OPTIMIZATION OF IN-SITU THERMOPLASTIC AUTOMATED FIBER PLACEMENT PROCESS PARAMETERS THROUGH DOE

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ABSTRACT

The Automated Fiber Placement (AFP) process has the potential to significantly reduce process time and manufacturing costs of thin-walled structures made of reinforced high performance thermoplastics. However, this potential only can be fully utilized if the consolidation of the reinforced material is achieved in-situ. The ambitious goal, in-situ consolidation, depends on a large number of parameters including the nip point temperature, process speed, compaction roller pressure and the mould temperature. Given the inherently coupled nature of some of these parameters and the lengthy time required by common testing, different Design of Experiments (DoE) studies with different testing methods were performed in order to describe the consolidation quality for an unheated and heated tooling. From these DoE studies, recommendations for testing methods and for process parameters for carbon-fibre reinforced PPS (CF-PPS) are made.

1. INTRODUCTION

In-situ consolidation of laminates produced with AFP depends on a large number of parameters, such as the user-defined (set) Temperature at the nip point, T_{set}, the layup speed, v_{layup}, the pressure inside the pneumatic actuator of the compaction roller, p_{roll} and the temperature of the tooling mould, T_{mold}. One of the most important laminate properties, which depends on the mentioned factors, is the consolidation quality. An illustration of the AFP process and the relationship between the input factors and the response is shown in Figure 1.

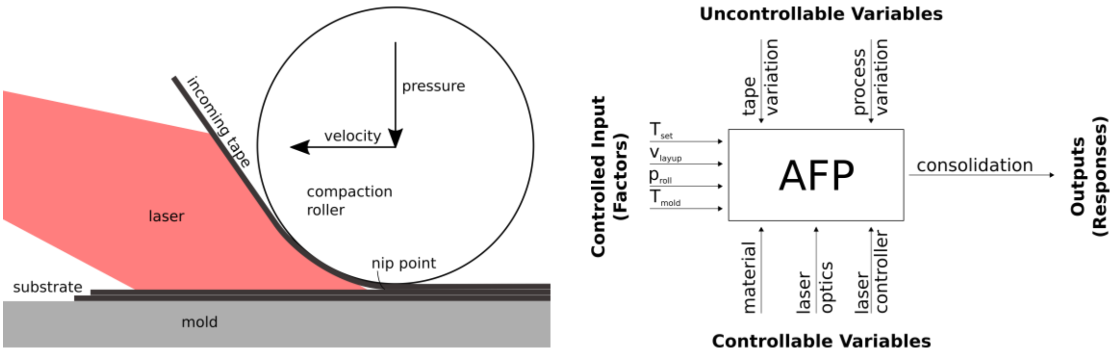

Figure 1: Illustration of AFP process (left) and simplified black box model of AFP process [1]

The optimization of the input factors for maximum consolidation quality requires a large number of experiments and is challenging because the interaction of the factors is unknown and uncontrollable variation exists. Therefore, the Design of Experiments (DoE) method was chosen to perform the optimization.

2. MATERIALS AND METHODS

In order to quantify the response, the consolidation quality, three different testing methods were examined: the Double Drum Peel (DDP) test, the double beam shear test and the single lap shear test. All specimens were produced at the tape laying facility at the DLR in Stuttgart, using carbon fibre reinforced PPS (CF-PPS) prepreg tape with a width of b = 12,7 mm. The tape laying facility implies a single tape winding head (STWH) as well as a multi tape laying head (MTLH) from AFPT GmbH, Dörth, Germany. For the production of all specimens, the MTLH was used.

2.1 Double drum peel test

The double drum peel (DDP) test was performed by measuring the adhesive energy of wound rings by unwinding the tape through two drums. The wound rings had an inner diameter of 201 mm and ten windings. Since no heated drum for production was available, T_{mold} was held at room temperature.

While the rings were unwound, the peel angle, β, drum torques, T_1 and T_2, rotational positions, α_1 and α_2, and the peel speed, v, were controlled. Figure 2 shows the setup of the experiment. The peel force, F, and mixed-mode energy release rate, G_c, were computed in a post-processing step. The tests were performed on the continuous peel test bench made by LF Technologies. [1] [2]

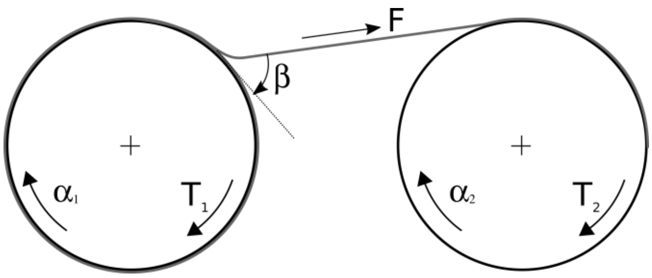

Figure 2: Double Drum Peel (DDP) test [1]

Prior to the testing, a preceding DoE study was performed in order to optimize the testing parameters β and v, e.g. for reduced fibre kinking, fibre bridging and overshoots. As a result, optimal testing parameters are given at $\beta = 21{,}1°$ and $v = 47{,}6\ mm/min$. The G_c-values with respect to the tape position, s, reveal a steady-state phase at a constant peel force with pure delamination. This region is automatically identified with self-written scripts by applying two different low-pass filters and used for the calculation of $G_{c,set}$, which was used as a characteristic measure for the consolidation quality. The aforementioned defects as well as an illustration of a representative processing of the recorded data can be seen in Figure 3. [3]

