THERMOPLASTIC IN SITU FIBER PLACEMENT FOR FUTURE SOLID ROCKET MOTOR CASINGS MANUFACTURING

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ABSTRACT

The main goal of the presented research was to enhance the Thermoplastic Automated Fiber Placement process towards industrial production of aerospace parts. Detailed process and hardware optimization of an *AFPT GmbH* placement head was performed with the main goal to establish a stable, robust process with optimized laminate quality. In situ consolidated laminates showed high mechanical properties with an increase in tensile strength of approximately 20% compared to press-consolidated laminates. Recorded process data highlighted the capability of the closed loop process control and of the hardware components to compensate tolerances of the raw material or the tooling. To demonstrate the process stability coupon test results and recorded temperature data during manufacturing were analyzed. Thermoplastic Automated Fiber Placement's technology readiness was demonstrated by manufacturing a 2.5 m long booster segment with 1.3 m in diameter.

INTRODUCTION

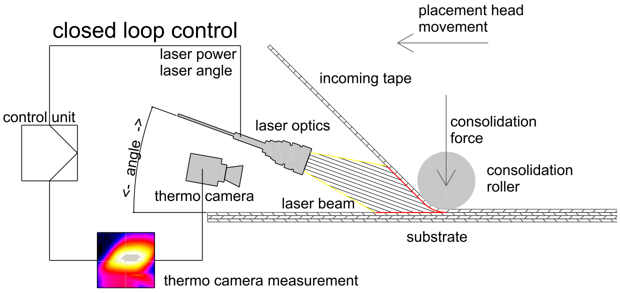
In the Thermoplastic Automated Fiber Placement (TP-AFP) process, tapes with carbon fibers embedded in thermoplastic matrix are deposited on individual paths and are activated by a heat source to melt and merge with the tapes deposited before. Tape by tape a composite part with individual reinforcement directions is generated.

TP-AFP with in situ consolidation is a promising technology because of its high degree of automation and efficient process chain with a small number of consumables and process steps. Due to unlimited part thickness and high tensile strength of the resulting laminate, this technology is especially well suited for large pressure vessels. Therefore, laser assisted TP-AFP process was chosen to manufacture a booster demonstrator for future launch vehicles.

TP-AFP EQUIPMENT

The *Technische Universität München* (*TUM)* owns a modified placement head, derived from tape winding technology from *AFPT GmbH* with the ability to process 1" to 2" wide tapes. This allows manufacturing parts with a curved surface with narrow tapes but also large but less curved parts with wider tape material, enabling high material throughput. The placement head is affixed to a *Kuka* robot which is mounted

on a linear axis with 3.5 m length. A 4 kW diode laser is used as heat source to melt the thermoplastic matrix in the tapes.
Manufacturing time and energy consumption can be reduced by an in situ consolidation of the laminate, avoiding reheating of the whole laminate and tooling in an autoclave. Therefore, the thermoplastic matrix of the incoming tape and of the substrate has to be heated precisely within the polymer's process window during placement. The temperature of the tapes and substrate is permanently controlled by a closed loop system, adjusting the laser power and laser angle to the actual material temperature, which is measured by a thermo camera (Figure 1, left).
The material temperature is continuously displayed in the control software and logged during lay-down to allow further analysis of the process.
The inner tooling for the booster casing was mounted on a windings axis, for a mixed TP-AFP / tape winding process (see Figure 1, right). The aluminum mandrel is segmented and can reduce its diameter by inner kinematics for demolding.



