AUTOMATED FIBER PLACEMENT: RELATION OF COMPRESSION SHEAR AND TENSILE TESTS OF TAPE LAYING AND WINDING

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ABSTRACT

The automated fiber placement process with in situ consolidation (AFPisc) performs the laydown and consolidation of fiber reinforced tapes using thermoplastic matrices in one step. To find processing windows at adequate placement rates to avoid subsequent consolidation processes is challenging, as correlations of test results from reference processes are not always given in this multiparameter experimental environment. In this work, wedge-peel-based processing conditions of carbon fiber reinforced polyamide 6 (CF/PA6) are further specified. Compression shear tests are investigated to characterize the layer bonding strength and correlated to basic tensile linear elastic properties. With additional split disk tests of rings, the substantial differences of tape laying and winding are further analyzed. The results reveal the importance of the parameter processing temperature, whereas the placement rate is of minor significance. A correlation of the matrix dominated compression shear and transverse tensile tests was found in contrast to those in fiber direction. A general increase of stiffnesses was found using the split disk tests. The transverse tensile stiffnesses in the range of 60 % to a pressed reference were increased to the range of 80 % using the split disk tests. Based on these experiments, a placement rate of 18 m/min is suggested.

1 INTRODUCTION

Highly automated composite production processes based on additive manufacturing principles using thermoplastic matrices, such as the automated fiber placement with in situ consolidation (AFPisc), have insufficient material performance at adequate placement rates that are mainly associated with the tape laying process. Although primary flight structures have been successfully build with the advantage of short and automated production [1], one of the main challenges is the development of adequate processing windows in a multifactorial experimental environment with a large number of potential influences of machine settings (e.g. placement rate, processing, temperature, laser spot size and incident angle, roller temperature, size and material, etc.), and proving its significance with a suitable test.

To solve this problem, experimental approaches have mainly focused on tests that address the layer bonding as laminate quality indicator [2]–[15]. A straightforward approach with simple specimen production and test implementation is the wedge peel test. However, the interpretation of the test result remains challenging, as degree of bonding and material ductility can contradict in the peel test response. With the close relation of peel strength and fracture toughness [16], this problem also exists in the laborious double cantilever beam test. Another option is the interlaminar shear strength test that has been widely applied on fiber reinforced high performance thermoplastic polymers, e.g. [6], [17]. Insufficient failure modes on more ductile thermoplastic polymers, such as polyamide 6, have been reported [18].

The transfer of a processing parameter set based on tests that characterize the laminate interface to a general linear elastic design parameter for structural design, such as Young's moduli, strengths or flexural properties, may not always be possible. As these tests address different aspects of material behavior, different sensitivities to the processing conditions are also observed. This has been demonstrated with the flexural stiffness and double cantilever beam test [10]. It has also been shown that the interlaminar shear strength does not always correlate with the flexural [19] or transverse tensile strengths [20]. It is therefore of importance to perform tests that address basic structural design parameters at the stages of process window development that can be transferred to the structural design of components and parts.

To address this, wedge-peel-based processing parameters of carbon fiber reinforced polyamide 6 (CF/PA6) from [7] are further analyzed. It was found that processing temperatures above 320 °C reduce the wedge peel strength at a placement rate of 6 m/min. Although the same material and test equipment, but a different fiber placement machine of the same company, was used, these results were not reproduced at the same placement rate. In addition, the increase in placement rate showed no effect on the peel strength [15].

In this work, the placement rate and the processing temperature (nip point temperature) based on the previous wedge peel results is further specified and transferred to parameters of structural design. First, another approach of layer bonding characterization is performed using the compression shear test to broaden the spectrum of potential suitable tests and correlate these to standard design parameters. The shear mechanism of this test is similar to the single lap shear test. In this, the shear strength was reported to positively correlate to higher degree of crystallinities [9]. Tensile tests in and transverse to the reinforcing fiber are conducted to estimate the basic linear tensile elastic design parameters of Young's moduli and strengths. Since the consolidation mechanism of winding and tape laying are often referred as different, because tape tension is transferred to consolidation force in the winding process, a transfer of the results is performed. For that purpose, tubes are produced and tested using the split disk test.

