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A novel method for carbon fiber reinforced thermoplastics production combining single point incremental forming and 3D printing

Zsolt Kállai[a], Doran Nettig[a], Johann Kipping[a], Jan-Erik Rath[a], Thorsten Schüppstuhl[a]

[a] *Hamburg University of Technology, Institute of Aircraft Production Technology, Denickestraße 17, 21073 Hamburg, Germany*

* Corresponding author. Tel.: +49-40-42878-2253. *E-mail address:* zsolt.kallai@tuhh.de

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Abstract

Dieless processes such as additive manufacturing or incremental sheet forming are becoming increasingly popular in manufacturing carbon fiber-reinforced components. They are a promising option for producing individual parts or small lot sizes without the need for expensive molds and can thus revolutionize the creation of patient-tailored prosthetics or high-end sports equipment. In this paper, the combination of robotic single-point incremental forming of carbon fiber-reinforced organo sheets with carbon fiber-reinforced 3D printing is presented. Combining those dieless processes in a novel process chain, complex parts with different geometric features could be produced without the need for adhesives or fasteners. The developed method begins with designing the desired component in CAD and its division into sections to be formed incrementally and sections to be 3D printed. For incremental forming, an organo sheet is cut to the necessary shape, sandwiched between a layup of dummy metal sheets, fixed on a clamping frame, and heated to the required forming temperature. Path planning for the robot is carried out based on a selected forming strategy, and the sheet is formed. Afterward, the part is transferred and fixed onto a robotic experimental 3D printing setup. The part's surface is 3D-scanned to provide the basis for the path planning algorithm. The slicer software generates non-planar layers based on the actual shape of the formed sheet and the desired geometry of the printed part section. After slicing, the code for the robot is generated and the print job is executed. Within this paper, the conceptualized process chain is presented and basic functionality is proven by manufacturing a demonstration part. The first results are promising to enable efficient manufacturing of complex components that combine different geometric features in small batch sizes. Future research will be conducted to analyze and optimize the process chain and its capabilities, especially regarding the resulting part quality.

Keywords: Additive Manufacturing; Incremental Sheet Forming; Carbon Fiber Reinforced Components

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1. Introduction

Fiber-reinforced plastics (FRP) represent an important material in all fields where lightweight parts with high mechanical performance are needed. Although the market was dominated by thermoset-based composites in the past, fiber-reinforced thermoplastics are gaining more and more attention. The possibility of applying manufacturing strategies such as forming, welding, and 3D printing, as well as their higher recycling potential, make them interesting for a lot of applications [10].

Fiber reinforcements often come in the form of textile sheets, making them well-suited for the creation of large shell-like parts. On the other hand, these often have to be combined with more complex geometric features for reinforcement structures, functional elements, and interfaces. Apart from the conventional joining of parts manufactured separately, this combination of geometric features can be created in the so-called Spri-Form process [12], which combines thermoforming and injection molding. First, a flat semi-finished fiber-reinforced thermoplastic sheet, a so-called organo sheet, is heated and subsequently formed in a press. Then, while still remaining in the mold, an injection system applies further, possibly short-fiber-reinforced, thermoplastic material onto it. In this way, complex structures can be added to the shell geometry of the formed sheet. Although this process allows for high design freedom, it still requires expensive molds in combination with large press and injection systems. It is therefore limited to high-volume production and less suited for small batches and prototypes. Furthermore, the injection molding approach only allows for neat polymer or short-fiber reinforced material for the added features. Continuous fiber-reinforced material is thus inherently limited to the shell domain.

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To eliminate the need for molds and enable the economical production of individual parts, dieless approaches have already been investigated in the past for both individual subprocesses. For the dieless forming of organo sheets, incremental sheet forming (ISF), originally developed for metal sheets, was applied. In the simplest approach, single-point incremental forming (SPIF), a sheet is circumferentially clamped and locally deformed with one CNC- or robot-guided standard tool such as a hemispherical tooltip [3]. Incrementally forming continuous fiber-reinforced organo sheets requires the fibers to be drawn into the forming zone, as stretching them is not possible [6]. Therefore, researchers [2, 1, 6, 4] incrementally formed a heated continuous fiber-reinforced organo sheet between two metal dummy sheets, protecting the FRP surface, transferring the deformation to the flexible fabric, and allowing it to slide between the metal sheets. Rath and Schüppstuhl [11] improved the part quality in this approach by optimizing the toolpath strategy to enable targeted shearing of woven fabrics.