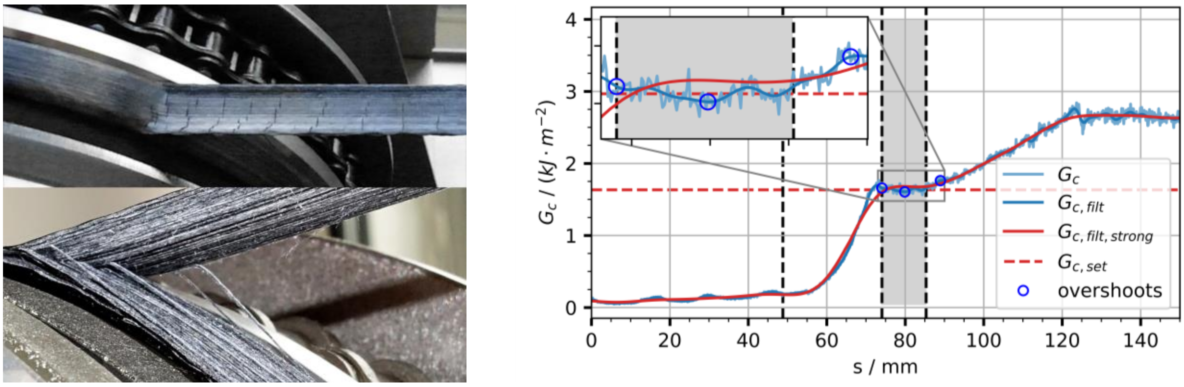

Figure 3: Possible defects: fibre kinking/ fibre bridging (left) and critical energy release rate G_c during peeling (right) [1]

2.1.1 Experimental Design

As mentioned, the purpose of the DoE study was to optimize and to compute a response surface. Therefore, an I-optimal design was chosen with 23 successful runs out of 25 total runs. The input factors were within the following boundaries:

- $280\ °C \leq T_{set} \leq 370\ °C$
- $4\frac{m}{min} \leq v_{layup} \leq 15\frac{m}{min}$
- $1\ bar \leq p_{roll} \leq 6\ bar$

According to the data sheet of the tape, no degradation of the PPS matrix system was expected below 370 °C. $G_{c,set}$ is used as response. Unfortunately, the Analysis of Variance (ANOVA) revealed a high model p-value of more than 33 %, indicating that the model is not significant relative to noise. Also, no significant model terms were identified.

Therefore, the experimental design was augmented with additional 18 successful runs out of 25 total runs, resulting in Block 2 of the DoE study. Since Block 1 already revealed that high p_{roll} values are beneficial for high $G_{c,set}$-values, the lower boundary for p_{roll} was raised to 4 bar. The augmented design also was an I-optimal design.

2.2 Double beam shear test

The double beam shear (DBS) test generates a stress state with minimum axial bending stresses while promoting regions with pure interlaminar shear stresses. The setup for the DBS test is based on the corresponding norm, [4], but since it is beneficial to reduce the number of layers in order to be able to produce more specimens in less time, some modifications to the norm were applied. First, the diameter of the rollers was reduced to 2 mm and adjacent rollers were put next to each other without clearance, as shown in Figure 4. This was done to increase the ratio of shear loading to bending loading. Also, the recommended thickness of the specimens was not met, but three different configurations were tested: 2-, 4-, and 8-plie laminates. The width of the specimen was left at tape width. Unfortunately, none of the tested configurations resulted in delamination, but in crushing and plastic deformation. Therefore, the tests had to be considered as invalid.

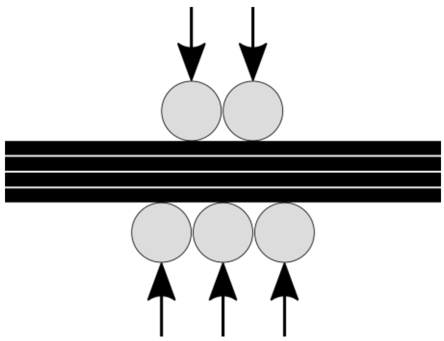

Figure 4: DBS test

2.3 Single lap shear test

The mould temperature was expected to have a high impact on the consolidation quality. A heated, flat tooling with the dimensions of 600 mm x 800 mm was available at the tape laying facility at the DLR in Stuttgart. Also, multiple tensile testing machines were part of the inventory. Hence, specimen were developed which could be manufactured and tested with the available equipment in large numbers in a short time: single lap shear specimens. They were produced by laying several tracks on top of each other with the AFP process. In the mid-plane, two thin Kapton films were positioned to locally separate the tracks. The separation of the top/ bottom plies above/ beneath the Kaptons film took place by inserting a thin metal foil between the Kapton films and the adjacent ply and then by slicing the corresponding plies with a sharp knife. During the tensile test, the load was transferred through the area between the films.

Pretests with CF-PEEK showed that two plies with overlap lengths of 5, 10, 15, 20, 30, 40 mm and a thickness of 50 µm of the Kapton films lead to fibre failure instead of delamination. A reduced thickness of the Kapton films resulting in 25 µm and two plies with 3 mm overlap length and four plies with 5 and 10 mm overlap length lead to delamination. The highest strengths were measured for 5 mm overlap length and four plies. Therefore, this configuration was taken, as shown in Figure 5.