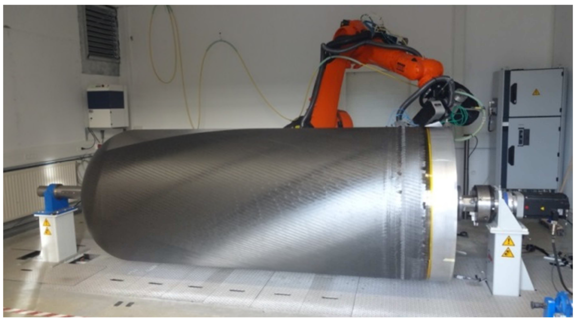


Figure 1: Principle of *AFPT's* closed loop controlled TP-AFP process (left) and TUM's TP-AFP facility

PROCESS PARAMETER OPTIMIZATION

Thermoplastic in situ fiber placement is a complex process with a multitude of influencing factors. To enable the manufacturing of the booster demonstrator process parameters were optimized on coupon level. Nine parameters were investigated to evaluate their influence on process stability and laminate quality. Unidirectional carbon fiber reinforced prepreg tape with polyphenylene sulfide (PPS) matrix was used.

Parameter Optimization Loop 1

The first process parameter optimization was carried out with the so-called wedge peel test (Figure 2, left). This test method is suitable for a large number of specimens due to its simple coupon manufacturing and testing. The method was described by Hulcher et al. and used for several thermoplastic fiber placement optimizations (ref. 1).
The influence of processing temperature, tool temperature, and compression force was investigated. Moreover, possible repair concepts and the influence of an additional heat treatment were analyzed. The basis parameter set was derived from a standard tape winding parameter set by *AFPT GmbH*. Only one parameter was varied each time.
The test results are shown in Figure 2. Nearly all determined peel forces were unexpected high and sometimes undesired failure by tape slicing instead of delamination occurred. The values were about two times higher than literature values of PEEK-specimens (ref. 2 and ref. 3).

For the repair concept unconsolidated specimens were heated from the outside by moving the placement head over the specimen with constant laser power and consolidation pressure, but without placing a new tape. With the first "post consolidation" step intimate contact between the two plies was achieved. This enabled a second "post consolidation" step with higher laser power to melt both plies without thermal degradation of the top layer. Peel forces equal to direct placed specimens were achieved with this two-step repair process.
Specimens heated in an oven to 150°C for 30 minutes ("Basis Tempered") showed a more brittle behavior of the PPS matrix due to its higher degree of crystallinity. This means that the in situ consolidated laminates with its high cooling rate can show a tougher behavior than composites consolidated in a press or autoclave.

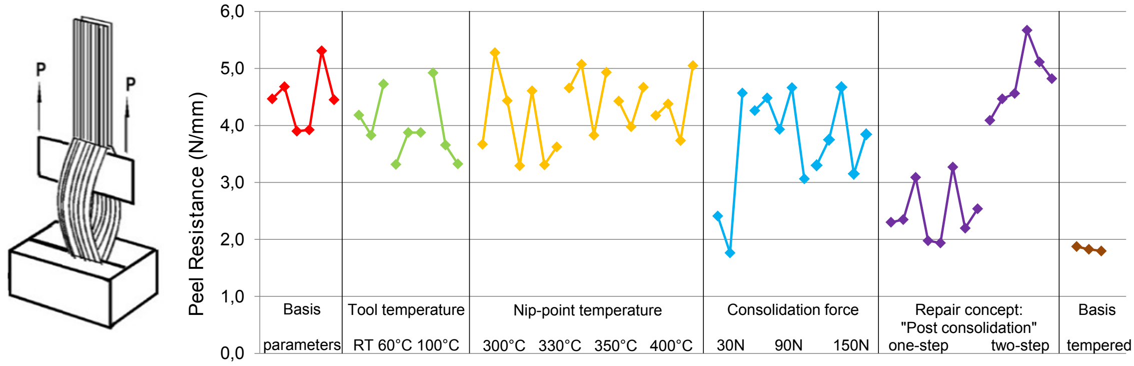


Figure 2: Principle of wedge peel test (ref. 1) (left); peel resistance of specimens with different production parameters (right)

Due to high scattering and small differences of the peel force the influence of different process parameters could not be sufficiently determined with wedge peel testing. Additionally, the evaluation of the peel test was complicated by the strong impact of crystallinity. But a good consolidation and very large processing window could be demonstrated.

