THE INFLUENCE OF THE TAPE PLACEMENT PROCESS ON PART CHARACTERISTICS BASED ON DIFFERENT UD-TAPE QUALITIES

M. Schulz[1], C. Buschhoff[1] , H. Janssen[1] and C. Brecher[1]

[1]Fraunhofer Institute for Production Technology, Steinbachstr. 17, 52074 Aachen, Germany
Email: malena.schulz@ipt.fraunhofer.de, clemens.buschhoff@ipt.fraunhofer.de
henning.janssen@ipt.fraunhofer.de, christian.brecher@ipt.fraunhofer.de
Web Page: http://www.ipt.fraunhofer.de

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Abstract

From a production engineering perspective, the freedom of design with composite materials offers an interesting possibility of product customization. A part can be structurally optimized by the right choices of materials and layups resulting in efficient weight and process time reduction. In addition, production technologies can influence the mechanical properties of the final part. The additive behavior of processing composites results in a higher risk of defects. This paper investigates how a production technology can enhance the status-quo characteristics of a semi-finished composite product. Up to three different qualities of unidirectional (UD) glass fiber reinforced polypropylene tape are processed with the laser-assisted automated tape placement process at the Fraunhofer IPT. By conducting three point bending tests the specimens' mechanical characteristics are evaluated. Microsections give an insight into the consolidation behavior after processing. The study shows that different qualities of thermoplastic UD-tapes can be adjusted to the needs of the final part after the automated tape placement process. It demonstrates how a process can be adapted dependent on the requirements of the final part and on the incoming semi-finished product.

1. Introduction

In recent years, diverse production technologies for the processing of fiber-reinforced plastics (FRP) have emerged in order to enable cost efficient production of composites in shorter production times. However, due to the costly material itself, FRPs still face some competitive disadvantages towards metals. The automated tape placement process (ATP) is a potential technology promising a flexible and adaptable processing of composites. Originally developed for the aerospace industry, it gains more and more attraction from cost sensitive industries, such as the automotive one, as it allows an automated production of load optimized, near-net shape components. The process has been developed for diverse composite materials, such as thermoset or dry-fiber, but it is mostly beneficial with using unidirectional, thermoplastic composites, so-called UD-tape. The in-situ ATP process with thermoplastics allows the direct consolidation of the material without the need of any further manufacturing steps [1]. In order to gain an in-situ consolidation the manifold process parameters have to be adjusted to the material and the needs of the final part. However, the many possibilities to influence the process highlights its high degree of flexibility, but also leads to difficulties in controlling the process [2]. This study investigates the possibility of the process to influence the final parts' mechanical characteristics by adapting the process parameters according to incoming UD-tape quality. A parametric study with three different tape qualities out of polypropylene and glass fiber (PP/GF) is conducted. Aim of the study is to increase the adaptiveness of the ATP process by investigating how the process can be adjusted to the incoming tape quality in order to produce sufficient part quality. Thereby, the costs of UD-tape can be reduced as less qualitative material can be produced.

2. The automated tape placement (ATP) process

The automated tape placement process is a manufacturing technology, which enables a flexible manufacturing of diverse composite materials and geometries. Within this study the in-situ ATP of preimpregnated UD-tape is considered, which is characterized by unidirectional (UD) fibers within a thermoplastic matrix. Due to the use of a thermoplastic matrix, the process of manufacturing composite parts is shortened as the in-situ tape placement process offers the production of near-net shape parts without any further consolidation steps [1]. For this reason, the technology offers a high potential for process automation leading to higher attractiveness for price sensitive industries, such as the automotive industry.

