Holistic optimization of the high-speed tape lay-up process using a digital twin

To boost series production of thermoplastic composites based on unidirectional tapes, economically- and ecologically-optimized tape placement strategies have to be established. The introduction of a digital twin reveals new hidden optimization potential, accessible through new user-friendly software.

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Thermoplastic composites allow the series production of highly-integrated composite parts by thermoforming and overmoulding within short cycle times. Some of the first serial products, such as door modules, confirm this approach. When processing thermoplastic fibre composites, material costs account for a significant proportion of the total costs. In practice, there is an offcut of 25-30% depending on the part's geometry. Therefore, it is important to take measures to minimize offcut and thus achieve resource-efficient and sustainable production. The next advancement in tailoring laminates, and therefore optimizing lightweight design and economic efficiency, is to use unidirectional (UD) reinforced tapes instead of woven fabric organo sheet, which are still used for most thermoplastic composite parts in serial production. An increased UD usage leads to a lower material input requirement due to the load path-compatible design of components.

How to optimize the tape lay-up process holistically and machine-independent?

To make the process more resource-efficient, an optimized, near-contour lay-up strategy is necessary. Using different tape widths within the same preform, it is possible to achieve both, a close-contoured lay-up and a short laying time.
The use of different tape widths results in many possible lay-up variants for a distinct ply. With increasing tape costs, a near-contour lay-up is more economic. Considering material- and process-driven costs, it is necessary to optimize the lay-up strategy depending on the chosen material and the distinct part geometry.
An intelligent algorithm is needed that achieves the full optimization potential on the first try.
To meet modern requirements for sustainable production, it is essential to take a holistic view of the production process instead of considering only economic aspects. Thus, the CO_2 emissions of the process and ma-

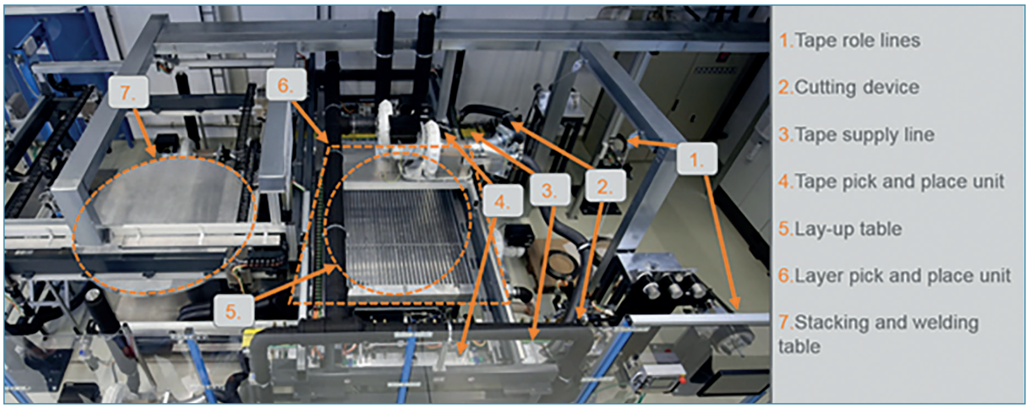

Fig. 1: Overview of the tape laying machine (TLM) with its main components: tape role lines, lay-up table and stacking and welding table

Focus

- Enhancement of machine-independent software for the manufacturing of thermoplastic preforms based on unidirectional reinforced tapes
- Implementation of a digital twin of the production environment
- Automated economic and ecological optimization of lay-up sequences considering tape costs, laying time, offcut, inventory, machine utilization, hourly rate and CO_2 footprint of the tapes used as well as energy consumption of the processing equipment
- Lay-up strategies based on investigations of material- and process-related effects on the mechanics of end-consolidated laminates, considering gaps between tape strips and influences of ultrasonic welding spots
- Tapping new potential of tape technology and opening up access to new markets/customers through an innovative system-independent software solution

terials used are becoming more and more important in the development of sustainable lightweight solutions. So far, there is no software known in research or industry that can use algorithms to optimize 2D high-speed tape laying in terms of cost, laying time, offcut and CO_2 emissions simultaneously. The goal of the project described in this paper is to develop a machine-independent software for different optimization strategies by implementing a digital twin of the production environment.