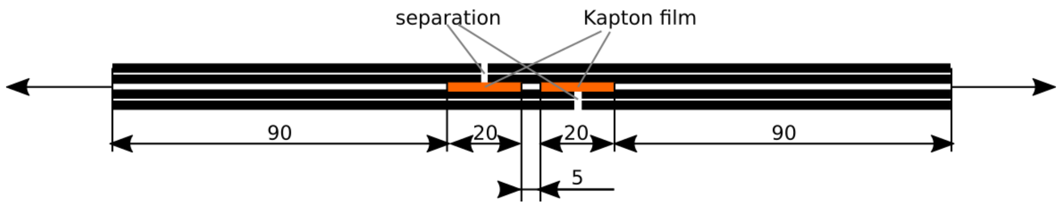

Figure 5: Single lap shear specimen

Since not all tracks could be positioned exactly on top of each other, the edges of each specimen were trimmed. The first ply consisted of 1" CF-PPS tape, which was placed and fixated manually on the mould. The maximum configurable tooling temperature was 250 °C and no local temperature gradient could be set. Therefore, the tooling temperature T_{mold} had to be defined as a blocking factor. With the used configuration, 15 tracks were placed next to each other and two specimens were cut out of each track, resulting in a total of 30 specimens per block. For an even higher production rate, the distance between the tracks could be reduced in future studies.

2.3.1 Experimental Design

Compared to the DDP DoE study, the experimental design was simplified to a face-centred central composite design, because effects of factors are hard to identify if the factor settings are close together and the variation is high, which was a lesson's learned from the DDP DoE study. Also, the maximum T_{set}- and p_{roll}-values were increased, because thermal degradation is not expected even at 410 °C if the exposure time is small and because the optimum T_{set}- and p_{roll}-values identified with the DDP DoE study were found at the upper limit. [5] The range of the v_{layup}-value was enlarged to increase a possible effect and to verify if v_{layup} indeed has no influence on the consolidation quality, as stated with the DDP DoE study. As a result, the factor settings were:

- $T_{set} \in \{330\,°C,\ 370\,°C,\ 410\,°C\}$
- $v_{layup} \in \left\{1\frac{m}{min},\ 7.5\frac{m}{min}, 14\frac{m}{min}\right\}$
- $p_{roll} \in \{3\,bar,\ 4.5\,bar,\ 6\,bar\}$
- $T_{mold} \in \{20\,°C,\ 135\,°C,\ 250\,°C\}$

The following responses were generated:

- $\tau_{max} = \frac{F_{max}}{b \cdot h}$: maximum smeared shear stress
- t: thickness of the specimen

The ultimate tensile load, F_{max}, was measured by the tensile testing machine and the width, b, and length, h, of the adhesion zone between the Kapton films were measured with a calliper. It has to be noted that the shear stress distribution is not expected to be constant. Therefore, the τ_{max}-value can't be interpreted as a material property.

Three blocks were tested with a total of 90 specimens. As a result, the response surface illustrated in Figure 6 was developed. The maximum τ_{max}-value of 49,7 MPa is found at $T_{set} \approx 392\,°C, v_{layup} = 1\frac{m}{min}, p_{roll} = 6\,bar, T_{mold} = 250\,°C$.

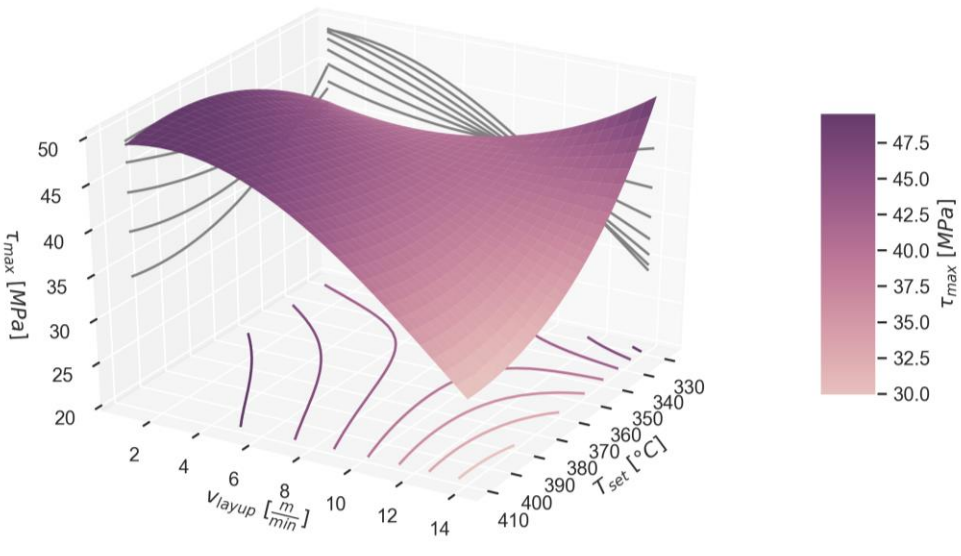

Figure 6: Response surface for $p_{roll} = 6\,bar, T_{mold} = 250\,°C$

Unfortunately, the layup speed would result in an unacceptable low production rate. Therefore, a multi-objective optimization was performed aiming at both maximizing τ_{max} and v_{layup}. The optimal members for certain layup speeds are illustrated in Figure 7.

