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Hot double sided incremental forming of continuous fiber reinforced thermoplastics: Process analysis and system design

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Abstract. Interest in fiber reinforced thermoplastics (FRTP) is increasing due to their superior recyclability and processability over thermoset composites, but the need for part-specific tooling constrains their application in small-lot production. Incremental sheet forming (ISF) presents a flexible manufacturing alternative. However, existing ISF methods, predominantly developed for metals, need to be adapted to the specific process requirements of FRTP. Prior research into the ISF of FRTP has focused on single-point incremental forming (SPIF). To enable new processing strategies, this work presents the development of a robot-based hot double sided incremental forming (DSIF) setup for FRTP. A process analysis serves as the basis of the design and integration of the core system components. The setup shows great potential as a platform to explore a wide range of new ways to advance the ISF of FRTP.

Introduction

Lightweight parts with a high strength-to-weight ratio are crucial to industries such as aerospace, automotive and high-performance sports. To achieve such properties, fiber reinforced plastics (FRP) combine fibers, such as glass, aramid or carbon fibers with a thermoset or thermoplastic matrix material. While the fibers offer high tensile strength and stiffness, the matrix stabilizes the part shape and transfers external loads to the fibers. While short fiber reinforced plastics can offer a cheap and easy-to-process alternative to metals, continuous fiber reinforced plastics can even surpass the performance of metals and are employed in lightweight structural components in planes, race cars etc. [1].

Fiber reinforced thermosets allow for easier impregnation of the fibers because of the low viscosity of the matrix precursors, allowing the hand-layup with a subsequent curing step as a prototype or low-volume production process [1]. However, fiber reinforced thermoplastics (FRTP) gain increasing importance due to their higher recycling potential and the possibility of welding and reshaping them. Due to their high matrix viscosity, FRTP parts are usually produced in a thermoforming process, where a preconsolidated FRTP sheet is formed in a heated press [1]. This process requires not only expensive press machinery but also part-specific molds. These molds contribute to increased part costs and high lead times, especially in low-volume production.

To address the issue of high tooling cost in sheet metal forming, incremental sheet forming (ISF) is a promising alternative for low-volume production and highly individualized parts. This mold-less manufacturing process can be best understood as the 3D printing of forming processes. A simply shaped tool, often with a hemispherical tip that is small compared to the part size, follows a three-dimensional path to incrementally form the desired shape into a circumferentially clamped sheet. While the process was first established with only one tool, called single-point incremental forming (SPIF), the process of using two opposing tools, called double sided incremental forming, has been demonstrated to significantly improve process outcomes in metal ISF [10]. FRTP's unique properties differentiate its process behavior and requirements distinctly from those of established systems for metals or polymers. While metal and polymer sheets are incrementally formed through stretching and thinning, continuous fiber fabrics require bending and shear as deformation mechanisms, as fibers can be considered inextensible [2]. Nonetheless, the last decade has brought forth research into the ISF of FRTP as well. Al-Obaidi et al. [3] first presented a setup for the SPIF of FRTP. They used a 3-axis CNC machine to incrementally form parts made of glass fiber reinforced PA6 with a hemispherical tool. Instead of directly forming the composite sheet they formed a multi-layer stack. This stack was made up of a lower aluminum sheet and an upper steel sheet, with the FRTP quasi-floatingly interposed between the metal sheets. This allowed the composite sheet to be drawn in during forming. To circumvent high friction or permanent bonding between metal sheets and composite, thin PTFE sheets were used as separation. The sheet stack was heated from below by a hot air blower. The heat input was dependent on the forming depth which necessitated an adapted heating strategy. Kalaei et al. [4] also formed woven glass-fiber reinforced PA6 with the same general setup. Instead of a hot-air blower, they employed infrared heating. Instead of a combination of aluminum and steel, they used two steel sheets. Emami et al. [5] used a similar setup. They too interposed the composite sheet, in this case continuous glass fiber reinforced PA6, between two steel sheets. The lower sheet was required to prevent burning the composite surface, and the top sheet was required to prevent surface defects from contact with the tool. The composite sheet was clamped together with the steel sheets instead of being quasi-floatingly supported. Consequently, fiber fracture occurred at elevated forming depths. Hou et al. [6] formed woven jute-fabric reinforced PLA. They used a heating plate in an enclosed chamber to heat a similar stack arrangement as Al-Obaidi. They also tried forming at room temperature and showed that forming without significant heating is impossible. Rath and Schüppstuhl [7] investigated the effect of different tool-path strategies on the forming of woven carbon fiber reinforced SAN, employing a setup similar to that in [3]. A conceptually identical sheet stack was heated to 180 °C-200°C by two hot-air blowers and formed with a hemispherical tip guided by an industrial robot. It was found that the global deformation of the metal dummy sheets due to the absence of a support tool leads to a deviation between upper and lower metal sheet, leaving room for the development of wrinkles in the FRTP. Furthermore, deconsolidation occurred in those regions due to a lack of pressure on the FRTP. While an optimized toolpath strategy was able to reduce this influence, a rigid backing plate supporting the edge of the formed geometry yielded better results. Thus, it is suggested that realizing a DSIF process for the incremental forming of FRTP would enable higher part accuracy and quality.