A digital twin allows cost-effective process optimization with multiple approaches

The experimental setup for the holistic optimization of the tape lay-up process uses the FORCE®-Placement high-speed tape laying machine (TLM) located at the Neue Materialien Bayreuth research Institute (Bayreuth, Germany) and the CAESA® Composites TapeStation (CAESA) software from SWMS Systemtechnik (Oldenburg, Germany). As shown in Figure 1, the TLM used can process two different tapes at the same time. It works according to the following process: one layer at a time is built on the lay-up table, which is hidden behind the layer pick-and-place unit in the centre of the image. The finished layer is then placed on the stacking and welding table rotated according to the desired fibre orientation. Each single layer is fixed relatively to each other by ultrasonic welding with four automatically-positioned sonotrodes.
The CAESA® TapeStation is an independent programming and simulation software for the automated laying of composite fabrics and tapes. It is used to simulate, visualize and analyse the laying of fibre-reinforced tapes based on a digital model. An automated workflow covers the entire process chain, from the development to the production of the component.
By implementing a digital twin in the newly-developed CAESA software, all the machine and process parameters involved in real processes, such as the number of tape role lines and sonotrodes as well as varying machine speed, can be simulated and displayed. The machine-independent approach is of great importance in this context: the digital twin can be easily adapted for different TLMs as well as for different configurations and expansion stages of a production line. The software also enables automated nesting. In this case, several lay-ups are built up in parallel depending on the geometry, resulting in shorter cycle times and thus higher production efficiency. Figure 2 gives an insight into the software. It shows the detailed digital twin with a simulation of a nested demonstrator.
The implementation of a digital twin, which exactly reproduces the real process environment, opens new potential for the software. By numerically mapping real processes, new approaches and optimization strategies can be implemented and evaluated, in a reliable and almost cost-neutral way.

An optimization strategy adaptable to individual requirements: costs, offcut, CO_2 footprint

The project's goal is to achieve a complete and machine-independent optimization of the preforming process. Using the CAESA software with a digital twin, the user can resort to different optimization strategies

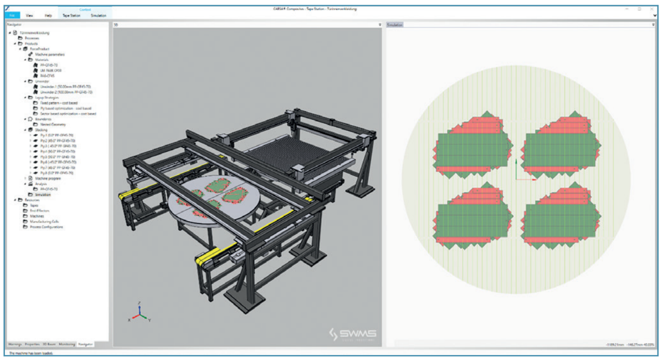

Fig. 2: Display of the digital twin with a simulation of the nested demonstrator lay-up in the CAESA software