In general, the in-situ tape placement process uses a heat source, such as a laser, which heats up the incoming thermoplastic tape as well as the substrate material up to melt temperature. The incoming tape is placed on top of the substrate, which is either the mold or the preceding placed tape layer, as shown in figure (Fig. 1). The welding between the incoming tape and substrate is executed by a consolidation roller by inducing force on the materials. Thereby, voids of the tape material can be compressed and further irregularities diminished [3]. By adding tape by tape and layer for layer, composite parts are manufactured. This characterizes the process as an additive process technology, which is based on the welding of the polymer matrix. [4]

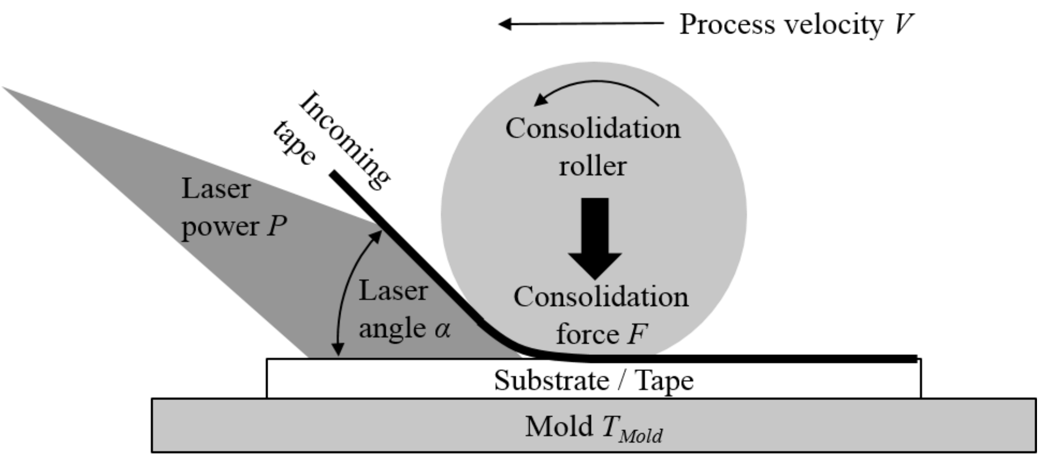

Figure 1. The automated tape placement process, adapted from [2].

From a theoretical perspective, the process can be divided into multiple mechanisms taking place during the process, such as heating phenomena, intimate contact and autohesion. A detailed description of the occurring mechanisms can be found amongst others in [1] , [5] or [6]. During the last decades several different models where established in order to model the tape placement process analytically or via computer simulation, such as with finite element analysis [7]. This research includes parameter studies investigating the influence of process parameters on laminate quality to verify these models, such as in [2], [8], [9], and [10]. The welding strength between each tape and layer is seen as the main factor for the laminate's quality. The authors Cheng et al. [10] summarize the outcome of different parameter studies as followed:

1. The process parameters during ATP strongly influence the laminate's quality.
2. The numerous interaction of process parameters need to be studied.

3. The developed models are submodels only focusing on specific mechanisms taking place during the process.

In can be stated that due to the high degree of flexibility especially regarding materials, its complex and highly non-isothermal nature, the theoretical modeling of the automated tape placement is difficult. The manifold parametric studies in this field underline the challenge of modeling the process making it difficult to establish a holistic model.

The stated studies often neglect a further process characteristic of the tape placement process as they mainly focus on one specific tape. Having different tape qualities of one material combination is a further degree of freedom. This is of interest in order to decrease the costs of the incoming tape material by accepting lower impregnation quality. For this reason, this study takes three different tape qualities of one tape material into consideration. This study assumes that the in-situ ATP is capable to diminish defects of the tape, such as a high surface roughness, and to achieve higher laminate quality.

3. Process study

Within this paper, a parameter study is conducted to investigate the influences of process parameters during tape placement on the part's mechanical characteristics. A full-factorial 2^3 design of experiments is chosen for the production of three point bending test specimens produced with the laser-assisted tape placement process. For the specimens three different tape qualities out of polypropylene and glass fiber are used. By conducting three point bending tests the specimens' mechanical characteristics are evaluated.