The additive manufacturing of FRP is an active research topic. The benefit of being able to print both short and continuous fiber-reinforced material, to control the fiber orientations and to print directly on non-planar surfaces makes fused filament fabrication (FFF) the most suitable process for printing FRP. Non-planar printing has been demonstrated to enable printing stiffening structures onto curved surfaces [13, 8] and manufacturing load-oriented parts, where the anisotropic material is aligned with the principal stress directions [5, 9].

This work presents the conceptualization and first tests of a novel process chain combining incremental sheet forming of continuous fiber-reinforced organo sheets with non-planar fiber-reinforced 3D printing. This combination allows for a highly flexible process that overcomes the drawbacks of traditional approaches, requiring no molds and, in principle, being capable of using continuous fiber reinforcements throughout the whole part.

First, the process chain is functionally conceptualized, and the fundamental requirements are analyzed. Secondly, the necessary hardware and software modules that are used to achieve the targeted functionality are described. The sub-systems are combined and used to produce a first demonstration part that shows the general applicability of the developed process. Lastly, the results are discussed, and the necessary next steps to further the development of the process are described.

2. Process conceptualization

2.1. Process chain

The process chain of the developed system is shown in Figure 1. It can be divided into functions concerned with information processing and the processing of the part from a semi-finished material to the final part. The information processing starts with the target CAD geometry, which must be divided into sub-geometries for the forming and printing processes. The individual geometries are then used to plan the printing and forming paths and to generate the processing instructions.

The sheet material must be equipped with a known feature or marker that provides a reference for the incremental forming system, which, in the simplest case, could be the known sheet dimensions. It is then inserted into the forming system and the forming system is referenced to the sheet. Subsequently, the forming process can start according to the planned instructions. The sheet needs to be heated to the forming temperature and deformation is locally introduced through tool movements relative to the sheet.

After the ISF process is completed, the part is transferred to the printing system. Here, the part is scanned to both reference the printing system and adapt the printing paths to the actual geometry of the formed part, which will always differ at least slightly from the target geometry. Then the printing process is executed. The relative movement of nozzle and part is generated according to the adapted paths. The material is supplied as one or possibly multiple filaments. It is heated above its melting temperature and extruded onto the sheet. The sheet is heated as well to improve the bonding of the extruded material to its surface. After the printing process is finished, the finished part can be removed.

2.2. Requirements

In the ISF system, the organo sheet must be sandwiched between two metal dummy sheets to allow its in-plane movement during forming to avoid fiber breakage or pull-out. Still, the clamping force of the metal sheets must be high enough to compress the organo sheet to suppress uncontrolled movement and deconsolidation. The part's position and orientation must be referenced to the forming system to ensure the geometry is formed correctly. Furthermore, to soften the matrix and allow the formability of the part, the ISF system needs to be able to heat the part globally to a specific temperature and hold this temperature throughout the forming process. The end-effector must supply sufficient force to deform the layup permanently and apply adequate pressure onto the metal sheet to reconsolidate the part. Depending on the requirements of the parts to be formed, the tool must be moved with sufficient accuracy and in a workspace large enough to accommodate the target geometry.

To enable printing on a curved surface, a 3D printing system capable of non-planar material placement and obtaining information on the actual surface of the formed part is required. Material placement can be achieved using any 3D printing hardware for short and continuous FRP that deposits material according to the curved surface while avoiding collisions between the nozzle and the print surface. However, due to additional degrees of freedom and increased flexibility compared to gantry-based 3D printers, robot-based 3D printing systems are preferred. These systems allow the nozzle to be oriented according to the normal vector of the print surface. Robots also enable complex print paths, which could be used for local strengthening of the printed part or adding features such as fixation points and creating integrated parts.

