Investigating TP-AFP process parameters through a mechanical testing approach

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Abstract. The present work investigates a non-standard approach for tuning TP-AFP process parameters, employing an in-house-designed setup for CF/PEEK ring coupons production and mechanical testing to assess interlaminar shear strength ($ILSS$). The TP-AFP setup features a laying head based on hot gas torch heating source, controlled pressure on a compaction roller, IR thermal monitoring, all operated by a six-degrees-of-freedom (DOF) robotic anthropomorphic arm. Through a non-standard split-disk setup, $ILSS$ is thus evaluated, with its relation with key process parameters such as laydown speed, pressure, and temperature investigated. Although there is a high scatter level of the mechanical characterization parameters of the specimens, the analysis highlights how there is a direct dependence between the AFP process parameters - especially the temperature - and the $ILSS$ values calculated through the split-disk testing carried out.

Introduction

The growing demands of the Industry 4.0 era, coupled with the need for both enhanced manufacturing efficiency and production flexibility, have led to a surge in automation within the fiber-reinforced polymer composite industry. The quest for solutions that balance process quality, versatility, and efficiency has driven the adoption of robotic automated processes and three-dimensional printing of continuous-fiber reinforcements. Among these, automated fiber placement (AFP) which involves the deposition, the compaction and the consolidation in-situ of pre-impregnated narrow bands to form complex multilayer laminates, stands out as a prominent technique [1]. The AFP is a versatile process consisting of full six degrees of freedom and is capable of laying tows on a mold or mandrel simultaneously cutting, stopping, and restarting individual tow. One of the most attractive aspects of such process is its control of individual tows (also termed as "tow steering") which makes AFP capable of laying material on curved and complex shapes [2]. Furthermore in recent times the developing of thermoplastic composites has seen a notable increase driven by their peculiar characteristics of enhanced damage tolerance, high impact resistance, resistance to chemicals and cryogenic temperatures, extended shelf life, low storage costs, weldability, and recyclability [3,4].

The in-situ consolidation process - or fusion bonding - can be subdivided in four main phases, listed below in Fig. 1. In the first two stages the tows undergo heating and then are brought into contact under pressure. As the interfaces meet, polymer chains diffuse and entangle across the microscopic level through the so called autohesion process once interlaminar voids have been suppressed. Upon solidification, the polymer chains become fixed, leading to the development of mechanical strength at the interface. For engineering polymers such as PEEK with moderately high molecular weight, the diffusion of polymer chains is likely constrained during in-situ consolidation due to the brief transient time at elevated temperatures. Nevertheless, effective interfacial strength can be achieved with a sufficient number of polymer chain entanglements [5].

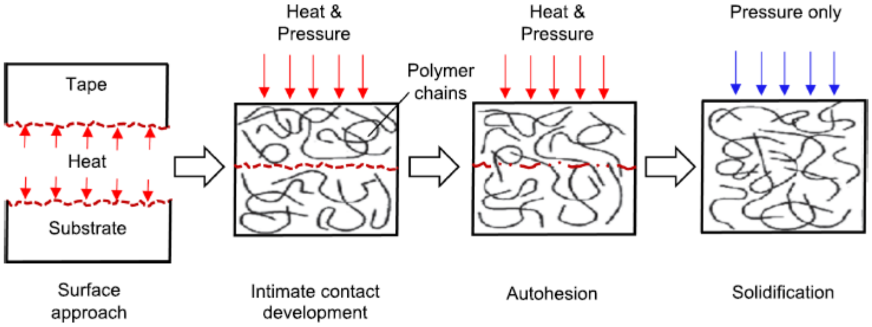


Figure 1: Main phases of the in-situ consolidation of thermoplastic composites process [5]

The stages of the AFP process are presented below in Fig. 2. A very short portion of the towpreg and substrate is heated rapidly to the polymer matrix melting temperature. The molten surfaces are then pressed together by a compaction roller. The heated thermoplastic towpreg and substrate finally cool and solidify.

