

Thermocouple based process optimization for laser assisted automated fiber placement of CF/LM-PAEK

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Lars Brandt , Dominik Deden, Jonas Harig, Frederic Fischer and Michael Kupke

Abstract

Self-commitments and increasing legal requirements lead to the compulsion to reduce carbon dioxide emissions in commercial aerospace. One viable approach is the reduction of structural mass, that would reduce emissions for every flight. This is especially true for high cadence single aisle aircrafts. However, high quantities are required in this segment. To achieve these goals the newly developed low-melt Poly-Aryl-Ether-Ketone (LM-PAEK), a high-performance carbon fiber-reinforced thermoplastic composite was chosen to build a full-scale multi-functional fuselage demonstrator (MFFD) in order to develop an automated process that shows these savings. Single-step automated Fiber Placement (AFP) with in-situ consolidation offers distinct advantages in this field with its short curing times and especially by eliminating high amounts of waste otherwise caused by vacuum bagging and related tasks for post-consolidation in an autoclave. In order to ready this technology for future aircraft production this paper demonstrates how the processing window for LM-PAEK tape (TC1225) provided by TORAY was established. By closely linking robot and end-effector data with positionally accurate thermocouple measurements, the determined mechanical properties at coupon level and micro-sections of the manufactured specimens can be precisely correlated. This holistic approach is independent of the placement equipment and may enable global comparability within the community working in the field of thermoplastic AFP. In conclusion the procedure is evaluated and possible simplifications are discussed.

Keywords

carbon fiber reinforced plastics, thermoplastic automated fiber placement, process optimization, mechanical properties, carbon fiber/low melt polyaryletherketone

Introduction

To date, most commercial aircrafts utilizing composites rely on thermoset technology where manufacturing processes are robust and fully industrialized. Short and medium range single-aisle aircrafts are largely made of aluminum as the weight advantage of composites during operations so far could not compensate for the additional material costs during production. In light of the climate change, Europe introduced its Green Deal and the target to reduce its CO₂ emission to at least 50% (compared to 1990 levels) by 2030.¹ To meet the goals for sustainable aviation, lightweight solutions will play a key role as the greatest potential for CO₂ reduction lays within the service time. For new, rapidly developing aviation programs carbon fiber-reinforced thermoplastics offer distinct advantages with unlimited shelf life, out-of-autoclave processing, short cycle times, weldability and recyclability. Thermoplastic Automated Fiber Placement (T-AFP) without post-consolidation

could largely reduce lead time and recurring cost for vacuum bagging and thus be an enabler for a broader use of CFRPs in aircraft components. An important aspect of the industrialization of T-AFP is the definition of optimal process parameters for a given material. The operational point for a specific material should be independent from the used machinery and thus solely rely on the most important process variables which ultimately define the laminate quality: temperature, pressure and layup velocity. In the

Center for Lightweight Production Technology (ZLP), German Aerospace Center (DLR), Augsburg, Germany

Corresponding author:

Lars Brandt, Center for Lightweight Production Technology (ZLP), German Aerospace Center (DLR), Am Technologiezentrum 4, Augsburg 86152, Germany.
Email: lars.brandt@dlr.de

Data Availability Statement included at the end of the article

following, a holistic approach for the determination of process parameters is investigated which uses the information of externally measured temperatures from various points and depth of a T-AFP laminate in combination with the overlaying position of the machine. The generated data gives information on the internal processes of the T-AFP and is used to generate optimal process parameters.

State of the art

Experimental work to find process parameters usually rely on trial and error approaches. Qureshi et al. manufactured CF/PEEK rings and laminates to analyze the correlations between process parameters and mechanical properties. Main focus of the work was a hot gas system, however an ILSS value of 78.9 MPa (85% of the autoclave baseline) is given for a sample manufactured with laser heating.²

Comer et al. compared CF/PEEK laminates produced by laser assisted T-AFP with an autoclave reference. Mechanical properties were determined by interlaminar shear strength (ILSS), open hole compression (OHC) and wedge peel testing. Via a small trial series process parameters with varying layup speeds (8–12 m/min), mold temperatures (20–250°C) at a constant target temperature of 420°C were identified. Although these values have not been refined, the AFP laminate reached ILSS values of 70%, Interlaminar toughness of 134% flexural strength of 68%, flexural stiffness of 88% and OHC strength of 78%.³

Francesco et al. evaluated the interlaminar shear strength of CF/PEEK over different layup velocities. They found that higher rates lead to reduced mechanical performance. The highest ILSS value was measured at a lay down rate of 200 mm/s with 40.0 MPa.⁴

