COMPARISON OF HEAT SOURCES FOR AUTOMATED DRY FIBRE PLACEMENT: XENON FLASHLAMP VS. INFRARED HEATING

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ABSTRACT

Automated Dry Fibre Placement (DFP) is considered a viable technology for preform production of advanced composites. In this process, the heat source crucially determines the achievable lay-down rates and thus ultimately the effective productivity. Therefore high energy density heat sources are desirable. In this context, flashlamp heating is a promising technology especially for large part production. In this study, the Heraeus humm3 flashlamp system is benchmarked to infrared (IR) radiators in terms of peel strength and heat distribution at various lay-down speeds. For this purpose a parameter study is conducted to identify suitable processing parameters for binder activation. A significant increase to lay-down speeds of 30 m/min compared to 6 m/min with infrared heaters is accomplished with enhanced controllability of the process regarding the energy transfer into the material. The temperature profiles measured indicate more uniform distribution along the tracks. Subsequently the opportunities and limitations of applying a flashlamp heat source in a DFP process are discussed.

1 INTRODUCTION

Recent applications for automated dry fibre placement combined with out-of-autoclave (OoA) resin infusion are the wings and wingbox of the IRKUT MS-21 [1] and the rocket booster demonstrator of the ARIANE 6 [2]. These examples proved the technology's readiness for large aerospace structures. The selection of heat source for binder activation is crucial due to its impact on key process factors. Process characteristics like the achievable lay-up-speed, process controllability, binder activation, adhesion between the plies and therefore the effective productivity are affected by the performance of the heat source.

Xenon flashlamps for automated fibre placement applications emit non-coherent light in the spectral range between 0.2 µm (ultraviolet, UV) and 1µm (infrared, IR). The power output is tuned by the combination of voltage, pulse length and frequency of the gas discharge lamp. The high energy pulses are focused and guided through a quartz-bloc towards the target material [3,4]. The suitability of the technology for dry fibre placement was initially demonstrated in trials achieving surface temperatures of 180 °C and placement rates of up to 1 m/s [5,6].

Commercial infrared radiators transmit energy by electromagnetic radiation in the spectral range between 0.8 µm and 6 µm. The penetration depth into the material increases with decreasing wavelength. Short-wave radiators, like those used in this work, can penetrate up to several tenths of a millimetre [7]. However, IR lamps achieve lower heating rates at reduced controllability due to slow response, i.e. obtain significant residual heat after being switched off [5].

Rapid diode laser heating on the other hand, requires significantly less power compared to flashlamp systems to achieve comparable surface temperatures but in terms of health and safety requirements protective housing is typically needed [8]. Flashlamp systems also have the advantage that a broader heating area can be realized to heat the nip point, as well as the incoming tape.

Despite a high energy density, flashlamp heating can be operated in an open production environment contrary to a laser heat source. Therefore flashlamp systems may be a viable substitute for standard IR-heaters. To date a comprehensive evaluation of the temperature distribution and binder activation by flashlamp-based DFP is not available. This work thus shows differences in how dry fibre tape materials are bonded to each other by binder activation in a robotic DFP-process with standard IR-heaters and a flashlamp. The placed samples are tested in a T-peel test to compare the binder activation and study the connection quality between adjacent plies. The temperature distribution and adhesion between the plies is used to assess the suitability of flashlamp heating for DFP.

2 EXPERIMANTAL METHOD

The DFP end-effector applied in this study processes dry fibre tape with 50 mm in width. The material in question consists of Toray T800 SC 24k carbon fibre rovings with glass fibre weft threads in canvas weaving. It is coated on one side with CeTePox AM 4052 R provided by CTP Advanced Materials. The binder has an activation temperature of 83 ± 6 °C. The original setup of the DFP head features two dual lamp IR emitters with nano reflectors (QRC) type B with a length of 125 mm (60 mm heated length) and a cross section of 23 × 11 mm from Heraeus Noblelight. The output power of each lamp is 470 W at 115 V. The IR-heaters are applied at full power throughout this study.

The flashlamp has a maximum output power of 6 kW. Three parameters define the output power: voltage, frequency and pulse duration. Since the voltage parameter of the flashlamp cannot be changed during the process, the pulse duration is modulated to vary the power output. For this purpose, an analogue signal corresponding to the lay-up speed was used as the controlled variable.