Due to material and process inaccuracies during the forming, a certain deviation between the target surface and the actual surface is unavoidable. To enable precise material placement, the

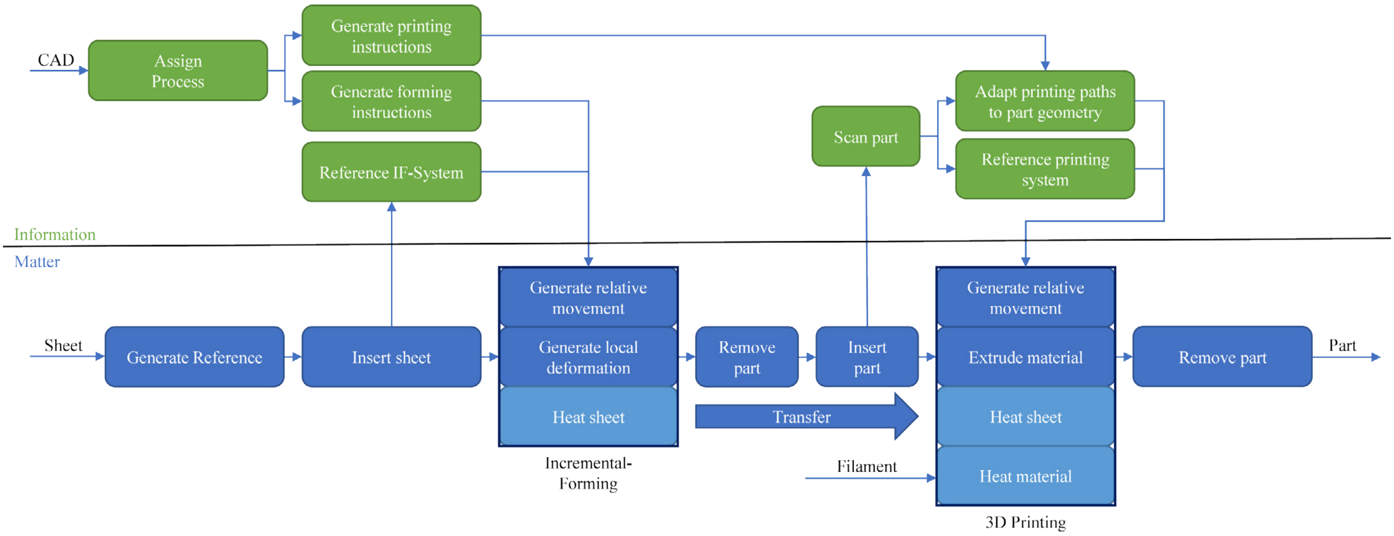

Fig. 1. Process chain of the combined forming and printing process.

robot paths for printing must consider the actual surface. Moreover, it is an important referencing step to establish the relative position of the part in the robot's coordinate system. Without accurate surface data and the precise position of the part, the risk of collisions of part and printing hardware, as well as the risk of material misalignment, gaps, or overlaps, increases. These issues could hinder the printing process and negatively affect the quality of the printed part. To overcome them, a laser line scanner is applied to obtain the position and surface of the formed part, creating the curved surface that serves as the base for printing.

To generate the manufacturing instructions for the robotic printing system a framework software is necessary. This software has to incorporate offline slicing and path planning on the substrate geometry of the formed part in order to produce the target geometry of the printed part. The algorithms for slicing and path planning should be modular to enable methods with different objectives to be used interchangeably. A simulation of the movement of the robot should enable the user to check the feasibility of the operation. The scanning sensor has to be integrated into the software to enable the generation of updated paths with the scanned surface. The scanned data has to be converted into a closed mesh, and the slicing procedure is repeated with the same parameters to obtain the updated manufacturing instructions. The software should then post-process these instructions and send them to the robot controller for execution.

3. Demonstration of functionality

In this section, a demonstrator part is created with the existing incremental forming and sensor-supported 3D printing processes to demonstrate the feasibility of the combined method.