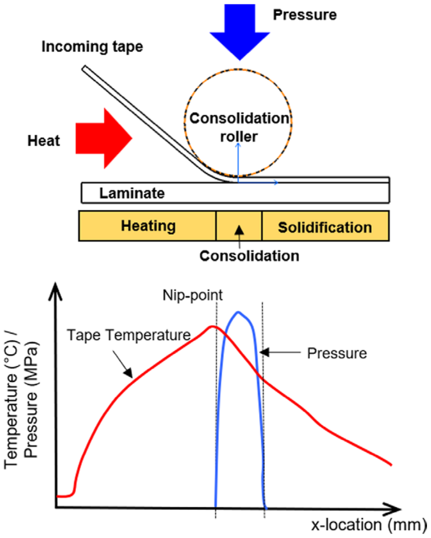


Figure 2: In-situ consolidation process of thermoplastic towpreg placement [5]

This approach offers the advantage of rapid in-situ processing without the need of autoclave curing but despite the potential benefits, the TP-AFP ISC process still faces several challenges such as lower mechanical properties that must be addressed.

Interlaminar shear strength, together with void content, crystallinity and fracture toughness, is a representative indicator of manufacturing quality. A summary of optimised processing parameters based on evaluation of single lap shear testing (SLS) on various thermoplastic composites is presented below in Table 1. It is also important to notice that the "optimised" processing parameters are strictly dependent on the machine setup and material system. In the cited studies [6-9] samples were manufactured usually by planar geometries while in the present work the study has been carried out manufacturing ring shaped SLS coupons.

Table 1: Summary of thermoplastic polymer matrix optimization studies featuring SLS

Material	Heat source	Laydown speed	Compaction force or pressure	Tool temperature	Ref.
CF/PEEK	Laser	200 – 800 mm/s	1025 N	Unheated	Di Francesco et al. [6]
CF/PEEK	HGT	57 – 95 mm/s	333 – 556 N	20 – 150 °C	Qureshi et al. [7]
CF/LM-PAEK	Laser	125 – 250 mm/s	0.6 MPa	20 and 200 °C	Schiel et al. [8]
CF/PEI	HGT	0.5 – 3.5 mm/s	75 – 275 N	100 – 140 °C	Sabido [9]

Di Francesco et al. [6] indicates the increase in material laydown velocity reduces the degree of crystallinity in in-situ consolidated CF/PEEK. On the other hand, Schiel et al. [8] reported that the deposition rate did not affect crystallinity of in-situ consolidated CF/LM-PAEK.

HGT based heating is only able to achieve approximately 60% of the interlaminar strength of autoclaved parts and it decreases with deposition velocity according to Qureshi et al. [7]. Lower heating efficiency by convection lead to insufficient time to melt the PEEK polymer matrix for adequate autohesion.

Materials and Methods

The material used in this investigation is a unidirectional thermoplastic prepreg tape consisting of Poly-ether-ether-ketone (PEEK) reinforced with standard modulus carbon fibers (whose trade name used by Cytec is APC-2).

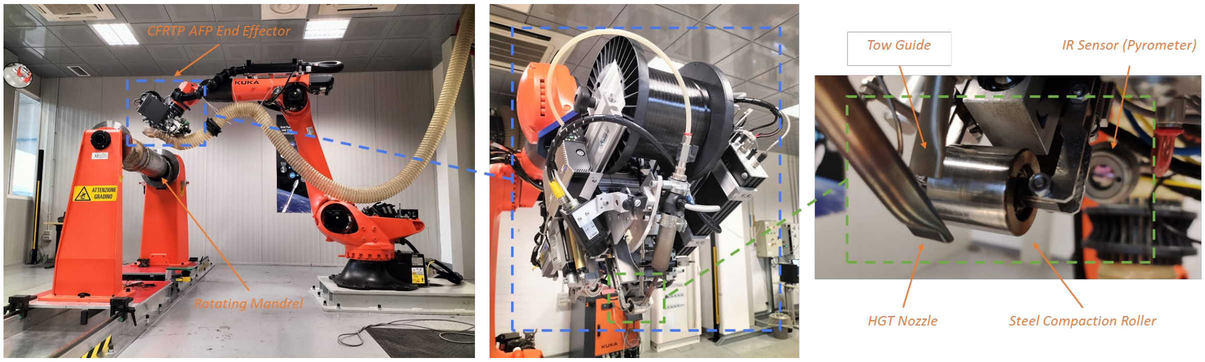
PEEK is by far the most commonly used thermoplastic in tape placement processes. The main properties of CF/PEEK have been listed in Table 2.