A review of existing metal and plastic DSIF systems will be omitted here for brevity. The main difference to SPIF systems is the denominating use of two opposing tools each guided by independent actuators [8]. All previous studies investigated only the SPIF of FRTP. DSIF, however, could be a very promising process to increase consolidation and part accuracy. This work therefore analyzes the specifics of the FRTP DSIF process to then develop a robot-based hot DSIF system enabling the investigation of the DSIF process for (continuous-) FRTP forming.

Process and System Analysis

Requirements. The general requirements of a DSIF system can be derived from current state-of-the-art metal DSIF applications [8-11]. The system must ensure path flexibility, allowing the forming of various part geometries, while avoiding collisions and kinematic singularities. Insertion and removal of the workpiece have to be enabled. The design should be modular to adapt to different part size requirements and ergonomic to allow user-friendly and safe operation. Additionally, the system should facilitate tool changes and enable force measurement and control.

The two tools can be referred to as Master and Slave tool, with the Master being position controlled and the Slave creating a defined supporting force [9].

To allow the DSIF of (continuous) FRTP, the system must support a quasi-floating sheet layup and provide uniform global heating as seen in the state-of-the-art on the SPIF of FRTP [3-7]. The specific requirements for the system developed in this work are as follows: The sheet dimensions are derived from the standard size of the chosen main supplier for the semi-finished sheets. In this case these are Ensinger® TECATEC FRTP sheets with an edge length of 615x615 mm. The workspace for forming is defined based on preliminary experiments [7], revealing a realistic global wall angle of 60°, and geometrical analysis, considering the inextensibility of the fibers. 250 mm are therefore chosen as the workspace depth. In the opposing direction this depth is heuristically reduced to 100 mm as any part can be oriented such that its main forming direction points into the 250 mm direction. The system should, however, be modular to accommodate different sheet sizes and shapes. FRTP sizes and shapes should be continuously adjustable within the limits of at least two distinct metal sheet sizes. In this case, these accommodate a full size and quartered TECATEC sheet respectively. The system should ideally also accommodate FRTP sheets with cut-outs and other non-standard features. In general, interfaces should be designed with modularization in mind, to enable extensive parameter studies.

The requirements for the clamping system have been derived from preliminary investigations on the SPIF forming setup described in [7]. Clamping the outer 50 mm of the layup, applying forces of 80-160 kN per edge, has proven to be well suited for the process. The dummy sheets must apply a force to the FRTP sheet, but the FRTP may not be fixed along its edge to avoid fiber breakage. Reliable positioning of the FRTP sheet relative to the layup, of the layup relative to the frame, and of the frame relative to the robot will be crucial for achieving reproducible results.