3.1. Forming

The paths for the ISF-process are shown in Figure 2. The paths are generated using a z-level set approach. Isocontours of the elevation of the target geometry are extracted at specified isovalues as defined by the layer height in z-direction. The tool path follows these contours, starting from the outermost one with the smallest isovalue, successively working its way down. Further information and a study on possible tool path strategies can be found in [11]. The test geometry used in this work is a simple dome shape with a diameter of 115 mm and a height of 25 mm. Based on preliminary investigations, the layer height and tool speed are chosen to be 0.5 mm and 20 mm/s, respectively.

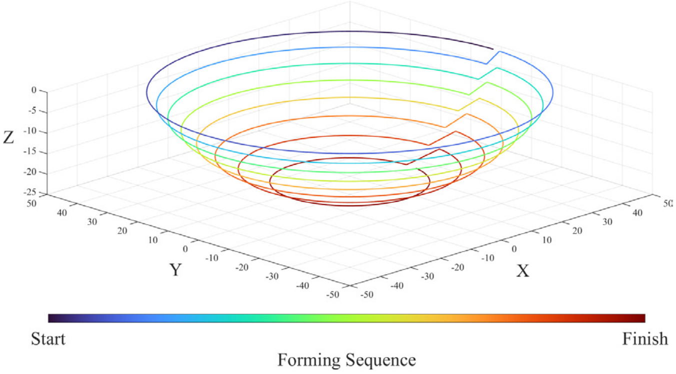

Fig. 2. SPIF process elevation contour paths and forming sequence (layer height 3.125 mm for visibility).

The SPIF process is carried out on the manufacturing system described in detail in [11] and shown in Figure 3. An ABB IRB 660-205 industrial robot is used to move the steel 1.2210 tool with a hemispherical tip of 20 mm diameter. The twill woven carbon fiber-reinforced PA12 organo sheet TECATEC PA12 CF50 T200 OS, manufactured by Ensinger, with 3 layers, 0.7 mm thickness, and 50 % fiber-volume-content is sandwiched between an upper DC04 steel and a lower EN AW-1050A aluminum sheet of 0.8 and 0.5 mm thickness, respectively. The steel sheet with higher thickness is used for good formability and wear resistance in direct tool contact, while

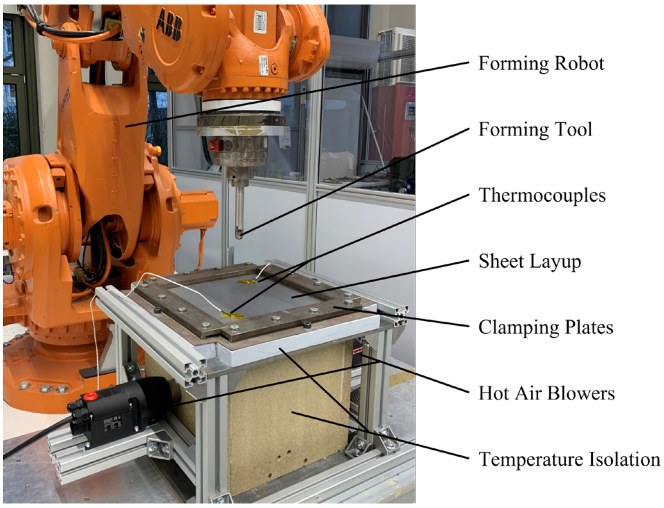

Fig. 3. Setup used for the incremental forming of the test part [11].

the more ductile aluminum sheet is an ideal, easily deformable backing plate. PTFE sheets of 0.05 mm thickness separate the organo sheet and the metal sheets to allow sliding and prevent adhesion. The auxiliary sheets are clamped along their outer edge. A rigid support plate/template with a hemispherical cutout of 105 mm diameter is placed below the sheet stack to localize the deformation. The lower supporting sheet is aligned manually to markers on the holder and placed on top of the template. The organo sheet is placed in its center by using spacers of known length. The upper sheet is then added and the stack is secured by loosely tightening the clamping screws. Applying the full clamping force before heating could lead to buckling of the sheets due to heat expansion. The sheet stack is heated from below with two hot air blowers. The temperature on top of the upper sheet is measured at two locations with thermocouples and a temperature controller is used to achieve a fast and accurate heating to the target temperature of 190°C. After the target temperature is reached, the sheet stack is finally clamped by tightening the screws to 70 Nm of torque with a torque wrench. With the stack clamped and heated, the incremental forming can start with the execution of the robot program until the target geometry is reached. After the sheet stack has cooled down, it can be removed, and the part can be transferred to the printing system. For a more detailed description and visualization of the forming setup and process, the reader is referred to [11].

