NUMERIC OPTIMIZATION OF IN-SITU CONSOLIDATED PANELS WITH DIFFERENT TAPE SEQUENCE STRATEGIES

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ABSTRACT

Automated fibre placement with in-situ consolidation is a fast and flexible manufacturing process for thermoplastic composites, though high thermal gradients and inhomogeneous heating combined with semi-crystalline matrix behaviour create high warping and internal stress. At the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt – DLR) in Stuttgart, simulations were implemented to predict the influence of the manufacturing process on the final warping and stress. The first step to optimize the process was the modification of the sequence, in which the tapes were placed. The results were verified against panels manufactured in the same sequence. The warping was measured using 3D-scans. Finally, an optimal tape laying sequence with minimal warping was determined.

1. INTRODUCTION

For the European Clean Sky 2 large passenger aircraft project (LPA), the DLR Institute of Structures and Design in Stuttgart and Augsburg in cooperation with Premium Aerotec, Aernnova and Airbus develop a new manufacturing and structural approach for a single aisle aircraft within the multifunctional fuselage demonstrator (MFFD) project. While traditional fuselages are made from aluminium, the MFFD will be manufactured entirely of carbon fibre reinforced thermoplastics, specifically using a low-melt polyaryletherketone matrix system (LM-PAEK). The ability to be welded and hot-formed may significantly reduce production cost even though initial material costs are higher compared to aluminium. Automated fibre placement (AFP) with in-situ consolidation (ISC) is used for the production process of the fuselage skin as a single-stage process.

In this process each tow is heated above the matrix melting point using a focused heat source, for example a laser and a compaction roller to fuse it to the preceding layer. The addition "ISC" indicates that no further consolidation steps are needed. The matrix of the laminate and the added tape coalesce and solidify during cool-down, welding both parts together. Due to the high temperature gradients both spatially and temporally, the final part quality strongly depends on the process parameters and tool configuration. Inappropriate parameter combinations can lead to high warping and internal stress due to inhomogeneous crystallization and cool-down shrinkage effects. Determining optimal parameters with an experimental setup is both time consuming and expensive. Process simulations provide a cost-effective solution and also an opportunity to investigate unconventional methods to minimize non-desirable effects. Developing a process simulation for the AFP-process with ISC provides an interesting challenge due to the highly dynamic nature of the process and the nonlinear behaviour of the semi-crystalline matrix. In the beginning of the project a basic simulation setup for simple panels was created and verified [1]. This paper demonstrates a first practical application of this setup by investigating the influence of different tape placement sequences on the final part.

2. EXPERIMENTATION

2.1 General AFP setup

The DLR-team in Stuttgart uses an automated fibre placement machine by the company AFPT which heats the material with a 6 kW laser (laser-assisted AFP, L-AFP). The processing parameters of this machine for carbon-fibre reinforced LM-PAEK (CF/LM-PAEK) have been optimized experimentally [2]. The panels manufactured with these parameters form the basis for the process simulation development.

The exemplary panel chosen for the simulation consist of 16 layers forming a 648 mm × 428 mm quasi-isotropic panel with a nominal uncompressed thickness of 3.168 mm. The stacking sequence is [90°/-45°/0°/45°]2s. The tapes are heated up to 470 °C and placed with a speed of 72 mm/s onto the laminate. The tooling itself is held at a temperature of 200 °C, which is below the matrix melting point but above the crystallization initialization temperature. The robot is able to place three tapes with a width of 12.7 mm simultaneously, resulting in an effective tape width of 38.1 mm for the simulation. The resulting panel is measured after cool-down using a GOM Atos 5 3D scanning device, which uses two stereo cameras to photograph a projected pattern on the part to calculate the relative position of the scanned surface. The device can be equipped with lenses with different focal lengths to either scan large parts or capture smaller parts in more detail. For the panel lenses with medium focal lengths were used for good resolution while keeping the necessary number of scans low. The warping of the panelthe main comparison between simulation and reality.