Stokes-Griffin and Compston varied process set temperature (400–600°C) and layup velocity (6 and 24 m/min) and compared ILSS values for CF/PEEK laminates. Temperature gradients have been predicted by a process model, likely because measurements are delicate at higher temperatures. ILSS values to the benchmark values were comparable for both 6 and 24 m/min at set point temperatures above 550°C.⁵

Samak et al. investigated the influence of embedded defects such as gaps and overlaps. Ring shaped, CF/PEEK samples were manufactured that showed ILSS weakening of approx. 3% for gaps. Highest ILSS values reached are 48.2 MPa, a benchmark value is not provided.⁶

Saenz-Castillo et al. compared several out-of-autoclave processes for CF/PEEK. For laser-assisted AFP an ILSS of 71 MPa was found which compares to 65% of a hot press laminate.⁷

The effects of process parameter variation on mechanical properties for CF/PPS has been investigated by Zhao et al. Set point temperature was varied between 280–380°C at 3.6–12 m/min layup speed. Additionally, tool temperature

was altered between 40 and 120°C and compaction force between 500–2000 N. Nine laminates were manufactured and morphology, voids, crystallinity and ILSS were evaluated. Highest crystallinity was reached with 46% at tooling temperature of 120°C. The latter sufficiently prevented cold crystallization. Results showed that better resin distribution and lower void content was reached at higher compaction pressures and laser temperatures. Consolidation force and layup velocity were identified as main quality factors in this work.⁸

Chen et al. investigated the influence of process parameters with respect to the crystallinity and void content. They found that interlaminar void content dominated the mechanical properties. The ILSS value for CF/PPS is 49.2 MPa which is approximately 75% of the autoclave treated laminate.⁹

Chadwick et al. complemented the research on CF/PPS by identifying the correlation between heated tooling and tempering for a given set of process parameters. They showed that ILSS and transverse tensile stresses improve at tooling temperatures up to 250°C and that tempering can improve matrix tensile strength for laminates with a homogeneous morphology.¹⁰

Raps et al. have published work on CF/LM-PAEK AFP, where they evaluated the process parameters using a cubic design of experiments. Set point temperature was varied between 350–470°C, placement velocity between 1 and 15 m/min, compaction pressure between 2 and 6 bar and tooling temperature between 20 and 250°C. Instead of laminates, specially developed specimen were produced by placing four layers of 1/2" UD tows. Their single lap shear strength was measured subsequently. The simplified specimen were used in order to reduce the overall effort and test a statistically significant amount of specimen. It was found that the heated tooling increased bonding strength and crystallinity. A higher nip point temperature led to an increased bonding strength whereas the consolidation force demonstrated no greater influence within the measurement processing window. Also, CF/LM-PAEK showed no dependency between layup velocity and bonding strength which was attributed to the low melt viscosity of the matrix.¹¹

Table 1 provides a summary of all mechanical properties identified by the studies above. This reference shows that process parameters are commonly varied arbitrarily within the settings range of the available layup machine setup. This leads to a high dependency between the hardware, the process parameters and the laminate quality even if laser assisted AFP is the only considered process. In addition, temperature controllers are commonly fed with data generated by infrared camera sensors. They highly depend on a correctly adjusted emissivity which is influenced by optical properties of the material, the temperature and the angle of measurement.

Table 1. ILSS and tensile mechanical values for NIR-laser assisted AFP.

Material	FAW	Mechanical Property	Measurement method	max. Value AFP		
	[g/m ²]			[MPa]	Reference value ^a	Reference
AS4/PEEK	146	ILSS	ASTMD2344	78.9	85%	2
	143	ILSS	ASTMD2344	~ 98.0	103%	5
	145	ILSS	ASTMD5868	40.0	67%	4
	150	ILSS	ASTMD2344	48.2	—	6
	145	ILSS	EN2563	71.0	65%	7
IM7/PEEK	150	ILSS	EN2563	78.0	70%	3
T700/PAEK	194	ILSS	Single lap shear	33.6	—	11
CF/PPS ^b	150	ILSS	ASTMD2344	49.2	~ 75 %	9
	150	ILSS	ASTMD3846	62.3	—	8
AS7/PPS	185	ILSS	ISO 14130	72.7	—	10
		Perpendicular tensile	EN2597	36.0	—	

^aAutoclave/Hot-Press.

^bFiber unspecified.

~ derived from chart.

In this study a thermocouple-based optimization method is proposed which will allow for a machine and emissivity independent process parameter identification. The process is explained and validated on CF/LM-PAEK laminates and optimal parameters for the material are identified.

Experimental setup

The material, provided by Toray Advanced Composites, is a T700 carbon fiber reinforced Poly-Aryl-Ether-Ketone with low melting temperature of 305°C (TC1225 PAEK, fiber areal weight 194 gsm).