3.2. Scanning

The experimental setup used for printing is described in detail in [7], featuring a 6-axis ABB IRB 2600-20/1.65 robot. The robot carries the printing system and scanning sensor while the print bed is stationary within the robot's working range. The setup is equipped with multi-material printing hardware featuring two separate print heads that are mounted on the robot flange at an angle to enable fast switching between the materials. One of the print heads has been constructed to print continuous FRP, while the other works with conventional 3D printing filaments. This configuration allows the fabrication of parts created with multi-material 3D printing.

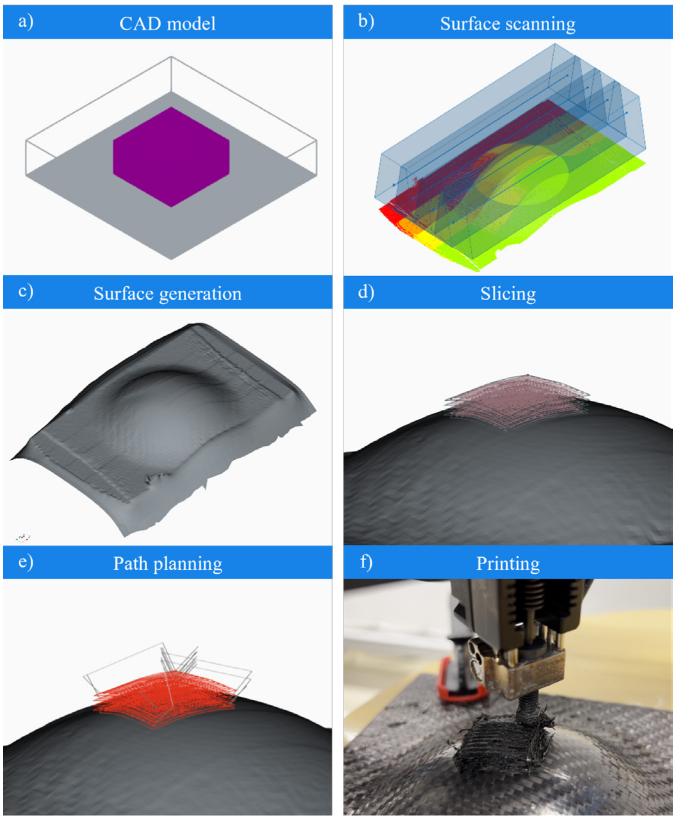

Fig. 4. Workflow of the sensor supported 3D printing process.

Once the incrementally formed part is transferred to the printing system, it is secured to the print bed. For scanning, a Keyence LJ-V7080 blue laser light sensor is used, offering 800 measurement points per profile. Before starting the scanning procedure, the sensor must be calibrated. This involves positioning the surface to be scanned at the center of the sensor's measurement range to ensure accurate capture of deviations on the curved surface. Scanning is conducted at a robot speed of 5 mm/s, with the sensor triggered at 10 Hz to synchronize the robot's position and scanned profile. Figures 4 a)-c) illustrate the scanning procedure. Initially, a target geometry is defined. Based on this geometry, overlapping scanning paths are created to ensure complete surface coverage. After creating the scan path, a robot program is generated, including scan parameters such as scanning speed and commands for manipulating the trigger signal. This program is then loaded onto the robot's controller and executed. Once the scanning paths are completed, the data stream containing the robot's positions is retrieved from the robot controller and matched with the corresponding scan profiles. The scan paths are then stitched together, and the outlining points are filtered out to create a mesh. Finally, the surface mesh is smoothed, and the surface to be printed on is visualized.