Table 2: Material properties of unidirectional CF/PEEK

Property	CFRTP
Prepreg	APC-2
Fiber	AS4
Fiber volume fraction V_f	60%
Tape width	6.35 mm
Melt temperature T_m	343 °C
Glass transition temperature T_g	143 °C
Crystallization enthalpy H_{ref}	122.5 Jg^{-1}

The CFRTP AFP setup consists of a laying head based on hot gas torch (HGT) heating source, controlled pressure on a stainless steel compaction roller (30 mm diameter, 30 mm width) and IR thermal monitoring. The head is moved by a six DOF anthropomorphic arm (KUKA KR240 R2900-2). Tapes are laid down on a steel cylindrical mandrel with 300 mm diameter (see Fig. 3a). The end effector in Fig. 3b enables the placement of a single 0.25” unidirectional prepreg tow.

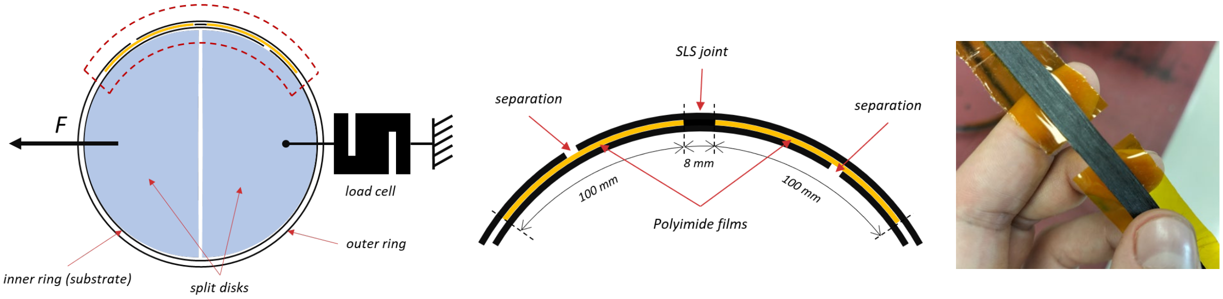
The heat source plays a crucial role in the key manufacturing parameter of in-situ consolidation process. Currently radiant heating using near-infrared (NIR) lasers are more commonly used in AFP. However, despite having lower thermal efficiency, HGT heating is still being used for in-situ consolidation due to its lower capital costs and ease of implementation. With HGT there is also a reduced risk of damaging the matrix, compared to methods involving CO_2 and NIR laser, which can affect the interfacial adhesion through matrix burning. As can also be seen in Table 1, usually the laydown speeds of AFP with laser heating source are higher than those equipped with HGT systems.



(a) **(b)** **(c)**

Figure 3: CFRTP AFP Cell (a) and details of the end effector (b) and its components (c)

Ring shaped SLS specimen was produced according to the following approach: a first layer of CF/PEEK (*inner ring*) was laid down on the tooling surface, then polyimide films (Kapton) with a thickness of 50 µm was subsequently placed in two 8-mm-apart separate courses perpendicular over the ring stripes and after that one more layer (*outer ring*) was placed on the first track of every substrate ring (see Fig. 4a). To evaluate the bonding region (see Fig. 4b-c) the tapes were cut through on opposite lying sides, one cut on the inner ring and a second cut on the outer ring (Fig. 4a). The shear force thus takes effect in the predefined region in between the Kapton films. The purpose of polyimide films is to create delamination zones upstream and downstream of the bonding region. The area highlighted in red Fig. 4a has been detailed in Fig. 4b.



(a) **(b)** **(c)**

Figure 4: SLS coupon scheme (a) and detail of the bonding region of a coupon (b) and (c)

During the tensile test the load was transferred with a split-disk approach as described in Fig. 4a and in Fig. 5. This approach, utilizing non-planar coupons instead of flat ones, was chosen for two key reasons: first, cylindrical specimens better mimic the actual behavior of the material in the presence of multiaxial stresses (i.e. in pressure vessels applications). Second, they minimize the impact of edge effects, a common issue with thin planar samples.