3.1. The tape placement system

The tape placement system at the Fraunhofer IPT is robot-based and uses a diode laser as energy source for the process. The self-developed tape placement head is fixed to a conventional KUKA robot and allows to flexibly adjust the system either to tape placement or to tape winding. In this case, a flat and heatable aluminum table is chosen as the mold. The system allows to adjust the process parameters laser power P, the consolidation force F, the laser angle α, mold temperature T_{Mold} and the production velocity V (see Fig. 1). It also enables the tracking of the real-time values of P, F as well as the temperatures of the incoming tape and substrate close to the nip point.

3.2. Tape characteristics

New in this study is the usage of three different tape qualities. The tape is out of polypropylene and glass fiber (PP/GF). The used tapes differentiate in the amount of cavities, fiber distribution as well as considering the roughness and waviness of the tape's surface. According to literature, these factors influence the weld strength based on the intimate contact model [9] and, thus, the mechanical characteristics of the part. Figure (Fig. 2) shows microsections of each tape (named A, B, C). The figure indicates that tape C shows lowest quality due to its inhomogeneous fiber distribution. Tape B and A have similar fiber distribution but differ in the amount of cavities, which are lowest in tape A.

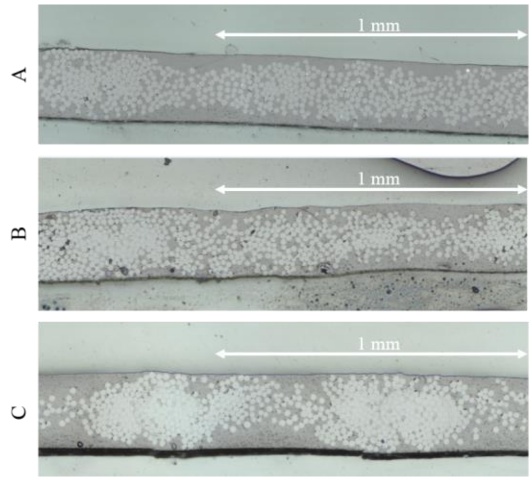

Figure 2. Microsections of three different PP/GF tapes.

In addition, surface quality of each tape is measured by a the laser scanning system "scanCONTROL 2900-25" of Micro Epsilon, Germany. This allows the evaluation of roughness and waviness according to [11] as well as to find correlations regarding the specimens' mechanical characteristics. The results, as shown in figure (Fig. 3), demonstrate that tape A and B mainly differentiate in their waviness and that tape C strikes due to its higher roughness.