3.3. 3D printing

Figures 4 d)-f) depict the printing process using the scanned surface. Initially, the target geometry, a simple rectangular cuboid (20x20x4 mm) in this demonstration, is sliced according to 3D printing parameters provided by the user, such as path width, layer height, and infill. The first slice is created parallel to the scanned surface, and subsequent layers are morphed layer by layer to form the target geometry. After slicing, path planning is executed, which involves generating robot trajectories for printing and additional movements, such as travel movements. Before printing, the paths are simulated to check for nozzle-work piece collisions and ensure all robot path points are reachable without singularity. Once the simulation is complete, the post-processor generates the robot-specific code, which can then be used for printing on the experimental setup.

For the printing process, fiber-reinforced filament from Raise3D, ”PA12 CF+”, is used, which is based on Polyamide 612 (PA612) and contains 15 wt.% short carbon fibers. This filament is heated to 270°C, while the print bed with the clamped part is heated to 90°C. Printing is executed for all layers, except the first, at a robot speed of 10 mm/s, where the material flow is synchronized to the robot's speed. The printed part has 20 layers, where the first layer is split into two sublayers with a layer height of 0.1 mm while the remaining layers are printed with 0.2 mm. The placement of the first layer is crucial as it needs to adhere to the formed sheet to enable the fabrication of the part. It is expected that the radiating heat from the nozzle and the printed material can reheat the matrix material of the formed part, enabling a solid connection. Therefore, positioning the nozzle as close to the surface as possible is highly recommended. However, to avoid blocking the nozzle outlet due to direct surface-to-surface contact, the smallest feasible distance of 0.1 mm is selected for the printing of the first sublayer. To increase the surface warming effect of the nozzle, the printing speed is reduced to 5 mm/s. After completion, the second sublayer is placed with the same parameters as the first one. After visual examination, the printing process continues with increased speed. During the printing procedure, no additional adhesives are used; the bonding of the matrix material of the sheet and the 3D printed material ensures the adhesion of the part. Furthermore, cooling of the workpiece is unnecessary, as the reduced printing speed allows the placed material to solidify adequately before the next layer is placed. After printing, the demonstrator part is cooled down and removed from the platform.

3.4. Results

The initial incremental forming of the demonstrator part was successful. The sheet stack was heated to the desired target temperature and the top surface temperature stayed within a tolerance of ± 5°C. It was subsequently formed to the target geometry. The final geometry of the formed part has a height of 23.25 mm, slightly lower than the target of 25 mm. The transition from the formed dome to the planar region is very smooth. The outermost diameter of the formed region is about 117.5 mm, significantly larger than the 95 mm that would result from the target dome geometry. The finished part displays high surface quality, with no signs of wrinkling or fiber tear. The surface of the dome, particularly at the top, is matrix-rich and exhibits a smooth, even finish. However, the foot of the dome and the outer planar areas show a lower matrix content and higher surface roughness, which can be associated with a deconsolidation of the material.

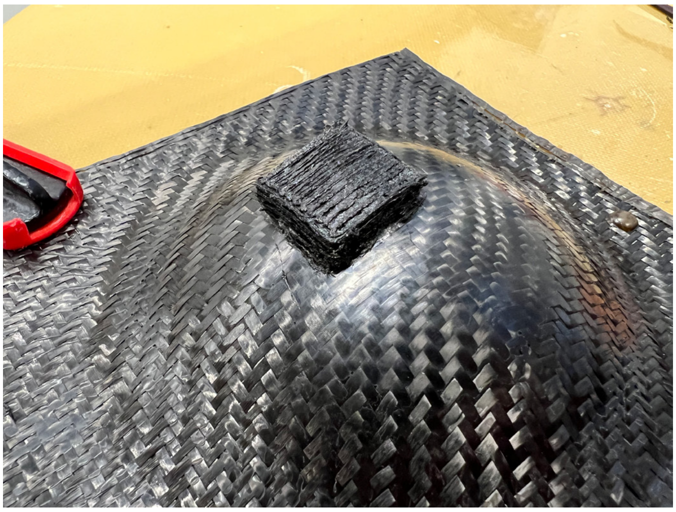

Fig. 5. Demonstrator part of the combined process.

