EXPERIMENTAL ANALYSIS OF THE COMPACTION BEHAVIOR OF THERMOSET PREPREG TAPES DURING AUTOMATED FIBER PLACEMENT

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Abstract

Compaction is a key characteristic of prepreg lay-up realized during deposition and through additional vacuum debulking steps. The necessity and frequency of debulking is often based on trial and error, unquantified experience or manufacturing specifications of manual lay-up. Automated lay-up offers potential to improve compaction during deposition allowing a minimization of additional debulking steps.

In this study Automated Fiber Placement process parameters and debulking frequency were varied with regard to their influence on laminate compaction, that was measured using a 3D triangulation scanner. The results were evaluated with a linear regression model. Dominating effects were found for process temperature and debulking frequency. Interdependencies between many parameters display the complexity of the overall process and its analysis. It is shown that a replacement of a major part of the compaction effect of debulking is possible with an adjustment of Automated Fiber Placement process parameters for the given setup.

Future studies have to extend this research to complex geometries and investigate the influence of the analysed uncured laminate compaction on final laminate quality after autoclave curing.

1. Introduction

The Automated Fiber Placement (AFP) process has advantages regarding deposition accuracy and flexibility, reproducibility and potential lay-up rate for composite manufacturing compared to manual lay-up. Although AFP is fully established in aerospace manufacturing there is an ongoing need for a deeper process understanding and optimization.

The compaction of a laminate is realized during deposition and through additional vacuum debulking steps. There are no established public standards for the definition of debulking parameters often leading to trial and error or experience based settings. Automated lay-up using the AFP process offers potential to improve compaction during deposition allowing a minimization of additional debulking steps.

In recent publications, process parameters are typically optimized regarding deposition quality and deposition rate [1] not taking into account ancillary processes like vacuum debulking. Other studies are limited to lab-scale compaction trials [2]. Publications on general compaction of prepreg do not cover typical AFP process conditions in terms of compaction rate and cycles [3].

Lukasewicz et al. [1] conducted experiments using a lab scale model of an AFP head to systematically vary tape temperature during lay-up and analyse its influence on voidage and laminate quality. The study indicates that laminate quality can be significantly increased by AFP process parameter variations.

Nixon et al. [2] conducted experiments focussing on ply stacks with varying fiber orientations, systematically varied temperature up to 90°C and long compaction times corresponding to hot debulking or autoclave conditions. The study shows increasing mutual blocking of layers with decreasing layer thickness, as well as a transition from shear to perculation flow around 70°C using thoughened thermoset prepregs.

A study by Hall et al. [3] exhibits variations of ply thickness, lay-up architecture and laminate temperature up to 90°C. It shows the elastic-plastic response of prepregs being non-linear. The study focuses on bulk compaction conditions not covering AFP lay-up.

Lukasewicz and Potter [4] studied the time dependent through-thickness compaction modulus at lab scale and found a linear elastic and non-linear plastic deformation behavior under AFP specific lay-up conditions.

Previous experiments analysed AFP process times and identified anxilliary processes like vacuum debulking as non-neglectable time consumers [5].

This study investigates the compaction behavior of prepreg tapes for full scale AFP processing conditions in combination with vacuum debulking. A series of experiments was performed to analyze the influence of AFP process parameters and debulking frequency on laminate compaction and lay-up quality.

2. Materials and Methods

2.1 Experiment Procedure

Sample plates of 300x300 mm and 16 plies were laid up with different parameter settings in a full factorial experiment design. The varied parameters were heat input via lamp power of the infrared (IR) heater (P_{irlamp}), compaction force of the silicone roller (F_{roller}), lay-up velocity (v_{layup}) and debulking frequency (see Table 1).

Thickness measurements were performed after every 8th ply and after debulking if applicable.

Table 1. Process parameter setting variations.