2.1 Flashlamp integration and process parameters

The flashlamp was integrated into the DFP end-effector with three degrees of freedom (DOF) – two translatory and one rotary DOF. This way the position and angle of the quartz relative to the nip point can be adjusted separately. Preliminary trials showed that a distance of 50 mm at an angle of 30° relative to the tool surface ensures good heating results without the quartz interfering with the incoming tape. The setup of the flashlamp is displayed in Figure 1.

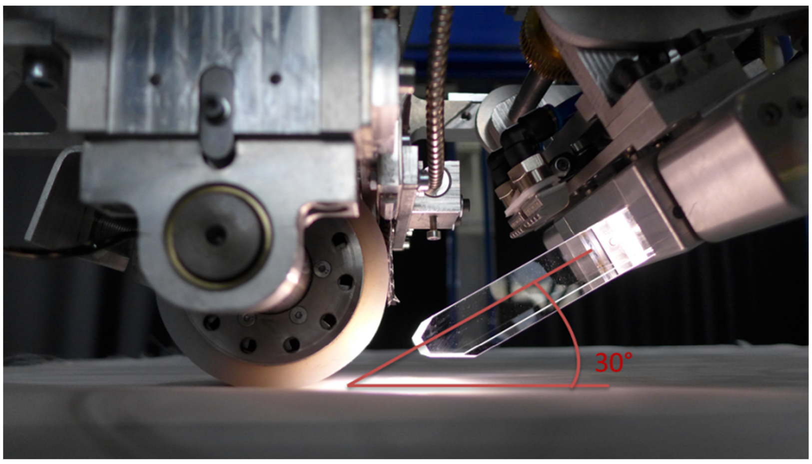


Figure 1: Flashlamp position relative to the compaction roller and tooling

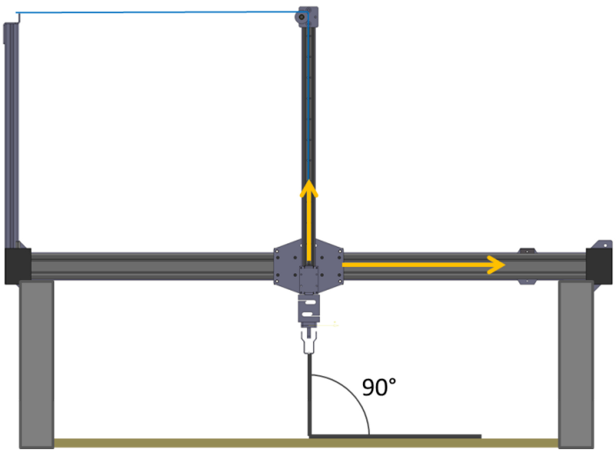
A frequency of 60 Hz was chosen to prevent a stroboscopic effect that occurs at lower frequencies and is potentially irritating and unpleasant for workers in an open production environment. Further, the pulse duration was set to $t_{pmin} = 0.5$ ms and $t_{pmax} = 2$ ms respectively for all trials. The pulse duration varies between those values during the process in order to control the energy output of the lamp according to the lay-up speed. Finally, the voltage was set from 160 V to 190 V to reach binder activation temperatures of 90 °C to 125 °C respectively, at a speed of 30 m/min. For the first layer an increase of roughly 30 V was necessary in order to reach similar temperatures, due to heat loss over the aluminium surface. An overview of the process parameters and corresponding power outputs is given in Table 1.

Layer	Temperature [°C]	Voltage [V]	Power output [kW]
1st layer	85	190	4,40
1st layer	100	200	5,07
1st layer	115	220	5,85
2nd layer	90	160	2,58
2nd layer	105	175	3,38
2nd layer	120	190	4,40

Table 1: Overview of the used flashlamp parameters and corresponding power output

2.2 Peel test

In order to assess the quality of the activation a peel test was conducted. The test appliance design was built inspired by the ASTM D 6862 standard test method for 90° peel resistance of adhesives. The test bench is shown in Figure 2. It is driven by a linear axis that moves horizontally and thereby pulls a carriage upwards that is held by a rope hoist. Thus, the peel of angle is mechanically kept steadily at 90°. The yellow arrows in the schematic indicate the relative movements (Figure 2, left).



