MANUFACTURING SIMULATION OF THE IN-SITU TAPE LAYING PROCESS FOR THERMOPLASTIC CARBON FIBER REINFORCED TAPES

Daniel Fricke[1], Georg Doll[1], Sebastian Nowotny[1], Kamyar Gordnian[2], Alireza Forghani[2], Anoush Poursartip[2]

[1]Deutsches Zentrum für Luft- und Raumfahrt
Pfaffenwaldring 38-40
70569 Stuttgart
Germany

[2]Convergent Manufacturing Technologies
403-6190 Agronomy Rd
Vancouver, BC
Canada, V6T 1Z3

ABSTRACT

In-situ automatic tape laying is a lean, cost-efficient process for manufacturing of large fiber-reinforced thermoplastic parts. During this process, non-uniform heating of the material may induce residual stresses and distortions. Therefore, further processing steps such as consolidation in a hot press or autoclave is required, which result in increased manufacturing time and cost.

Residual stresses and distortions can be controlled by adjusting the process parameters and altering the tool geometry. Optimal process parameters and tool geometry can be acquired by trial and error, which further increases development time and cost. Alternatively, process simulation can be used for identifying these optimal parameters, with decreased cost and effort.

Creating these simulations requires both, application of complex boundary-conditions and development of proper material models, which keep track of process state variables, such as crystallinity.

In this paper, the development and application of tape laying simulations for carbon fiber/PEEK thermoplastic composites at the research facility German Aerospace Center (DLR) and software company Convergent Manufacturing Technologies is explained. Simulation results are compared with experimental measurements.

1. INTRODUCTION

Using fiber-reinforced plastic (FRP) materials is often a time-consuming and work-intensive task. For a thermoset matrix the sheets have to be cut and draped, followed by a resin infiltration if no prepreg is used. The final curing and thermal treatment can last for hours or days, during which the part has to be pressurized in an autoclave or a press if a high fiber volume fraction has to be reached. The effort can be reduced by using a thermoplastic matrix, which also allows for further possible processing methods like forming and welding. An in-situ automatic tape laying process further increases production speed and reduces effort but introduces new challenges.

1.1 Thermoplastic Composites

Most modern FRP consist of carbon-, glass- or aramid-fibers embedded in a thermoset matrix like epoxy resin. The matrix can be stored separated from the fibers to be used during an infiltration or combined as a prepreg. After compacting and optional infiltration, the matrix is cured and hardens irreversibly. Curing is triggered by previous addition of hardeners and accelerators and/or by heating. After curing the matrix remains hard and can only be processed via machining. [3]

FRP with thermoplastic matrices work differently. The matrix can be stored separated from the fibers in sheets or together as a prepreg. For manufacturing parts, the stacked sheets have to be heated over the matrix melting point. During the process, the molten thermoplastic matrix impregnates the fibers and adapts to the desired form. By cooling down, the matrix solidifies again and the part stays in form. In contrast to thermosets, thermoplastic FRP can be molten and solidified multiple times, albeit quality changes with manufacturing technology [5].

1.2 Automated Tape Laying

Tape laying describes a manufacturing process where a robot lays a FRP-tape onto a tool. Repeated tape laying next and on top of each other, with different orientations, produces the final part. Thermoplastic tape laying exists in two variants. The first one requires an additional post consolidation using an autoclave or oven. In-situ tape laying can omit this step, the consolidation occurs during the laying process.

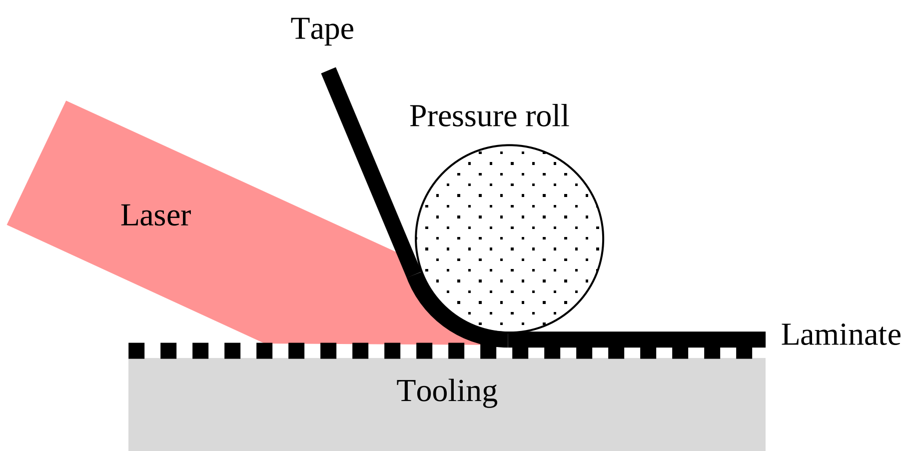

Figure 1: tape laying with in-situ consolidation

A robot for thermoplastic in-situ tape laying is equipped with a head which consists of a roll of stored tape, a pressure roll, a laser and a cutting mechanism. The tape is pressed onto the laminate with the pressure roll. The laser heats the area between tape and laminate and melts both components while the pressure roll presses them together. During cooldown and solidification, both components are connected. The part is finished afterwards, no further consolidation is needed. Only final machining remains.