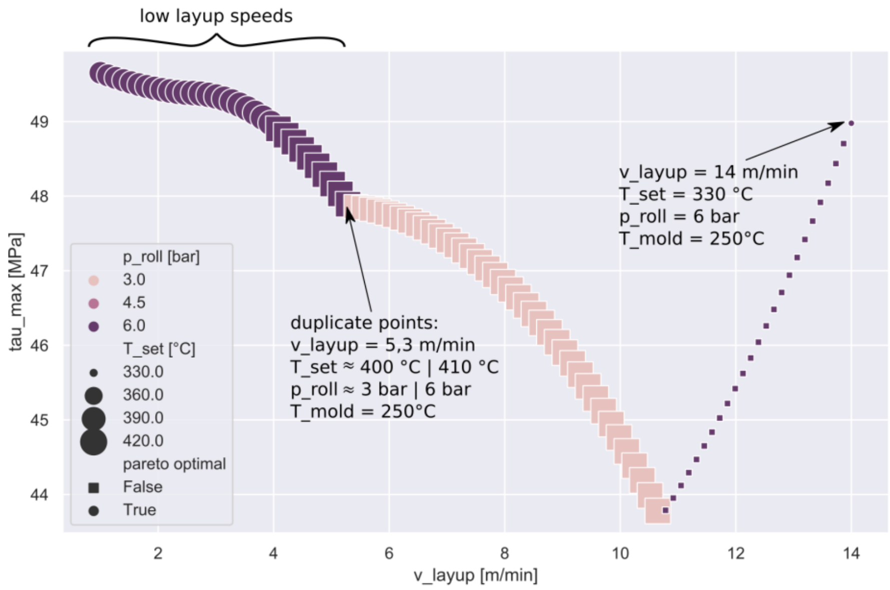

Figure 7: Pareto front and other optimal members

The figure reveals three points, which might show an adequate compromise between consolidation quality und production rate.

- $T_{set} \approx 400\ °C, v_{layup} \approx 5{,}3 \frac{m}{min}, p_{roll} \approx 3\ bar, T_{mold} \approx 250\ °C$
- $T_{set} \approx 410\ °C, v_{layup} \approx 5{,}3 \frac{m}{min}, p_{roll} \approx 6\ bar, T_{mold} \approx 250\ °C$
- $T_{set} \approx 330\ °C, v_{layup} \approx 14 \frac{m}{min}, p_{roll} \approx 6\ bar, T_{mold} \approx 250\ °C$

These points were used for confirmation by producing and testing ten specimens per confirmation point. All experiments were examined in an ANOVA.

3. RESULTS

3.1 DDP tests

With the second Block implemented in the study, the model got significant relative to noise with a model p-value of only 0,13 %. The only significant model terms are T_{set} and p_{roll}, v_{layup} was not identified as a significant model term. The lack of fit was not significant relative to pure error with a lack of fit p-value of 68,46 %. The equation in terms of actual factors is given in Equation 1 and an illustration of the response surface described by the equation is shown in Figure 8.

$$G_{c,set} \approx 403{,}93 \frac{kJ}{m^2} + 2{,}38 \frac{kJ}{m^2 °C} \cdot T_{set} + 49{,}17 \frac{kJ}{m^2 bar} \cdot p_{roll} \qquad \text{Equation 1}$$

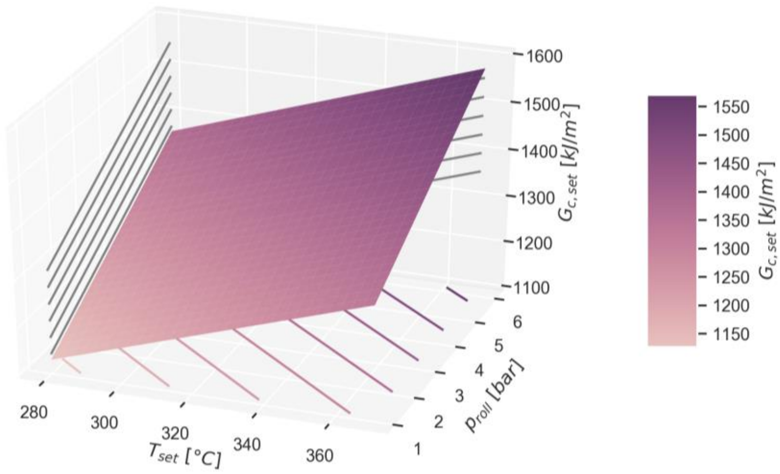

Figure 8: Response surface for $G_{c,set}$

The maximum $G_{c,set}$-value within the aforementioned boundaries for the DDP test is calculated for $T_{set} = 370\ °C$ and $p_{roll} = 6\ bar$. The derived $G_{c,set}$-values of all experiments are shown in Figure 9.