The results of this work show a dependency of the mechanical properties on the processing temperature of matrix dominated tests (transverse tensile and compression shear test). This is in contrast to the tensile tests in fiber direction, where a higher processing temperature increases the stiffness, while the strengths maintain constant. The increase of the placement rate from 6 m/min to 18 m/min shows no substantial change in all test performed at the same processing temperature. An increase of the stiffness of the split disk test in comparison to the flat specimen in and transverse to the fiber was found. However, the mechanical properties of the transverse tensile pressed reference were not reached. A potential reason for this are dry fiber filaments in all AFPisc specimens. Although an increase of the placement rate from 6 m/min to 18 m/min is reached, a subsequent consolidation remains recommended to further increase the mechanical performances.

2 MATERIALS AND METHODS

2.1 AFPisc system

The machine used in this work is a robot mounted AFPisc system from AFPT GmbH, Dörth, Germany. It consists of a laser heating source from Laserline GmbH, Mühlheim-Kärlich, Germany that is controlled using a thermal camera. Note that the emissivity of the measured near nip point temperature is set to one. A consolidation roller with a silicone rubber jacket with a diameter of 64 mm was used, that represents the mid-sized roller from [14]. A consolidation force of 370 N was applied during the experiments, which results in a gaussian like pressure profile with a consolidation length of circa 16 mm.

2.2 Material

Slit tape in which the width of 12 mm and a thickness of 0.13 mm of carbon fiber reinforced PA6 Clestran® CFR-TP PA6 CF60-01 from Celanese Corporation, Irving, Texas, USA was used to produce the specimens. The base of the split disk specimens consist of the short carbon fiber reinforced PA6 AKROMID® B2 ICF 40 black (5020) from AKRO-PLASTIC GmbH, Industriegebiet Brohltal-Ost, Im Stiefelfeld 1, 56651 Niederzissen, Germany.

2.3 Specimen preparation

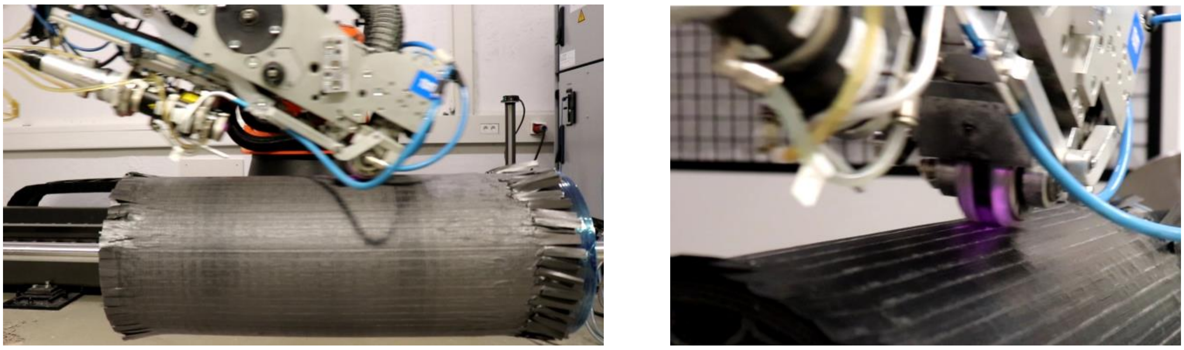
Plates were produced in order to investigate the behavior of the temperature and placement rate of tensile general elastic design parameters of a transverse isotropic material. A full factorial experimental design was chosen. The factors are displayed in Table 1. These parameters are based on previous work in which wedge peel tests were performed [15], [21]. The substrate/tool consisted of an aluminum plate that was maintained at room temperature. To characterize the quality of bonding of the single layers, a compression shear test was performed. With a testing speed of 0.5 mm/min, specimens of circa 2 mm in thickness (16 layers), 10 mm in width and 5 mm in height were tested in direction of the reinforcing fiber. Tensile tests in fiber direction and transverse to the reinforcing fiber according to DIN EN 2561 and DIN EN ISO 527-5 were produced, respectively. The widths of the transverse tensile specimens were increased to 50 mm to better match the 10 kN load cell that was used on the quasi-static universal testing machine. The clamps were covered with sandpaper in contrast to the specimens in fiber direction, where taps were glued onto the specimens according to the standard.

