Manufacturing of a Thermoplastic Door Surround Structure

Daniel Fricke, Georg Doll, Simon Bauer, Karsten Reifegerste
Deutsches Zentrum für Luft- und Raumfahrt e.V. (German Aerospace Center), Institute of Structures and Design, Stuttgart, Germany

Abstract:
Thermoforming of thermoplastic composite structures can produce high quality parts with extensive throughput. However, high performance thermoplastic matrices often suffer from large warping due to the increased temperature required by the process and the crystallisation of the matrix. Complex geometries can also cause folds and ripples in the fibres which reduce performance. Those imperfections have to be countered by changes to the preform holder and by cuts in the preform. A detailed simulation process chain respecting crystallisation and thermal shrinkage during the cooldown is necessary to compensate spring-in. The simulation process chain has to be supported and validated by experiments. Folds in the laminate can be examined by detailed forming simulations if sufficient material and process data can be provided.
At the German Aerospace Center in Stuttgart the process chain was applied to a generic segment of a door surround structure. Using a detailed material model for carbon fibre reinforced low-melt polyaryletherketon (CF/LM-PAEK), the warping during the cooldown was simulated and used to modify the tooling. A forming simulation afterwards showed thickness changes due to shearing and folding of the preform. Different strategies were tested to minimise these effects. The whole process chain was verified with multiple manufactured parts using the modified process.
Keywords: Thermoplastic composites, Thermoforming, Process simulation

Introduction

Thermoplastic composites become more prominent in various industries due to their excellent mechanical performance and the potential of high process speed and recyclability. With thermoforming, a process where the material is heated above the matrix melting point and then moulded into complex geometries, very high throughput and economical manufacturing costs are achievable. However, this process is susceptible to spring-in during cooling, which can reduce the final geometric accuracy of the part. By implementing a geometric change into the tooling in the opposite direction of the spring-in, the effect can be counteracted. The exact angle can be determined by executing iterative process simulations of the cooldown with a detailed material model respecting changes due to various thermal effects like thermal expansion and crystallisation.

State of the Art

Thermoforming is a multi-stage process. A preconsolidated organosheet is heated above the matrix melting point, for example by using infrared heaters. The sheet is then inserted into a hot press with a heated mould. The mould is heated above the matrix glass transition temperature but below the melting point. The press has to be closed as fast as possible to minimise heat loss of the organosheet. After a few seconds in the press the laminate has cooled down to the mould temperature. The press can be opened again and the part can be extracted and cooled down to room temperature.

The thermoforming process has been extensively examined both with experiments and simulations. Chawla [1] gives a general overview of different manufacturing processes of thermoplastic composites. Chapman et al. [2] detailed the numerical analysis of the manufacturing of thermoplastic composites, while Hsiao [3] showed a typical optimisation of the thermoforming process.

Methods

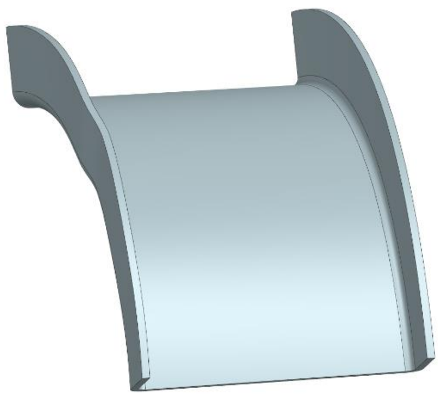

Fig 1: *Door surround section*

For the demonstrator thermoforming part, a section of a door surround structure of an airplane fuselage (Fig. 1) has been chosen. This part incorporates a straight flange and a curved flange with a joggle (right and left side of Figure 1 respectively). The geometry imposes a high degree of deformation on the organosheet and provides a challenging part to process. Added to the process steps detailed in this work, the part will be

joined to other structures via resistance welding as described in [4].
Both fabric laminates and UD layers are used for the component. The layer structure is quasi isotropic and has a thickness of 4.7 mm. The matrix material is LM-PEAK. A Rucks KV 330.00 thermoforming system (Figure 2) is used for thermoforming.