Especially thermoplastics with high melting points like PEEK (390 °C) are a big challenge for this manufacturing method. The selective heating via laser creates an inhomogeneous heat distribution and thus high heat stresses. Barring good compensation, manufactured parts are deformed and have high internal stresses. [2] To optimize manufacturing and minimize deformations and stresses extended tests are necessary which negates the advantages in manufacturing cost and speed. Manufacturing simulations are a viable alternative.

1.3 Manufacturing Simulation Basics

To avoid expensive and time-consuming tests to optimize the in-situ tape laying process for every part, manufacturing simulations provide a solution. In this case a thermal-structural simulation is used which also includes chemical processes inside the material like crystallization. Using these simulations, the highly dynamic and inhomogeneous temperature distribution and its consequences can be displayed.

The employed simulation software by Canadian company Convergent is available as independent program RAVEN for 0D-2D-simulations and as plugin for ANSYS and ABAQUS for full 3D-simulations. Both versions implement an advanced CF-PEEK material model with temperature dependent and heating/cooling rate dependent material properties and chemical processes. For 3D-simulations, a transient thermal simulation is used as starting point. The temperature distribution is calculated and supplemented with chemical processes. For thermosets, these chemical processes take the form of reactions and curing, while thermoplastics mainly use effects like crystallization. For this paper, COMPRO with ANSYS was used.

These results are sent to a structural simulation and translated into deformations and internal stresses. It is also possible to activate and deactivate contacts during simulation, for example to simulate the removal of tooling. [4] This simulation creates the foundation for optimizations of tool, layup and heat input. Using a sufficient number of simulated configurations, a minimization of tolerances and internal stresses can be achieved.

2. EXPERIMENTATION

2.1 Press-Formed L-Shape

To verify the numeric PEEK-model, an experimental configuration for a press-formed CF-PEEK-part has been developed. Pre-consolidated organosheets are being formed into a 90°-angle with a heated press. After cooldown the spring-in-angle is being measured.

2.1.1 Simulation

With the simulation, the cooling behavior of the angle is being investigated. The tooling itself is made of steel and held at 290 °C. The organosheet is being press-formed after pre-heating up to 390 °C. After deformation of the sheet, the simulation starts and the part cools down. At 290 °C (tooling temperature) respectively after 30 seconds pressure is increased from 2.2 MPa to 5.5 MPa while the temperature remains constant to support the crystallization of the PEEK. 3 minutes later the tool opens and after further 30 seconds the part is removed from the tool and cools without pressure down to room temperature.

The organosheet layup consists of 12 unidirectional layers in 0°/90° symmetric orientation with a total thickness of 1.55 mm. The sheet is 120 mm long and 60 mm wide. It is folded in the middle of the long side. The tooling consists of two monolithic steel parts (upper and lower). This is an approximation for the real modular part presented in 2.1.2.

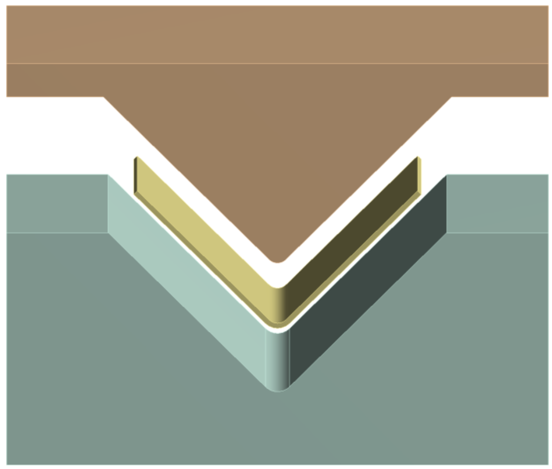

Figure 2: top and bottom tool and deformed organosheet for the simulation

As mentioned in 1.3, the simulation is split into a thermal and a structural part. The thermal part calculates temperature distribution and chemical processes. A constant temperature boundary condition of 290 °C is applied to the tools, while the part has a fixed starting temperature of 390 °C and thermal contacts with the tool surfaces. Due to the cooldown during transfer from the pre-heater to the press (compare 2.1.2), a second simulation uses a starting temperature of 330 °C for the part and 270 °C for the tool. After 3 minutes and 30 seconds the tool opens, which means that the top part of the tool is removed and all contacts including this part are deleted. A convection boundary condition is applied to the top surface of the angle for initial cooldown. 30 seconds later this procedure is repeated for the lower part of the tool and the angle cools down to room temperature.

In the structural simulation, the results from the thermal simulation are used as input to calculate thermal strain and stress. Additionally, the pressure of the press process is applied. Both tool parts are pressed together at 2.2 MPa, which is increased to 5.5 MPa after 30 seconds. 3 minutes later the boundary condition and all contacts with the tool's top part are deleted to simulate the opening press. After 30 additional seconds the bottom contacts are also deleted and the angle is free to deform as it cools down.

Due to the large thermal mass of the tool, the part itself shows an approximately homogeneous temperature distribution, which also makes the crystallinity of the matrix approximately identical over the whole part at the same time. Since the layup is symmetric, the only spring-in trigger is the press-formed deformation and subsequent asymmetric behavior of the part. The results will be discussed in 3.1.

2.1.2 Experiment

To verify the spring-in-simulation conducted in 2.1.1, an experimental setup for press-forming 90°-angles. A pre-consolidated CF-PEEK organosheet is heated to 390 °C using infrared heaters, moved into a multi-part tool inside a heating press and press-formed to create a 90°-angle. After cooldown, the spring-in angle is measured and compared with simulated results.