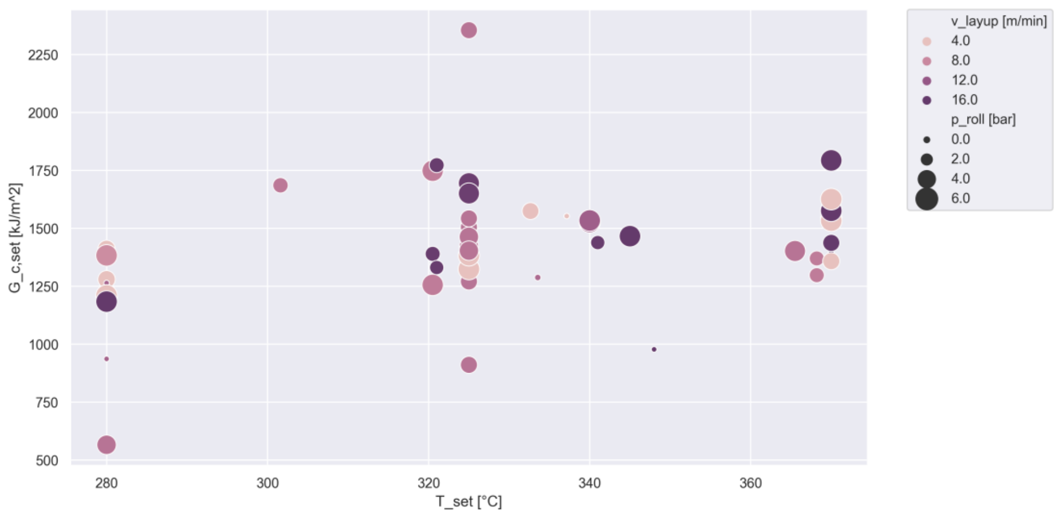

Figure 9: Critical energy release rates $G_{c,set}$ derived from DDP tests

The maximum number of replicates in the experimental design is four. For this setup $(T_{set} = 325\ °C, v_{layup} = 9{,}5 \frac{m}{min}, p_{roll} = 4\ bar)$ a mean value of $1307 \frac{kJ}{m^2}$ for $G_{c,set}$ and a standard deviation of $252 \frac{kJ}{m^2}$ was calculated, which is about 19 % of the mean value. The broad distribution of the results is unsatisfying. Figure 10 confirms the poor prediction capability of the response model.

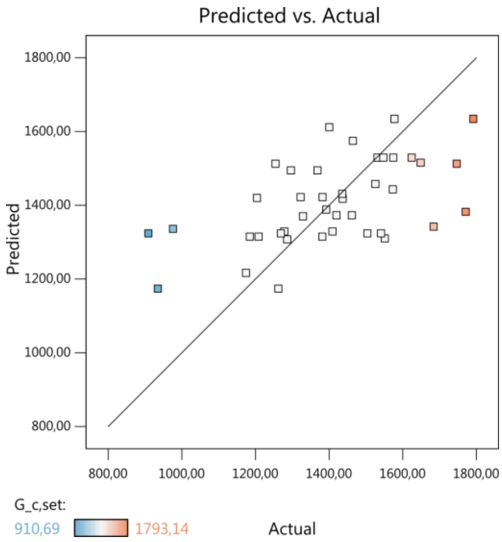

Figure 10: Predicted vs. Actual plot

3.2 Single lap shear tests

All experimental results, including the confirmation runs, are shown in Figure 11.