Fig.2: *Rucks KV330.00*

The 500·500 mm² organic sheet is heated to the appropriate temperature in an infrared heating field and then transported to the press station and formed as quickly as possible. The organic sheet is fitted with type K thermocouples. These are located in the middle of the laminate and in the area of the formed component.

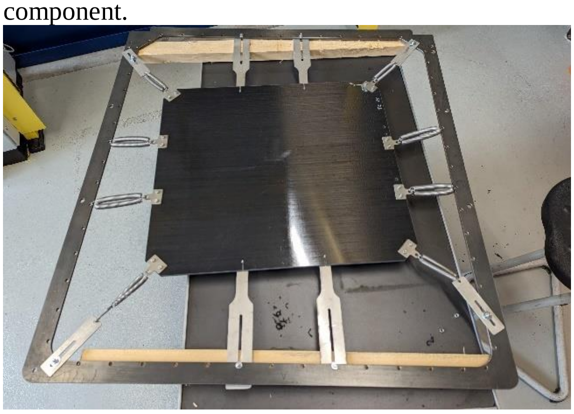

Fig. 3: *Clamping of the 500·500 mm² organo sheet*

The organic sheets are clamped or placed with both a spring and a holding system (Figure 3). This is adjusted in advance using a simulation and iteratively adapted during the course of the test campaign.
The organic sheet component is heated to approx. 390°C and moved into the press in the shortest possible time, where it is formed at approx. 85 bar machine pressure, which translates to 11 bar on the part. Figure 4 shows the thermal history of both the part and the tool as well as the movement of the press and the sheet transfer tray.
The process simulations to predict the spring-in were conducted using the numeric simulation software Ansys 2020R2. A custom semi-crystalline material model developed by Gordnian [5] for polyetheretherketone (PEEK) and modified by Teltschik [6] for LM-PAEK was implemented to predict mechanical changes in the material. An example of using the material model for Automated Fibre Placement (AFP) with a detailed explanation of the material calculations can be found in [7].

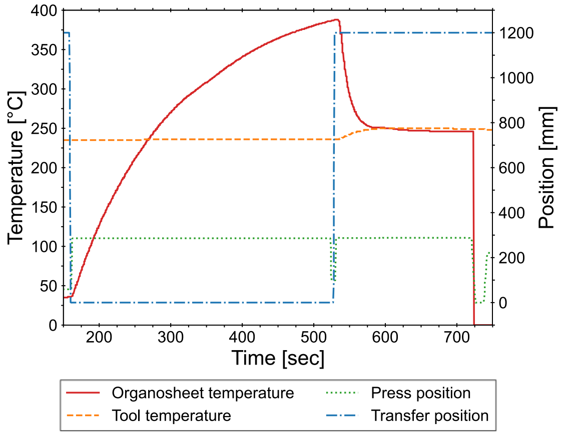

Fig.4: *Parameters of the thermoforming process*

The spring-in simulation starts when the press has been closed, so no shearing influence was considered at this time. The laminate has been simplified for the simulation by combining multiple layers into single elements, thus reducing the required computing power. The simulation process involves two connected steps.
First, the thermal history of the part was calculated. The part started at the pre-heated temperature of 390°C with heat transfer boundary conditions to the 230°C mould. After achieving equilibrium and holding for a few seconds, the heat transfer was replaced by a lower heat transfer coefficient to a 20°C environment, simulating demoulding. During this step, the thermochemical effects of crystallisation were also calculated.
The thermal history was transferred to a structural simulation. Here, during the first part, the pressure of 11 bar was applied to the surface. When changing the thermal boundary condition, the pressure was also lifted.
The final deformation was exported as stl and compared to the intended geometry, with the difference used to create a new starting geometry for the simulation. The process was repeated until the difference between the simulation result geometry and the target geometry was negligible. After manufacturing of the parts, 3D-scans were used to verify the simulation results. A GOM Atos 5 3D-scanner was used to obtain the true geometry.
In addition to the cooldown simulation, a forming simulation was set up using esi PAM-Form 2022.5. The goal of this simulation was the identification of creases after forming and examine different strategies to minimise creasing. Therefore, the simulation was reduced to simulating only a single layer to reduce the required simulation time and examine more variants.
The organosheet was fixed in the corners by flexible linear elements to simulate the clamping of the real

