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XENON FLASHLAMP BASED IN-SITU AUTOMATED FIBER PLACEMENT OF THERMOPLASTIC COMPOSITES

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ABSTRACT

Thermoplastic automated fiber placement is a highly automated, lean manufacturing process and with in-situ consolidation may lead to wider distribution of advanced composites. An opportunity for flexible, cost-effective production of aerospace components is found in the usage of new heating systems such as the pulsed xenon flashlamp, since it renders the use of complete safety housing unnecessary. In this work, a flashlamp heating system is characterized by a process parameter study and compared to laser assisted AFP (LAFP). The flashlamp system does not include a closed-loop controller to precisely adjust the nip point temperature, thus the impact of the tunable input parameters on the nip point temperature is investigated. Subsequently the laminate quality is examined, using single-lap shear specimen. The trials show that flashlamp heating is not yet able to compete with LAFP in terms of lay-down rates and shear strengths. Still, with modifications to the system it may be a promising approach.

1 INTRODUCTION

Automated fiber placement (AFP) of advanced thermoplastic composites has led to increased interest in the technology and considerable efforts to achieve one-step in-situ consolidation due to recent technological advancements such as controllable and affordable laser heating, robot-based end-effectors and the introduction of high quality (low-void) thermoplastic prepregs [1].

As is known, AFP is a highly transient process involving heating, consolidation and cooling within the shortest time frame. During these three stages, different phenomena occur, involving material flow, bonding and crystallization, governed by temperature and pressure evolution [2–4]. The main issues are typically the bonding between the layers, residual stress and the void content. Ideally, the degree of bonding (D_b) as described by Mantell *et al*. [5] reaches full adhesion between the layers. For aerospace applications one usually strives to reach less than 1% void content.

In order to make the thermoplastic AFP in-situ process attractive for a wide range of applications it is necessary to improve the robustness of the process but also to establish new heat sources for large part production. As lasers emit coherent light of high intensity, the costs for safety measures in production are significant. Flashlamp heating may thus be a viable alternative for the AFP process. The broad light spectrum emitted by a xenon lamp is highly diffuse, thus rendering complete safety housing unnecessary. However, the flashlamp technology must also show that comparable layup speed, and thus productivity, can be achieved.

This paper presents the recent advancements of in-situ AFP with the Heraeus humm3^{TM}-system (6 kW, 2 inch heated width) that is currently evaluated at the Centre for Lightweight Production Technology (ZLP) of the German Aerospace Center (DLR) in Augsburg. The achieved processing quality is compared to LAFP (Laserline 6 kW diode laser) performed at the Institute of Structures and Design in Stuttgart.

2 STATE OF THE ART

Laser assisted AFP has been in development for nearly three decades now. Layup rates started with 25 mm/s and have risen significantly. Current research suggests that thermoplastic materials such as CF/PEEK show best material properties at 6 m/min [1]. Process improvements were achieved by accurate laser positioning and the adjustment of the angle of incidence. Best results emerge when the material is heated near the nip point, under the consolidation roller. In order to improve the prediction and controllability of the process heat transfer models were designed.

In a comparative study, CF/PEEK laminates manufactured with LAFP and autoclave showed that LAFP processing leads to lower material properties. With limited through thickness heating, and comparably high cooling rates, insufficient crystallinity and a larger number of voids occur. This results in reduced inter-laminar shear strength by 70%, flexure strength by 68% and flexure stiffness by 88%. However, inter-laminar toughness was increased to 134% [2].

In 2017, Williams and Brown introduced a new heating system based on a xenon flashlamp. Thermoset prepreg, thermoplastic composites and dry fiber tape have been processed with the new heat source. It is suggested that the flashlamp system may have advantages over the laser regarding its smaller size on the layup end-effector and especially due to the fact, that no laser safety housing is required [3]. In recent advancements, a power control function was developed and a steady nip point temperature could be established. From first observations, xenon flashlamp heating needs significantly more power when compared to diode lasers, mainly due to the diffuse energy from the flashlamp heats a wider area around the nip point region. It is clear that the flashlamp heats from ambient to process temperatures more slowly. This is likely to have effects on the thermal profile through the thickness, and consequently the residual stresses in the part. Furthermore, the cooling after lay-up is expected to be significantly different for the flashlamp, when compared with laser heating [4]. For laminates manufactured with flashlamp assisted AFP (FAFP), a comprehensive evaluation of material properties is not yet available.