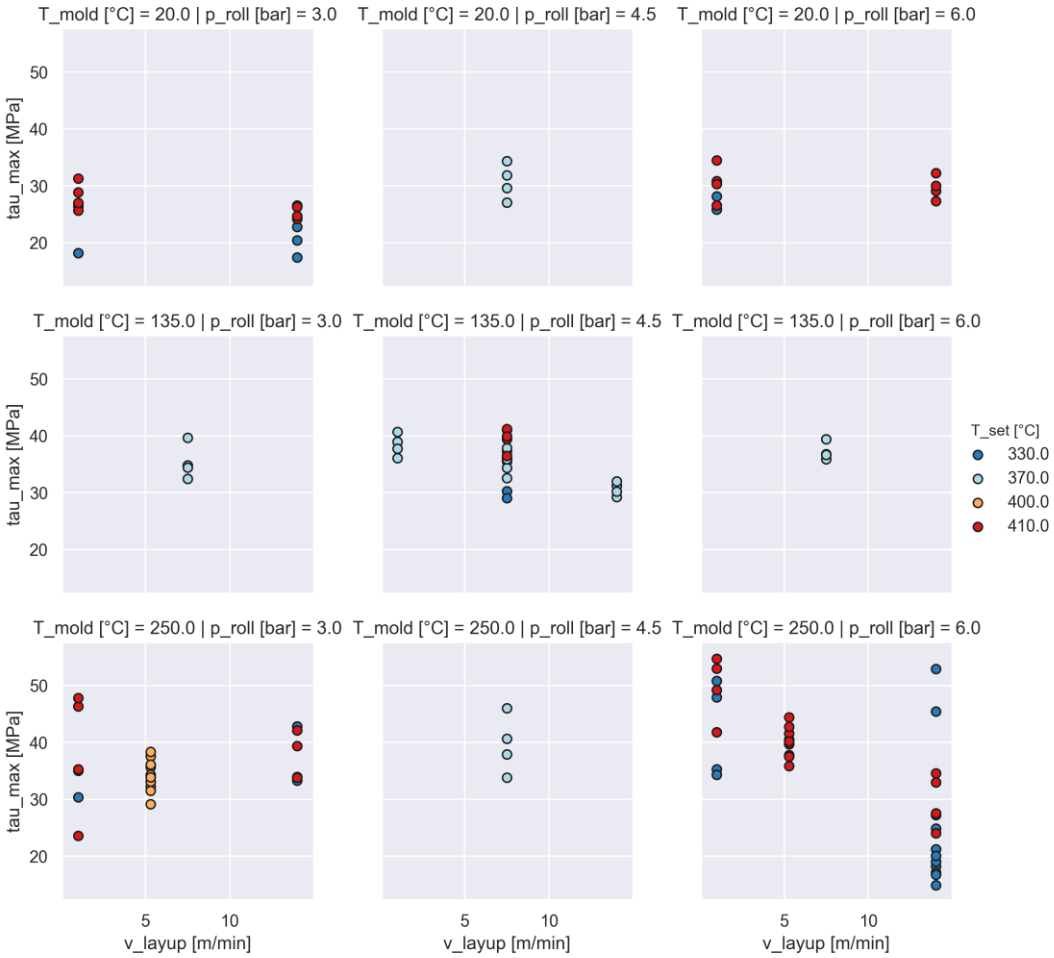

Figure 11: Experimental results for τ_{max}

The ANOVA results imply that the model is significant with model p-value < 0,01 % and that the Lack of Fit is not significant relative to pure error with a p-value of 47,15 %. The absolute value of the response "thickness" is not of importance, but the thickness t might be a good indication for material compaction resulting in high shear strengths. Therefore, the correlation between τ_{max} and t as illustrated in Figure 12 was examined and reveals a weak to medium negative correlation. The linear regression line and the Kendall rank correlation coefficient of -0,38 confirms this impression.

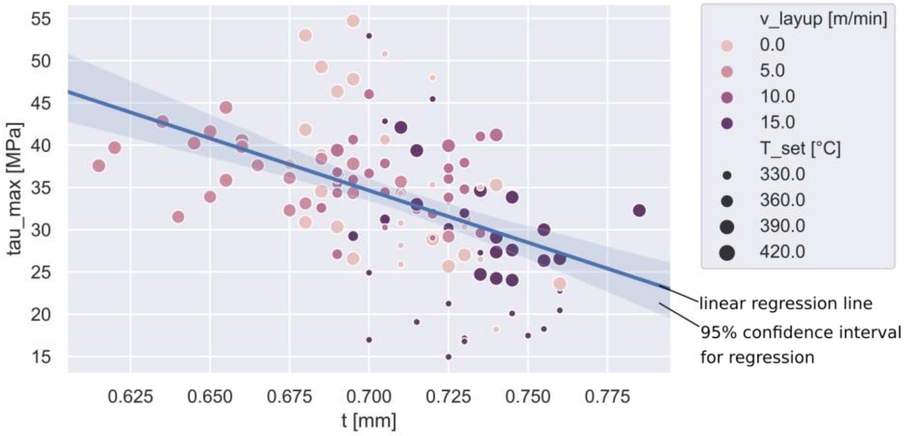

Figure 12: Correlation between the shear strength and material compaction

The analysis of the confirmation points reveals that the prediction of the response surface was not adequate: the measured τ_{max}-values are significantly lower than the predicted ones, especially for the high layup rate of 14 m/min. Both outliers shown in Figure 13 were measured during the DoE study prior to the confirmation runs and caused the response surface to make inaccurate predictions. The deviation is within a reasonable range, e.g. the standard deviation of the ten samples with $T_{set} = 410\ °C$ and $p_{roll} = 6\ bar$ is calculated to 2,4 MPa, which is 6,1 % of the mean value of 40,0 MPa.

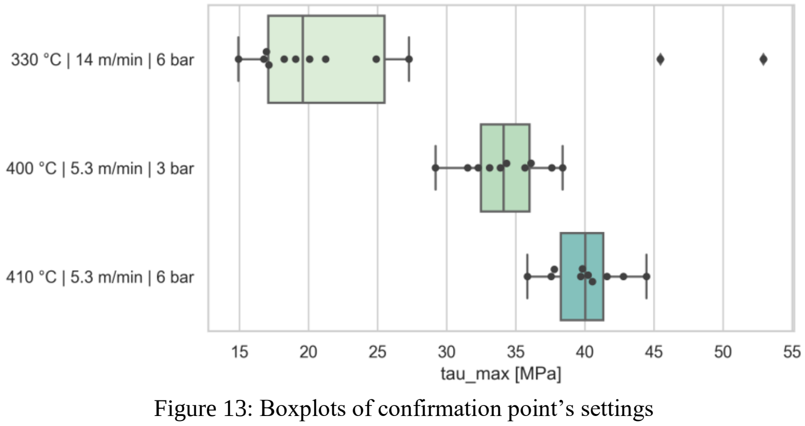

Figure 13: Boxplots of confirmation point's settings

Invalid entered process parameters can be excluded as a reason for the outliers by checking the logged data during production. Incomplete separation of the top/ bottom plies of the specimen is also unlikely because this would have become visible at the fracture surface. Therefore, the cause of the outliers remains unknown. A new response surface and new pareto front were calculated. The updated equation is given in Equation 2 and the corresponding response surface can be seen in Figure 15.