The organosheet layup is similar to the one used in simulations. Additionally, a sheet made of CF-PEEK fabric is used for the first tests to establish the experimental setup and for comparison with the UD-setup. Both setups are equally thick and can use the same tool. To record the organosheet temperature, a thermocouple is placed between the sheets.

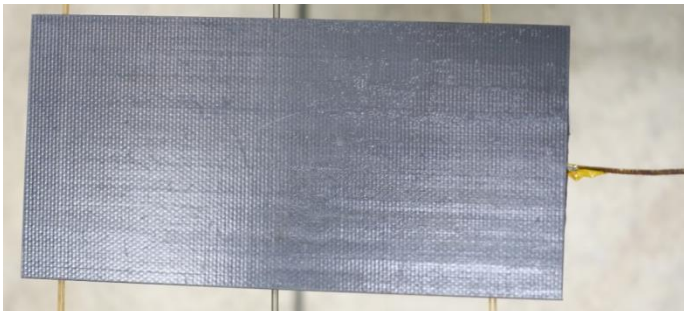

Figure 3: organosheet for press-forming with integrated thermocouple (right)

For this part, a new modular tool has been developed. In future experiments, the influence of sheet thickness and radius will be examined. The tool sections around the top and bottom radius are separate modules and very easy to manufacture. The tool can be adapted to different radii and organosheet thicknesses using different modules. The main modules are equipped with several holes for thermocouples to measure the tool temperature.

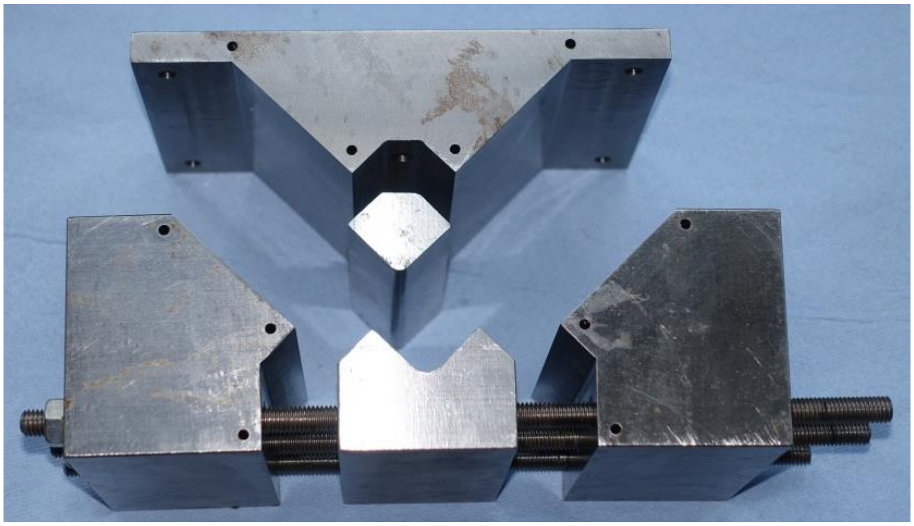

Figure 4: modular tool for press-forming 90°-angles

An infrared array is used to heat up the organosheet. The sheet is placed on a tray which is also used for transporting the heated layup to the press tool. The press tool remains closed until the transfer occurs to minimize heat loss of the tool. The transfer time has to be as short as possible, since the thin organosheet cools down very quickly in the air. During the first few tests, the sheet cools down to 330 °C before the press closes again. The detailed press-forming cycle is described in 2.1.1 and is not repeated here. Both pressure and part and tool temperatures are stored for the whole cycle. The results are discussed in 3.1.

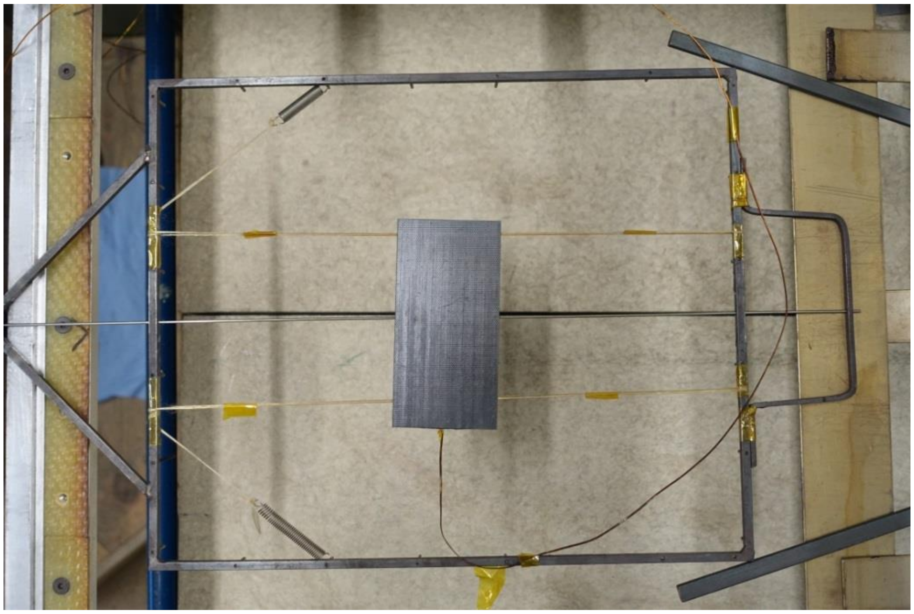

Figure 5: organosheet on tray

Figure 6: press-formed organosheet in press right before the tool is opened

2.2 Tape Laying

In contrast to press-forming, tape laying with in-situ consolidation is a highly dynamic process with inhomogeneous heat distribution. This results in additional challenges both in simulations and experiments. In section 2.2.1 the general setup principle for simulating this process is explained, albeit without direct physical counterpart. Section 2.2.2 shows the setup of the tape laying installation at the German Aerospace Center (DLR) in Stuttgart, Germany. Manufacturing parts and analyzing the process is explained there.