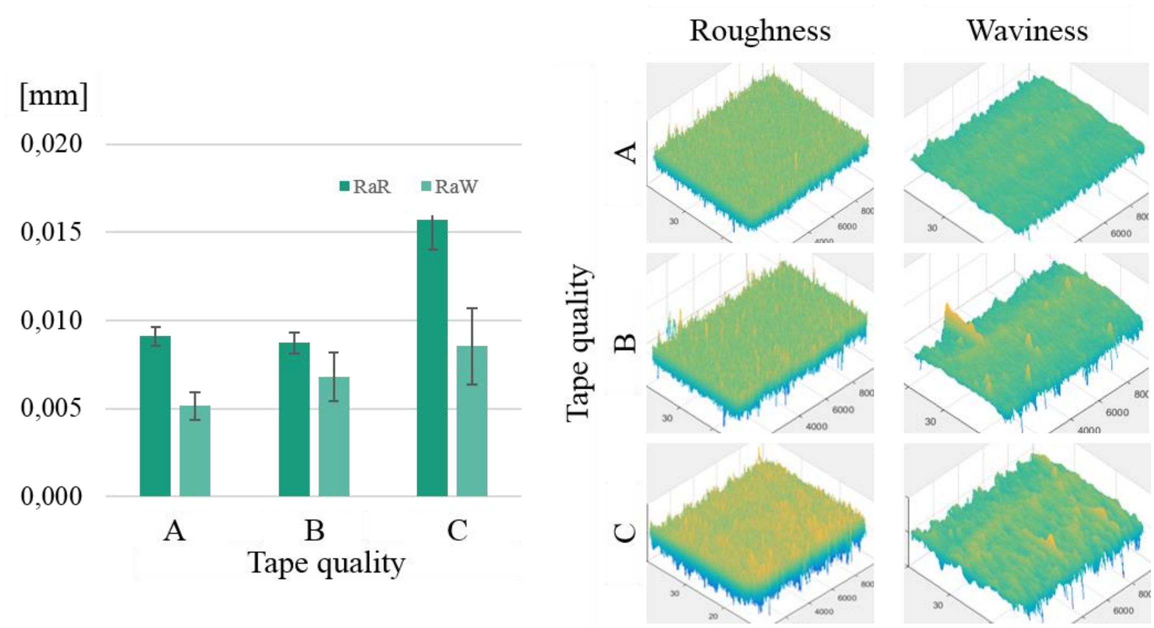

Figure 3. Evaluation of surface quality of three PP/GF tapes.

3.3. Experiments

For each tape quality an organosheet with 0° fiber angle and eight layers having a staggered arrangement were manufactured. The staggered arrangement is chosen as it improves the overall cohesion of the tapes in a solely 0° laminate. The parameter variations shown in the table (Table 1) were considered. The chosen window of process parameters is based on prior investigations and according to best practice values. In total, 12 organosheets were manufactured each providing 10 specimens of 60 mm length and 15 mm width. The average thickness of the specimens is 1,7 mm.

Table 1. Parameter variations for each tape quality A, B, C.

Parameter variation	P (W)	F (N)	T_{Mold} (°C)	α (°)	V (mm/s)
#1	600	100	120	-1°	150
#2	600	200	120	-1°	150
#3	700	100	120	-1°	150
#4	700	200	120	-1°	150

The specimens' characteristics are evaluated quantitatively by a three point bending test (DIN ISO 14125) as well as qualitatively by microsections. The three point bending test is chosen as it offers a conclusive characterization of the manufactured composite part while having a straightforward experimental setup without tedious preparation of the specimens. The specimens are exposed to a multi-axial stress state consisting of tensile, compressive and shear stresses assuming a linear behavior of the material [13]. This loading setup allows the investigation of different fracture mechanisms caused by normal stress. However, it also has the risk of overinterpreting the results due to its non-uniform stress state. The loading of the specimen during the three point bending test is highly local compared to tests such as a tensile test, which deforms the whole specimen. For this reason, the three point bending test is affected by the statistical distribution of defects. This can result in higher mechanical strength values than the ones from tensile testing [13]. Microsections give an insight into the distribution of defects within the specimens which is why they are conducted in this study.

4. Results and Discussion

4.1. Results

The results of the three point bending tests are illustrated in figure (Fig. 3). For each tape quality (A, B, C) the flexural strength values σ_B including their standard deviations s are given with respect to the parameter variations in table (Table 1). The precise values are stated in table (Table 2) and are normalized regarding the actual thickness of the specimens. The microsections of each trial are shown in figure (Fig. 4).