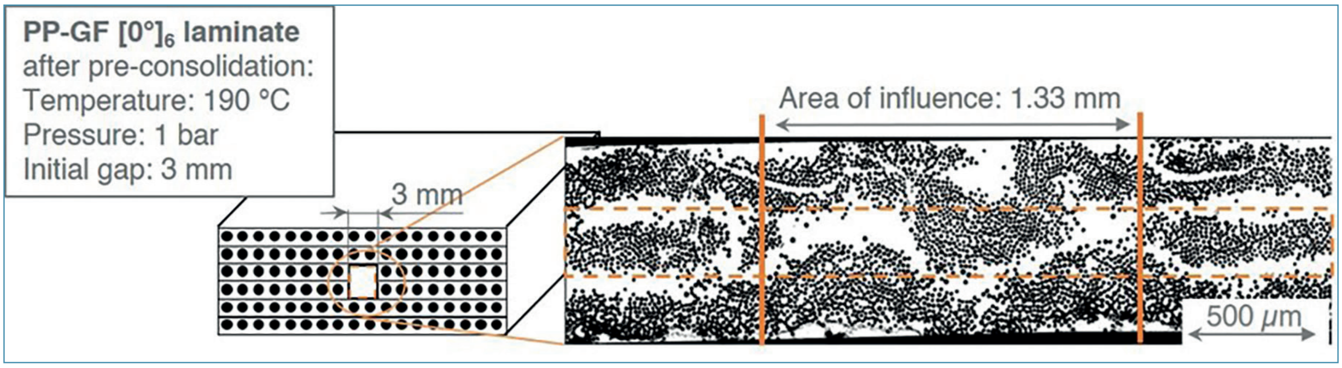

Fig. 3: Cross-section of a PP-GF laminate with a 3-mm original gap (dashed box) after consolidation; the highlighted area of influence shows collapsed layers

according to his needs. The optimization can focus on minimizing the process costs, offcut or CO_2 footprint.

One step to a close-contoured preform, and thus to reduced offcut, is to implement an angle cutting system. To avoid unnecessary offcut, the cutting angles are selected considering that the subsequent strip exhibits the same angle at its beginning as the previous strip at its end. Another approach to component optimization is to determine optimum material widths. The width is calculated based on the features of the TLM used, e.g. the number and specifications of tape role lines. This information must be transferred to the CAESA software and can be adjusted easily. Once these are known, specific widths can be determined according to the desired laminate structure. To ensure that the algorithm results are always transparent to the user, a digital twin of the system, which enables a simulative optimization of the laminate, is necessary. The process can be simulated and tested before actually producing the component.

The possibility of using different material widths in one stacking presented the project team with complex problems. The analysis of the part geometries is the first essential step to achieve the best starting point for planning the lay-up. The resulting parameters are the basis for further optimization. The interaction of the different input values and the many possible combinations of tape and gap widths, as well as a specific optimization goal, required new, intelligent algorithms. Therefore, the different optimization targets for cost reduction, off-cut reduction, lay-up time and CO_2 minimization were considered separately. For each target, the main influencing factors were determined and integrated into the calculation algorithms. Since production time is another important aspect of the manufacturing process, all the influencing parameters are considered by the software. This also includes welding energy and time, depending on the selected tape material. The focus of the optimization strategy influencing the lay-up can be selected by the user. When reducing production time, wider strips are used. On the other hand, the narrower strips are preferred if the offcut is minimized. Cost- and CO_2-optimized strategies are a combination of both. Machine utilization, hourly rate and CO_2 footprint of the tapes used, as well as energy consumption and emissions of the processing equipment, are considered. The user can choose the optimization strategy depending on what is most important to the product. But there is further potential in the 2D lay-up procedure. The question: "How can it be ensured that a change in the process parameters does not have a negative effect on the mechanical properties?" must be raised. The answer is given by material analyses regarding the lay-up process and their consideration by the CAESA software.

A detailed look at properties

The influence of important process parameters and their effects on the laminate properties are part of the holistic optimization approach. To enable CAESA to conduct these optimizations, the unidirectional tape used and its processing conditions had to be examined. Two of the investigated factors presented as examples here are the gaps between tape strips and the ultrasonic (US) welding spots. The gaps result from tape coverage tolerances and can be exploited to save individual strips by optimizing the lay-up. The US welding spots are required to fix the UD-reinforced strips together for later handling of the preform.

The inter-tape gaps were explored using PP-GF and PA6-CF unidirectional laminates, each with a 45% fibre volume content (FVC). 1 to 6-mm gaps were introduced between two strips (Figure 3 shows a 3-mm gap). The structural analysis after end consolidation in the FORCE process revealed that all the gaps could be filled entirely with matrix and fibres during consolidation. Pores, however, could not be detected in the cross section. Yet, there is an influenced area left, where fibre deflections, locally-reduced fibre volume fractions and collapsed layers are present (see Figure 3). For PP-GF, the area of influence could be reduced to a minimum of 32% of the original gap width and for PA6-CF, a maximum reduction to 62% of the original gap width could be achieved. Based on the results, an acceptable gap width between tapes can be set depending on the user's requirements. The number of strips used, and therefore material and laying time, can be minimized by the software based on these results.