The AFP equipment used in this study comprises a KUKA industrial robot KR120 with a layup head by AFPT (multi tow laying head, MTLH) for the deposition of 3 × 1/2" tapes. The system includes a closed loop control with an infrared camera as nip point sensor. As heat source a Laserline LDM 6000 infrared diode laser with a wavelength spectrum of 980–1040 μ m is used.

A minimal invasive thermocouple sensor setup was developed to decrease measurement errors. Thermocouples Type K with a diameter of 20 μ m are wrapped with a neat LM-PAEK foil for isolation of the wires against the carbon fibers. Hereby the welded tip of the thermocouples is left outside the isolation to directly measure the temperature on the laminate. The isolated thermocouple is spot-welded with a BRANSON 2000 LPe: 40:0.50.4T ultrasonic generator and a 5 mm horn, to the composite layer at defined positions. All data is recorded by a HIOKI-LR8400 with a frequency of 100 Hz which is crucial to evaluate all relevant heat conduction effects at high layup speeds. Usually localization of the measurement is done relatively, measuring either the layup time or using the maximum temperature. In this

paper the position is tracked using a digital encoder to ensure a precise localization of the temperature data.

The three CFRP tapes are placed simultaneously with constant laser power and thermocouples are subsequently welded onto the fifth layer to rule out tooling effects, i.e., to assure a minimum heat dissipation through the substrate to the tool. The setup is depicted in Figure 1, the placed tapes have a total length of 600 mm. The thermocouples are placed at a distance of 40 mm (in layup direction) to each other. They are placed in an area of the track where no run-in effects, such as acceleration of the machine, are expected. Layup velocity is held constant at 7.5 m/min at first and measurements are conducted while the sixth layer is placed. All trials were performed with a constant consolidation pressure of 6 bars. Pretrials with power levels ranging from 2300 to 3000 W were used to identify the evaluated power levels of 2300, 2450 and 2600 W. For these power levels the temperature profiles are detailed by additional thermocouple measurements subsequently.

The closed loop system is fed with the nip point temperature measured by the infrared camera. It is not adjusted to the temperature dependent emissivity of the material, but instead uses a constant emissivity of 1.0. Thus, the temperature is overestimated systematically. To translate the constant power levels into control temperatures, layup with constant power levels are repeated without deployment of thermocouples to prevent interferences. The data from the thermal cam is then analyzed to determine an average set point temperature in the constant range of the layup for each power level for eight consecutive layers each.

Once set point temperatures are determined, the closed loop control allows to keep the temperature constant for changing layup velocities. To reduce the test laminates needed, the experimental procedure is conducted as follows:

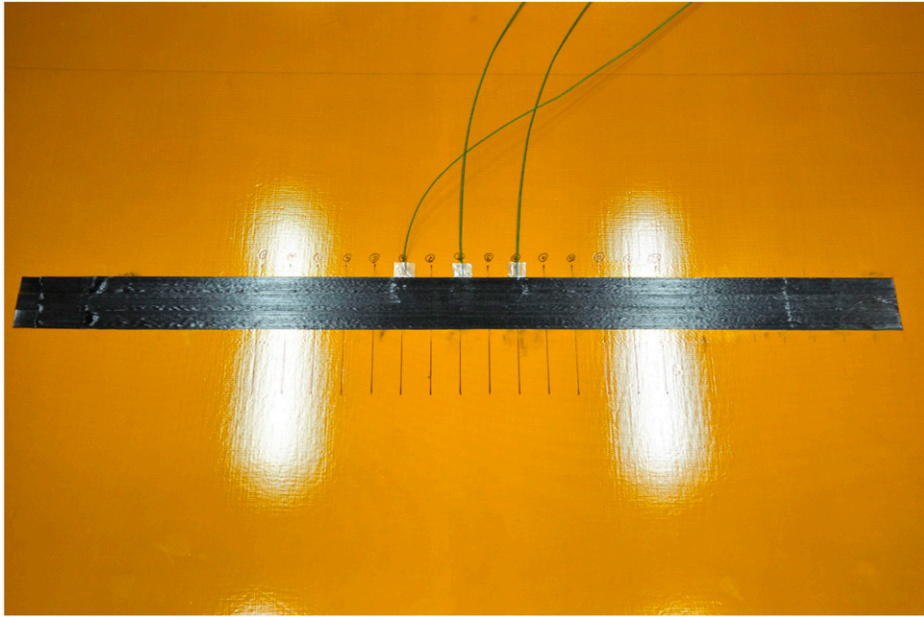


Figure 1. Three type K thermocouples in a distance of 40 mm atop the fifth placed 600 mm long UD-layer.

first the superior processing temperature is examined by manufacturing of three laminates with the corresponding set point temperatures and a constant layup rate of 7.5 m/min which has been identified as a suitable processing speed for placement on unheated molds with regards to mechanical performance by Dreher et al.¹² They are tested and benchmarked with mechanical and thermoanalytical testing and microsections.