Parameter	Unit	*Low -*	*High +*
P_{irlamp}	[W]	159 (50%)	318 (100%)
F_{roller}	[N]	100	500
v_{layup}	[m/s]	0.04	0,12
Debulking	[-]	-	15 min at RT after every 8th ply

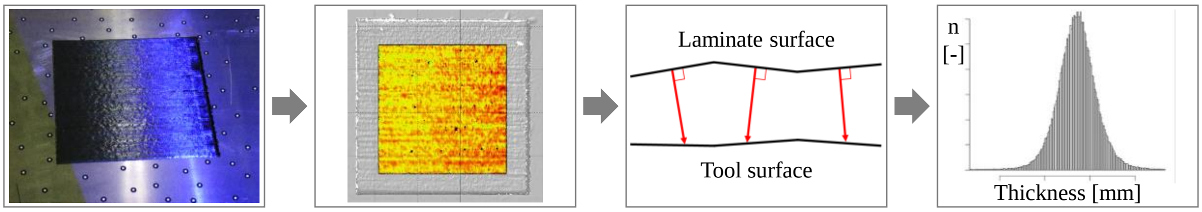
The goal to analyze the laminate quality after deposition without autoclave curing required a 'soft curing' method preserving the laminate properties as deposited. Based on the methods by Lukasewicz et al. [4] and Nixon et al. [2] a stepwise curing cycle was developed starting at a low temperature level and curing the laminate to highest isothermally reachable degree of cure (DOC) before raising the temperature to a higher level. This shall keep the viscosity as high as possible and mitigate flow mechanisms. Sufficient durations at isothermal levels were extrapolated from material characterization results [6] and checked via differential scanning caliometry (DSC). The resulting cure cycle starts with 18 h at 60°C followed by 4 h each at 70°C, 80°C, 90°C, 100°C and 120°C leading to a DOC of around 60 %. The influence of this curing cycle on the laminate was not yet evaluated but is assumed to be low enough allowing at least a relative comparison of different samples.

2.2 Equipment and Materials

The lay-up was carried out on an AFP machine by *Coriolis Composites SAS* consisting of a placement head mounted on a industrial six axis robot depositing 8 tapes of 3.175 mm (1/8 inch) width on a flat aluminum tool. The used silicone compaction roller had a diameter of 40 mm at a width of 30 mm. Heat was applied with an infrared lamp with a max. power of 318 W. The used material system was HexPly 8552 IM7 UD slit tape with a width of 3.175 mm [7].
The thickness measurements were performed with an optical triangulation 3D scanner. The used *ATOS Triple Scan* system by *GOM GmbH* projects structured light on a surface and detects the reflection with two cameras leading to a point cloud representing the scanned surface. The system has a random spheric spacing error of 0.028 mm per pixel given a measurement volume of 1400x1050x1050 mm and a resolution of 3296x2472 pixels. [8]
Using the entire population of around 100.000 usable measurements per experimental plate and assuming the absence of systematic errors with a constant desired plate thickness, the theoretical confidence interval of the mean to a significance level of 0.05 decreases to ±0.549 10^{-3} mm around mean value. This confidence interval represents the accuracy of the measurements being condensed to one mean value per experiment plate. [9]

2.3 Evaluation Procedure

The generation and evaluation of the thickness measurements included severeal steps (see Figure 1). The empty tool was scanned before lay-up as reference capturing the tool surface as well as the reference points around the laminate area. After lay-up the uncured laminate was scanned perpendicular to fiber direction again including the reference points. Reference and laminate scan were exported as point clouds and positioned based on the reference points. A rectangular area with 25 mm distance to the laminate edge was defined as measurement area. Perpendicular vectors between the polygonised surfaces defined the thickness of the laminate for each polygon area. Mean and standard deviation of the thickness distribution values was calculated as input for the regression analysis.



Laminate scan Point cloud Deviation vectors Thickness distribution

Figure 1. Thickness measurement approach.

Voids were analyzed for 3 samples per experiment plate according to ASTM D3171-09 [10] with weight and density measurements based on DIN EN ISO 1183-1 [11].

A linear regression model was set up to evaluate the influence of the varied parameters on compaction and laminate quality. Linear regression analyses allow the determination of coherences between covariates and a target variable. The target variable is assumed to be dependent on a set of covariates following a regression line with a Gaussian error term (see Equation 1).

$$\bar{y}_j = \beta_0 + \sum_{i=1}^{n} \beta_i x_{ij} + \epsilon \tag{1}$$

Using the method of least squares, the regression coefficients β_i for each covariate x_i are estimated. The impact of each covariate on the target variable can be judged by their regression coefficient's scale multiplied with the respective covariate. If the covariate consists of one variable, the corresponding regression coefficient determines the magnitude of this variable's main effect. If two or more variables are multiplied to create a covariate in case of an interaction of these variables, the regression coefficient gives information about the change of one variable's impact under different manifestations of the other variable. Like this, clear coherences between the target variable and all covariates can be identified, checked for significance and quantified. [9]

3. Results and Discussion

The setup of a linear regression model allows the interpretation of main effects caused by the single parameters (Figure 2) and their interdependencies (Figure 3).