3 EXPERIMENTAL SETUP

Parameter studies are conducted in order to establish optimized parameters for both heat sources. Using the design of experiment (DoE) method, interrelations between layup speed, compaction pressure, and tooling temperature on the achievable lay-down quality are investigated. A central composite design was chosen for process optimization via the response surface method. The recorded data was analyzed with the software Design Expert.

3.1 Flashlamp

For this investigation a flashlamp is equipped to a layup head developed for laser assisted AFP. The setup is depicted in Figure 1 showing the end-effector (single tow winding head type) from AFPT mounted on a KUKA KR120 R2700 HA robot. The quartz light guide was fixed at an angle of 18° to the tooling and at a distance of 40.8 mm from front face to nip point. This position was predefined by the end-effector design.

High quality melt impregnated CF/PPS ½” UD-tape was used for the benchmarking of the two heat sources. The matrix system has a glass transition temperature of about 90°C and a melting temperature of 290°C. Hence, processing temperatures of above 330°C are required.

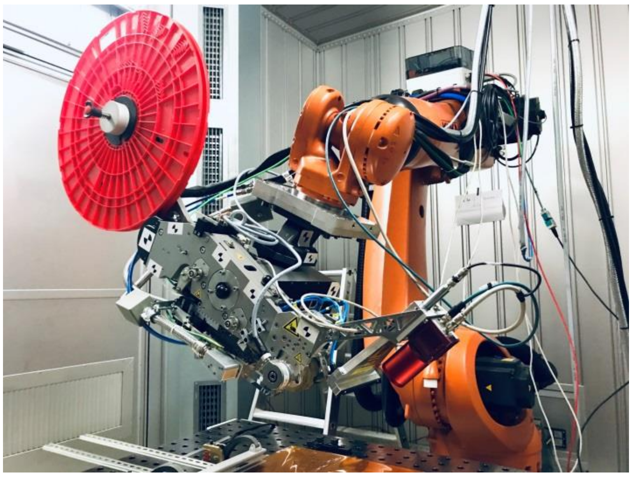

Figure 1: Setup FAFP head

For the flashlamp the controllable factors are lay-down speed, pressure onto the compaction roller and tooling temperature. As the pulsed xenon light source has no closed-loop control of the lay-down temperature at this time, it is accounted for as a response in the DoE. The temperature is measured at the nip point between the sample surface and the compaction roller via thermal imaging. The controllable factors were varied within three defined levels:

Factor	Units	Low	Mean	High
Lay-down Speed	m/min	1.8	2.4	3.0
Pressure	bar	3	4.5	6
Tooling Temperature	°C	20 (RT)	90 (≈ T_g)	180 (>T_g)

Table 1: Controllable factors in flashlamp AFP

As mentioned, DoE was carried out for both the flashlamp and the laser heating. Each design point has eight repeated measurements and the center point has six replicates to estimate the pure error. For the flashlamp the center point has been set at a lay-down speed of 1.8 m/min, a compaction roller pressure set to 4.5 bar and a tooling temperature of 90°C. 48 samples are produced in the center point of a total of 165 samples.