Parameter Optimization Loop 2
The aim of the second optimization loop was to achieve a stable process with minimized imperfections inside the composite. Micrographs were used to investigate imperfections like voids or cracks. Density measurements at three different positions of the test plates were used to evaluate the porosity of the specimens. While the peel test specimens consisted only out of two tapes consolidated on each other the specimens for the second optimization were cut out of a 2 mm thick unidirectional laminate. These test plates were more realistic regarding degree of crystallinity, residual thermal stresses and imperfections like gaps or overlaps. The test plates consisted out of more than 100 individually placed tape tracks including all TP-AFP process steps like tape start and cutting. Thus, the process stability could be investigated by evaluating the occurred process malfunctions.
Table 1 shows the parameter variations performed. "0" indicates the best laminate quality with no defects, highest density and/or best process stability and "1" indicates worst quality or the occurrence of a certain defect.

Table 1: Process parameter variation ("0" indicates best quality, "1" = worst quality)

Parameter variation	Density	Micro-cracks	Voids	Porosity	Process stability
Baseline	0.5	0	0	1	0.2
33% Placement speed	0	1	1	1	0.8
200% Placement speed	1	0	0	1	0.4
Focal spot +27%	0.4	1	1	1	1
Process temperature -30°C	0.7	0	0	1	0
Process temperature +50°C	0.4	1	1	1	0.6
Tape tension 50%	0.5	0	0	1	0.2
Tape tension 300%	0.5	0	0	1	0.6
Low raw material quality	0.7	0	0	1	0.6
Compaction pressure +67%	0.5	0	0	1	0.2

Although the process temperature in the nip-point is controlled by a closed loop system, the placement speed has a major impact on temperature distribution during placement. The heating time, energy input and heat penetration depth increases for slow placement velocities. This led to a small reduction of porosity inside the tape as can be seen in Figure 3 and also created the highest composite density. On the other hand, a deeper heat penetration increased the residual stresses and led to microcracks and strong deformation of the test plate. Moreover, process malfunctions like deconsolidation caused voids and porosity between the plies (Figure 3). Larger dimensions of the laser focal spot also increased heating time and heat penetration depth. Laminate density was slightly increased but process malfunctions and strong residual stress occurred.

High process temperatures can also reduce overall porosity but led to problems as described for the slow placement rate.

The tape tension had a minor impact on micrographs and laminate density but increased tape tension was found to improve fiber alignment and placement accuracy. On the other hand too high tape tension created tape slipping at the beginning of the tape placement process.

The raw material quality, mainly porosity, has large influence on the resulting composite quality (ref. 4). Figure 3 shows two micrographs from laminates produced from two different tape materials, one with high initial porosity and one with high quality. Initial porosity of the tape material can hardly be reduced by TP-AFP. However, at the bonding interface of the plies no new porosity was introduced by the process.

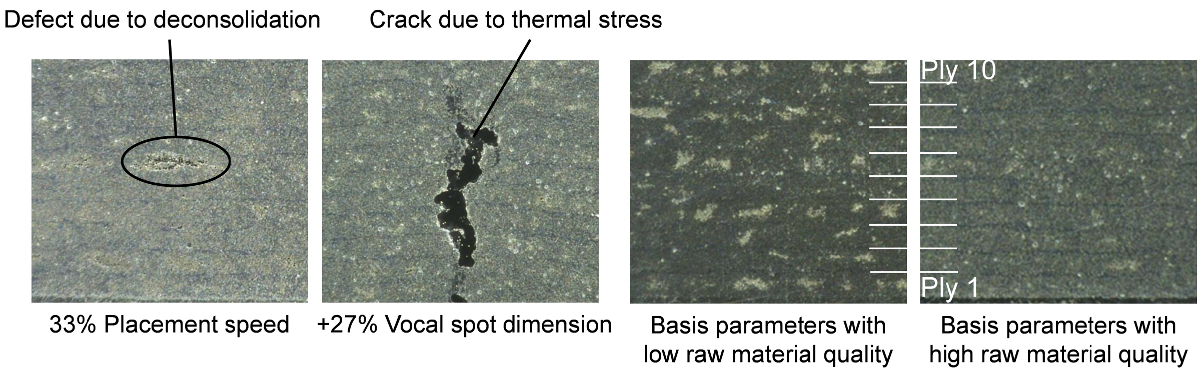


Figure 3: Micrographs of unidirectional specimens

The compaction force had only minor impact on the micrographs and process stability but density slightly increases.