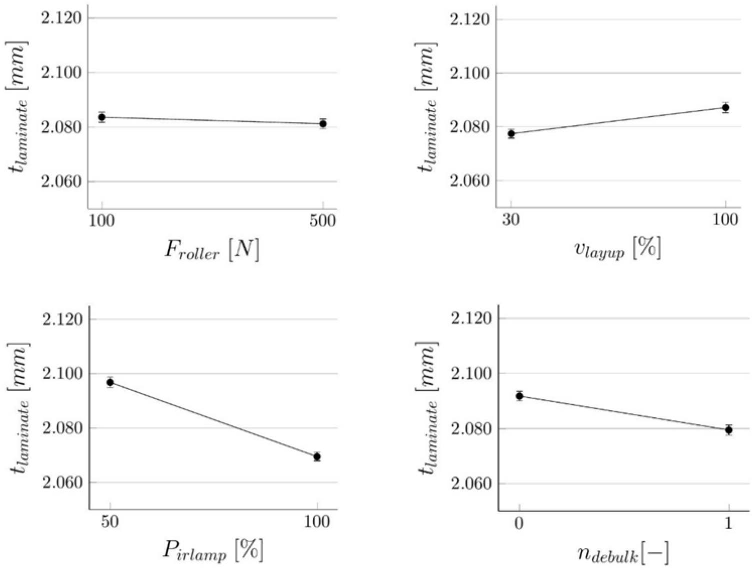


Figure 2. Single effects of parameter variations on compaction.

The variation of the compaction pressure F_{roller} (Figure 2 top left) does not show a significant effect on the measured mean thickness when looking at it without interdependencies. Lay-up velocity v_{layup} (Figure 2 top right) shows a negative effect on the overall compaction meaning higher velocities lead to less compaction. The process temperature being represented by the variation of the heat input P_{irlamp} (Figure 2 bottom left) shows a comparably strong positive influence. High process temperatures reduce the resin viscosity leading to a higher compaction of the laminate. The application of debulking shows a positive influence on compaction (Figure 2 bottom right). A quantification of the influences is to be handled with care as interdependencies are included in the visualization of Figure 2.

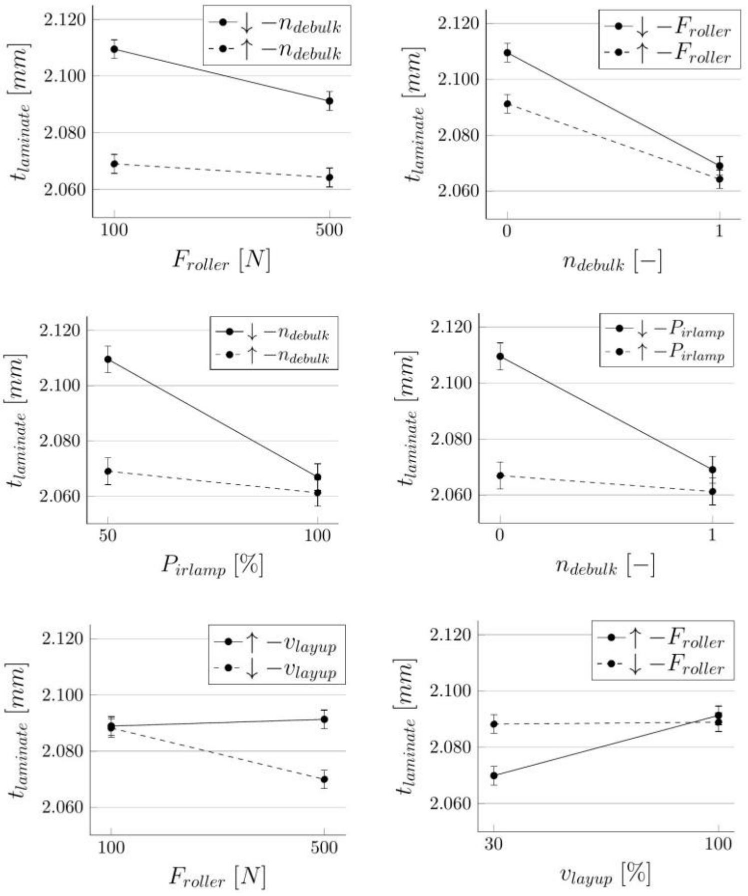


Figure 3. Interdependent effects of parameter variations on compaction.