Parameter	Value	Unit
Temperature	280, *320	°C
Placement rate	6, 9, 18	m/min

**no split disk test*

Table 1: Full factorial experimental design

The bases of the split disk specimens were printed using a CEAD Flexbot, from CEAD Group BV, Schieweg 25, 2627 AN, Delft, Netherlands. A nozzle with a size of 2 mm was used to print tubes of 600 mm length in a programmed continuous helix path. The inner diameter was 220 mm, which matches the split disk testing fixture. 16 layers of the thermoplastic tape were placed and bonded onto the printed tubes using the AFPisc process in 0° (Figure 2) and circa 89° (to reach full coverage of the surface), which in turn represent specimens in and transverse to the fiber direction. Specimens with widths of 25 mm were machined out of each of the rings. In order to compensate the printed structure of the test, specimens without an attached laminate were tested and subtracted by a linear rule of mixture using the areas of cross sections. Prior to the testing, the disks were covered with grease to enable slippage. A testing speed of 2 mm/min was used. The strain measurement was performed using digital image correlation in a section with a distance to the gap of the disks to diminish bending effects on the strain measurements (Figure 3).



(a) (b)

Figure 2: Split disk specimen production for the transverse tensile test placing 0° layers using the AFPisc process from the side view (a) and to the nip point (b)

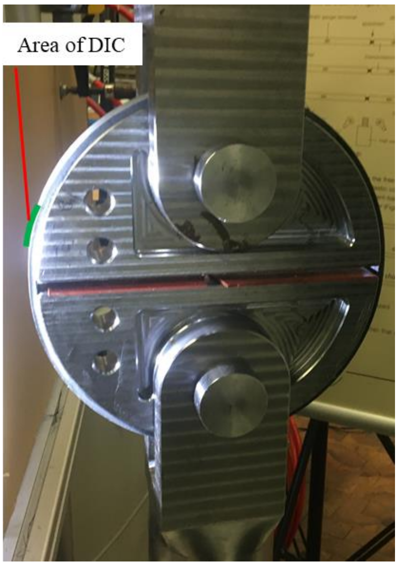


Figure 3: Split disk test fixture with marked area of digital image correlation (DIC) for the measurement of the strain

3 RESULTS AND DISCUSSIONS

3.1 Compression shear test

Figure 2a qualitatively displays different failure modes of the compression shear test. Characterized by a steep slope of the force response, a sudden force drop is the valid mode of failure. The crack propagates throughout the entire interface that separates the layers. In contrast to the invalid failure mode, the pressure initiation surfaces are maintained intact. The invalid failure is characterized by a compression of these pressure initiation regions of the specimens, which are compressed and slowly sheared off. No distinct layer separation is achieved. Thicker specimens have larger areas of contact to the testing fixture to overcome this type of failure. This however requires additional production of plates other than those that are used for the tensile specimens. Of 7 specimens tested in every series, only one series had two invalid specimens, while all the other series had no more than one invalid failure.

The results of the compression shear tests are displayed in Fig. 2b. A trend was revealed showing that higher processing temperatures reduce shear strength. This is in contrast to the wedge peel test reported by [21], where no such effect was found, but did result in a high standard deviation. No distinct influence on the shear strength to the placement rate was found. The independence of this processing parameter of the compression shear tests is in accordance to the results that are obtained from the wedge peel test [15].