To ensure ergonomic and efficient operation, a maximum manual handling weight of 25 kg and layup change time of 10 minutes should not be exceeded. For the forming process, a maximum force normal to the sheet of 3 kN, with momentary peaks of 6 kN is assumed based on force measurements in previous works on FRTP SPIF [3] metal DSIF [10]. The in-process deflection of the clamping frame should be limited to 0.1 mm, to limit its influence on part accuracy. Movement capabilities must include 3-axis operation within the entire task space, with optional 6-axis movement where realizable.

Temperature management is crucial for this application. Sheet temperatures of up to 300°C should be achievable to test the forming of any technical thermoplastic material above its melting point. Operating times are estimated to be within 480 minutes based on preliminary investigations. Heating must be homogeneous, and all materials in the heat flow must be appropriately heat-resistant, with sensors, electronics, and robots maintained at temperatures below 60°C. Energy losses and heat spread should be minimized as much as possible to allow for efficient operation.

Functional Analysis. The functional structure of the FRTP DSIF system is shown in Fig. 1. It can be separated into the five subsystems *base platform, clamping system, tooling, heating system* and *motion control system*. The *base platform* provides structural support and configurability to the system. It should be adjustable to accommodate different future layup sizes. Most importantly, it establishes a fixed reference frame between the layup and the manipulators and provides the necessary support to the layup to resist the force of the tools thus enabling the targeted deformation. The *clamping system* secures and releases the sheets before and after the forming process. The dummy sheets have to be aligned with each other. The FRTP sheet has to have a known relative position to them and is then clamped between the dummy sheets. The entire layup has to be positioned and secured on the base frame. A modular configuration interface should exist to accommodate different layup sizes. Once forming is complete, the clamping force must be removed, and the layers must be separated to extract the formed FRTP part. The *tooling system* is responsible for the positioning and configuration of the forming tools. Different geometries should be selectable. The tool has to be securely attached to the robotic end-effector to withstand the forming forces. The connection should minimize positional variation in the tooltip so that only the tool length has to be calibrated after a tool change. The *heating system* heats the FRTP sheet to increase its formability. This involves controlled heat generation. The generated heat needs to be distributed uniformly across the layup while localizing the heat input such that other components of the forming system are isolated and protected from the heat influx. After the forming is complete, the heat needs to be removed from the layup, to cool the FRTP down before removal, ensuring the formed shape is retained. The *motion control system* governs the robotic movement. Using the defined target geometry, tool paths are generated for both the master and slave tools. The master tool path defines the primary tool motion, while the slave tool path is synchronized with the master. To apply a constant support force, the slave tool path needs to be online-compensated based on the measured process forces. The master tool path could also be compensated based on the force measurements at its tooltip and a model of the joint and link stiffnesses.