2.2 Simulation setup

The first challenge of the simulation was the material model for the thermoplastic matrix. At the University of British Columbia (UBC) a material model for carbon-reinforced polyether ether ketone (CF/PEEK) was created by Gordnian [3] and is distributed by Convergent Inc. The material model simulates crystallization rate based on the temperature, temperature gradient and current degree of crystallinity and apply its effects onto various mechanical parameters. The model can be used in the commercial finite element software Ansys. At the DLR in Stuttgart, the model was modified to be easily adapted to other semi-crystalline thermoplastic materials by Teltschik et al. [4]. An adaption to CF/LM-PAEK was created afterwards. Figure 1 shows the simulated crystallization behaviour of the matrix during cooldown.

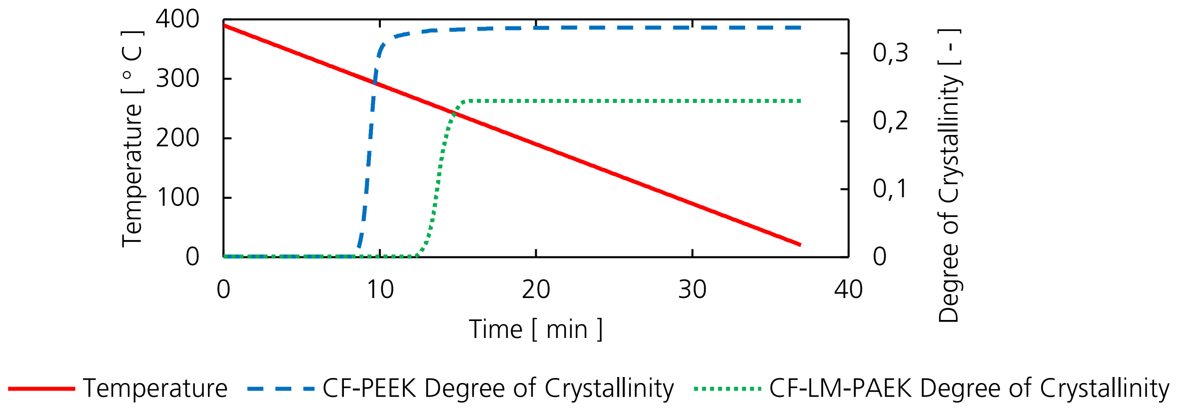

Figure 1: simulated crystallization behaviour of the material model during cool-down

The development of the simulation setup is described in great detail in [5] and [1]. The panel is created with elements small enough to cover individual layers and to provide sufficient resolution for the laser thickness. All elements not belonging to the current tape or to those already processed are deactivated. An automated script generates a three-dimensional table for each tape to specify a heat transfer distribution along the tape for a given time. This distribution forces the tape to heat up to the processing temperature at the current position of the laser and allows cool-down to equilibrium conditions at the remaining length. With time elapsing, the forced temperature moves along the tape, simulating the moving laser. After reaching the end of the tape, the “laser is switched off”, meaning that the boundary condition is deactivated and the temperature can bleed off into the surrounding panel material, the tool and the air. The robot moves to the starting point of the next tape, which initiates a new time step in the simulation to repeat this procedure with the new tape.

The thermal history created by this setup is inserted into a new structural simulation. In this simulation the panel is fixed by boundary conditions onto the tool during the manufacturing process. The thermal gradients and changes are translated into crystallization effects and internal stress. After the final tape placement and cool-down, the fixation is deactivated and the panel can deform freely. During this deformation it is fixed in space by virtual anchor points to prevent rigid body motion. These anchor points were set in both lower corners and the upper right corner. These edges thus show a warping of 0 mm. The warping of this virtual panel was verified by optical measurements of the physical panel using the GOM Atos 5 optical measuring device mentioned above (see figure 2). The scan of the panel was also virtually fixed at the described edges so that the warping is comparable.

