforms and must be derived individually for each component and is part of the digital process chain (see section 5).

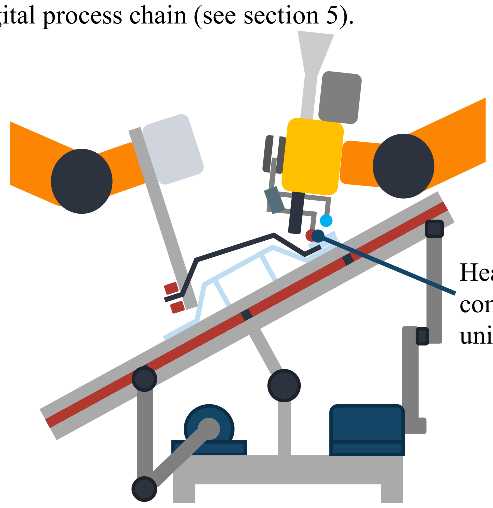

Fig. 8. Handling and joining

The handling and joining process described is not limited to one preform per component. If further preforms are required for reinforcement, the preforming, handling and joining can be carried out iteratively, which allows complex reinforcement structures to be created. Continuing printing between the joining of two preforms is also possible.

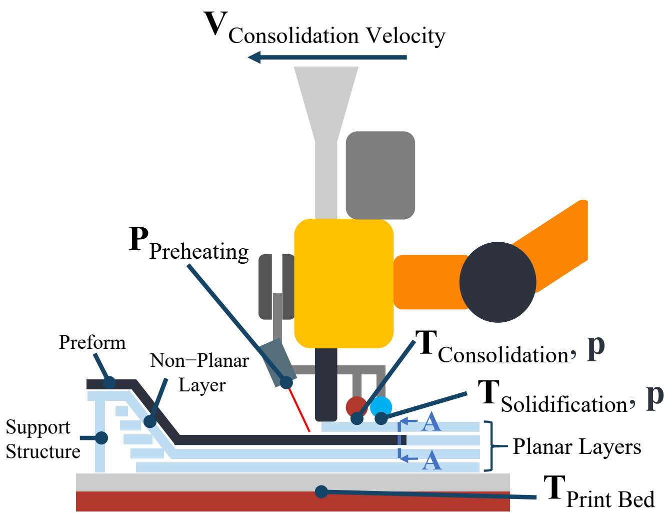

Fig. 9. Planar and non-planar layers and overview of relevant process parameters during consolidation

4.2. Overprinting and Consolidation

As usually in additive manufacturing the base component is first made up of planar layers, i.e. the individual layers have a constant height relative to the print bed. The non-planar layers surrounding the preform (as already described in section 4.1) are matched to the geometry and orientation of the preforms to ensure that no large voids are present and no wrinkles are formed during the overprinting and consolidation. An example subdivision of the base component into planar and non-planar segments can be seen in Fig. 9.

The system illustrated in Fig. 9 can be used to set various process parameters. The heated and movable compressing units allow the pressure p and the temperature for consolidation ($T_{Consolidation}$) to be controlled. The heated print bed ($T_{Print\ Bed}$) is necessary for both the adhesion of the layers to each other during the 3D printing process and for quickly reaching the consolidation temperature in combination with the additional infrared heater (controlled via power $P_{Preheating}$). The movement of the robot can be used to influence $V_{Consolidation\ Velocity}$ and thus the effective consolidation time. A controlled cool down and solidification is possible due to a lower temperature $T_{Solidification}$ of the second compressing unit. The extrusion temperature is already predefined for a good material flow during 3D printing and is therefore not adjusted. The overall objective is to achieve the temperature and pressure profile shown in Fig. 10 throughout the entire interface between the UD tape and the 3D printed layers. The idealized temperature and pressure profiles refers to the section A-A in Fig. 9 and represents the time course from the heating phase, through consolidation and subsequent solidification. As the state of the art shows, such profiles provide ideal results for the consolidation of thermoplastic composites [13].