2.2.1 Simulation

To implement the process in simulations, a few simplifications are used. The tapes are already in place when the simulation starts. The tape "laying" process only uses a heat source moving along the tape. The bottom layer is firmly connected to the tool respectively has an applied fixed boundary condition which is removed after cooling the part. The laser is also replaced by a convection boundary condition with similar heat output. Since the simulation's main use is determining the effect of heating, the actual heat source is not relevant as long as its output remains the same.

The part used as an example for the simulation consists of six tape stripes oriented in [0°/90°/0°]. Since the complexity and number of boundary conditions increases with each tape, a minimum number, which still has multiple orientations, was used. The tapes are 25 mm wide, which represents common 1 inch tapes (25.4 mm).

Like the simulations for the press-formed angles, the first simulation is a thermal transient one. Since boundary conditions with variations in both time and spatial location are not possible in ANSYS, a replacement with multiple boundary conditions was created. Each boundary condition heats a small stripe of tape for a very short time, before it is deactivated and the next condition is activated. As a representation for the laser, a "convection" boundary condition is used because it can be applied in a flexible way. It consists of a heat transfer coefficient and an ambient temperature. For this simulation the temperature is constant and the coefficient is applied over the width of the tape. The principle is shown in Figure 7. The laser moves along the tape in the direction of the arrow. In simulation, the convection coefficient has a peak value at the position of the laser, as shown in the lower diagram. Tapes which are not "placed" yet are held at a constant temperature of 22 °C. Additionally, a convection boundary condition is applied to the surface and bottom of the part to represent the heat exchange with the environment.

The "laser" needs approximately 0.4s to move along one tape. One second later he moves along the second tape. This delay ensures a good cooldown time for the new tape and allows the heat do move inside the whole part. The bottom tapes are already "placed" and are not heated separately, but since the laser is aimed between two tapes, those tapes are heated together with both middle tapes.

Following the thermal simulation, a structural simulation is carried out. At the moment this simulation is very simple and only fixes the bottom tapes until all tapes are "placed" and the part has cooled down. In-plane deformations are allowed to reduce internal stresses of neighboring tapes. Afterwards deformation is allowed.