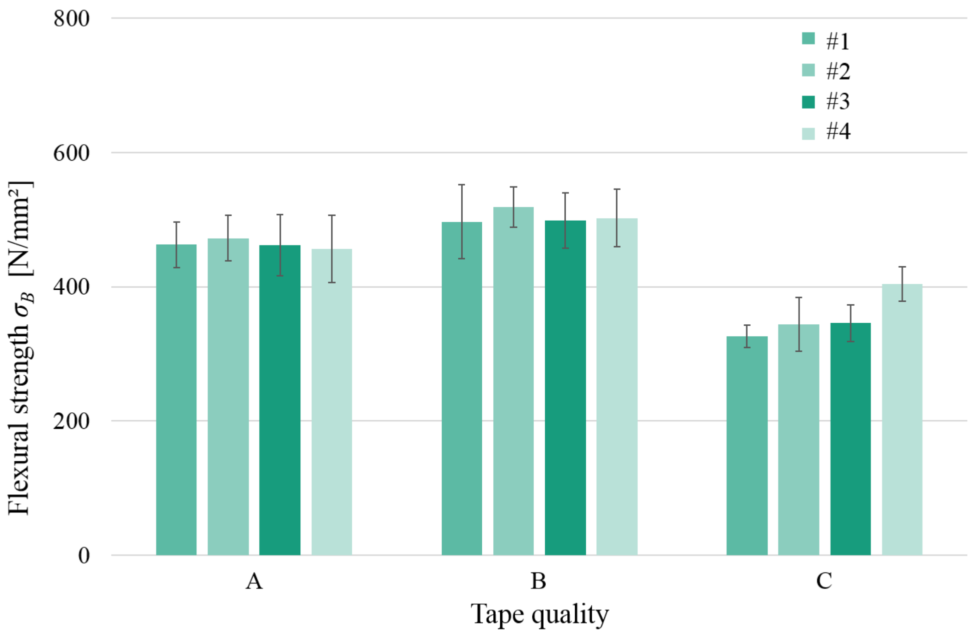

Figure 3. Results of the three point bending tests with different PP/GF tape qualities.

Table 2. Results of the three point bending tests.

Tape quality	Parameter variation	σ_B (N/mm²)	s (N/mm²)
A	#1	462,55	34,35
A	#2	472,25	34,13
A	#3	461,86	45,29
A	#4	456,13	50,28
B	#1	497,02	54,81
B	#2	519,14	30,06
B	#3	498,71	41,18
B	#4	502,36	42,83
C	#1	325,86	16,83
C	#2	343,83	40,16
C	#3	345,79	27,22
C	#4	404,00	25,61

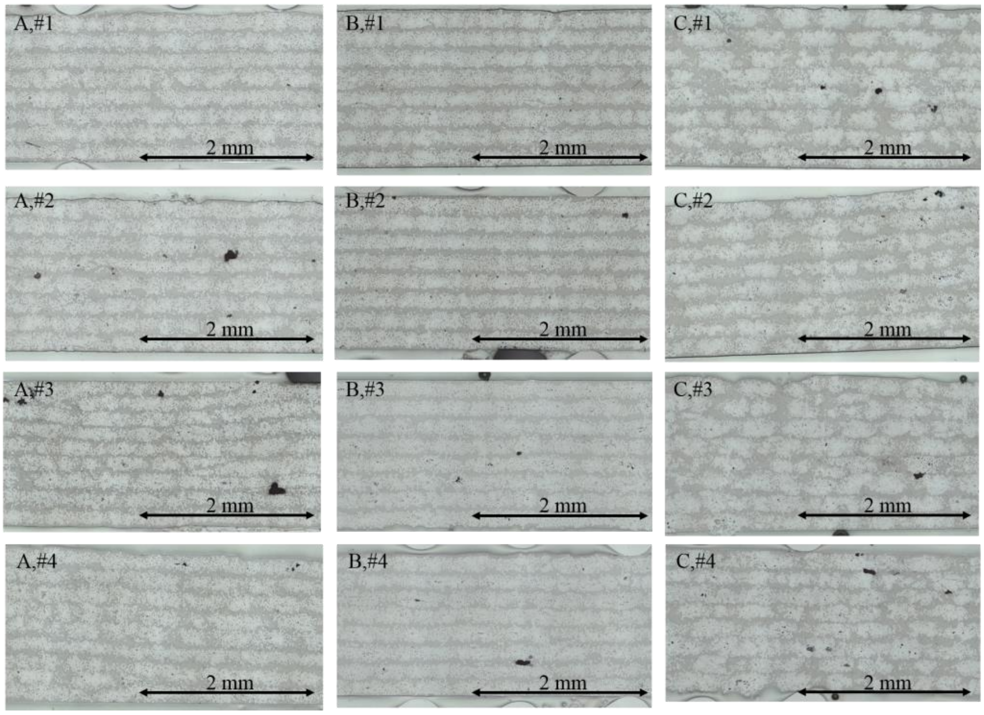

Figure 4. Microsections of the manufactured specimens for each tape quality (A,B,C) and parameter variation (#1,#2,#3,#4).