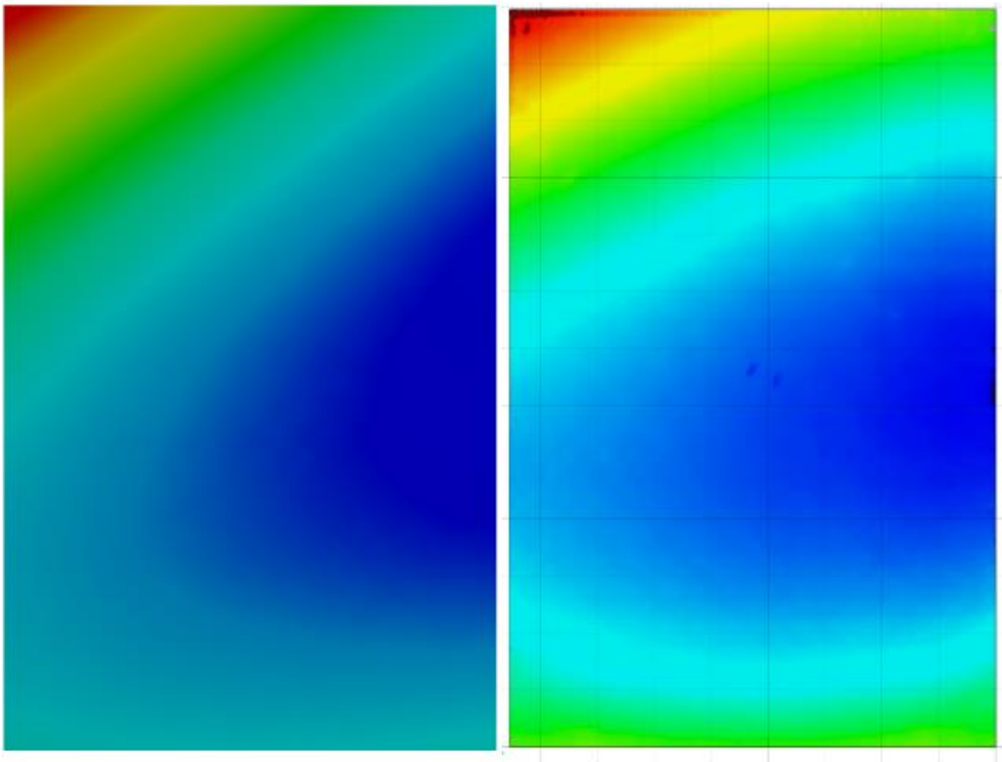

Figure 2: comparison of simulated (left) and measured (right) warping of a panel; the colour represents warping perpendicular to the image plane; range: -3 mm (blue) to +4 mm (red)

2.3 Tape placement

The tape placement sequence typically follows a simple linear pattern. The first tape of the layer is placed at one side or edge of the panel. The next tape is placed adjacent to it. This is repeated until all tapes of this layer are processed. Figure 3 shows two examples.