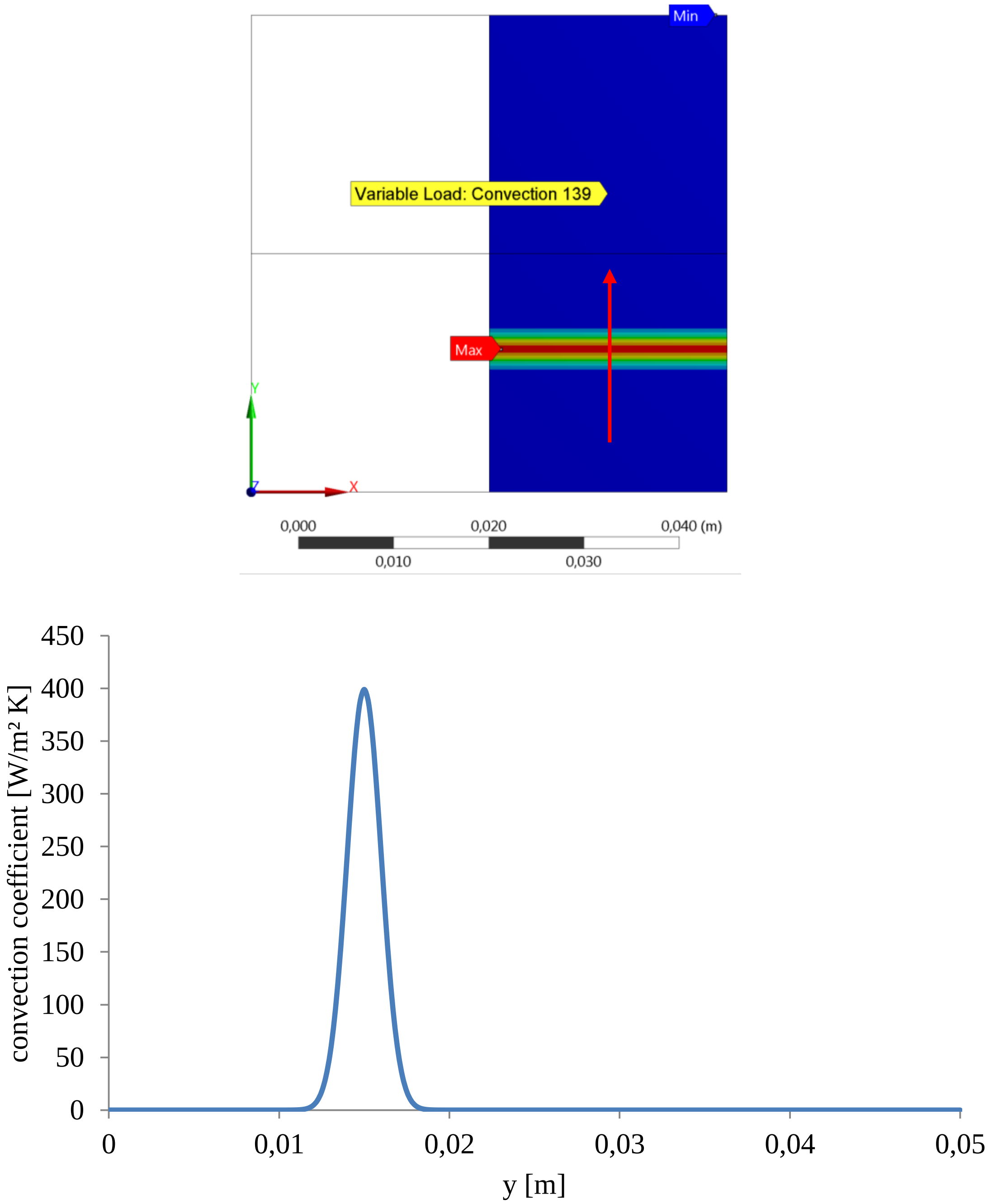

Figure 7: heating boundary condition of simulated tape laying parts

2.2.2 Experiment

Experimental verification of simulations conducted in 2.2.1 is more difficult than l-shaped simulations and experiments in 2.1. The simulated tape laying part is way too small for real manufacturing at a tape laying machine. Additionally, it doesn't cover all characteristics which appear in a real-world part. For example, a tape laying machine usually needs a small strip of tape before and after placing the tape for the actual part. This is not yet achieved in this simulation, but can have significant impact on part quality. On the other hand, using manufactured parts for the simulation is not (yet) reasonable, as those parts are too complex to set up as a simulation model. Advanced automation in model creation can solve this problem in the future.

Instead, the simulation's results are qualitatively compared to generic manufactured parts from DLR Stuttgart's tape laying machine. Since there is a wide variety of parameters to calibrate, the indirect comparison is possible. Since the focus of this work is simulation and general verification of models, direct comparison with tape laying parts will occur at a later point.

3. RESULTS

3.1 Press-Formed L-Shape

During the simulated press-process, the organosheet quickly cools down to tool temperature. After sinking below the melting point of 340 °C, the crystallization process starts and quickly approaches 0.33. The crystallization process is almost finished when the tool is opened and the part is removed. During the following 5 minutes, the part cools down to room temperature. Simultaneously, the spring-in effect becomes visible. During tool opening, the angle immediately jumps to a spring-in angle of 2°. As the temperature sinks, the spring-in angle climbs until it reaches 5° at room temperature. The simulation shows no difference for different starting and tool temperatures. The simulated process is shown in Figure 8.