In addition, laminates are manufactured at higher velocities of 15 m/min and 24 m/min as well as lower velocities of 1.5 m/min and 4.5 m/min. These specimen are tested accordingly to investigate the impact of the velocity on the process.

Mechanical characterization is conducted via ILSS tests and backed up by tensile strength tests perpendicular to the fiber orientation. All specimen are compared to a benchmark T-AFP laminate that is post-processed with a hot press. For the ILSS testing short beam strength test specimen are produced according to DIN EN 2564. Perpendicular tensile strength is tested applying DIN EN 2597 with test specimen type B. Both tests were conducted on a universal ZwickRoell 50 kN testing machine. Additionally, microsections are prepared to give a visual impression of fiber matrix distribution.

Crystallinity was determined by differential scanning calorimetry (DSC) conducted on a Netzsch DSC 214 Polyma. Five equal specimen for each set of processing parameters were measured at a heating rate of 10 K/min to the maximum temperature of 350°C, then held isothermal for 3 min, and cooled down with a rate of 10 K/min. Each specimen underwent a second consecutive heating cycle

which would lead to an increase of crystallinity given by the reduced cooling rate as compared to the quenching during the actual fiber placement process. The crystallinity X_c is derived from the differing heat flows between sample and reference (i.e., an empty crucible), and calculated from the area below the enthalpy curve during crystallization and melting. The equation is given by:

$$X_c(\%) = \frac{|\Delta H_m| - |\Delta H_c|}{\Delta H_{ref}(1 - w_f)} \quad (1)$$

with a reference (maximum) enthalpy ΔH_{ref} of 130 J/g, and a fiber weight fraction of about 67%.

For the evaluation of the melt peak area, i.e., the melt enthalpic the limits were set to 255°C and 330°C with a linear baseline.

Results

Power levels

Figure 2 shows the mean temperature profiles for all three power levels investigated. For every power level eight measurements were taken into account to compensate for variances in measurements. The melting point for LM-PAEK is at 305°C (indicated as red dotted line) and glass transition temperature is 147°C. The black dashed lines resemble the surface area covered by the conformable, silicone rubber. All three power levels were selected in a way that the corresponding temperature is below T_m after the consolidation roller (T_{Cons}). In the nip point mean

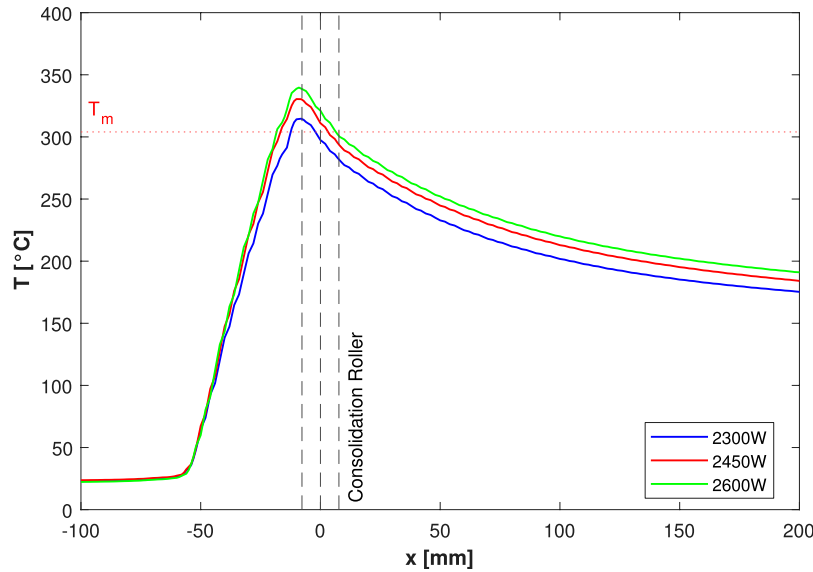


Figure 2. Mean temperature profiles for 2300 W, 2450 W and 2600 W laser power.

temperatures (T_{NP}) vary between 314 and 339°C. Table 2 gives an overview of the measured temperature before and after the consolidation roller at the three power levels.

Temperature profiles show that an power increase in steps of 150 W does not lead to an equidistant increase of the temperature levels. This can partially be attributed to the fact that the absorption of laser radiation by the tape itself is temperature dependent and non-linear. Further, the heat dissipation is expected to increase with higher temperature gradients. Finally, the measured temperatures are prone to a certain measurement error given by the accuracy of the thermocouples. Nevertheless, the three parameter sets do cover a broad range of possible profiles, where the maximum temperature has to be above melting temperature and below it after the consolidation roller. For these power levels temperature set points were identified in consecutive layups. The corresponding temperatures are also listed in Table 2 labeled as T_{SP} for comparison.