The TLM considered in this work uses ultrasonic welding for fixing the individual tapes to one another. Different weld energy levels for a fixed ultrasonic generator power output influence the welding time and therefore the processing time. The analysis and optimization of the ultrasonic welding process revealed that the tensile strength of end-consolidated unidirectional PP-GF laminates reduces significantly with increasing weld energy (by increasing welding time and/or amplitude), up to -72% in the welding area (see Figure 4). The microscopical analysis of the fibre-matrix interface revealed that increased weld energies deteriorate the fibre matrix bond in the laminate, restricting the introduction and transfer of loads within the composite. The non-polar nature of the PP matrix supports this behaviour. The PA6-CF-laminates, on the other hand, did not show such correlations of weld energy and tensile strength. Equally, the fibre-matrix bond was not affected by the weld energy. Recommended weld energies (PP-GF: 35-70 J; PA6-CF: 20-60 J) for the two materials were derived from these results, guaran-

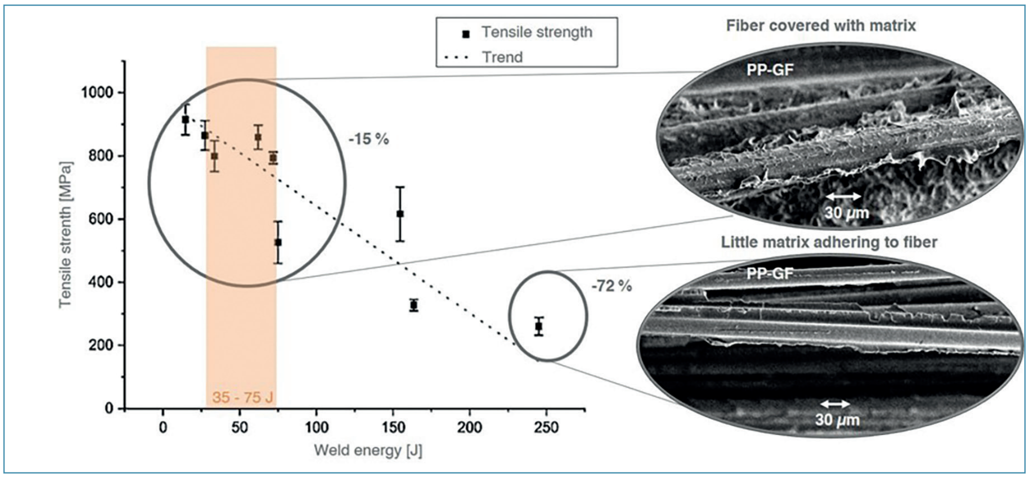

Fig. 4: Tensile strength in the welding spot of ultrasonically-welded PP-GF UD laminates with different weld energies and representative REM pictures characterizing the fibre-matrix adhesion

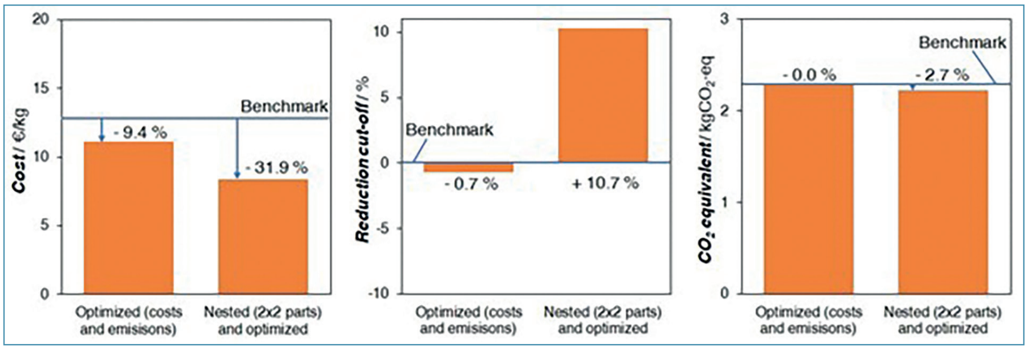

Fig. 5: Different lay-up strategies and their benefits compared to an unoptimized benchmark lay-up calculated for a PP-GF demonstrator part using the NMB TLM

teeing secure welding of the laminate. Due to the time dependency of the welding process, this also influences the lay-up time. Therefore, weld energy levels with a short welding time are preferable. The results for the optimal welding process parameters were imported into the software.