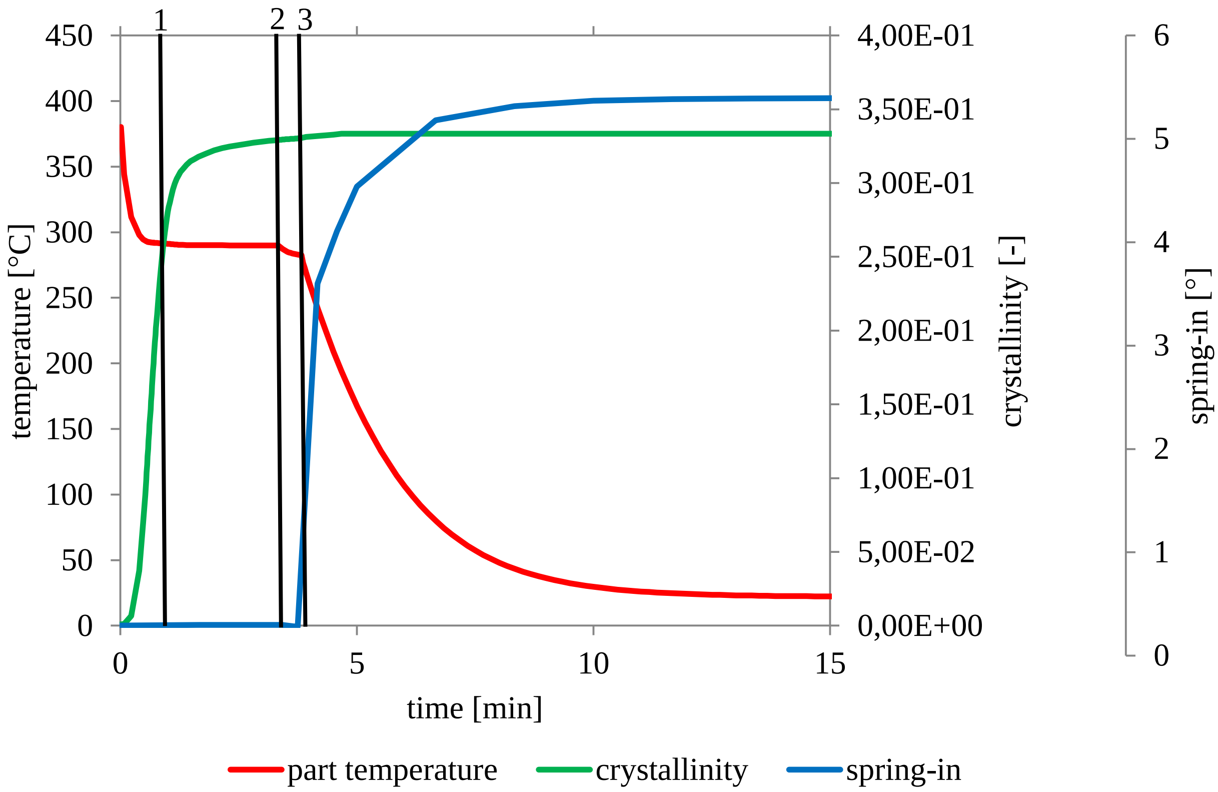

Figure 8: temperature, crystallinity and spring-in of a simulated 90°-angle: 1. pressure increases; 2. press opens; 3. part is removed

A big challenge for the experiments is the transfer of the pre-heated organosheet from heater to press. During this 5-10 second transfer the sheet cools down to 330 °C and begins to solidify. The press-forming occurs with a partially solidified part, which alters the internal stresses so that the final spring-in angle is changed. The first parts show a spring-in angle of about 2-4°. Figure 9 shows temperatures and pressure of one part during the transfer, highlighting important points. The time axis point of origin is the start of pre-heating the sheet. After opening the press (1), the heated organosheet is removed from the pre-heater (2) and placed into the tool (3). During this transfer, this sheet cools down to 340 °C before the press closes and reaches 320 °C when the press finishes closing (4). The resulting spring-in angle of 2°-4° shows that this process needs further optimization before a direct comparison to simulations is reasonable.

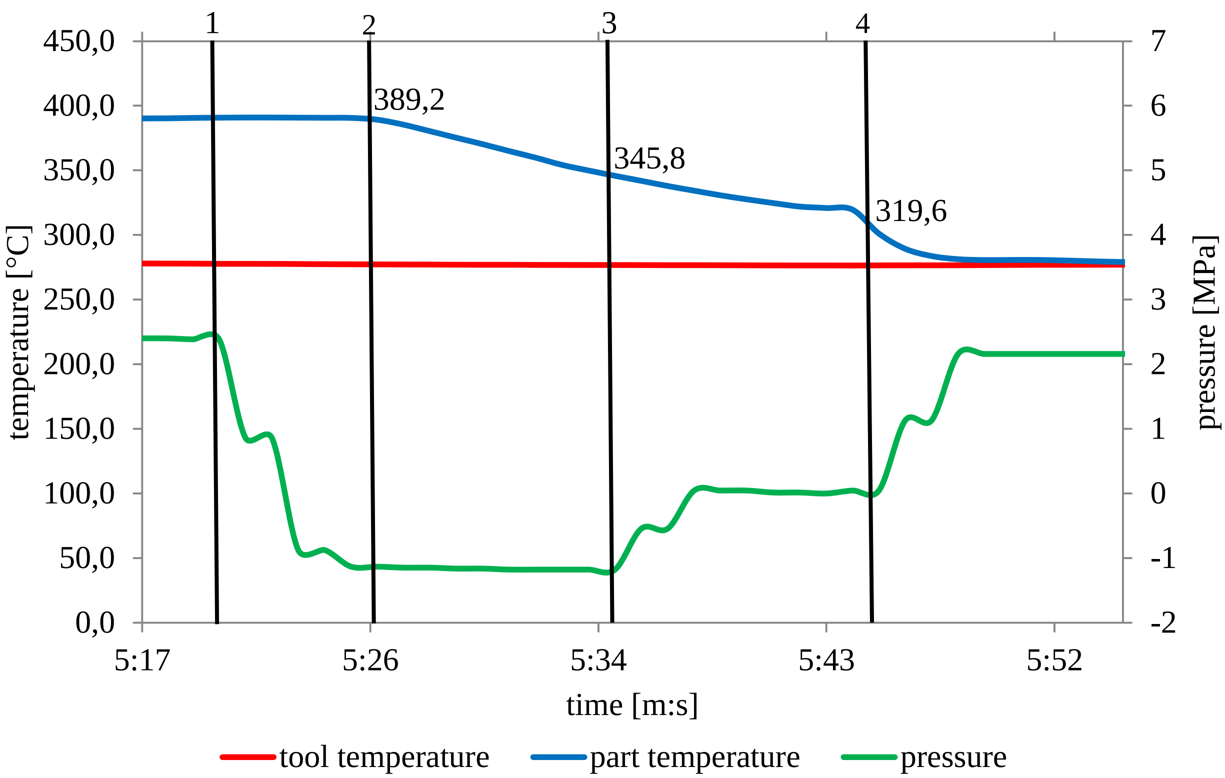

Figure 9: experimental temperatures and pressure during sheet transfer to press of part P019-3: 1. press opens; 2. part is removed from pre-heater; 3. part is placed in press and press begins closing; 4. press finishes closing

An increase of the pre-heating temperature from 390 °C to 420 °C offers a solution, as seen in Figure 10. During experiments with this temperature, the part cools down to 345 °C when the press is fully closed. Since this is above PEEK's melting point of 340 °C, the whole forming process occurs with liquid PEEK. Table 1 shows that the later specimen show a more uniform spring-in angle and better reproducibility. The improved cycle is used with both materials to maintain the comparability.