3.2 Laser

For LAFP a similar setup was used: a multi tow layup head (MTLH) from AFPT was employed in the trials to lay up the identical CF/PPS ½” UD-tape. The MTLH is an advanced version of the STWH. Key differences are an improved stiffness, a cooled compaction roller with a thinner (4 mm) layer of silicon and optional processing of up to three tapes at a time. The system is capable to control the temperature in the nip point via thermal imaging. Thus the controllable factors for LAFP are the set temperature in the nip point, lay-down speed, compaction pressure and tooling temperature. In parallel to the flashlamp trials the parameters were altered within the following levels:

Factor	Units	Low	Mean	High
Temperature nip point	°C	330	370	410
Lay-down Speed	m/min	1.0	7.5	14
Pressure	bar	3	4.5	6
Tooling Temperature	°C	20 (RT)	135 (>T_g)	250 (>T_g)

Table 2: Controllable factors in laser AFP

3.3 Single-lap test

As response function of the input factors the peel force was determined by a mechanical single-lap test, designed by Dreher *et al*. [5]. Four UD-tapes are placed on top of another with two 25 mm wide and 25 µm thick Kapton films in 5 mm distance applied to the sample center plane, i.e. in between the layers two and three (see Figure 2).

The tape pairs are separated by inserting a metal foil between the Kapton and the plies as protection for the opposing tapes. Subsequently the specimen is cut with a sharp knife or scalpel from atop and below. Thereby the load is merely transferred through the inter-laminar layer between the plies, during tensile testing.

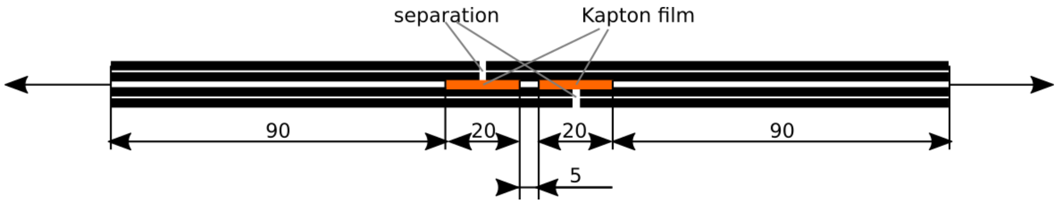

Figure 2: Single lap shear specimen

All specimens were produced on plates heatable up to 250°C. For improved adhesion and reduced first layer challenges a heat isolator is placed under the first ply of each specimen. The tensile test determines a peel force $F_{\max}$ from which one calculates the shear stress, where b and h define the shear surface:

$$\tau = \frac{F_{\max}}{b \cdot h} \tag{1}$$

4 RESULTS

For LAFP tests with a total of 90 specimens a surface response is illustrated in Figure 3 [5]. According to the fit model, the highest lap shear strengths (color-coded in red) are reached at a nip point temperature of 410 °C, a lay-down speed of 1 m/min, a compaction pressure of 6 bars and a tooling temperature of 250 °C.

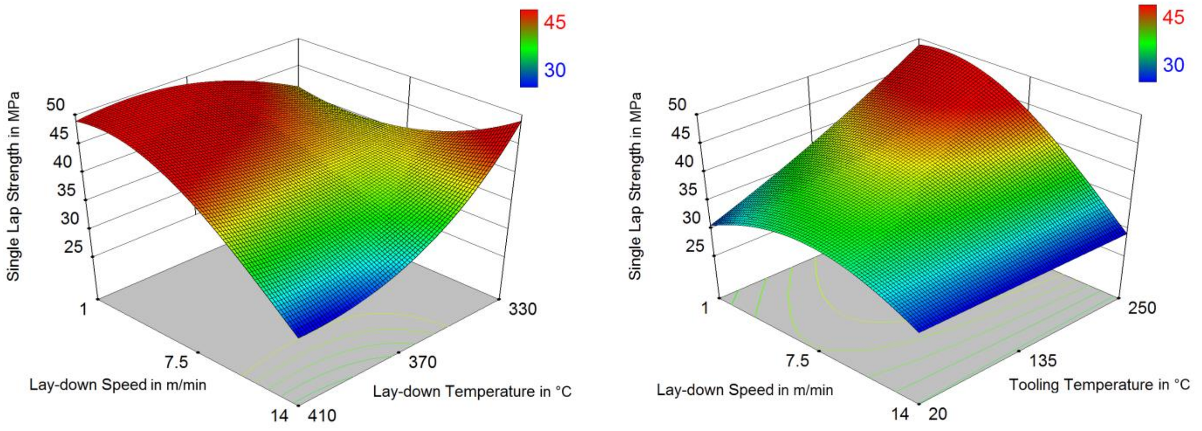

Figure 3: LAFP - Response surface for p = 6 bar, T_{mold} = 250 °C (left), response surface for T_{Set} = 410 °C (right).