4.2. Discussion

The evaluation of the flexural strength in figure (Fig. 3) shows that the differences between tape A and B are low. In addition, their strength values are mostly within the given standard deviations so that both tape qualities do not significantly differentiate in their mechanical characteristics. The microsections of tape A and B indicate that the slight deviations in flexural strength may be due to the inaccurate layup. The staggered arrangement of each layer resulted in an inhomogeneous distribution of layers and fibers in some areas of the laminate, as it can be seen in microsection A,#4 in figure (Fig.

4). The differences can also be caused by process induced defects such as in the case of A,#3 (black spots indicate defects). In contrast, the differences between tapes A, B towards C are higher. Tape C has lower flexural strength values approving that the tape quality of C is lower. In addition, the microsections of the laminates with tape C show that fiber distribution is more inhomogeneous and has more cavities compared to tape A and B. Interestingly, the parameter variations with tape C indicates that a change of process parameters has a positive influence on the mechanical characteristics.

Investigating the interactions between the process parameter variations give an insight into the effects of each process parameter. Within this study, the overall analysis shows that the tape quality has the highest effect on the flexural strength, followed by consolidation force F and laser power P. The effect of the process parameters F and P are to a much lower extent giving the conclusion that their influence is mostly irrelevant. However, having a solely look at the effects on each tape quality A,B,C demonstrates that the process parameters laser power and consolidation force have an effect, especially in the case of tape C. Here, laser power and consolidation force positively influence the strength values. In the case of tape A and B, the process parameters F and P do not have a significant effect on the flexural strength. Most of the values lie within the given standard deviations.

In summary, the small differences between tape A and B confirms the prior statement that both tape qualities do not differ to a high extent and for this reason result in similar mechanical characteristics. It also implies that the tape placement process cannot positively influence the mechanical characteristics of the incoming tape material. However, as both incoming tape qualities A and B are estimated to be of sufficient quality and do not have many defects, it is more unlikely that they are positively influenced by the tape placement process. In contrast, the results from tape C indicate that a lower tape quality with more defects can be positively influenced by the tape placement process. It is unclear from this study which characteristics of the tape C has the highest potential of being influenced by the tape placement process. A possibility is that the higher surface roughness of tape C is more likely to be changed by the right choice of process parameters. Considering the intimate contact models from literature [9] it can be assumed that higher force and laser power decrease the roughness of the tape during the process due to the decreased viscosity. This would result in improved weld strength and laminate quality.

Nevertheless, the trials have to be considered carefully as they do not include all possible variations of the process, e.g. laser angle and mold temperature. Additionally, the 2^3 design of experiments only covers a small process window. The results imply that there are possibilities that the tape placement process is able to enhance parts out of lower PP/GF-tape qualities by adjusting process parameters. In order to give a significant statement further investigations with an increased number of process parameters are needed.

5. Conclusion

This study gives a first impression how different qualities of thermoplastic UD-tapes can be compensated or adjusted to the needs of the final part after the automated tape placement process. A basic parametric study with three different tape qualities of PP/GF tape and process parameters of the laser-assisted tape placement process is conducted. The results show that adjusting the process parameters, such as laser power and consolidation force, primarily has an effect on bending strength values for lower tape qualities with higher surface roughness. However, in order to make conclusive statements further investigations are needed as the study in this paper only covers a limited window of possible parameter variations. In conclusion, this study introduces the idea to adjust the process parameters according to the incoming tape quality and dependent on the requirements of the final part. It gives a new perspective on productive and efficient manufacturing of composite parts out of UD-tape based thermoplastic composites.

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