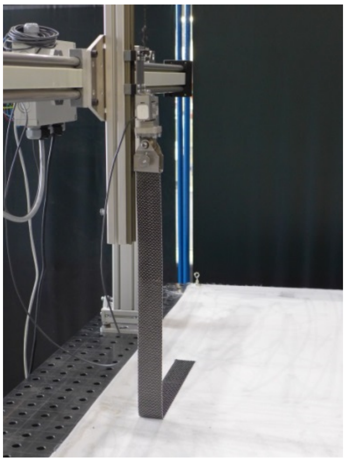


Figure 2: Peel tester – schematic from CAD (left) and during test of the first layer test (right)

For the test a loose beginning of 200 mm at the end of the placed tape was clamped to the peel tester at a 90° angle. Therefore the adhesive force was tested in reversed lay-up direction. The peel of force was measured by a load cell (HBM S2M 50N) that is installed between the clamp and the vertically moving carriage. The total tested length was 680 mm at a peel-off speed of 100 mm/min as specified in the test standard ASTM D 6862.

2.3 Temperature measurement

The temperature in the nip point was measured with a thermographic camera (FLIR AX-5 IR). The camera was fixed on the side of the end-effector aiming to the nip point. The lay-up of each tape was captured and analysed with the FLIR software (FLIR ResearchIR Max 64-bit). For the evaluation the average temperature over the width of the tape was determined.

2.4 Lay-up trial procedure

Two different scenarios were tested: first layer and consecutive layer. As a lay-up surface for the first layer a peel ply has been used in the past in order to enhance roughness for the adhesive binder. The peel ply itself was fixed with a spray-on adhesive to the aluminium surface. Further, for the consecutive layers the bottom tape had to be fixed to the surface, since the layer to layer adhesion was stronger than the adhesion between the first layer and the surface. Thus, one tape was fixed with double sided adhesive tape to the surface and the consecutive tape was placed on top. This way the first layer stuck to the surface when the consecutive layer was peeled. The lay-up speed for IR-heating was set to 6 m/min which is the maximum speed at which the necessary activation temperatures are achieved. The speed limit for the flashlamp heating was 30 m/min which is the maximum lay-up speed of the end-effector. The compaction roller that is made from silicon was forced onto the tape by a pneumatic piston pressurized with 3 bar. Five tapes were tested for each layer and parameter set. Thus, the peel forces for a total of 10 IR- and 30 flashlamp heated tapes were analysed.

3 RESULTS AND DISCUSSION

In general the process is stable with both heat sources. However, significant differences in the adhesive forces of the tapes depending on their lay-up temperature and speed can be seen. The detailed results and analysis are given below.

3.1 Temperature distribution over the tape

The resulting mean temperatures over five tapes for different heating setups are given in Figure 3. The standard deviation for all setups is within 3 % to 4 % of the nominal mean temperature. This indicates that the temperature is evenly distributed over the tape.

For flashlamp heating more energy is required for the first layer than for the consecutive layer. Comparable temperatures are for instance reached at 4.4 kW (190V, 2 ms, 60 Hz) for the first layer and 2.6 kW (160V, 2 ms, 60Hz) for consecutive layers (see Figure 3, colour coded in blue). By contrast, the differences between first and second layer using the IR-lamp are negligible.

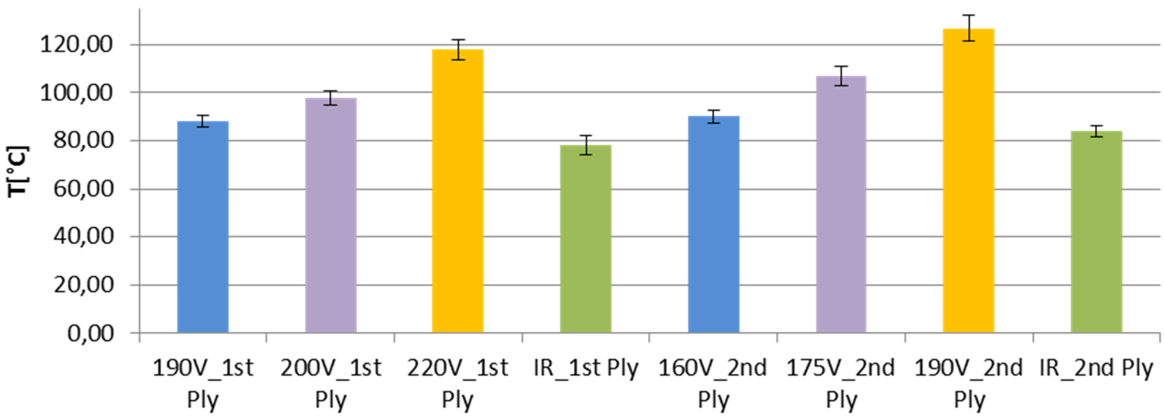


Figure 3: Mean temperatures of different setups during activation

In order to assess the heat sources during the heat-up and cool-down a comparison of the temperature distribution of the first layer for IR- and flashlamp-heating is given in Figure 4. Because of the different lay-up speeds of the two heat sources, the time and therefore the amount of measured data points varies for both graphs.