The scanning process performed as expected, effectively generating scanning paths based on the target geometry. The scanning speed though was limited by the slow communication between PLC and robot controller. The scanner could be calibrated effectively. The surface of the formed part was accurately digitized by integrating the robot position data with the scan profiles. Based on this digitization, the printing paths were successfully adapted to the scanned base surface geometry. The scanning process exhibited a high degree of automation due to the embedding into the framework software, and the parts could be referenced to the tools and robot coordinate systems.

The 3D printing on the dome surface was also successfully executed. The print took approximately five minutes to complete. The printed non-planar base layer adheres well to the surface of the formed dome, maintaining the intended geometry. Manual testing confirmed good adhesion between the printed and formed sections. However, the printed geometry exhibits gaps and lacks sharp contours.

4. Discussion and outlook

In this work, a novel manufacturing process was proposed and analyzed with regard to its requirements and potential realization. The process was shown to meet the specified requirements and demonstrated by successfully manufacturing a simple work piece. The degree of automation achieved was notably high, primarily due to the implementation of a robust framework software, which streamlined various aspects of the manufacturing process.

However, to establish the proposed manufacturing process as a viable option for future applications, several critical issues need to be addressed. The primary challenges encountered in the incremental forming process were the inhomogeneous distribution of the matrix material and the local deconsolidation of the part. Gravity and tool movements could lead to a matrix movement toward the top and center of the dome. Furthermore, findings in [11] suggest that pressure applied by the tool onto the top metal sheet leads to a better consolidation of the part judging by its surface appearance. Areas without or with tool contact only early in the process, such as the base and periphery of the dome, therefore, tend to show deconsolidation and a matrix-poor surface. Advanced path planning techniques should be employed to improve matrix homogeneity. Additionally, experimenting with lower temperatures and increasing the overall speed of the process could mitigate this issue. The dimensional deviations of the formed part can be attributed to spring-back and the inability to form perfect sharp angles, which are both to be expected from the employed method. Spring-back compensation in the path planning and the use of a supporting second tool might alleviate these issues.

The appearance of gaps in the printed subcomponent could partly be caused by oozing. The hygroscopic nature of polyamide poses a significant challenge. The evaporation of bound water and the subsequent formation of bubbles may have contributed to the gaps observed in the printed paths. This effect could be minimized by actively controlling the humidity of the environment in which the filament is stored both before and during printing. Optimizing material flow through proper retraction procedures and purging the nozzle after positioning movements between layers could reduce these issues, albeit at the cost of increased production time. Further addressing the issue of gaps, print parameters such as layer height and line width should be optimized. Controlling the temperature of the print environment, regulating airflow, and managing the humidity levels could also significantly enhance print quality.

Enhancing adhesion between components is crucial for the integrity of the final part. This can be achieved by more effective heat transfer, potentially through the use of an external heat source. Pull-up tests should be conducted to assess the adequacy of the adhesion. Employing advanced path planning and slicing methods, such as load-oriented strategies, can significantly improve the structural performance of the printed parts. The use of continuous fiber-reinforced materials would further enhance the mechanical properties of the final product. Additionally, exploring different material pairings for better compatibility and adhesion is important. This could involve experimenting with alternative materials to find the optimal pairing for the process. To streamline the manufacturing process, creating an experimental setup capable of handling multiple processes without transferring the workpiece would be desirable. This setup would integrate various stages of the manufacturing process, thereby reducing the risk of errors and improving overall efficiency.

In conclusion, the proposed manufacturing process offers several advantages, including low development cost for prototypes, on-demand manufacturing of parts, the possibility of printing continuous fibers, and increasing the cost-effectiveness of small lot size production due to the elimination of molds. Addressing the identified challenges and implementing the recommended improvements can make this process a highly effective and competitive alternative in the manufacturing industry.

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