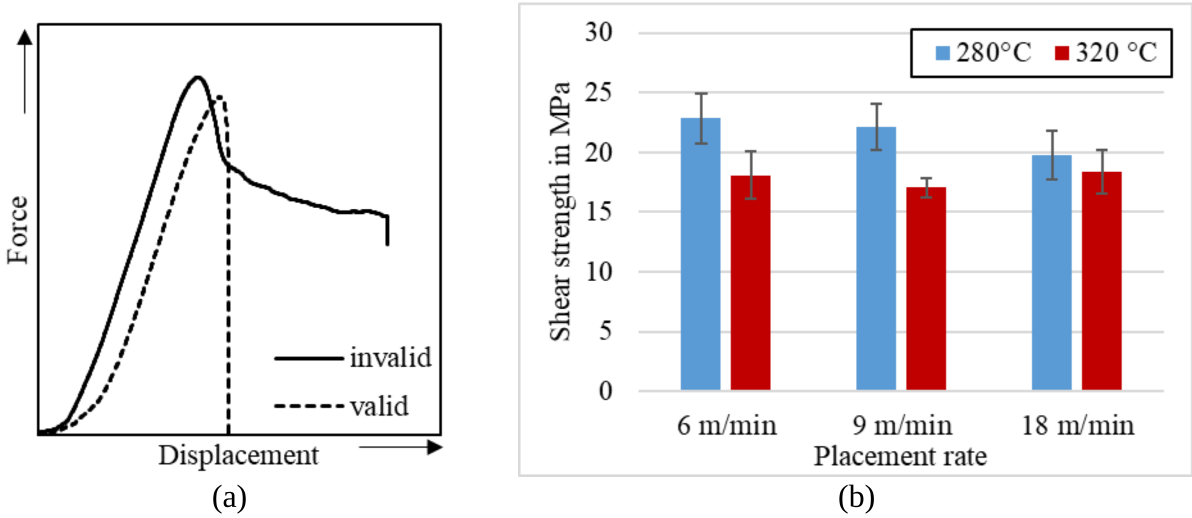


Figure 2: Valid and invalid modes of failure of the compression shear test (a) and shear strengths resulting from the AFPisc process at different placement rates and nip point temperatures (b)

3.2 Tensile tests

The stiffness derived from the tensile tests in fiber direction is displayed in Figure 3a. An insensitivity of the response of an increase in placement rate for both of the processing temperatures of 280 °C and 320 °C was measured. A processing temperature at the nip point at 320 °C exceeds a Young's modulus of 100 GPa of the mean values, which is above those specimens at the lower processing temperature. Figure 3b shows the dependency on the processing conditions to the strength of the material in fiber direction. A peak strength is reached at a placement rate at 9 m/min at 280 °C processing temperature, although this strength is not significantly above a placement rate of 18 m/min at both of the processing temperatures. With the exception of this peak, no trend of placement rate and processing temperature is revealed.