Interlaminar shear strength

All ILSS measurements showed plastic deformation and no single or multiple shear failure. Due to this failure mode the results in Table 3 have to be interpreted qualitatively. Nevertheless, the results can be used for comparison within the herein described entire test series. Plastic deformation of the test specimen showed no decline in the applied forces thus two tangents are used for evaluation. Figure 3 shows an example evaluation with two tangents to separate elastic and plastic deformation. A robust value was used for the comparative evaluation using the intersection of the two tangents fitted on the elastic and plastic section of the graph,

Table 2. Power levels and resulting nip point and residual heat.

Power level	T_{NP}	T_{Cons}	T_{SP}
[W]	[°C]	[°C]	[°C]
2300	314	282	465
2450	330	294	500
2600	339	301	525

τ_S is the measurement value at this intersection point. In total ten specimen were tested for each parameter set.

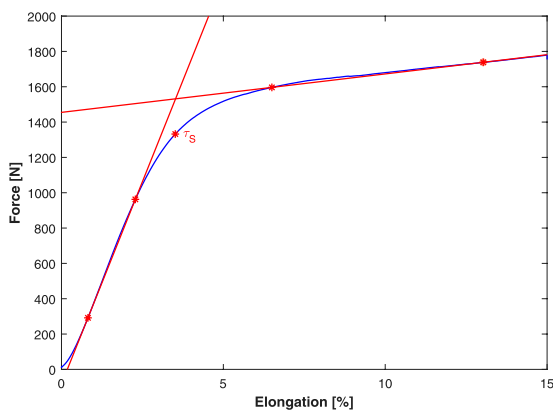
For the variation of the temperature set point, the highest values for τ_S are reached at 500°C and 525°C. For both shear strength is 67% compared to the benchmark. The lowest values are reached for a set point temperature of 465°C. The standard deviation of the tested ILSS samples is generally low at 1.2 MPa or below. Based on the overall mechanical performance the constant set point temperature of 500°C was selected for the layup velocity variation. It can be observed that ILSS values drop with increasing layup speed. For 15 m/min and 24 m/min a shear strength of 60% and 52% respectively is reached, compared to the benchmark. Thus ILSS values indicate a decrease in mechanical performance for higher process speeds. Lower layup speeds of 1.5 m/s and 4.5 m/s however measured at 72% and 69% shear strength of the benchmark, which is above the 7.5 m/s results.

Perpendicular tensile strength

First the test specimen placed at different set temperatures were tested. From each set at least ten specimens failed

Table 3. ILSS results.

v_{Layup} [m/min]	T_{SP} [°C]	τ_s [MPa]	Standard deviation [MPa]	τ_s compared to benchmark [%]
1.5	500	52.3	0.6	72
4.5	500	49.8	1.1	69
7.5	465	47.0	1.1	65
7.5	500	48.4	1.1	67
7.5	525	48.2	1.2	67
15	500	43.7	0.9	60
24	500	37.8	0.9	52
Benchmark (hot press)	—	72.7	0.8	—

**Figure 3.** Example evaluation ILSS for $v_{Layup} = 15$ m/min and $T_{SP} = 500^\circ\text{C}$.

according to the norm. The mean of the valid test specimen is displayed in Table 4. There is a significant difference in the ultimate tensile strength for samples placed at 7.5 m/s with the highest value of 36.3 MPa at a set point temperature of 500°C . Set Point temperatures of 465°C and 525°C reach 30.3 MPa and 32.0 MPa respectively. Besides the best mechanical strength the standard deviation of these specimen was lowest at 3.4 MPa for the 500°C set point compared to 4.5 MPa at 465°C and 7.1 MPa at 525°C .

Furthermore, variation of the layup velocity shows that the overall highest tensile strength of 37.4 MPa was reached with a medium layup velocity of 1.5 m/min with a standard deviation of 3.9 MPa. However, considering the standard deviation, this value is on the same level as values generated at 7.5 m/min. Specimens placed at 4.5 m/min have similar strength with a better standard deviation. This indicates a plateau in mechanical strength for lay-up speeds at this set point temperature before it drops for layup speeds of 15 m/min or higher. Higher layup velocities result in a severe drop in tensile strengths of 27.7 MPa and 13.2 MPa for 15 m/min and 24 m/min respectively. The standard deviation at

increased layup speeds was measured at 4.3 MPa for 15 m/min and 2.3 MPa at 24 m/min.