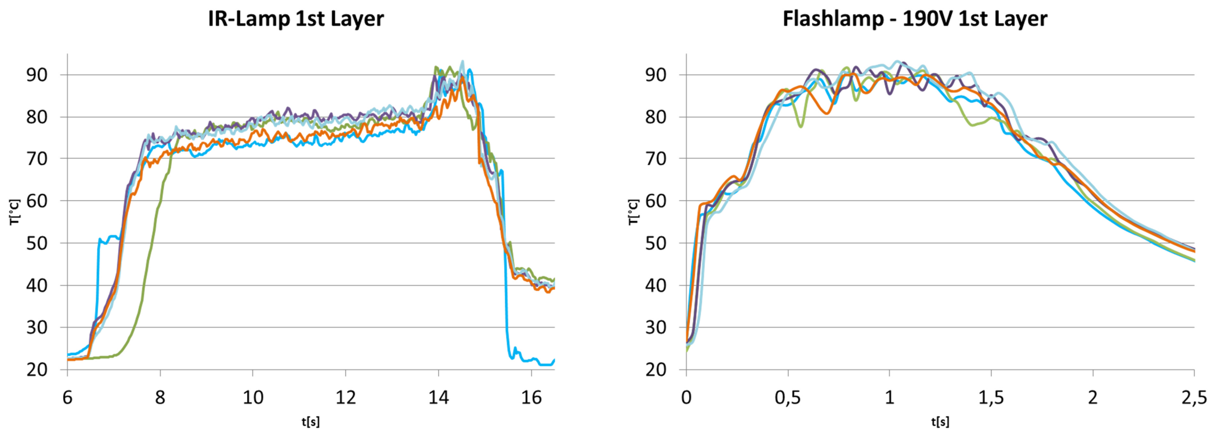


Figure 4: Comparison of temperature distribution for IR- (left) and flashlamp-heating (right)

The heating time is defined as the time interval it takes to reach 70 °C – the temperature at which activation was found in preliminary trials – from ambient temperature. Mean heat-up times for the different flashlamp settings were measured between 0.43 s and 0.57 s. For the IR-lamp mean heat-up times were measured at 1.09 s for the first layer and 1.41 s for the second layer. The graph for the IR-lamp also shows an increase in temperature at the end of the track. This can be explained by residual heat and a consequentially delayed cool down during deceleration.

Apart from the heating times determined, we saw a delayed switching of the IR-lamp during trials. This latency in the temperature behaviour of the IR-lamp can be seen in Figure 4, where the adhesion at the beginning of the track placed with IR-lamps is not given.

3.2 Peel forces

The peel forces vary depending on the lay-up surface. The lay-up on peel ply shows maximum peel forces of 1.2 N to 0.4 N depending on the setup (IR- or flashlamp) and parameters of the flashlamp. The parameter sets for the flashlamp are depicted Table 1. The comparison of the average peel forces of the first layer (with five repetitions) is shown in Figure 5. The direction of lay-up is from right to left, since the tapes were tested from end to start.