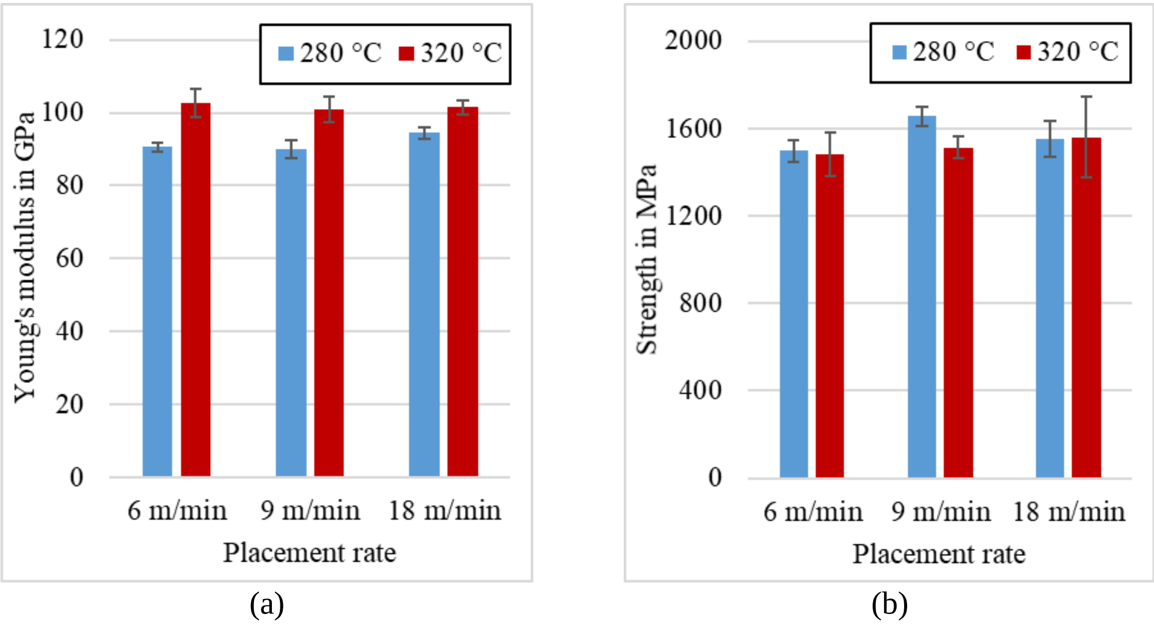
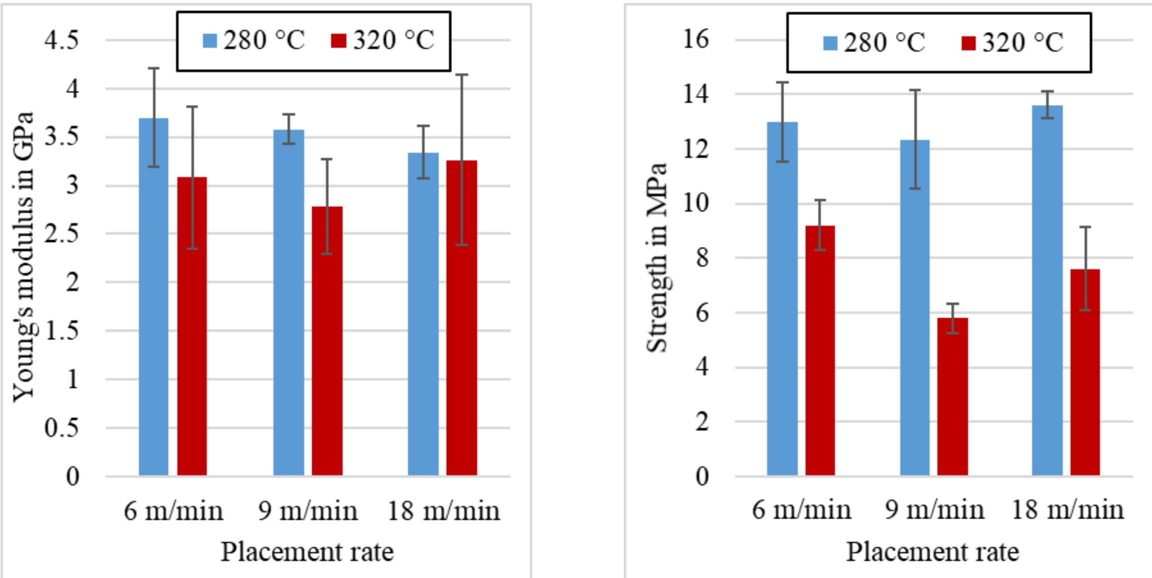


Figure 3: Tensile test results in fiber direction at different placement rates and processing temperatures at the nip point with the Young's moduli (a) and strengths (b).

In contrast to the stiffness of the tensile results in fiber direction, the transverse tensile stiffnesses with a processing temperature of 280 °C are slightly above those of 320 °C (Figure 4a). The placement rate of 18 m/min is an exception, where no difference in stiffness is found. At each of the processing temperatures, the Young's moduli show no dependency on the placement rate. With the strengths displayed in Figure 4b, the independence of the strengths to the placement rate is demonstrated, with an exception at a rate of 9 m/min at 320 °C processing temperature. The lower processing temperature of 280 °C generally results in higher strengths. For comparison, the same material processed in the press process has resulted in a Young's modulus of 6.08 MPa and a strength of 32.55 MPa [22]. It is obvious that the dry carbon fiber filaments of the transverse specimens that are exposed after failure contribute to this reduction (Figure 5). In the press processed specimens, no such dry fibers were found [22]. Other effects that reduce the AFPisc mechanical performances, such as internal residual stresses, insufficient layer bonding, degree of crystallinity and fiber undulations require further analysis to allow a precise differentiation. A comparison to the matrix dominated compression shear test (Figure 2) reveals a similar trend of the correlation of the processing parameters.



(a) (b)

Figure 4: Tensile test results transverse to the fiber direction at different placement rates and processing temperatures at the nip point with the Young's moduli (a) and strengths (b).