Door inlay demonstrator

The saving potential of the holistic optimization approach was calculated for a demonstrator part (shown in Figure 7) containing a tape-based preform inlay with a $[0°/-45°/45°/90°]_s$ lay-up. The saving potential of optimized narrow and close-contoured tape laying is shown in Figure 6 for three different tape types, compared to single wide tape strips.

The economic optimization of that same preform with CAESA resulted in a part cost reduction of up to 31.9% for PP-GF compared to an unoptimized close-contoured narrow tape benchmark. Here, the full potential of the optimization algorithm was exploited. Custom tape widths derived from the virtual preform analysis and the potential to manufacture multiple preforms simultaneously (nesting) yielded significant savings, as shown by the results in Figure 5. Single lay-ups optimized with CAESA (Optimized) reduced part costs by 9.4% only, while counter-intuitively increasing the cut-off by 0.7% with no CO_2 reduction. This resulted from the inclusion of machine operating cost and emissions. When focusing on economic efficiency, those outweighed potential PP-GF material savings for single part lay-ups. Better results were achieved by laying down four parts at the same time (nesting 2x2 parts) and optimizing them with CAESA. While further reducing the costs, 10% cut-off and roughly 3% CO_2 emissions were saved too.

The same demonstrator was used to validate the results (Figure 7). Glass fibre-reinforced unidirectional PP tapes with widths of 50 mm and 100 mm were installed on both tape role lines of the TLM. The machine code provided by the CAESA software was read by the machine to determine the width, length and position of each layered tape. The 50 J weld energy was chosen according to the results previously obtained for PP tape. The acceptable gap width between two parallel tapes was set to 3 mm.

Compared to state-of-the-art alternating tape strip laying without optimization (starting point and gap width), the amount of tape used per part was reduced by 51 g (5.3%), from 970 g to 919 g for an optimized lay-up, as calculated by the CAESA software.

The simulation predicted a weight of 950 g for the alternating and 900 g for the optimized lay-up (5.3% reduction). This reduction proves the potential of the software. The nearly constant weight offset between experiment and simulation can be traced back to an inaccuracy probably due to the rounding of the tape's areal weight. Further off-cut reduction would have been possible by choosing a tape width determined by an optimization algorithm. Due to the limited number of tape widths available in stock, this option was not chosen.

An additional possibility to reduce material scrap even further is to use angled cuts at the tape ends.

Following the tape laying step, the stacked preform fixated by the welding points was pre-consolidated in a double-belt press at a temperature of 230°C and a minimal closing pressure to ensure close contact, which was found out to be ideal for the material used. The resulting laminate was shaped to the final part geometry with minimal scrap by waterjet cutting the pre-consolidated stack. In the subsequent step, thermoforming was used to achieve a complex part geometry. The door cover demonstrator was then formed in combination with overmoulding. The finished lay-up is shown in Figure 7.