Figure 3 shows interdependencies of different parameter combinations that were significant according to the linear regression model. The interaction of the two parameters included in one plot rises with the slope difference of the two regression lines. The graphs in the top, middle and bottom line are groups showing the same set of interdependencies. Left and right graph have a swapped base for better comprehension of the effect.

Figure 3 (top) shows the interaction of compaction force F_{roller} and debulking. They both have a positive effect on laminate compaction. The application of higher compaction forces reduces the compaction potential of debulking but still the effect of debulking is dominating. With applied debulking the effect of an increased compaction force is not significant anymore.

Process temperature set by P_{irlamp} and debulking show a strong positive interaction on the compaction result (Figure 3 middle). With applied debulking the effect of P_{irlamp} is reduced to a minimum. The other way round, a high process temperature reduces the compaction potential of debulking to an insignificant minimum.

Compaction force and lay-up velocity also show significant interaction (Figure 3 bottom). An elevated compaction force has a significant influence on the compaction result just for a low lay-up velocity. With high lay-up velocity the influence of higher compaction forces is reduced to an insignificant amount.

Table 2 shows the regression coefficients and p-values of the linear regression model. The thickness measurements were summed up to one mean value per experiment plate as input to the regression model. This led to a low sample count for the model making the p-value only a rough first indicator for significance. For more validity the impact of the effect as a combination of regression coefficient and absolute parameter value in combination with the p-values was evaluated.

Table 2. Results of the linear regression model.

Covariate	*Regression coefficient*	*p-value*
P_{irlamp}	-8.528 10^{-4}	0.00112
F_{roller}	-6.785 10^{-5}	0.08020
v_{layup}	-6.247 10^{-5}	0.68233
debulking	-7.865 10^{-5}	0.00551
humidity	1.256 10^{-3}	0.15258
P_{irlamp}:debulking	6.959 10^{-4}	0.01833
F_{roller} : v_{layup}	7.373 10^{-7}	0.11233
F_{roller} : debulking	3.376 10^{-5}	0.27351

Figure 4 shows micrographs of the soft cured laminate of different samples. The schematic (a) visualizes the lay-up consisting of 16 plies with single tapes of 3.175 mm width. The tapes are staggered by 50 % tape width from ply to ply.