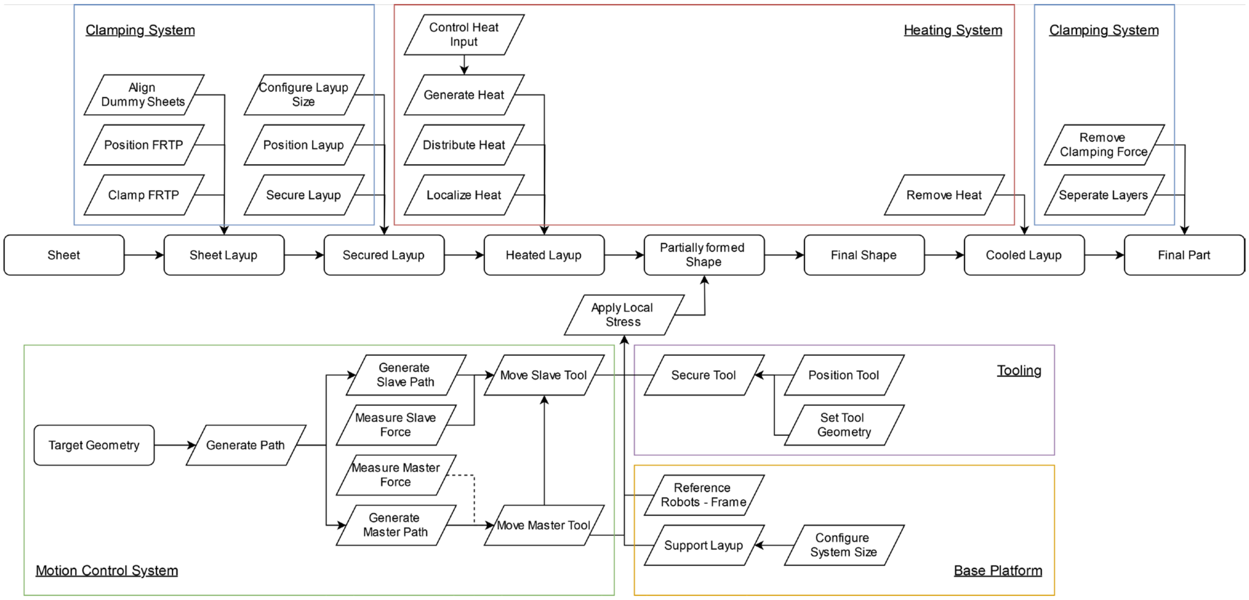


Figure 1 – Functional structure of the hot DSIF of FRTP

System Design

The system design is carried out following the subsystem structure identified in the process analysis. The *base platform* subsystem is shown in Fig. 2 and consists of the platform, the robots (two KUKA KR300) and the steel frame. The subsystem realizes the fixed reference between the main system components, takes on the forming loads and serves as the base interface for the other subsystems. The 2.45x4.00 m steel platform is sized so that the entire system could be moved or shipped with standard equipment. On this footprint, the steel frame is designed to maximize the available workspace. Additionally, it is designed with reconfigurability in mind. The top truss, bottom rail, and the components of the central H-Frame carry equally spaced threaded attachment points. These allow for flexible positioning and reconfiguring without the need to rebuild the entire steel frame. The same attachment points serve as the interface to the clamping system. Enabling a wide range of clamping systems to be attached to the base frame. Different sheet shape or size requirements, different configurations or different positions can therefore be accommodated by the same base frame. The current configuration keeps the H-Frame all the way to one side and the robots on the opposing one. This configuration is chosen for several reasons: The diagonal placement of robots and H-Frame allows for the mitigation of singular robot poses, as the wrist is angled for all positions with a tool orientation orthogonal to the clamping system. Additionally, this placement enables the utilization of the especially strong joint 1 of the robots for most of the movement in the main forming direction. The placement furthermore requires only one side of the system to access all relevant components for use and servicing.