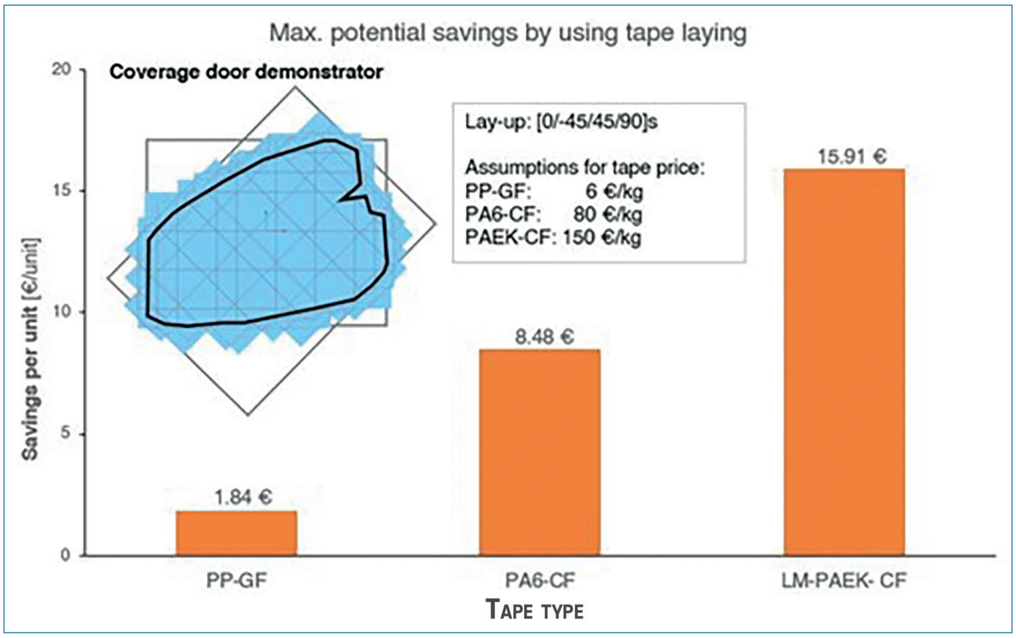

Fig. 6: Comparison of the maximum possible financial benefit per produced part, resulting from the reduced scrap rate of different tape widths to a sufficiently wide single tape without machining costs

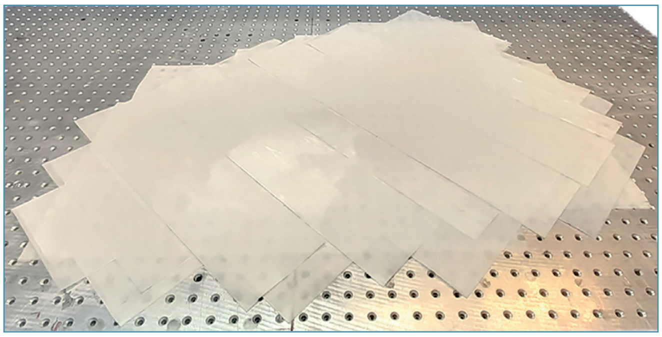

Fig. 7: Lay-up of the door panel demonstrator made from PP-GF tape as a preform

Conclusion

The project with the newly-developed CAESA software is a leap towards series production for thermoplastic composites based on UD tapes. New process optimization potential was unlocked by the introduction of a digital twin. Over the project period, a wide-ranging optimization of the tape laying process resulted in a part-dependent maximum cost reduction of nearly 32% for the presented case, with the additional benefit of an emission reduction close to 3%. This was achieved by including an extensive analysis of the material performance and processing properties in the software. Therefore, the specific parameters of the real TLM were re-created in a digital twin to include the complete processing chain into the optimization process. Thus, it is possible to generate optimized lay-up data aiming at minimum waste, laying time or costs, respectively. Combining numerical optimization with a digital twin makes it possible to consider economic and ecological aspects within the early development phase of fibre-reinforced lightweight parts. ◻

Focus

The project is a collaboration between:

- SWMS Systemtechnik Ingenieurgesellschaft mbH (SWMS), a consulting and technology company that offers software solutions for the automated production of composite components to support processes from design to manufacture. All manufacturing steps are virtually represented by digital twins, which guarantees a continuous software-supported process chain.
- Neue Materialien Bayreuth GmbH (NMB), a non-academic research institution that develops novel material variants and the associated energy-efficient processing technologies for lightweight structures based on polymers, metals and composites. NMB tailors sustainable solutions to optimize existing materials and production processes for specific applications.
- REHAU AG + Co, which was part of the project as an associated partner, is a leading global provider of advanced polymer and composite products for industry and automotive applications. As a tier-one supplier, REHAU contributed practical industrial expertise so that the entire project could be carried out in a practical and use case-driven manner.

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