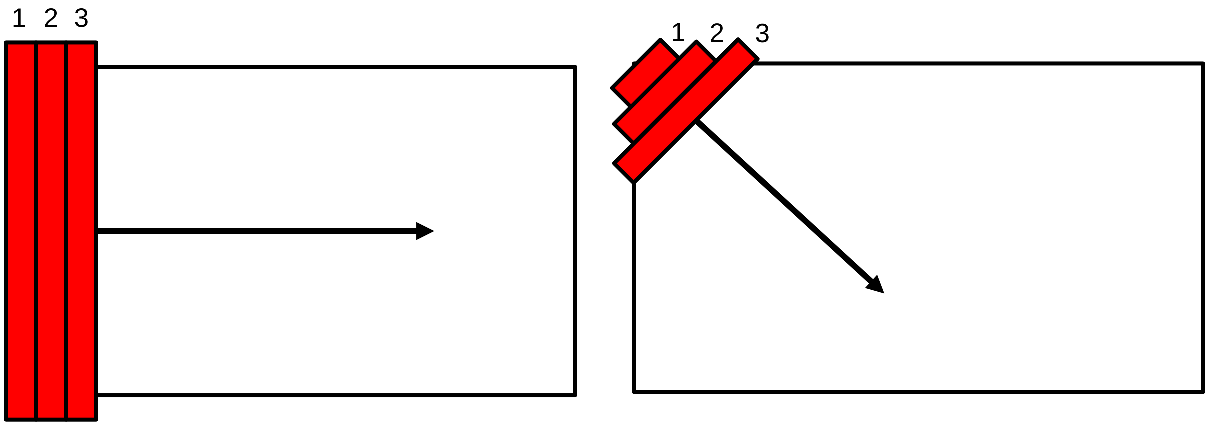

Figure 3: standard tape placement pattern; left: 90°-layer, right: 45°-layer

A first optimization approach for process simulation is the variation of this pattern. Due to the high thermal gradient of the process, the heating process not only influences the currently processed tape but also parts of the surrounding tapes and laminate. Due to the placement of the tapes adjacent to each other this influence is concentrated in one area which may lead to additional warping and inhomogeneous crystallization behaviour. The effect is also concentrated on one side of the panel and slowly moves to the other side, creating an asymmetric load. Varying this pattern may be advantageous to minimize warping and improve tolerances.

Three new patterns were identified for analysis. These patterns aim to distribute the heat to different parts of the panel and create a more symmetric load. Figure 4 illustrates these patterns. The first pattern places the tapes in an alternating manner at the edges, moving gradually inward. For the second pattern this is inverted. Starting in the middle, new tapes are placed increasingly further outward. The third and final pattern imitates the standard pattern but uses two advancing fronts instead of one, thus keeping the distance between both fronts the same. These patterns are identified as o-pattern (outer start), i-pattern (inner start) and c-pattern (constant distance) as opposed to the s-pattern (standard).

For better comparability, the warping was measured only perpendicular to the panel. While this reduces the comparability to physical parts, this poses no disadvantage since the aim of this work is a comparison of simulated results.

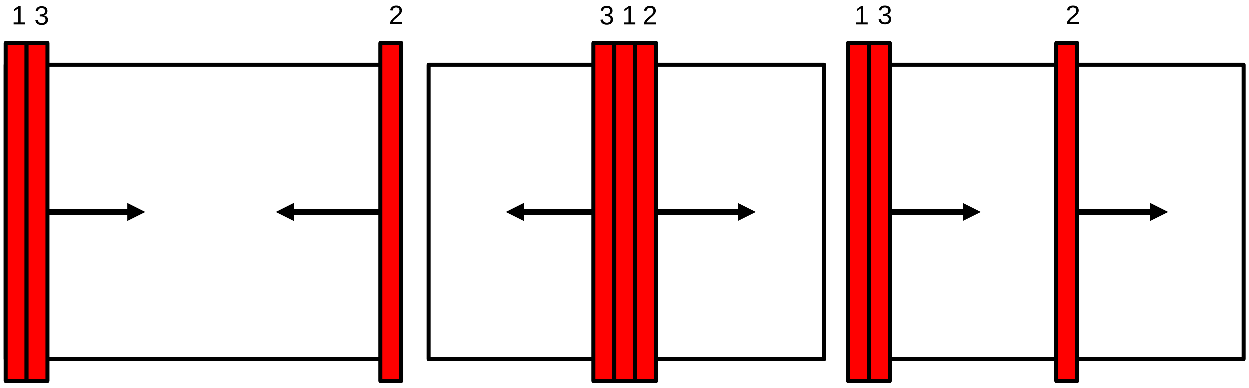

Figure 4: three new patterns for panels; left: o-pattern, middle: i-pattern, right: c-pattern

3. RESULTS

3.1 Simulation results

The quality and magnitude of the warping of the simulated panel varies significantly with each pattern. Figure 5 shows the warping with colour representation as seen from above. The magnitude of the deformation is added in the caption.