Figure 2 – Base platform consisting of machine bed, robots and frame

The *clamping system* is designed for the specific sheet layup necessary to facilitate the forming of continuous FRTPs. It also takes modularization, ergonomics and parallelization into account. The main difference to existing clamping systems for FRTP ISF is the use of a two-step approach. The sheet layup is stacked and clamped on a table. The clamped layup is shown in Fig. 3 a). Four clamping strips are used to clamp the sheet by tightening several screws. The entire assembly is then moved to the clamping frame, positioned and secured with toggle clamps as shown in Fig. 3 b). This entails several benefits: It allows for the horizontal positioning of the FRTP sheet, which is then secured by the clamping force. Even though the sheet is quasi-floatingly supported and placed vertically, the two-step process removes the need for additional positioning aids. Furthermore, the separation of the clamping and securing functions allows for a more ergonomic process. The more labor and time-intensive procedure of assembling and clamping the layup can be performed at a horizontal layup table which is specifically designed with ergonomics in mind. Only the task of placing and securing the layup in the clamping system is kept to the comparatively less ergonomic position and environment of the plant. The separation also enables the separation of force requirements. The layup force can be much higher and more easily varied, while the securing force is fixed and faster to apply. Additionally, the two-step process allows for parallelization. The subsequent layup can be prepared while a forming process is still ongoing. Similarly, a formed part can be removed and replaced while it is still warm. This increases efficiency by reducing the machine downtime between processes. To ensure the rigidity of the clamping system and integrate it with the base frame, all components are mounted to a square 20 mm thick stainless steel base plate that interfaces the base frame attachment points via eight L-brackets along its circumference. This interface entails that the base plate should be thermally separated from the heating system to avoid thermal expansion of the bolted connections or the toggle clamps. The insulating material at least partially lies in the load flow of the toggle clamps and requires complex shapes, e.g. for the hose attachment flanges. To address these challenges, the machinable high compressive strength Thermax SF 850 insulation material, shown in orange in Fig. 3 b), is used. To be able to process two sheet size ranges without reconfiguring the entire system, the securing system can be used to secure a reduction assembly shown in Fig. 3 c) which serves as a smaller version of the clamping interface.

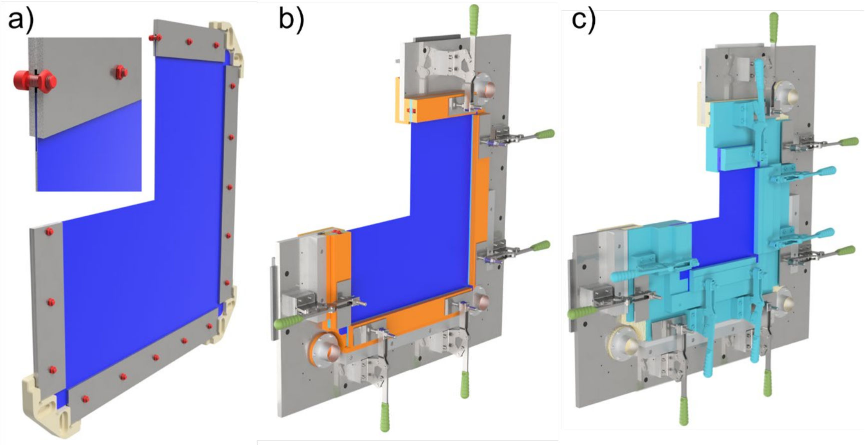


Figure 3 – Clamping system: a) clamped layup, b) secured layup, c) reduction module

The *tooling* is mainly designed to allow a flexible and heat-resistant tool change system with high stiffness. The tools for the hot and cold sides of the setup are shown in Fig. 4 a) and b) respectively. To avoid collisions with the part the tools require a sufficient clearance angle. Another driver of this requirement is the avoidance of collisions between tool and clamping system. Consequently, the tools possess a clearance angle of over 70° at 80 mm tip-length over their entire length. These could be increased further with a longer tooltip (1), albeit accepting the inherent stiffness loss. Tool changes are done via a collet system (2) – a simple, space-efficient and heat-resistant tool changer. The cylindrical shaft of the chuck is, in turn, secured to the root connector (4) by a locking assembly (3). This allows for further configurability and could be used to clamp more complex end effectors. (4) as the base of the cascaded tool chain provides alignment, fixation and rigidity. Each tool is connected to the respective robot via a six-axis load cell (8). When integrating tooling and heating system, the load-cell on the hot side needs to be decoupled from the heat-flow. It is shielded from the heating system via a cooling coupler (5). This coupler reduces the contact area to the root connector and an insulation chamber (6) steers the heat flow towards the outside of the coupler. Internal spiraling coolant channels (7) withdraw the remaining heat-flow and ensure that the maximum operating temperature of the load cell is not exceeded. The load cell is mounted to the robot flange via two adapter plates (9). A numerical thermal analysis revealed that air cooling would not sufficiently protect the load cell on the hot side at maximum operating temperature. Using water as the coolant, on the other hand, allows for efficient shielding.