Micrographs

The following micrographs exhibit the cross-sections of the UD-samples produced at different processing conditions. The images were produced with a Keyence VHX 5000 digital microscope on a VH-Z250T objective with $\times 250$ magnification. An area of approximately $11\text{ mm} \times 3\text{ mm}$ was scanned and automatically stitched to show an overall panorama. From these panoramas a representative section was chosen. In general, the 12 layers of each sample remain distinguishable to the human eye. Dark spots are associated to intra- and interlaminar voids.

Figure 4(a) shows the reference sample of a post-consolidated T-AFP laminate hot press molded according to the processing instructions by TORAY. The processing conditions are confidential; however, it may be stated that the material is obviously consolidated at far higher pressures, with a longer dwell time and at reduced cooling rates as compared to in-situ consolidation. Thus, the resulting sample thickness of $2020\ \mu\text{m}$ (or $\sim 168\ \mu\text{m}$ consolidate ply thickness) is significantly lower as compared to the other laminates. This sample is without visible voids. However, regions with low fiber content are to be found, especially at the interfaces between adjacent layers. The fiber-volume content thus varies noticeably.

The samples produced at 7.5 m/min each with varying set point temperature all exhibit a comparable amount of intra- and interlaminar voids (refer to Figure 4(b)–(d)). The thickness of samples are given in Table 5. The expected thickness according to the consolidated tape width given from the product data sheet would implicate a thickness of $2208\ \mu\text{m}$, i.e., a consolidated ply thickness of $184\ \mu\text{m}$. Increasing layup velocity results in growing ply thicknesses. The largest ply thickness can be observed for the highest layup velocity.

Table 4. Perpendicular tensile strength results.

v_{Layup}	T_{SP}	Tensile strength	Standard deviation	Comparison to benchmark
[m/min]	[°C]	[MPa]	[MPa]	[%]
1.5	500	37.4	3.9	44
4.5	500	37.3	2.3	44
7.5	465	30.3	4.5	36
7.5	500	36.3	3.4	43
7.5	525	32.0	7.1	38
15	500	27.7	4.3	33
24	500	13.2	2.3	16
Benchmark (hot press)	—	85	3.6	—

The as-delivered tape shows a significant amount of intrinsic pores, thickness variation and frequently areas were fibers at the tow surface are not impregnated with matrix (Figure 5).

The input tape quality in term of thickness tolerances translates into local waviness that accumulates and shows at the sample surface. The same is true for dry areas at the tow surface which will lead to interlaminar voids as no flow of thermoplastic matrix across the interface is possible. Finally, intralaminar voids are merely compressed during the consolidation, i.e., as long as pressure is applied through the compaction roller. Hence, at increased processing velocities where through-thickness heating of the tape is limited the voids and pores of the as-delivered tow material remain largely unaffected as matrix flow is limited. This effect is especially visible on the sample produced at 24 m/min where the amount of pores is noticeably higher compared to the samples produced at lower speeds.

Differential scanning calorimetry

For each sample produced at defined processing parameters DSC entropy curves were recorded, the resulting values are gathered in Table 6.

At a constant processing velocity of 7.5 m/min a maximum crystallinity of 14.8% is reached at the highest temperature of 525°C. This may be attributed to the fact, that crystallization is promoted with laminate temperatures being above 220°C comparably longest during cool down (see green temperature curve Figure 2). Varying the processing velocity from 1.5 m/min to 24 m/min and keeping the processing temperature constant at 500°C shows no trend in the degree of crystallinity, with an average of 10.9 ± 0.7 over all five process speeds.

Averaging all specimen, a maximum, and reference crystallinity of approximately 24.5% with a standard deviation of 1.0% is reached after the samples are heated and cooled again.

Discussion

The results show that perpendicular tensile and interlaminar shear strength are on a comparable level for process speeds below 7.5 m/min at a set-point temperature of 500°C measured by the infrared camera of the layup end-effector. This plateau drops significantly for higher processing speeds. This was especially severe in the results of the perpendicular tensile strength. The operational set point translates into temperatures measured with thermocouples of 330°C at the nip point right in front of the compaction roller and 294°C behind it. Cool down beneath the consolidation roller to below the melting point of the material is thus achieved.