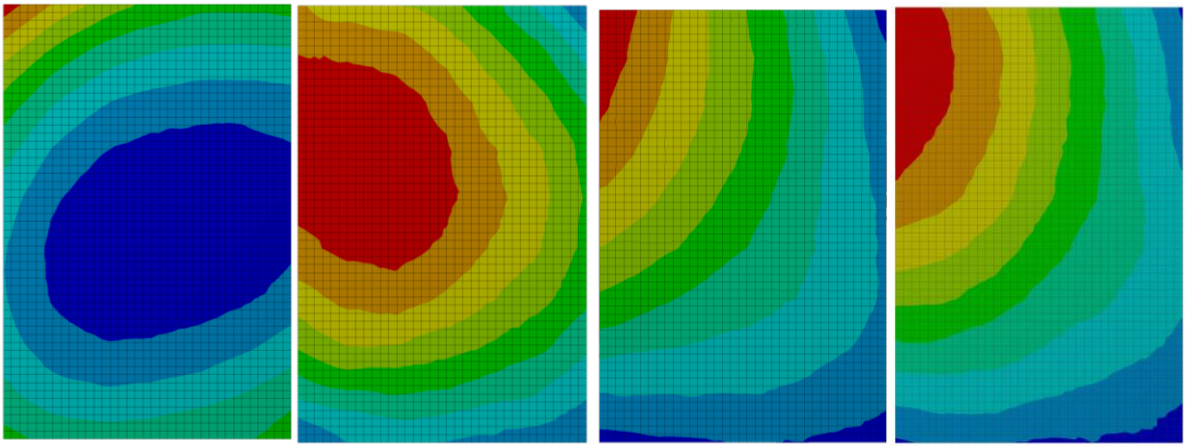

Figure 5: simulated warping perpendicular to the panel, using blue for the lowest and red for the highest warping value; from left to right: s-pattern (-1.8 mm to +1.2 mm), o-pattern (0 mm to +1 mm), i-pattern (0 mm to +1.8 mm), c-pattern (0 mm to +1.4 mm)

The absolute magnitude of warping is lowest for the panel with o-pattern, even though the area with high warping is larger than those of panels with other new patterns. The pattern and magnitude of the i- and c-pattern are similar to each other, while the s-pattern as a baseline shows a very different warping and is also the only panel which is warped in negative direction.

3.2 Discussion

The simulated warping of these four panels shows high influence of the placement pattern on the final part. The high warping of the baseline s-pattern could be expected since this process is the most asymmetric and non-homogeneously distributed one. An interesting observation is the warping in negative direction, which none of the other panels demonstrate.

The difference between the warping of the o- and i-pattern-panels is also an important observation, since these patterns are basically an inversion of each other. The reason for the lower warping of the o-pattern is probably that both fronts only meet in the middle of the panel and concentrate the heat there after the whole layer is completed. The i-pattern starts in the middle and leads to a heat concentration before the rest of the layer is processed and can lend additional strength to the whole structure.

The c-pattern is an outlier since it shows lower warping than both the s- and the i-pattern but higher warping than the o-pattern. There are probably two reasons for that. The constant distance between the two fronts does not allow a meeting of these fronts, so there is by definition no higher concentration of the heat. This is an advantage against all other patterns. The constant distance however is also more asymmetric than the o- and i-pattern, leading to a more inhomogeneous heat distribution over the whole panel. Both of these opposing influences lead to the demonstrated result.

4. CONCLUSIONS

4.1 Conclusion

It could be demonstrated that variations in the tape placement pattern of panels manufactured by AFP with ISC lead to significant changes in the final panel warping. Not only the magnitude but also the shape of the warping changes with each pattern. Two factors seem to influence the warping and can be mitigated by the placement pattern:

1. Placing tapes successively next to each other creates heat concentrations which do not cool down as fast as single tapes and influence the warping. Leaving space between consecutively placed tapes reduces warping.

2. Focusing tape placement on one side of the panel leads to an inhomogeneous thermal load over the panel, which increases warping. Placing the tapes in a symmetric or partially symmetric pattern reduces warping.

These two findings show that the standard pattern of placing tapes is flawed and can be improved. In this work the o-pattern, which starts placing tapes at opposing edges and moves gradually inward, leads to the smallest warping due to the highly symmetric pattern and leaving the heat concentration of placing tapes next to each other until the end when the structural strength of the panel can counteract the warping. There are probably more effective patterns, including those with more than two placement fronts. These will be investigated in future works.

4.2 Outlook

In addition to researching new placement patterns, the AFP process simulation itself will be enhanced and refined. In particular the simulation of curved structures is very important for the aerospace industry. A prototype capable of simulating cylindrical and conical structures is currently worked on and more complex geometries will also be included.

For the current simulations, the results presented in this paper need to be verified by additional practical AFP experiments and 3D-scans. Further work is recommended to quantify the exact influence of the two factors shown in 4.1 on the final part quality.

5. ACKNOWLEDGEMENTS

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