organosheet. The mould was being closed with the speed used in the real press. When reaching the final “closed” position, the simulation ended. For examining the results, a visualisation to highlight creases was chosen. To reduce creases, various configurations with different cuts and modifications to the organosheet were examined and compared to the real process results.

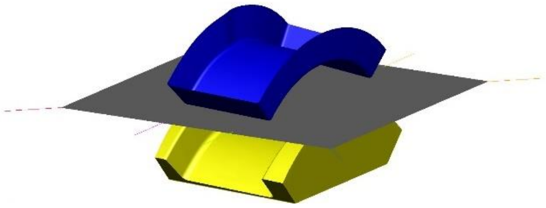

***Fig. 5:** initial setup of the forming simulation*

Results

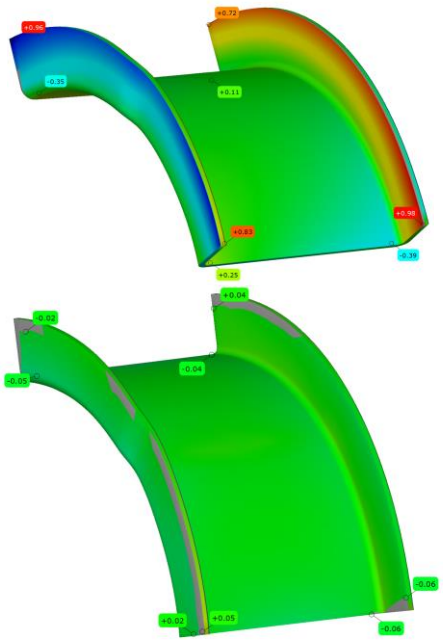

***Fig. 6** simulation results compared to target geometry; top: first iteration, bottom: final iteration*

For the cooldown simulation, multiple consecutive iterations were conducted. Each time the new start geometry of the simulation was modified to counteract the spring-in. After 4 iterations the difference between the target geometry and the simulation result was negligible. The first and last iterations are shown in Figure 6. A solid steel mould was manufactured according to the modified geometry.

Inserting the organo sheet into the press (starting at 527 seconds) and closing the press (finished at 531 seconds) takes less than 5 seconds. The thermocouple, which is inserted in the middle of the laminate, does not lose any temperature during the running-in time. This could be seen in Figure 7, which shows a detailed view of Figure 4. Only when the mould is closed does the laminate take on the temperature of the mould. The tool is still heated by the laminate by approx. 10K.

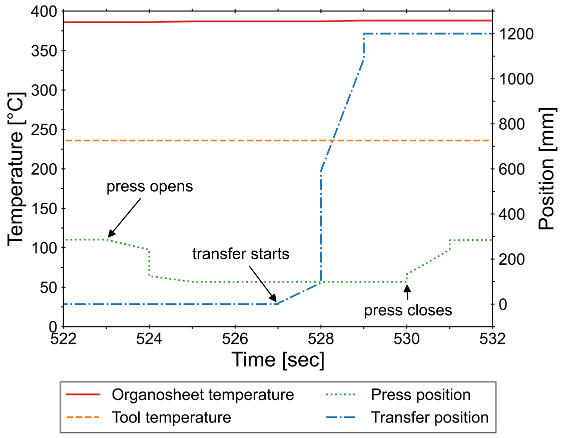

***Fig. 7:** Details of process parameters during thermoforming*

Various clamping variants were tried out accordingly. It was not possible to completely prevent creasing with such a complex shape. Figure 8 shows an example part after the thermoforming with highly visible creases.