$$\tau_{max} \approx 2{,}35 + \begin{pmatrix} 5{,}23\ MPa/°C \\ -44{,}43\ MPa/\ \frac{m}{min} \\ 84{,}41\ MPa/bar \\ 8{,}95\ MPa/°C \\ 7{,}41 MPa/\ \frac{m \cdot bar}{min} \\ 0{,}76 MPa/\ \frac{m \cdot °C}{min} \\ 1{,}16\ MPa/(bar \cdot °C) \\ -0{,}03\ MPa/°C^2 \\ -0{,}22 MPa/\ \frac{m \cdot bar \cdot °C}{min} \end{pmatrix} \cdot 10^{-2} \cdot \begin{pmatrix} T_{set} \\ v_{layup} \\ p_{roll} \\ T_{mold} \\ v_{layup} \cdot p_{roll} \\ v_{layup} \cdot T_{mold} \\ p_{roll} \cdot T_{mold} \\ T_{mold}^2 \\ v_{layup} \cdot p_{roll} \cdot T_{mold} \end{pmatrix} \qquad \text{Equation 2}$$

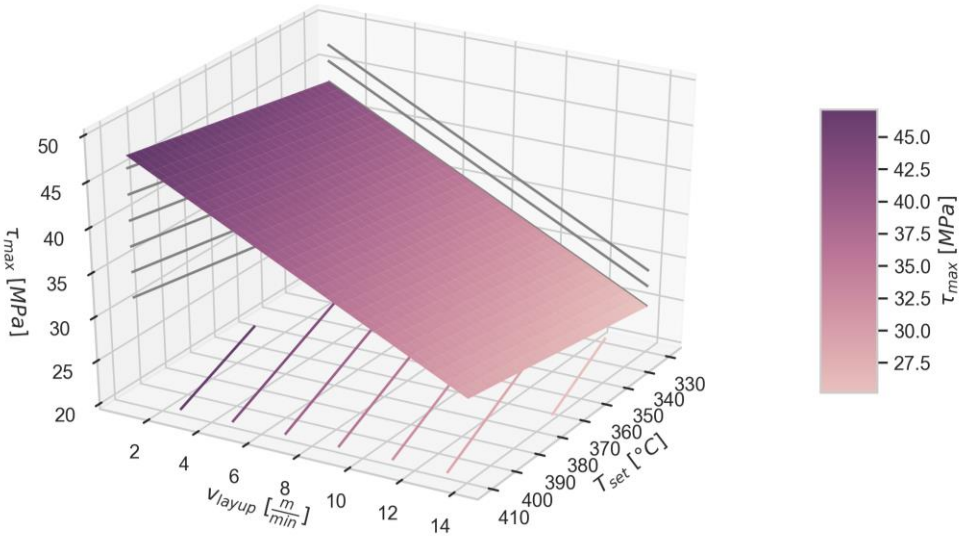

Figure 14: Response surface for $p_{roll} = 6\ bar, T_{mold} = 250\ °C$

All optimal members on the pareto front shown in Figure 15 share the maximum T_{set}-value of 410 °C. The highest τ_{max} –values are still predicted for minimum layup speed. Also, T_{mold} and p_{roll} are set to maximum values for the global maximum. If minimum layup speeds are restricted, τ_{max}-values decrease and optimal members are only found for reduced T_{mold}-values. At about 8,7 m/min, a sharp transition for optimal members from $T_{mold} \approx 173\ °C$ to 210 °C and from $p_{roll} = 6\ bar$ to 3 bar is predicted. The optimal process parameters as well as τ_{max} do not change significantly for even higher layup speeds.

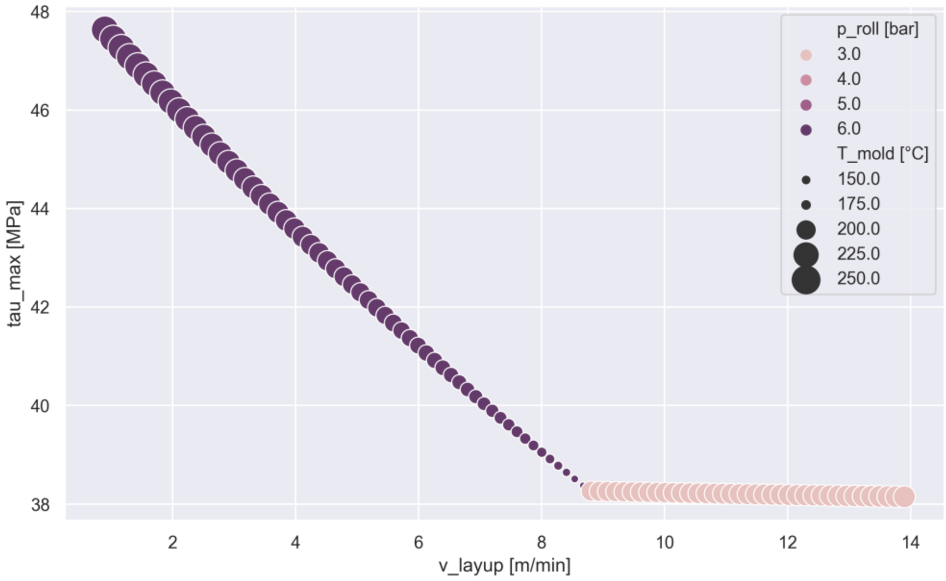

Figure 15: Pareto front, $T_{set} = 410\ °C$

The prediction of the response surface as shown in Figure 16 is satisfying. The two outliers in the lower right corner correspond to the outliers in Figure 13.