As this parameter set would lead to inacceptable low production rates a multi-objective optimization of maximal shear strength and layup velocity was conducted. Three promising process points were identified and experimentally validated. The results are shown in Figure 4. The high single-lap shear strength values at comparably low set temperatures of 330°C and high lay-down speeds could not be verified but were found to be statistical outliers. The model was consequently adjusted. At a set temperature of 410°C in the nip point, a lay-down speed of 5.3 m/min and 6 bar compaction pressure, the highest strength values are achieved. The mean shear strength of 40.0 MPa is measured with a standard deviation of 2.4 MPa (6.1%).

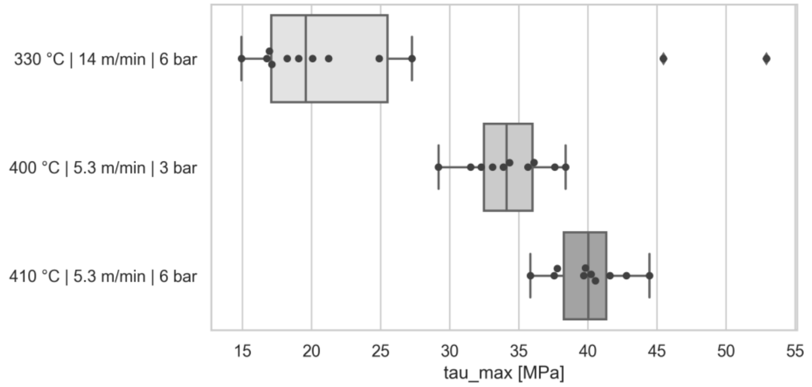

Figure 4: LAFP - Boxplots of confirmation point’s settings

In a similar method to the LAFP the flashlamp process was tested. In order to characterize the influence of processing parameters the lay-down temperatures at various set points are evaluated. The lay-down temperature is restricted by the maximum power output of the flashlamp at 6 kW and mainly influenced by the distance between nip point and heat source, the lay-down speed and the tooling temperature. In order to reach necessary process temperatures the speed is limited to a maximum of 3 m/min. At relatively high lay-down speeds the nip point temperature is reduced below the required temperature of at least 330°C, if the tool is not heated (see

Figure 5).

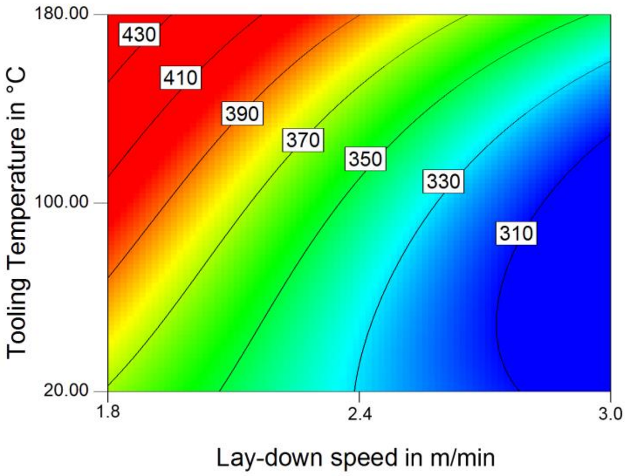

Figure 5: FAFP - Contour plot of the lay-down temperature (at 6 bar compaction pressure)

The overall average of all response data gives a nip point temperature of 350.9 °C, thus well within the processing window of the matrix system PPS ranging from 40 K above the melt temperature, i.e. 330 °C to 450 °C in order to prevent degradation. The standard deviation associated with the experiment is 5.2 °C (1.5 %). Therefore a stable nip point temperature may be set even without a closed-loop controller.