Tensile force F was applied to pull the split halves apart until failure. The external radius of the two half-disks had the same length of 150 mm as the mandrel used to manufacture the specimens in order not to introduce deformation of the composite rings during the test. Friction between the specimen and metal fixtures was minimized.

The average ILSS was computed according to the following equation:

$$\overline{ILSS} = \frac{F_{max}/2}{w \cdot l} \tag{1}$$

(a) **(b)**

Figure 5: SLS test setup for average ILSS determination (a) and with coupon mounted on during test execution (b)

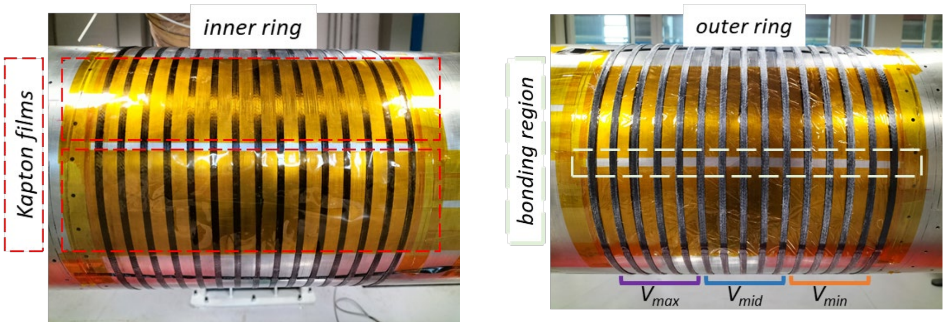
The ultimate tensile load, F_{max}, was measured by the load cell and the width, w, and length, l, of the adhesion zone between the Kapton films were measured with a calliper. It has to be noted that the shear stress distribution is not expected to be constant. Although the followed test approach is not standardized, the results obtained can still be considered representative for the purposes of optimizing the AFP process parameters through the evaluation of consolidation quality as will be discussed further.

An amount of 60 ring coupons has been manufactured - 15 for each deposition set - and during laydown operations all relevant process parameters (temperatures, compaction pressure, laydown speed) have been in-line monitored and recorded. Process variables settings are summarized in Table 3. The compaction force was set by choosing the pressure p_{rs} operating in the pneumatic actuator of the vertical suspension of the roller. It was equal to 2 bars for SET 01-03 and to 1 bar for SET 04. Laydown speeds of the outer rings were varied within the single SET assuming three different values with an increasing trend (see Table 3 for details). The tool was unheated.

Table 3: Process Variables Setting

SET ID	Coupons Count	HGT air flow set [l/s]	HGT voltage set [V]	v_{ls} [mm/s]	p_{rs} [bar]
01	5 / 5 / 5	59.9	165.8	6.3 / 13.1/ 19.7	2
02	5 / 5 / 5	60.0	164.2	6.3 / 13.1/ 19.7	2
03	5 / 5 / 5	59.0	165.3	6.3 / 13.1/ 19.7	2
04	5 / 5 / 5	60.6	165.3	2.8 / 6.3 / 9.8	1

Fig. 6 shows the coupons manufactured within a single deposition set with highlighted (Fig. 6b) the 5-element subsets with varying laydown speeds.



(a) **(b)**

Figure 6: A typical set of in-situ consolidated ring coupons with inner layers (a) and outer layers (b)

Results

The results of the mechanical testing are summarized below in Fig. 7. The box plot graph shows the average interlaminar shear strength value ($\overline{ILSS}$) for each subset of 5 element across the different laydown speeds v_{ls}. The median value was also highlighted by horizontal markers. Variations in the deposition speed showcase distinct influences on the $\overline{ILSS}$ values. For instance, in SET 02, as the v_{ls} increases from 6.3 to 19.7 mm/s, there's a discernible decrease in the $\overline{ILSS}$ mean values, coupled with a reduction in the standard deviation. Conversely, SET 03 illustrates an upward trend in $\overline{ILSS}$ mean values with increasing deposition speed, accompanied by a minimal standard deviation at 13.1 mm/s. Maximum mean value of $\overline{ILSS}$ for SET 03 is 24.9 MPa at 19.7 mm/s laydown speed. Also SET 04 demonstrates the impact of varied deposition speeds (from 2.8 to 9.8 mm/s) on $\overline{ILSS}$, revealing fluctuations in mean values and standard deviations with a slightly increasing trend.