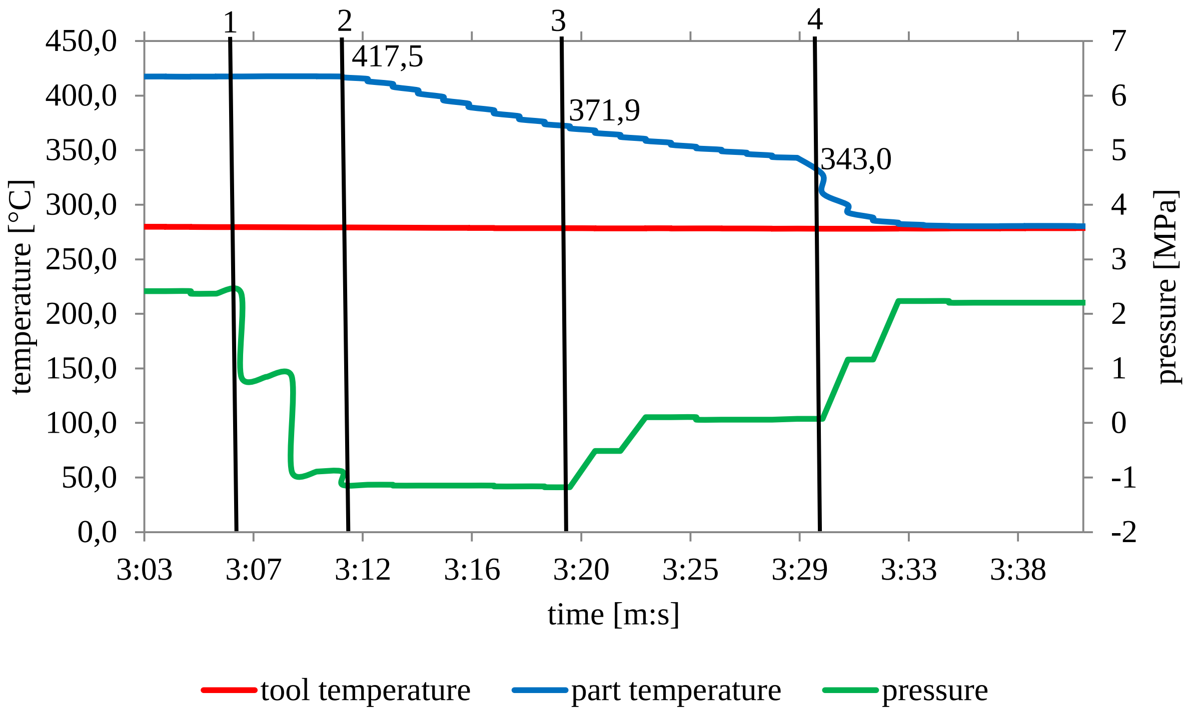

Figure 10: experimental temperatures and pressure during sheet transfer to press of part P019-7: 1. press opens; 2. part is removed from pre-heater; 3. part is placed in press and press begins closing; 4. press finishes closing

Table 1: designation and spring-in angle of press-formed specimen

Designation	**Material**	**Pre-heating (°C)**	**Spring-in angle (°)**
P019-1	UD	390	2
P019-2	Fabric	390	4
P019-3	Fabric	390	2
P019-4	UD	420	3
P019-5	Fabric	420	4
P019-6	UD	420	3
P019-7	UD	420	3
P019-8	UD	420	3

When comparing these results with simulations, the smaller spring-in angle of the experiments is obvious. This is most likely a result of the constraints of these simulations. Since they only show the behavior of the specimen after forming during the cooldown, any effects of the deformation itself is ignored. These effects include movement of the layers against each other due to the radius. These movements occur, as the edges of the specimen show in Figure 11, but they may be partially impeded by interlaminar shearing forces and introduce different internal stresses. These stresses may reduce the spring-in effect. Examining the area around the radius with microscopes will be part of future research.

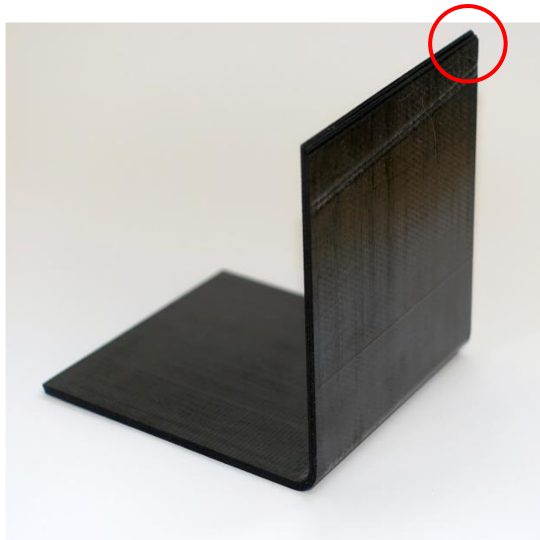

Figure 11: press-formed angle P019-6 with shearing movement of layers

3.2 Automated Tape Laying

Setting up the simulation environment is complicated compared to the press-forming simulations. Since the laser is moving along the tape and ANSYS doesn't support moving boundary conditions [1], the movement has to be replaced by switching multiple similar boundary conditions with slightly peak on and off in a row. For this simulation with very short tapes and simple geometry, about 40 single boundary conditions per tape have to be created, resulting in 160 boundary conditions for six tapes (the two bottom tapes don't need those). This effect scales with size, making simulations of big parts not yet feasible. This problem can be removed by developing suitable automatic simulation setups.