Figure 6 illustrates the lay-down temperatures at 6 bar compaction force. The lay-down compaction pressure influences the lay-down temperature. At a lay-down velocity of 3 m/min with unheated tooling the layup temperature declines 42.5 K from 3 to 6 bar. This effect is reversed at a tooling temperature of 180 °C and a velocity of 2.4 m/min. The lay-down temperature ascends approximately 9,3K with the increase in compaction force.

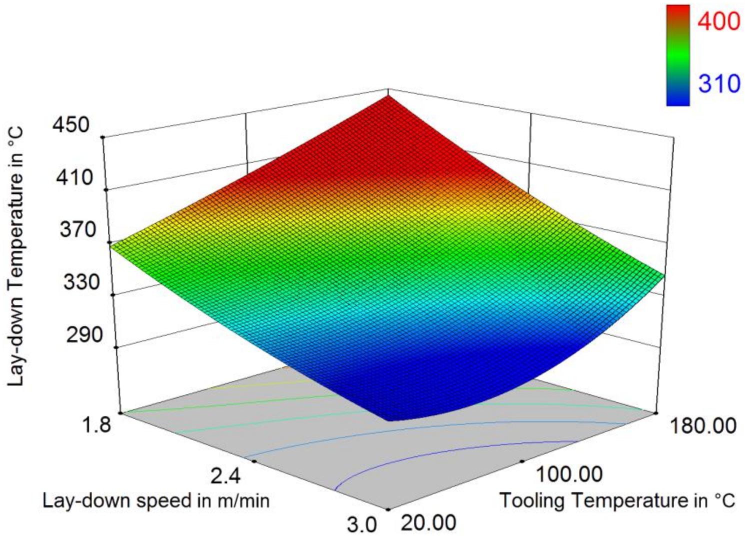

Figure 6: FAFP - 3D-Surface of the lay-down temperature for p = 6 bar, with temperatures below 330°C color-coded in blue.

The single lap strengths for the flashlamp assisted AFP are shown in Figure 7. The mean lap shear strength is 10.2 MPa, at the center point of the experiment setup with a standard deviation of 1.6 MPa (15.7 %). A strong dependency upon lay-down speed and tooling temperature was found. The highest shear strength of approximately 18 MPa was measured at 180 °C tooling temperature, a lay-down speed of 3 m/min and 6 bar compaction pressure. High tooling temperatures at low lay-down speeds led to degradation of the matrix. As a result no lap shear strength could be established.

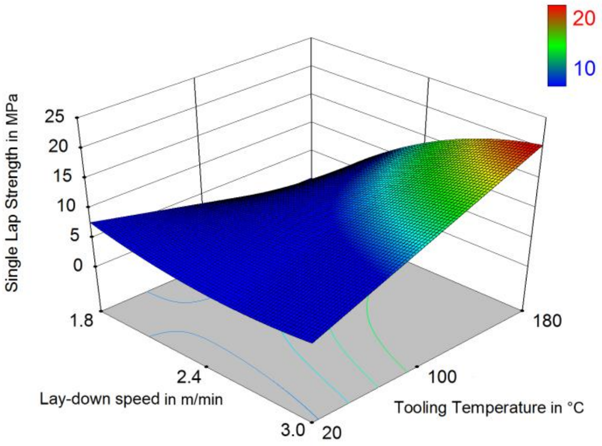

Figure 7: FAFP - Single-lap strength for p = 6 bar.

In general, the highest lap shear strength values were reached at 6 bar compaction pressure. However, a significant influence of the pressure is not verifiable.

5 DISCUSSION

Overall the best specimen values are at the corners of the response surfaces for the flashlamp as well as the laser assisted process. In DoE, this is not ideal as the variance at the edges is higher and less replicates were done compared to the center point.