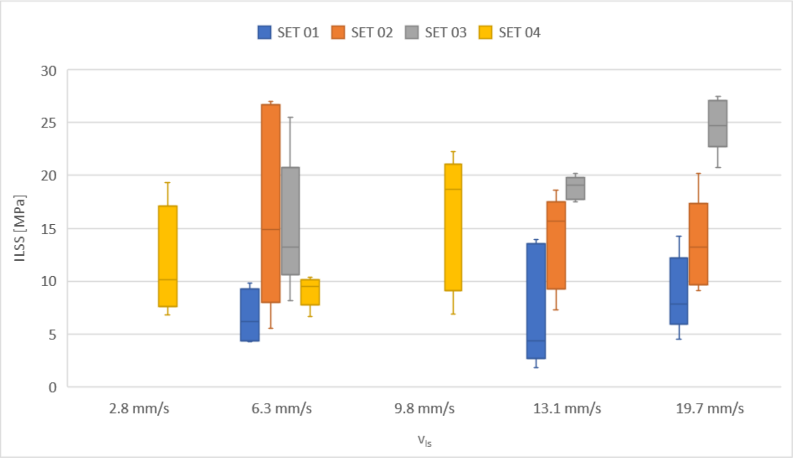
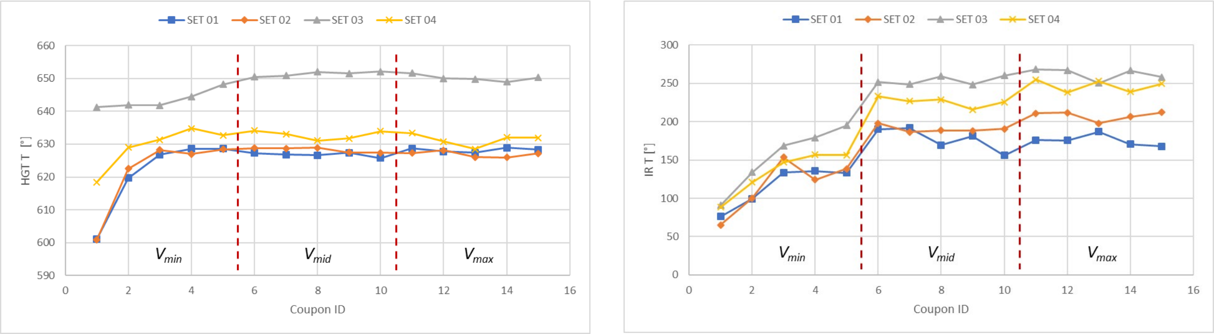


Figure 7: Box plot of the average ILSS over set laydown speed

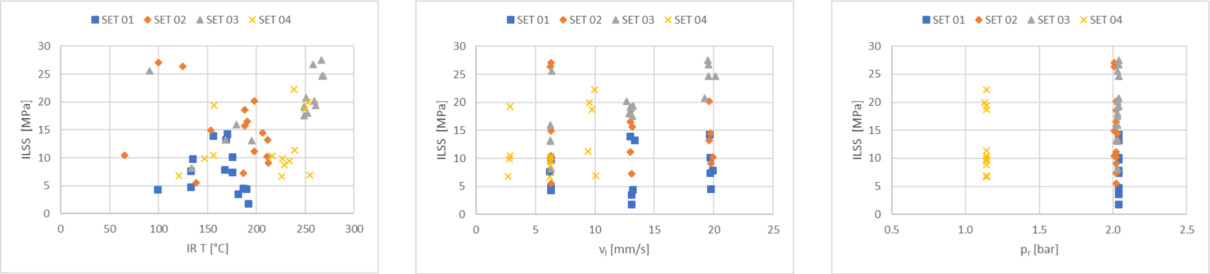
According to the graphs depicted in Fig. 8a, SET 03 and exhibits higher HGT thermocouple temperatures compared to SET 01-03. This aspect is also present in the temperature measured downstream the deposition area $IR\ T$ (evaluated by the pyrometer) and reported in Fig. 8b. The $IR\ T$ graph, however, highlights the effects of the heating of the mandrel as one proceeds with the deposition of the rings within a single set. Such aspect seems to have been the process parameter that influenced the $\overline{ILSS}$ the most.