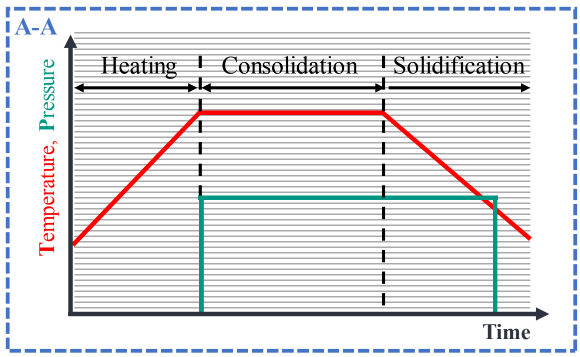

Fig. 10. Temperature and pressure profile for a high degree of consolidation

The exact process parameters depend heavily on the material, but for semi-crystalline thermoplastics the general rule is that consolidation takes place close to the melting temperatures. For armorphous thermoplastics, the glass transition temperature is sufficient. The consolidation times for armorphous and semi-crystalline thermoplastics are usually a few seconds, and the consolidation pressures are also a few MPa and even less than 1 MPa [14]. During the solidification phase, controlled cooling under pressure takes place, which ensures that no air voids can form and subsequently reduce the degree of consolidation due to a sudden decrease in pressure.

In the further development DOEs will be used to determine ideal process parameters. The aim is to optimize bonding between UD tapes and printed layers. For this purpose, the bonding will be investigated with tensile tests. Preliminary tests have already shown that a combination of high pressure and high temperature can damage the UD tape and the printed layers. This can have a negative influence on bonding and on the shape of the components and must be taken into account in the planning and execution of the DOEs.

5. Digital Process Chain

As with conventional 3D printing, the objective here is also to derive the machine code for the production of the reinforced component in a fully automated procedure. The usual digital process chain in 3D printing consists of creating the desired part in CAD and then transferring the model as a .stl CAD file to a slicer to create the machine code. The slicer generates the required machine code (G-code) with the trajectories and process parameters needed. For an ideal integration of the preforms (produced according to the process in section 3), their shape, position and orientation must be taken into account during slicing. For this purpose, the geometry data (shape, position and orientation) of the preform are subtracted from the .stl model of the entire component. The resulting .stl model of the base component is divided into planar and non-planar segments with the help of a slicer, whereby the non-planar areas are used to simplify the integration of the preforms. Skews between planar and non-planar areas are mainly realized with the movable print bed. In addition, the areas to be consolidated must be taken into account during slicing. The required process parameters (consolidation temperature, pressure etc.) are provided from a database. For the automated handling, insertion and joining as described in section 4.1 only the end positions of the preforms are specified. The actual trajectory planning is outsourced to existing programs for offline programming of robots. The G-code must contain appropriate queries for the synchronization of the two robots.

6. Summary and Outlook

In this paper, an overview was given of a new process chain for the flexible production of thermoplastic FRP components. The already developed and validated process for preforming UD tapes enables the flexible production of high-quality continuous fiber reinforcement structures. Improved angular accuracies using radiation heater were shown as well as a method for deriving the shape from .stl CAD files (see section 3.1 - 3.3). With the help of a second collaborating robot with extrusion and consolidation unit as well as a movable print bed, large thermoplastic components with continuous fiber reinforcement will be produced in the future. The basic process required for this was shown in section 4.1, along with the necessary equipment. The essential consolidation process was described in detail in section 4.2, in particular the influence of temperature and pressure on the bonding process. In addition to rapid production, the combination of highly pre-impregnated fibers and the use of non-planar 3D printing is expected to achieve significantly better mechanical properties than possible in the state of the art. To achieve this objective, the prototype robot-guided local consolidation unit must be further developed and suitable process parameters determined experimentally. In addition, existing non-planar slicers are further developed and applied for this application to create a digital process chain for automated process planning.

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