With these parameters a knock-down to 67% in ILSS and 43% in tensile strength were found compared to the hot pressed benchmark laminate. The mechanical performance values decrease with higher layup speeds. ILSS testing - the standard designed for thermoset composites - renders failure modes typical to the more ductile thermoplastic matrix composite. According to the norm, the values can thus only be used for comparison within this dedicated test series. Laminate quality, inspected via microsections, identified voids in interlaminar regions. A comparison with the as-delivered prepreg material showed that the tape surface is partially dry, i.e., without sufficient matrix to cover the single fibers. These dry areas cannot be filled during the highly transient process of in-situ consolidation where matrix flow is limited. Conclusively, areas of low interlaminar bond strength will occur with the investigated tape. It must be noted, that the material itself is still under development at TORAY. With an increase in material readiness level we expect significant improvements of the overall laminate quality. The consolidated ply thickness (CPT) correlates negatively with mechanical properties of the test specimen - the lowest thickness giving highest mechanical results - and may thus serve as an indicator for the degree of consolidation. For the samples produced at high

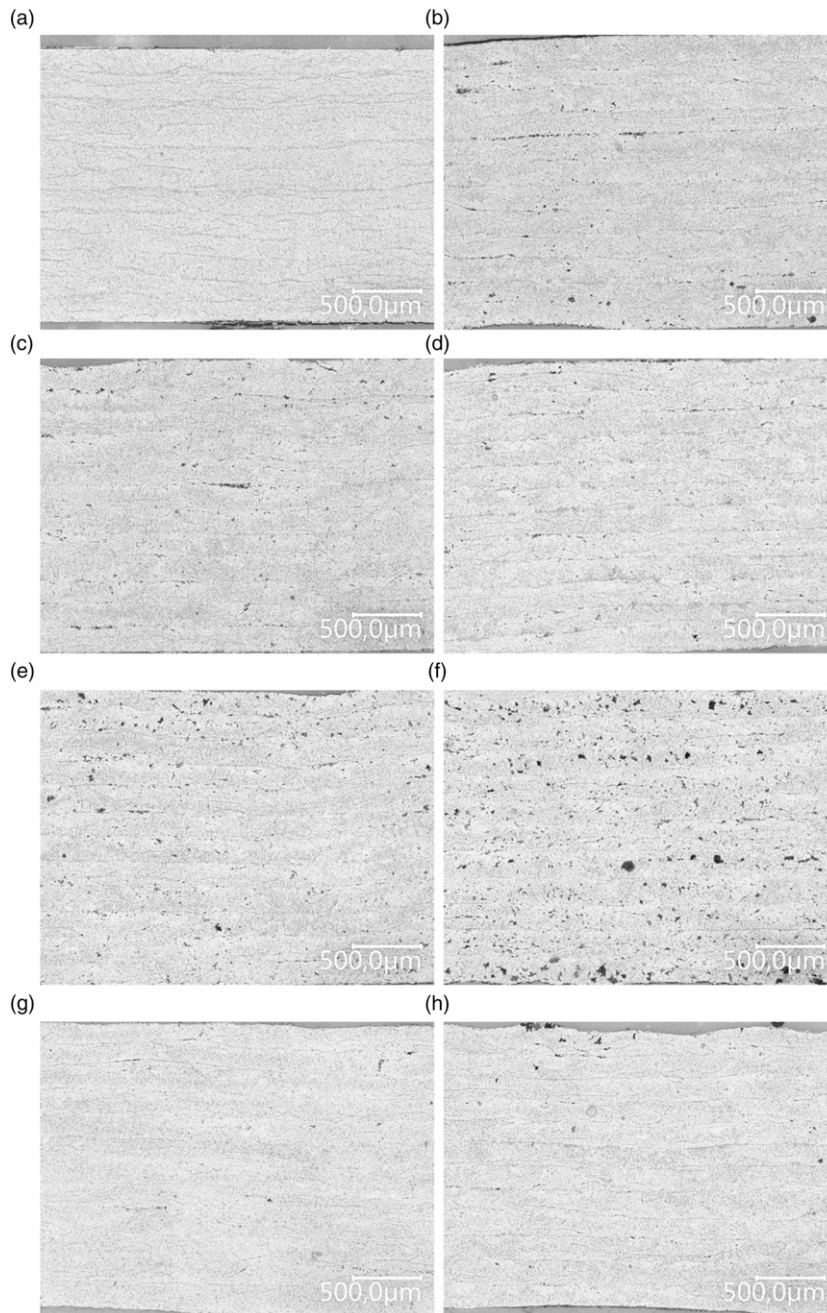


Figure 4. Micrographs cross sections CF/LM-PAEK (a) Hot press benchmark, (b) $v_{Layup} = 7.5$ m/min, $T_{SP} = 465^{\circ}\text{C}$, (c) $v_{Layup} = 7.5$ m/min, $T_{SP} = 500^{\circ}\text{C}$, (d) $v_{Layup} = 7.5$ m/min, $T_{SP} = 525^{\circ}\text{C}$, (e) $v_{Layup} = 15$ m/min, $T_{SP} = 500^{\circ}\text{C}$, (f) $v_{Layup} = 24$ m/min, $T_{SP} = 500^{\circ}\text{C}$, (g) $v_{Layup} = 4.5$ m/min, $T_{SP} = 500^{\circ}\text{C}$, (h) $v_{Layup} = 1.5$ m/min, $T_{SP} = 500^{\circ}\text{C}$.

processing speeds and higher set temperature the CPT can be attributed to the fact, that laminate temperatures just behind the compaction roller are higher which may favor deconsolidation and swelling of pores.