***Fig 8:** Part without trimming after forming*

The clamping variations were also monitored in the forming simulation. The results for the unmodified shape are shown in Figure 9 on the left. The part exhibits creases all over the surface.

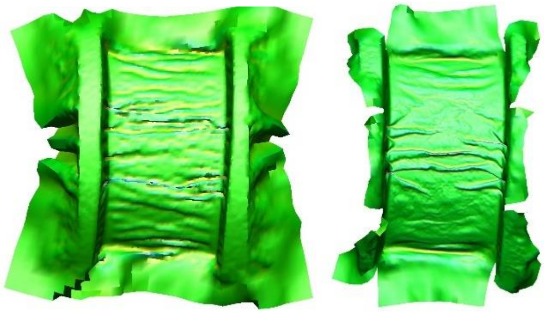

***Fig. 9:** simulated creases of the initial (left) and a modified (right) organosheet configuration*

By shortening the flange and adding two cuts into the sides down to the final trimming line, the creases could be reduced massively. However, due to the curvature of the part it was not possible to eliminate creases completely. The resulting creases for the modified part are shown on the right side of Figure 9. The area between the cuts in particular (shown in the middle of the image) still exhibits large creases, which was also reflected by the behaviour of the real part.

By comparing a 3D-scan of the final part with the target geometry, an anomaly can be observed. While the straight flange was predicted correctly by the cooldown simulation, the curved flange with the joggle stayed in the position imposed by the tooling and exhibited no spring-in behaviour (Figure 10). The reason for the inability of the simulation to reflect this characteristic can be surmised to be the result of layer shearing due to the high degree of deformation of the part, which is not yet considered by the simulation.

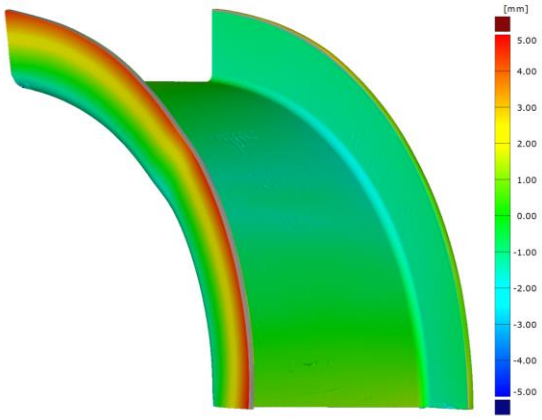

Fig. 10: *deviation between the manufactured part and the target geometry*

Conclusion

The process chain of the thermoforming process (Figure 11) could be successfully demonstrated. The spring-in could be partially predicted using advanced material models and the mould could be adapted to compensate. However, it was also shown that the simulation needs to be adapted to reflect the reinforcing behaviour of the curved flange by considering the shearing of the fibres due to the forming process.

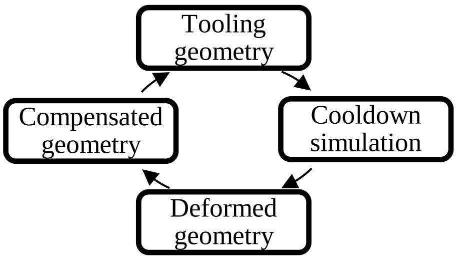

Fig. 11: *Process chain of cooldown simulation*

The forming simulation needed to achieve this were already performed and have been shown to accurately predict creases and shearing. These simulations have already been used to improve the preform.

The process itself has been proven to be very stable and fast, producing repeatable results in a very short time frame. By automating the design process and implementing shearing results from the forming simulation, the results can be further refined. Combining the forming and the cooldown simulation should better reflect the spring-in behaviour of complex geometries like the joggle. Future projects aim to improve the simulation setup for increased accuracy and reduced simulation time.

Acknowledgement

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