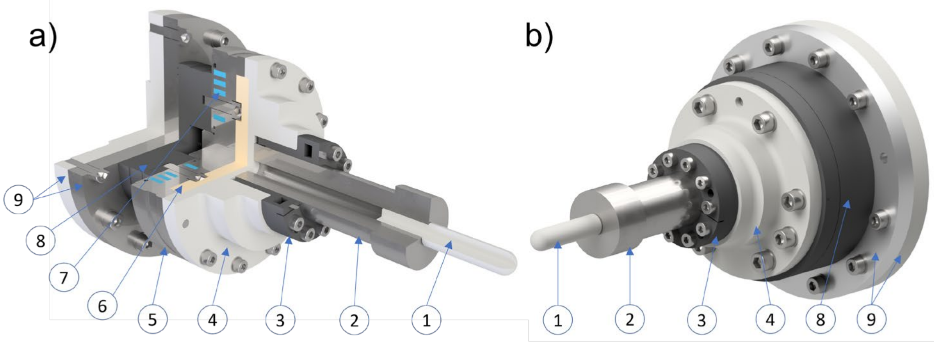


Figure 4 – Forming tools a) hot side tool with cooling coupler b) cold side tool consisting of: 1) tool-tip, 2) collet chuck, 3) locking assembly, 4) root connector, 5) cooling coupler with 6) insulation chamber and 7) coolant channels, 8) six-axis load cell and 9) adapter plates

The *heating system* is designed to allow for safe global heating while separating the rest of the setup from the thermal load and still allowing for complex double sided robot movements. In the existing systems, hot air blowers, thermal radiation plates and infrared lamps have been used. To increase energy efficiency and homogeneity, the system presented in this work uses a convective heating setup shown in Fig. 5. This removes the forming depth dependency of the heat input, commonly a problem in radiation-based systems, and improves efficiency and noise emissions compared to open-loop hot-air systems. A bespoke protective bag (3) out of flexible insulation material serves as a flexible oven wall integrated with the robot and tooling, allowing necessary tool movement. It is connected to the cooling coupler of the support robot (2) and the back of the clamping system, Thus, together with the clamping system, an enclosed chamber is formed. Insulating material (5/green) is placed on the back and front of the clamping system, on the chamber wall, and the air in- and outlets to steer the heat flow into the sheet layup (4). The hot air is pumped via a pipe (6) into the chamber through two inlets on the bottom front of the clamping system. Two outlet pipes (1) allow air recycling. The air is circulated by a Leister RBR radial blower and heated by a Leister LE 10000 DF-R. The air temperature is PID-controlled and the flow-rate can be manually adjusted. The internal chamber temperature can be measured via thermocouples at seven positions around the sheet. Further thermocouples could be directly attached to the layup. Sheet surface temperature could be directly measured with a thermal camera.

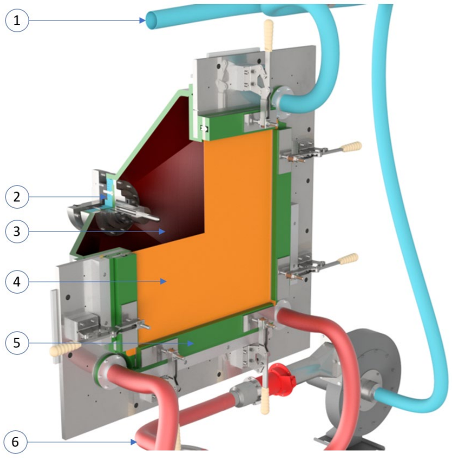


Figure 5 – Heating system based on a convection oven with flexible chamber walls with: 1) outlet pipes, 2) cooling coupler, 3) bag, 4) sheet layup, 5) insulating material and 6) inlet pipes