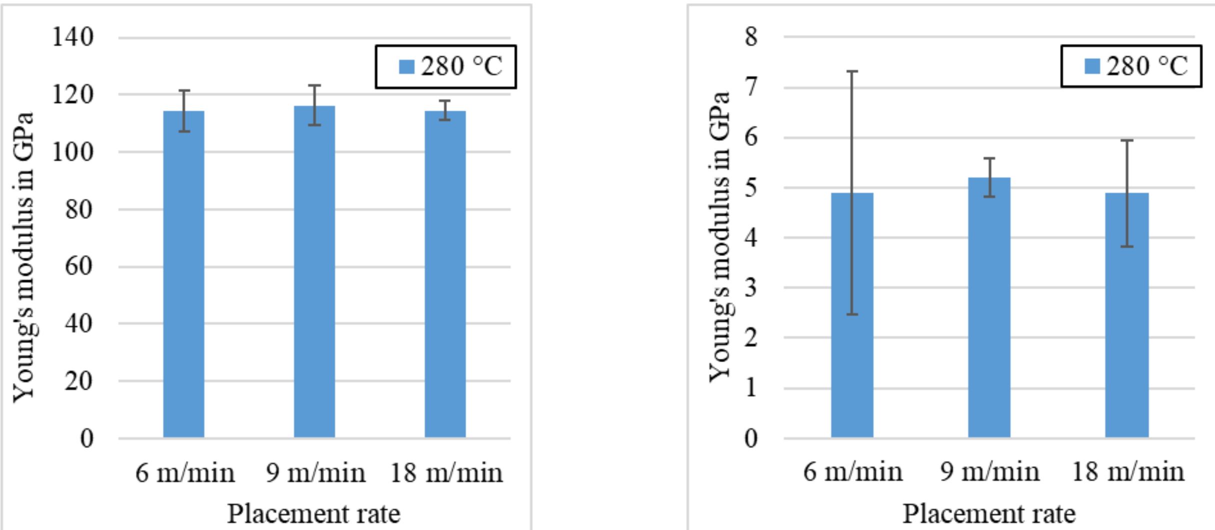
Summing up these results demonstrates that although the wedge peel tests shows no indication of a reduction of the mechanical performance in [15], [21] at the chosen parameters of this work, a higher processing temperature reduces the mechanical performances of matrix dominated tests (compression shear and transverse tensile). In fiber direction, the Young's modulus is increased using the nip point temperature of 320 °C without a pronounced increase in strength. The placement rate at 9 m/min at a nip point temperature of 280 °C results in the highest strength in fiber direction. Considering the sample size of 5 specimens of every series, the decrease at a rate of 18 m/min is of minor significance. It is therefore suggested to use a nip point temperature of 280 °C. The influence of the placement rate is of minor importance in contrast to the processing temperature. The transverse tensile properties remain insufficient in comparison in the press benchmark process. An improvement of this parametric study with the chosen parameter conditions results in no substantial increase of the mechanical performance.

Figure 5: Failure of a transverse tensile specimens reveal dry carbon filaments

3.3 Split disk tests

The results of the parametric study of the split disk tests are shown in Figures 6 a and b. In accordance with the tensile tests, no influence on the placement rate is found. The tests in and transverse to the fiber reveal an increase in stiffness in comparison to the tensile tests of the flat specimens. This increase cannot be entirely related to the effect of the translation into consolidation force of the tape tension in the winding process, since the production of the transverse split disk specimens can be considered as tape laying processes of 0° layers, whereas the quasi 90° (circa 89°) specimens in the winding process are the tensile specimens in fiber direction. One major advantage of the approach of using a stable polymer base is the dimensional stability, which is also present in the winding process that compensates residual strains from its rotationally symmetric geometry. Another reason for this increase could potentially be the friction between the specimen and the grease covered fixture, which cannot be fully eliminated, although no non-linear effects in the stress-strain behavior or stick-slip effects were observed. In addition, all tests revealed dry carbon filaments in the fracture pattern after failure of the specimens. A further increase of the mechanical properties, which do not contain dry filaments, is yet to be determined, but is likely that it improves the properties.

The determination of strength is not performed in this analysis due to the presence of the superimposed bending moment and tensile stress of the specimens in the gap between the two disks, which reduces the failure strains significantly. To determine strength, a modification of the specimen is suggested. This modification consists of a dog-bone-shaped notch as weakest point with enough offset to the gap of the disks. The length of the notch with a reduced width should enable constant stress distribution throughout the cross section. An alternative is a reduction of the thickness of the specimen at this section by machining, to create a region of defined failure.