(a) **(b)**

Figure 8: Mean HGT temperature (a) and mean IR temperature (b) evaluated during laydown process of each outer ring manufactured

Scatter plots between $\overline{ILSS}$ and other relevant parameters are reported below in Fig. 9. In particular Fig. 9a remarks the how higher temperatures – still below the degradation of the material - leads to higher $\overline{ILSS}$. Fig. 9b and Fig. 9c puts in relation respectively laydown speed v_l and compaction pressure p_r with $\overline{ILSS}$.



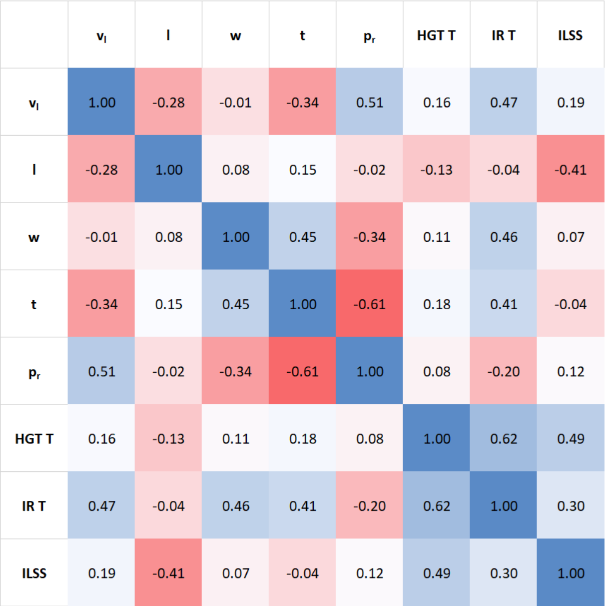
(a) **(b)** **(c)**

Figure 9: Average ILSS over HGT temperature (a) laydown speed (b) and compaction pressure (c)

Discussion

Although the $\overline{ILSS}$ values obtained from the data analysis may not have reached the desired level of satisfaction and also displayed a notable degree of scattering, it is essential to recognize that such variability is a common phenomenon in similar studies documented in the literature [7-8]. This scattering can be attributed to the intricate interplay among the numerous thermo-mechanical variables inherent in the processing.

In Fig. 10 a correlation matrix is proposed in order to evaluate the relationship between the different analyzed variables of the data sets. In addition to the expected correlations such as the inverse one between compaction pressure p_r and overlap thickness t, those that seem most interesting are the already described direct correlation between $\overline{ILSS}$ and $IR\ T$ and the inverse one between $\overline{ILSS}$ and overlap length l. This aspect seems to indicate that when the overlap length is kept lower, better bonding quality is obtained (higher $\overline{ILSS}$).



	v_l	l	w	t	p_r	HGT T	IR T	ILSS
v_l	1.00	-0.28	-0.01	-0.34	0.51	0.16	0.47	0.19
l	-0.28	1.00	0.08	0.15	-0.02	-0.13	-0.04	-0.41
w	-0.01	0.08	1.00	0.45	-0.34	0.11	0.46	0.07
t	-0.34	0.15	0.45	1.00	-0.61	0.18	0.41	-0.04
p_r	0.51	-0.02	-0.34	-0.61	1.00	0.08	-0.20	0.12
HGT T	0.16	-0.13	0.11	0.18	0.08	1.00	0.62	0.49
IR T	0.47	-0.04	0.46	0.41	-0.20	0.62	1.00	0.30
ILSS	0.19	-0.41	0.07	-0.04	0.12	0.49	0.30	1.00

Figure 10: Correlation matrix

Conclusions

The key findings of the research underscore that:

- the proposed split-disk testing approach has emerged as an alternative option – to those commonly used - for relate the process parameter of the TP-AFP cell with the interlaminar bonding properties of the manufactured coupons;
- such method needs further research to see if it truly captures a representative value of $ILSS$ and gives the same results as planar specimens;

- in the laydown speed ranges analyzed there is no decrease in $\overline{ILSS}$ with increasing speed;
- the parameter that most influences the quality of the bonding is the operating temperature of the hot gas torch and therefore the temperature on the mandrel in the deposition area.

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