The *motion control system* generates the robot paths based on a target geometry and guides their movement during the process. The toolpaths are generated by a custom contour-based path planning algorithm, which will be described in detail in a future publication. The target geometry is loaded as a triangulated surface. Next, paths are then generated from the surface mesh. The generated path is then offset along the surface normal in opposite directions to generate the master and slave tool paths. To ensure correct relative positioning of the master and slave tools, KUKA RoboTeam with geometric coupling and added motion synchronization is used. The slave is geometrically coupled to the movement of the master tool. Therefore, only small motion-synchronized reorientation movements are programmed for the slave, while its main global movement is executed based on the movement of the master tool. The slave tool must apply the target support force at all times. Because of sheet thinning, positional inaccuracies, thermal expansion etc., this is not achievable by a purely position-controlled slave tool [11]. Consequently, a force controller corrects its path online to compensate for such variations. The force control is implemented on the robot controller via the KUKA Robot-Sensor-Interface (RSI). For now, a basic PI controller is used that takes the scalar error (F_{err}) between target (F_{target}) and actual force magnitude (F_a) and corrects the distance between the master and slave tool based on this error and its time integral. A conceptual representation of the controller is shown in Fig. 6. The incremental length correction ($|P_{corr}*|$) is calculated from F_{err} by passing it through the proportional and integral gain. To get the absolute current correction length ($|P_{corr}'|$), the correction length of the previous step ($|P_{corr}|$) is added. $|P_{corr}|$ is calculated as the length difference between the slave's actual (P_a) and commanded position (P_c) relative to the master tool. $|P_{corr}|$ therefore serves as a buffer of all previous length corrections. P_c is simply calculated by subtracting the correction vector P_{corr} from P_a. In the last step, $|P_{corr}'|$ is multiplied by the normalized commanded position to get the correction as a vector that the robot controller uses to offset the slave's path according to the measured force.

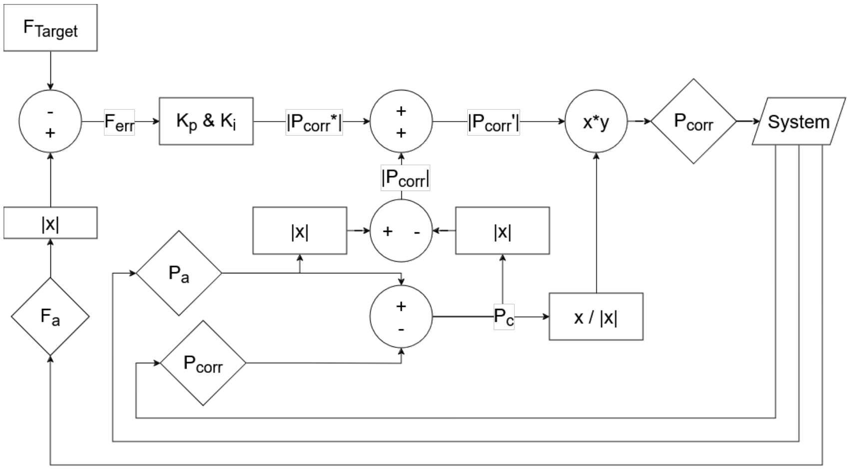
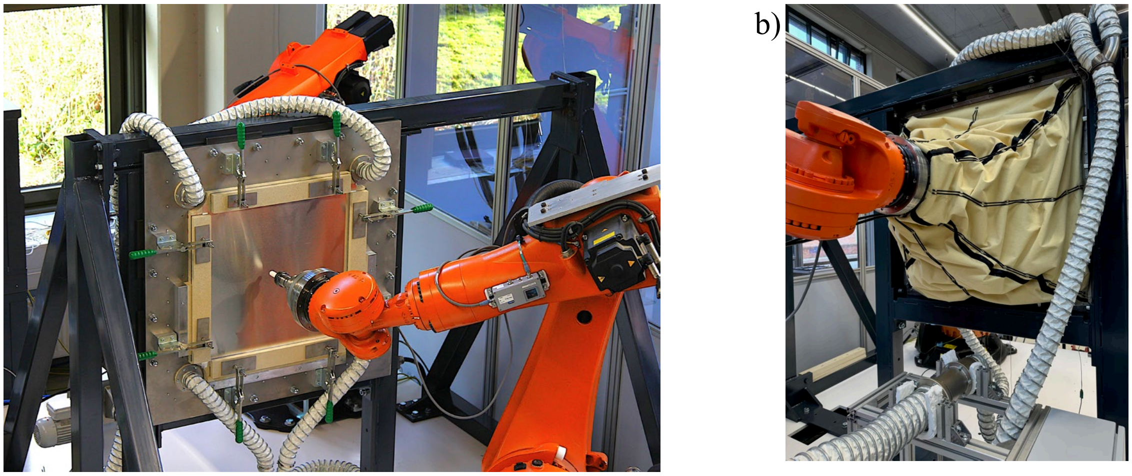