HARDWARE MODIFICATIONS

The optimization loop 1 and loop 2 showed a wide processing window for the chosen prepreg tape. However, certain process malfunctions could not be addressed by parameter optimization. Therefore, hardware components where improved, since their major impact on the process stability had been identified.

Cutting unit

The standard configuration of the cutting unit was not able to cut the tape material “on the fly”. Before cutting, the placement speed had to be slowed down. Otherwise rough cutting edges and high blade wear off occurred (Figure 4). Moreover, different placement speeds resulted in different laminate qualities as mentioned in Table 1. Processing with constant speed during cutting was essential to achieve a high material throughput and a consistent laminate quality.
A rotating bearing arrangement of the cutting unit allows a compensation of the relative speed between tape and placement head during the cutting process (Figure 4). By modifying the cutting unit a “cut on the fly” became possible up to a process velocity of 30 cm/s. At the same time, the endurance of the blades increased from 2.000 to 15.000 cuts.

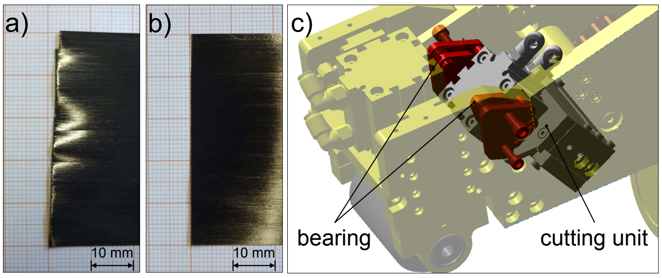


Figure 4: Cut tape edges with fixed (a) and rotable cutting unit (b); rotating bearing arrangement of the tape cutting unit (c);

Compaction roller

Due to the big difference in glass transition (T_g) and melting temperature (T_m), the chosen PPS-CF prepreg requires an active cooling to solidify the laminate under the compaction roller. When using 2” wide tape material, the roller temperature can exceed T_g due to the high energy input and the matrix material tends to bond to the roller. Moreover, sufficient flexibility of the compaction roller was needed to ensure a homogenous compaction pressure on double curved surfaces like the dome area of the pressure vessel. Several roller cooling concepts were investigated (Table 2):

Table 2: Cooling concepts for compaction rollers

	Concept 1: Flexible silicone roller (air cooled outside)	Concept 2: Flexible silicone roller (conduction cooled)	Concept 3: Rigid metal roller (water cooled inside)	Concept 4: Flexible silicone roller with water cooled core
Sketch				
Result				

The concept 1 and 2 are based on a thick silicone coat. A cold air nozzle, mounted on the placement head, provides the roller cooling in concept 1. Concept 2 shows the principle of the investigated conduction cooling by the water cooled counter roller that is linked to the compaction roller. The metal roller of concept 3 consists of a water cooled core and a non-flexible metal surface. In concept 4 a thin silicone coat is pulled over the water cooled metal core.
The roller surface of concept 1 and 2 tend to overheat because of the poor thermal conductivity of their thick silicone coat. This led to a limited service life and laminate deconsolidation for 2” tape material due to its high energy input. Concept 1 is suitable for manufacturing the pressure vessel due to the complex geometry in the dome area but only when using 1” tape material.
The solid roller (concept 3) provides sufficient cooling of the metal surface but allows no adaption to the complex tooling geometry. The resulting inhomogeneous compaction leads to a poor laminate quality.
Concept 4 showed the most promising results for 2” tape. Due to the water cooled core the absorbed heat energy dissipates more quickly. But the limited flexibility is only suitable for single curved surfaces like hoop layers or the reinforced areas on the pressure vessel.