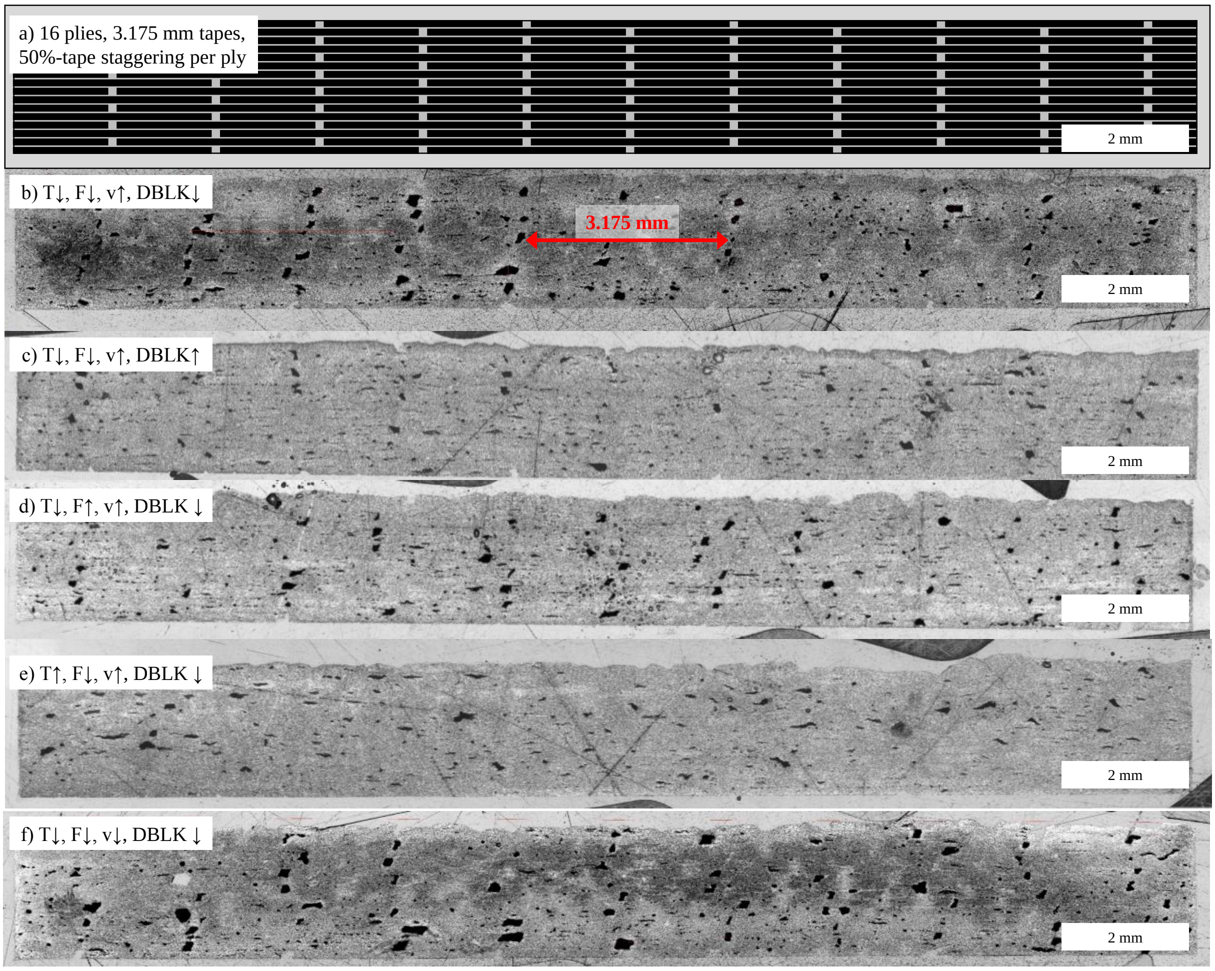


Figure 4. Micrograph images including (from top down): schematic, low compaction reference, high debulking, high force, high temperature and low velocity

The minimum compacted sample (b) shows clear porosity on the tape edges. Samples c) – f) show the effect of a single parameter as indicated on the picture. Especially debulking and higher process temperature show a positive influence on compaction indicated by a clear minimization of the porosity at the tape edges through shear flow of matrix. The overall porosity of all samples is still high compared to fully cured laminates due to the lack of vacuum or autoclave curing for the applied 'soft curing' method.

The linear regression model of the void content analysis showed a domination of single covariate effects, while identifying less significant interactions. It agrees with the model above in allocating strong significant void reducing effects to debulking and increased process temperatures. Other results of the model contradict the compaction measurements and the micrograph analyses. It is assumed that the chosen method of void detection with its accuracy of ± 1 % according to ASTM D3171 09 [10] is too imprecise for a linear regression analysis including parameter interactions. The applied 'soft curing' method is not yet proven to keep the laminate conditions unaltered and might bring further inaccuracies to the measurements.

The described insights indicate that a substantial fraction of compaction acheived during debulking can be shifted into the lay-up phase by the correct setting of AFP process parameters. It has been shown that a rise of laminate temperature by 20°C causing decreased resin viscosity has the potential to replace about 80% of the effect of a debulking step for the given setup. The dominating effect of process temperature is in very good compliance with Lukaszewicz et al. [1, 12], who conducted experiments on lab scale. This effect can be supported by an elevated compaction force, whose effectiveness is highly dependent on a low layup velocity.

4. Conclusion and Outlook

Layup experiments with variations of AFP process parameters and debulking frequency were conducted with regard to their influence on laminate compaction. Laminate compaction was measured using a 3D triangulation scanner. The results were evaluated using a linear regression model. The experiments show significant effects on compaction for the process temperature and debulking frequency as single factors and significant interdependencies for compaction force – debulking frequency, process temperature – debulking frequency and compaction force – layup velocity. It is shown that the effect of debulking can by major parts be replaced by adjusted AFP process parameter settings. Process temperature dominates the effect by far. Higher compaction forces in combination with low layup velocities bring only little improvement. The results indicate a potential for more efficient AFP manufacturing by a reduction of the debulking frequency.

In a next step the experiments have to be extended to more complex geometries including the risk of fiber waviness due to insufficient compaction. The parameter settings have to be extended beyond the limits of this study to fully grasp their compaction potential. Especially the indicated potential of elevated process temperatures justifies research on alternative heat sources, heated rollers or hot temperature debulking. The experimental results have to be compared to compaction simulation results for validation.
Further research is necessary to evaluate the influence of uncured laminate compaction on laminate quality after autoclave curing. This way the compaction demands during layup can be defined and optimized with the results of this study.

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