Figure 6 – Force control concept for the slave tool

The *base platform, clamping system, tooling, heating and motion control system* have been implemented and integrated to form the final setup, which is shown in Fig. 7 in its large sheet configuration, i.e., without employing the sheet reduction module. The process steps to operate the system are the following: The sheet layup is assembled on the layup table and clamped by tightening the screws. The layup can be attached to a crane and guided with removable handles. It is placed on the guidance blocks and secured with the toggle clamps. The heating system is started, and the sheet is heated to the target temperature. The sheet is then formed by the position-controlled master and force-controlled slave tool. After forming has finished, the heating is turned off, and the chamber is cooled down. When a safe handling temperature is reached, the layup can be removed and placed aside to cool down completely. A second layup may be prepared in parallel and could now be inserted to continue with another forming process. During the final cooling of the removed layup, the still clamped dummy sheets support the FRTP to maintain the formed geometry and counteract spring-back forces of the thermoplastic material. Finally, the clamping screws can be loosened and the finished part is removed from the layup.


a)

b)

Figure 7 – a) Final setup in the large sheet configuration; b) view from back

Discussion and Outlook

This work describes the methodological development of the first system for hot double sided incremental forming of continuous fiber reinforced thermoplastics. Requirements of general DSIF systems and FRTP ISF have been identified and combined. The functional analysis of the process deepened the understanding of the relevant components and revealed the systems subsystem structure. Subsequently, the subsystems base platform, clamping system, tooling, heating system and motion control system have been developed and integrated to generate a complete system, that meets the combined requirements of DSIF and FRTP ISF. The system is unique in enabling this combination. It is designed with modularity in mind so that many parameters such as tool-diameter, sheet size and geometry, heat input, forming forces etc. can be investigated for this process combination. On a subsystem level the main novelty lies in the clamping and heating system. The clamping system allows for the specific quasi-floatingly interposed sheet layup required for continuous FRTP ISF in a vertical position. This is achieved by separating the functions of clamping and securing the layup. The separation of these functions also has further benefits in increasing the ergonomics, modularity and parallelizability of the system. The heating system allows the transfer of the global heating common in FRTP SPIF to DSIF. The developed convective system has several benefits like energy efficiency and good heat containment. Its most important feature however lies in its integration with the other subsystems. The flexible chamber bag and cooled tool coupler integrate it with the robot system such that one tool can be moved inside the heated volume. At the same time the insulation reduces heat flow into the clamping system and frame to a minimum.

Future work will address the investigation of the systems performance on different metrics like the accuracy of the motion system and the finished parts, the speed, homogeneity and accuracy of the heating system, the consistency of the support force etc. Furthermore, the developed system paves the way for numerous investigations into the DSIF of continuous FRTP. Studies on the influence of the tool and sheet geometry, different layup systems and path planning strategies, heating and force control parameters will be necessary to optimize the systems performance and produce high quality FRTP parts. The methodological development in this work also enables the reproduction, adaptation and improvement for future system variants.

Acknowledgements

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