MECHANICAL PROPERTIES

The improvement of the tensile strength was the main goal of the process optimization to maximize the booster demonstrator performance. Mechanical properties were determined by mechanical testing of coupons manufactured with in situ consolidation. Table 3 shows the comparison between coupons manufactured with standard parameters, coupons manufactured after parameter and hardware optimization and specimens consolidated in a heated press (320°C for 15 min with 10 bar pressure).
The tensile strength could be improved by more than 40% compared to the first laminates and by 20% compared to press consolidated laminates. This indicated a straight fiber alignment with the optimized fiber placement process.
Also the porosity of the laminates was reduced by 27% and is at the same level as the raw material. However, the reference laminates, consolidated in a press, showed significant lower porosity. Due to the higher porosity the compression strength values are lower than the reference, but the difference is only 3% to 4%.
In summary the in situ consolidated laminates offer good mechanical properties.

Table 3: Normalized mechanical properties before and after process optimization

	Before process optimization	After parameter and hardware optimization	Reference (consolidated in a press)
Tensile strength 0°	84 %	120 %	100 %
Tensile strength 90°	188 %	138 %	100 %
Compression strength 0°	81 %	97 %	100 %
Compression strength 90°	87 %	96 %	100 %
Porosity (absolute value)	3.0 %	2.2 %	0.2 %

BOOSTER CASING DEMONSTRATOR

Within the framework of the project ComBo, a booster casing demonstrator was manufactured using the in situ TP-AFP process. The process research and demonstrator manufacturing was carried out together with *MT-Aerospace AG*, *University of Augsburg* and the *DLR Augsburg*. The demonstrator part consists out of

three basic elements: the skirt and the pressure vessel comprising the cylindrical shell and the dome, the reinforced connection area (Figure 5).
The wound vessel laminate is made of 32 layers and is designed to withstand inner pressure up to 90 bar. The skirt is needed for the connection to the main stage of the launcher and the connection area at the bottom of the booster casing transfers the loads to further segments or the rocket motor. Both, the skirt and the connection area are reinforced by short tracks to withstand the bearing loads of its connection elements during launch. The skirt has a laminate of 52 layers and the connection area at the bottom consists of 312 layers. The 2.5 m long booster casing demonstrator with a diameter of 1.3 m can be seen in Figure 5.

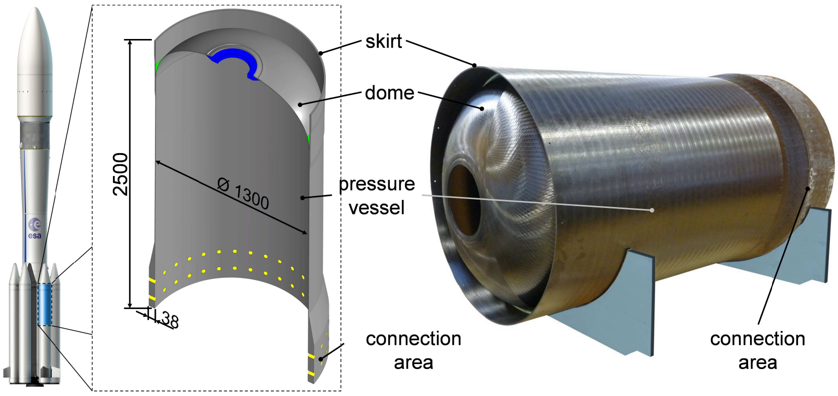


Figure 5: Filament wound and fiber placed demonstrator (ref. 5)

To prove the mechanical properties, the booster casing demonstrator will be tested until ultimate failure by inner pressure.