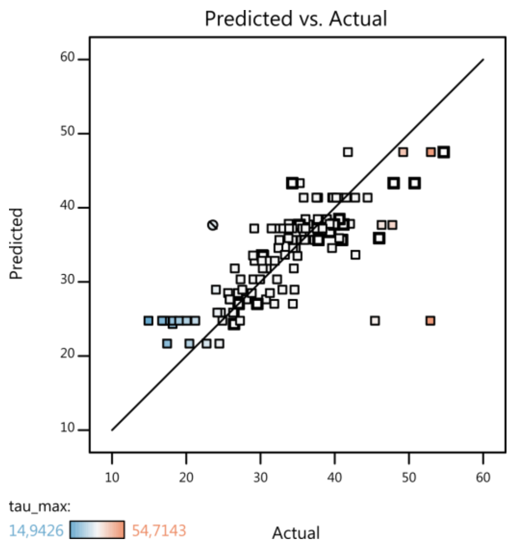

Figure 16: Predicted vs. Actual plot

4. DISCUSSION

Best results were generated with the single lap shear tests, therefore only these results are used for discussion. It is plausible that high T_{set}-values below degradation temperatures, high p_{roll}-values, high T_{mold}-values and low v_{layup}-values lead to high τ_{max}-values, since intimate contact of the tapes is ensured for a longer period of time with a lower viscosity of the matrix material. Since all parameters are set to extreme values for the global optimum, the boundaries of the DoE study might have been set too tight. T_{mold} and the subsequent cooling of the material is expected to have a high impact on the crystallinity in the interface region, where high crystallinities are linked with high strengths and with low cooling rates. [5] It can't be explained why lower T_{mold}-values at higher layup speeds are preferred until a plateau at 8,7 m/min is reached, as pointed out in Figure 15. It's also questionable why there's the plateau at very high layup speeds with low p_{roll}-values. Both matters should be verified by additional confirmation runs. If the results were confirmed, production at high layup speeds of 14 m/min would be very desirable.

All factors used in the DoE studies were nominal values, not actual/ measured ones. The accuracy of the studies might increase if further efforts were encouraged in order to derive actual factor values. More accurate T_{set}-values can be derived by preparing and calibrating the data from the infrared camera. v_{layup}-values are not constant during acceleration/ deceleration at the start and end of each track. Since these regions do not intersect with the fracture region, the nominal values of v_{layup} are expected to show a good accordance with the actual values. The pressure distribution on the interface region of the tapes generated by the pneumatic actuator pushing the compaction roller on the top tape is very complex. Reasons for the complexity can be found in the different temperature distributions of the compaction roller, the incoming tape and the substrate, affecting the stiffness/ viscosity of the present materials. Peaks of the pressure distribution are expected at the edge of the tape caused by the notch effect. First examinations also indicate that there is an interaction of the actual pressure with the layup speed. Further examinations are needed to develop a characteristic pressure value in the contact zone between the incoming tape and the substrate. Finally, T_{mold} is not constant throughout the tooling. Measurements with thermocouples could provide a solution for this issue.

Another limiting factor for the accuracy of the single lap shear DoE studies is the difficulty of the measurement of the overlap length. Also, it is difficult to place the fragile Kapton films at the exact distance of 5 mm, especially with a hot tooling. More exact positioning methods and measurement strategies are desirable.

The derived strength values of the single lap shear tests should not be taken as global interlaminar strength value. First of all, the strength values vary at the beginning and end of each track because of variations of the process speed and because these regions lack a possibility to apply tape tension and to position the incoming tape on the compaction roller. Second, the consolidation could differ if the fibre orientation of the incoming tape is different from the fibre orientation of the substrate, because the chance of fibres from the incoming tape and the substrate to "intermingle" is not given if the fibre orientations vary too much.

5. CONCLUSIONS & OUTLOOK

The optimum process parameters reveal a very low layup speed at only 1 m/min at very high temperatures ($T_{set} = 410\,°C, T_{mold} = 250\,°C$) and high pressure ($p_{roll} = 6\,bar$), which is plausible but not acceptable in terms of production rates. Nonetheless, the low speed could be accepted in selected areas where delamination is critical, e.g. at free edges or at stiffness jumps. [6] Good compromises for acceptable production rates can be found by considering the pareto front shown in Figure 15.

The single lap shear test is preferred over the DDP test because of its higher accuracy, the unproblematic use of heated toolings, the usability of standard tension testing equipment and because of the higher production rate of specimens. As a downside, the experimental setup of the Kapton foil on a hot tooling is difficult. Double beam shear tests could not be implemented successfully, but not all potentials are exploited and this testing method could increase the production rate, ease of use and accuracy even more. On the other hand, the full potential of the single lap shear DoE studies are not exploited as well. Several limitations and countermeasures were pointed out in the previous chapter.

Another interesting application of the presented single lap shear DoE study would be the optimization of the consolidation quality for post-consolidation processes in case of production failures leading to partially unconsolidated regions. Here, single tape pieces are placed locally on the substrate and no tape is fed during the AFP process. Hence, the laser is not directed in the interface region between the unconsolidated tape and the substrate, but on top of the unconsolidated tape. In this case, layup speeds of 1 m/min might already be too high. Also, an additional factor can be implemented in the DoE study: the number of post-consolidation repeat runs.

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