In general the flashlamp assisted AFP shows lower strength values (18 MPa) compared to LAFP (40 MPa at an optimized process point). Furthermore, the lay-down speed for the flashlamp system is significantly slower than the laser (3 m/min to 5.3 m/min). At a compaction pressure of 6 bar both heat sources produced the highest lap shear strengths. One explanation for the inferior results for the FAFP may be the uncooled, softer consolidation roller of the lay-up head. The trials also suggest that a more powerful flashlamp heat source would diminish the influence of the tooling temperature and layup at higher velocity could be investigated.

For FAFP the highest mechanical properties were reached at a nip point temperature of approximately 350 °C, a lay-down speed of 3 m/min and a tooling temperature of 180 °C. The response surface at 6 bar indicates that a higher tooling temperature leads to an increase in shear strengths. Processing at tooling temperatures above the glass transition temperature may have a distinct impact on the crystallization. With a re-crystallization temperature of 120°C for PPS, higher mechanical properties can possibly be attributed to the fact that these samples were annealed on the heated tooling [6]. However to implement additional heating of the tool is not favorable regarding the industrialization of the process. Another approach is to increase the heating rate and power of the flashlamp to remain within the processing window of the matrix (330 to 410 °C). Thus lap shear strengths of laminates placed on a tooling at room temperature could be enhanced.

6 SUMMARY AND OUTLOOK

A pulsed xenon light source being applied as a heating system for AFP is a comparably new technology. For thermoplastic tape laying the trials presented here show that other technologies like LAFP achieve higher lay-down rates with better inter-laminar shear strength values. However, the flashlamp system still achieved consolidation of CF/PPS. The data from the present study implies that a more powerful flashlamp may reach higher layup rates of 6 m/min for thermoplastic, i.e. within the range of LAFP. It is worth noting that the flashlamp system used in this study is rated at 6kW maximum electrical input power, which has proved sufficient in other studies to process dry fiber tapes at high speed [3].

Flashlamp heating for thermoplastic AFP is a promising application due to the lack of complete safety housings and the possibility of a wider heating area. Future work will need to examine if a more powerful system may overcome the shortfalls compared to laser heating. Higher power systems are available and the DLR Center of Lightweight Production in Augsburg is currently testing a system with 13 kW in power. Additionally the layup head used for LAFP is adapted for FAFP to achieve better comparability. In general, it is clear that further studies are required to investigate the heat transfer and distribution into the material to result in faster and higher quality thermoplastic layup.

REFERENCES

[1] A.J. Comer, D. Ray, W.O. Obande, D. Jones, J. Lyons, I. Rosca, R.M.O. Higgins, and M.A. McCarthy, “Mechanical characterisation of carbon fibre–PEEK manufactured by laser-assisted automated-tape-placement and autoclave,” *Composites Part A: Applied Science and Manufacturing*, vol. 69, Feb. 2015, pp. 10–20.

[2] K. Yassin and M. Hojjati, “Processing of thermoplastic matrix composites through automated fiber placement and tape laying methods,” *Journal of Thermoplastic Composite Materials*, vol. 31, Nov. 2017, pp. 1676–1725.

[3] D. Williams and M. Brown, “Xenon Flashlamp Heating for Automated Fibre Placement,” *Third Symposium on Automated Composites Manufacturing (ACM 3)*, 2017.

[4] P. Monnot, D. Williams, and M.D. Francesco, “Power Control of a Flashlamp-based Heating Solution for Automated Dry Fibre Placement,” *ECCM18 - 18th European Conference on Composite Materials*, 2018.

[5] P. Dreher, A.R. Chadwick, and S. Nowotny, “Optimization of In-situ Thermoplastic Automated Fiber Placement Process Parameters through DoE,” *SAMPE Europe Conference 2019,* Nantes, France: 2019.

[6] D.G. Brady, “The crystallinity of poly(phenylene sulfide) and its effect on polymer properties,” *Journal of Applied Polymer Science*, vol. 20, Sep. 1976, pp. 2541–2551.