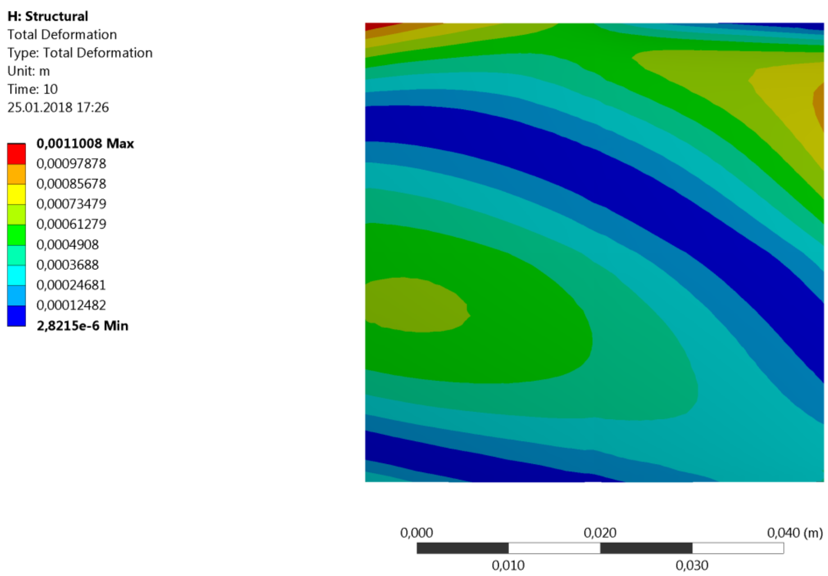

Figure 12: deformed simulated tape laid part

A symmetric and planar setup was used. In a heating press, this setup would guarantee minimal deformation due to cooldown. However, the inhomogeneous nature of the tape laying process creates high thermal gradients, which in turn cause internal stresses and deformations. Figure 12 shows deformations larger than 1 mm, which is very high for a symmetric layup in this size.

This effect is also evident with plates manufactured by a tape laying maching. Using the initial setup of the tape laying machine, simple plates would also deform in a similar way, as shown in Figure 13.

Figure 13: plate manufactured with initial tape laying setup [2]

While a direct comparison between a plate with hundreds of tapes and a simulation using six tapes is not sensible, the general deformation aspects of a real plate also appear in simulation. In both pictures, the top left corner is bent upwards, while the bottom left corner remains on the table. Other deformation aspects also show similarities. A first step for correcting these deformations was the installation of heated tools for layup, which maintain a higher temperature below the PEEK melting point, similar to the tools used in press-forming.

4. CONCLUSIONS

Manufacturing parts made of thermoplastic FRP using the in-situ automatic tape laying process is a fast and reproducible method for large, durable and light components. However, the process introduces new challenges concerning tolerance and internal stresses and deformations due to the inhomogeneous heat input. Rectifying these flaws using traditional test series requires a lot of time and resources. Manufacturing simulations offer a faster and cheaper solution.

In this paper the successful spring-in angle calculation of a press-formed angle was shown. The simulation successfully calculated part and tool temperature, deformation and crystallinity during cooldown. The initial deformation due to the press forming process could not be recreated though, which may be the source of slight inaccuracies concerning the spring-in angle. Further examination of the area around the radius can confirm this assumption.

The simulation of the tape laying process is basically the same as the press-forming simulation. The main differences are the highly dynamic boundary conditions to heat the tapes and the progressive addition of new tapes to the part. These dynamic aspects complicate the simulation. However, they cause mainly a high number of sequentially activated and deactivated boundary conditions with very similar aspects, which are easy to automate. Once automation protocols are successfully implemented, calculation of larger and more complex setups is possible and verification of the process parameters can be done. Small and simple setups already show promising results and show similar flaws like parts manufactured with similar parameters.

5. REFERENCES

1. Ansys, Inc (2017). Mechanical Users Guide. *ANSYS® Academic Research, Release 18.1, Documentation.* Canonsburg, USA
2. Doll, G., Dreher, P., Nowotny, S., & Calomfirescu, M. (2017). FFS - Thermoplastische Bauweisen für Sekundärstrukturen. *66. Deutscher Luft- und Raumfahrtkongress.* Munich, Germany.
3. Feiler, M., Ischtschuk, L., & Dudenhausen, W. (2003). Vacuum Assisted Resin Infusion (VARI): On the Way to Serial Production. *SAMPE 24th International Conference.* Paris, France.
4. Gordnian, K., & Poursartip, A. (2015). A Rate-Type Crystallization Kinetics Model for Process Modelling of Carbon Fibre PEEK Matrix Composites. *20th International Conference on Composite Materials.* Copenhagen, Denmark.
5. Horn, M., Keck, R., & Kaden, M. (2010). Influence of Production Technology on the Consolidation of Fiber Reinforced High Performance Thermoplastics. *ECCM 14.* Budapest, Hungary.
6. Horn, M., Wille, T., Hein, R. (2013). Novel Composite Tool Chain and its Application for Fiber Reinforced Thermoplastics. *34th SAMPE Europe Conference & Exhibition.* Wuppertal, Germany.