(a) (b)

Figure 6: Young’s moduli of the split disk test and different placement rates at a processing temperature of 280 °C, parallel (a) and transverse (b) to the fiber.

4 CONCLUSIONS

A parametric study of the AFPisc processing parameters placement rate and consolidation temperature using CF/PA6 material was performed. A correlation of processing parameters and mechanical performance was revealed on both of the compression shear and transverse tensile test. A transfer of these matrix dominated tests to the fiber dominated tensile test in fiber direction indicates opposing results with a higher stiffness at the higher processing temperature and the strength independent on the investigated temperatures. No distinct influence on the placement rate with the mechanical performance was found in either the matrix or the fiber dominated tests. Based on this analysis, a processing temperature of 280 °C and a placement rate of 18 m/min is suggested if the reduction of the tensile stiffness in fiber direction at this temperature can be accepted. A placement rate where the mechanical properties are significantly reduced, and whether this reduction can be overcome with an increase of processing temperature are yet to be determined. The split disk tests have improved the Young's moduli. A clear distinction between the mechanical performances of winding processes and tape laying cannot be made in this experimental design, since the transverse tensile specimen relates to a 0° tape laying on a tube, but increases the stiffness compared to the flat specimens. However, the properties maintain below press processed references. It is obvious that improving tape quality without the presence of dry carbon fiber filaments should be addressed in the future in further analyses.

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REFERENCES

[1] R. Engelhardt, S. Ehard, T. Wolf, J. Oelhafen, A. Kollmannsberger, and K. Drechsler, "In Situ Joining of Unidirectional Tapes on Long Fiber Reinforced Thermoplastic Structures by Thermoplastic Automated Fiber Placement for Scientific Sounding Rocket Applications," *Procedia CIRP*, vol. 85, pp. 189–194, Jan. 2019, doi: 10.1016/j.procir.2019.09.015.

[2] S. C. Mantell, Qiuling Wang, and G. S. Springer, "Processing Thermoplastic Composites in a Press and by Tape Laying—Experimental Results," *Journal of Composite Materials*, vol. 26, no. 16, pp. 2378–2401, Jan. 1992, doi: 10.1177/002199839202601603.

[3] R. Schledjewski and A. K. Schlarb, "Processing window of CF/PEEK for in-situ consolidation," presented at the SAMPE Europe International Conference, Paris, France, 2007.

[4] E. Oromiehie, A. K. Gain, and B. G. Prusty, "Processing parameter optimisation for automated fibre placement (AFP) manufactured thermoplastic composites," *Composite Structures*, vol. 272, p. 114223, Sep. 2021, doi: 10.1016/j.compstruct.2021.114223.

[5] Z. Qureshi, T. Swait, R. Scaife, and H. M. El-Dessouky, "In situ consolidation of thermoplastic prepreg tape using automated tape placement technology: Potential and possibilities," *Composites Part B: Engineering*, vol. 66, pp. 255–267, Nov. 2014, doi: 10.1016/j.compositesb.2014.05.025.

[6] C. M. Stokes-Griffin and P. Compston, "The effect of processing temperature and placement rate on the short beam strength of carbon fibre–PEEK manufactured using a laser tape placement process," *Composites Part A: Applied Science and Manufacturing*, vol. 78, pp. 274–283, Nov. 2015, doi: 10.1016/j.compositesa.2015.08.008.

[7] C. M. Stokes-Griffin, A. Kollmannsberger, P. Compston, and K. Drechsler, "The effect of processing temperature on wedge peel strength of CF/PA 6 laminates manufactured in a laser tape placement process," *Composites Part A: Applied Science and Manufacturing*, vol. 121, pp. 84–91, Jun. 2019, doi: 10.1016/j.compositesa.2019.02.011.

[8] P. Dreher, A. R. Chadwick, and S. Nowotny, "SAMPE Europe Conference 2019 Nantes - France," p. 13.

[9] I. Schiel, L. Raps, A. R. Chadwick, I. Schmidt, M. Simone, and S. Nowotny, "An investigation of in-situ AFP process parameters using CF/LM-PAEK," *Advanced Manufacturing: Polymer & Composites Science*, vol. 6, no. 4, pp. 191–197, Oct. 2020, doi: 10.1080/20550340.2020.1826772.