PROCESS EVALUATION

By analyzing the recorded process data and manufacturing protocols a detailed investigation of the process stability was performed. With the performed process optimizations and hardware modifications a stable process could be achieved. For the production of the first subscale demonstrators a large number of process malfunctions (ca. 20 malfunctions per 1000 tracks) occurred. The errors were caused mainly by curvature of the tape material and thickness tolerances of the previously placed laminate. After optimization the TP-AFP equipment was able to compensate these tolerances and the error rate was reduced to less than 1 error per 1000 tracks.
Figure 6 illustrates the resulting process-downtime before and after hardware optimization. Time for troubleshooting, prepreg spool changes, cutting unit maintenance and consolidation roller changes could be significantly reduced. Daily safety checks and quality assurance still consume about 15% of production time. For serial production a significant reduction of these values can be assumed.

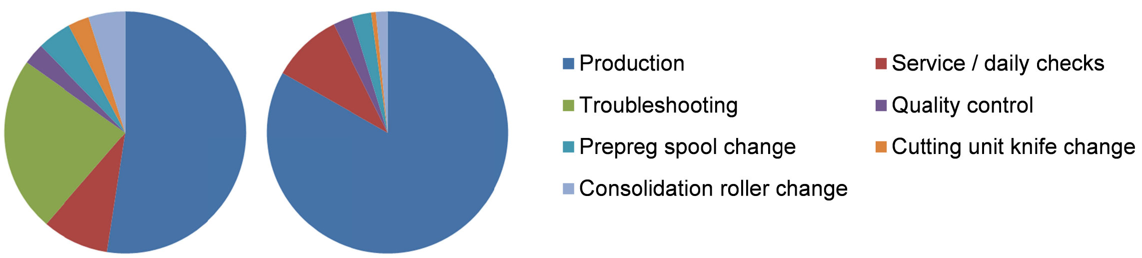


Figure 6: Time plots of the process steps before (left) and after (right) optimization

Figure 7 shows the temperature curve of one track over the pressure vessel dome. The recorded temperature data show small deviations in a range of ±20°C. Even in this complex area with placement speed variation and changing laminate thickness, the temperature deviation is still small.

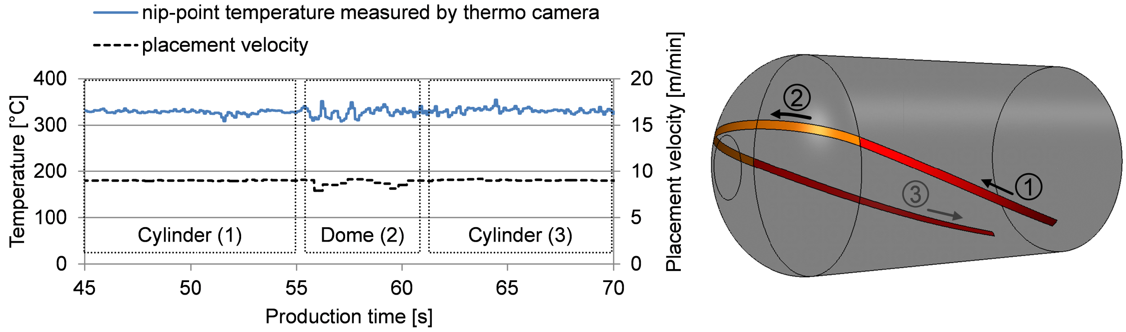


Figure 7: Recorded process data of a track placed over the pressure vessel dome

CONCLUSION

The TP-AFP machine with its closed loop control software proved to be capable to maintain the process window of the used matrix polymer PPS. Several process parameters were tested to optimize the process and laminate quality. The wedge peel test showed high peel resistance values but also high scattering for the varied parameter sets.

The biggest progress towards stable processing by TP-AFP was achieved by optimizing the hardware components like cutting unit and compaction roller. Stable processing reduced the error rate and downtime of the TP-AFP machine during manufacturing a 2.5 m long pressure vessel with 1.3 m in diameter. More than 400 hours of production time and over 50.000 individually placed tapes have proven the process stability and robustness for an industrial use of the in situ TP-AFP technology.

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