The reached crystallinities indicate a certain independence of the cooling rate within the described processing window, where the tows are quenched from just below the melt temperature to room temperature. Thus for

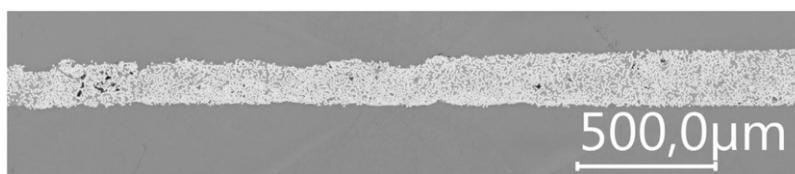
placement speeds of 7.5 m/s and set temperatures of 500°C a crystallinity of 11.8% is reached, i.e., approximately 48% of samples cooled at moderate rates of 10 K/min in the DSC. In order to increase the crystallinity in in-situ consolidation, one may use a heated tooling of 150°C to 200°C to reduce quenching and promote secondary crystallization. It should be noted, however, that such heating has major implication on

Table 5. Thickness laminates.

v_{Layup}	T_{SP}	Laminate thickness	Ply thickness
[m/min]	[°C]	[μ m]	[μ m]
7.5	465	1988 – 2188	174 ± 50
7.5	500	2092 – 2155	177 ± 16
7.5	525	2058 – 2427	187 ± 92
1.5	500	1951 – 2193	173 ± 61
4.5	500	2079 – 2169	177 ± 23
15	500	2063 – 2270	181 ± 52
24	500	2253 – 2409	194 ± 39
Benchmark (hot press)	—	2000 – 2021	168 ± 5

Table 6. DSC results.

v_{Layup}	T_{SP}	X_c	X_{max}
[m/min]	[°C]	[%]	[%]
7.5	465	12.5 ± 0.4	25.2 ± 0.7
7.5	500	11.8 ± 0.6	23.7 ± 1.3
7.5	525	14.8 ± 1.8	26.0 ± 1.1
1.5	500	11.1 ± 2.4	23.6 ± 1.0
4.5	500	10.7 ± 0.8	22.8 ± 0.5
15	500	9.7 ± 0.4	24.0 ± 1.1
24	500	11.1 ± 1.1	25.1 ± 0.9

**Figure 5.** As-delivered tape.

tooling designs and recurring costs during large scale production.

The overall approach of identifying machine independent, process parameters was successful. With this work we have determined a processing window for in-situ consolidation of LM-PAEK. Additionally, the temperatures measured on the laminate during the process are plausible with the determined mechanical performance of the laminates.

Conclusion

Within the examined process window for the carbon fiber-reinforced LM-PAEK the highest mechanical values were reached for placement speeds equal or below of 7.5 m/min and a nip point set temperature of 500°C, which corresponds to 330°C measured with the thermocouples. With regards to production a fast layup is favorable and thus the optimum for this process. Identifying and optimizing process parameters for in-situ consolidation via thermocouples demonstrated to be a sensible approach to configure the T-AFP process for a new LM-PAEK prepreg material. An advantage of this approach is the profound insight into the thermal history of the processed tows. Further, this approach is independent of the placement equipment used and especially the measurement inaccuracy given by the infrared cameras which allows for improved portability between different machines.

The T-AFP in-situ process showed its sensibility to as-delivered prepreg quality. With the material used in this work, which is not optimized for the in-situ process, we

find significant knock-downs for the mechanical properties determined by ILSS and transverse tensile strength when compared to hot press consolidated reference samples. Further investigations will be conducted with tows of resin rich surface and lower fiber volume content to improve matrix flow at the interface between overlaid tapes which should improve interlaminar mechanical performance. In general, it would be beneficial to use the measured temperatures as an input for process simulation and final validation. With a virtual representation of in-situ consolidation usage of embedded sensors might be reduced to a minimum and instant process setup gets feasible.

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Author Contributions

Lars Brandt: Conceptualization, Methodology, Writing – Original draft preparation. Dominik Deden: Conceptualization, Methodology, Writing – Review & Editing. Jonas Harig: Investigation. Frederic Fischer: Funding acquisition, Project administration, Writing – Review & Editing.

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Disclaimer

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

ORCID iD

Lars Brandt  <https://orcid.org/0009-0007-8608-0759>

Data Availability Statement

The authors confirm that the [data](#) supporting the findings of this study are available within the article [and/or] its supplementary materials.

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