[10] A. Khudiakova, A. J. Brunner, M. Wolfahrt, T. Wettemann, D. Godec, and G. Pinter, "On the investigation of quasi-static crack resistance of thermoplastic tape layered composites with multiple delaminations: Approaches for quantification," *Composites Part A: Applied Science and Manufacturing*, vol. 149, p. 106484, Oct. 2021, doi: 10.1016/j.compositesa.2021.106484.

[11] W. J. B. Grouve, L. L. Warnet, B. Rietman, and R. Akkerman, “On the weld strength of in situ tape placed reinforcements on weave reinforced structures,” *Composites Part A: Applied Science and Manufacturing*, vol. 43, no. 9, pp. 1530–1536, Sep. 2012, doi: 10.1016/j.compositesa.2012.04.010.
[12] M. A. Khan, “Experimental and simulative description of the thermoplastic tape placement process with online consolidation,” Institut für Verbundwerkstoffe, Kaiserslautern, 2010.
[13] B. K. Fink, J. W. Gillespie Jr, and N. B. Ersoy, “Thermal Degradation Effects on Consolidation and Bonding in the Thermoplastic Fiber-Placement Process,” Army Research Laboratory, Adelphi, MD, USA, Technical report ARL-TR-2238, 2000. Accessed: Mar. 10, 2023. [Online]. Available: https://apps.dtic.mil/sti/citations/ADA379718
[14] V. Zinnecker, V. Backmann, C. Stokes-Griffin, and K. Drechsler, “Laser-assisted thermoplastic tape placement: Effects of the consolidation roller diameter on the wedge peel strength of CF/PA6,” presented at the Sampe Europe Conference, Amsterdam, Netherlands, 2020.
[15] V. Zinnecker, C. M. Stokes-Griffin, and P. Compston, “Laser-assisted thermoplastic tape placement: Effects of thermal history and placement speed on wedge peel strength of CF/PA6,” in *International Conference on Composite Materials (ICCM22)*, Melbourne, Australia, 2019.
[16] H. Wittich, M. Evstatiev, E. Bozwelieva, K. Friedrich, and S. Fakirov, “Effect of crystallinity on the interlaminar fracture toughness of continuous glass fiber-polyamide composites,” *Advanced Composite Materials*, vol. 2, no. 2, pp. 135–152, Jan. 1992, doi: 10.1163/156855192X00161.
[17] A. J. Comer *et al.*, “Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave,” *Composites Part A: Applied Science and Manufacturing*, vol. 69, pp. 10–20, Feb. 2015, doi: 10.1016/j.compositesa.2014.10.003.
[18] P. M. Schäfer, “Consolidation of carbon fiber reinforced Polyamide 6 tapes using laser-assisted tape placement,” Technical University of Munich, München, 2018.
[19] M. A. Lamontia, M. B. Gruber, A. Systems, S. Drive, J. Tierney, and J. W. Gillespie, “Modeling the Accudyne Thermoplastic In Situ ATP Process,” in *SAMPE conference*, Paris, France, 2009.
[20] A. R. Chadwick, K. Kotzur, and S. Nowotny, “Moderation of thermoplastic composite crystallinity and mechanical properties through in situ manufacturing and post-manufacturing tempering: Part 1 – Mechanical characterisation,” *Composites Part A: Applied Science and Manufacturing*, vol. 143, p. 106286, Apr. 2021, doi: 10.1016/j.compositesa.2021.106286.
[21] C. M. Stokes-Griffin, A. Kollmannsberger, P. Compston, and K. Drechsler, “The effect of processing temperature on wedge peel strength of CF/PA 6 laminates manufactured in a laser tape placement process,” *Composites Part A: Applied Science and Manufacturing*, vol. 121, pp. 84–91, Jun. 2019, doi: 10.1016/j.compositesa.2019.02.011.
[22] Marina Plöckl, “Effect of Strain Rate on the Tensile, Compressive, and Shear Response of Carbon-Fiber-Reinforced Thermoplastic Composites,” Technical University of Munich, Munich, 2019.