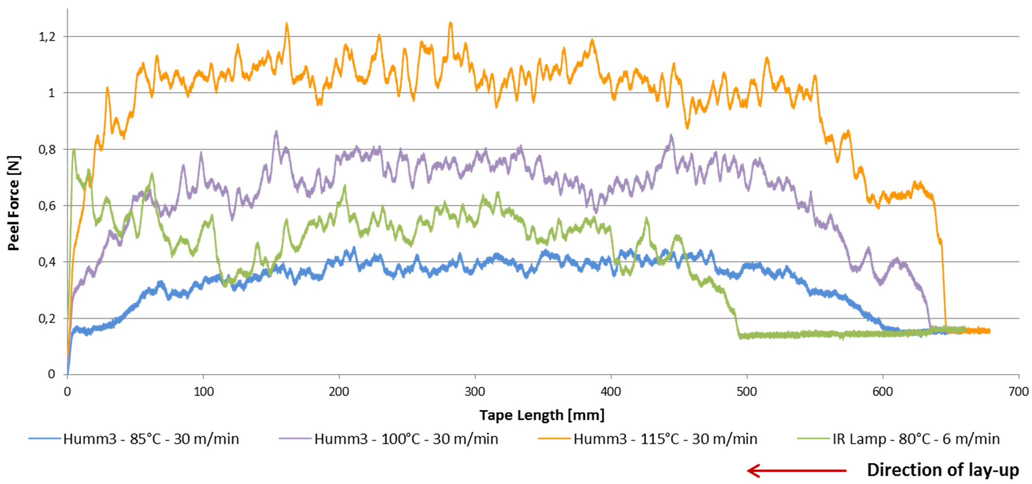


Figure 5: Comparison of the peel forces of the first layer

The green graph shows the adhesive forces for the tapes activated with IR heating. There is no adhesion for the first 190 mm of the tape. This corresponds with the delayed activation of the lamp that was seen during the trials. After that the adhesion forces rise and stay between 0.4 N to 0.6 N for the majority of the length. At the end of the Tape they reach a maximum of 0.8 N.

The progression of the peel forces of the tapes activated with the flashlamp system is consistent for the three parameter sets. However, the magnitude of the peel force highly depends on the surface temperature. Although the binders activation temperature is 83°C the adhesion at an activation temperature of 85° and a lay-up speed of 30 m/min is only 0.4 N at most, which is slightly less than what we see with the IR lamp at 80°C. Therefore not only the temperature, but also the lay-up speed has a significant impact on the adhesion. Nevertheless, the adhesion at higher speeds is stronger if nip point temperatures are increased as well. The second and third set of parameters for the flashlamp reach peel forces between 0.6 N to 0.8 N and 0.9 N to 1.2 N respectively. At the same time we see that the beginnings of the tape have been sufficiently activated. Therefore the peel force in the beginning of the tape increases steeply right from the start, as seen in the yellow graph for 115°C activation temperature in Figure 5.

The peel forces of the consecutive layer show a similar behaviour (Figure 6). The best adhesion is seen using the flashlamp at its highest energy output (4.4 kW, 120°C). With this setup, peel forces reach up to 1.8 N with adhesion over the entire length of the tape. All other configurations have an increase in peel forces compared to the first layer. The highest relative increase we see in the IR setup. However, the IR setup shows a slow heat-up and consequently no adhesion in the first 100 mm of the tape. Additionally, at the end of the tape there is a peak in peel force which can be explained by the latent overheating observed during the run-out of the tape.

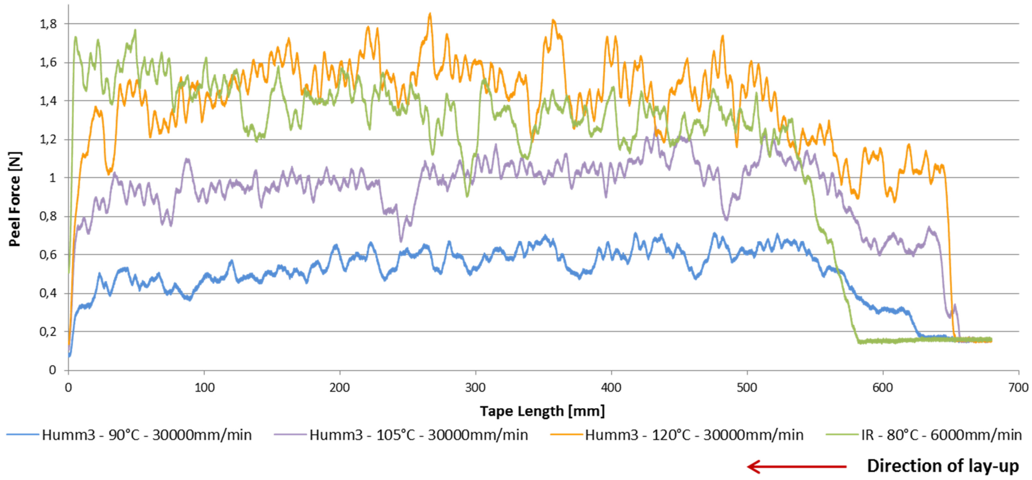


Figure 6: Comparison of the peel forces of the consecutive layer

3.3 Discussion

The relevant parameters for the heat source assessment for the DFP process are lay-up speed, temperature distribution and the quality of the activation. Comparing the lay-up speed of two 470 W heaters and a 6 kW flashlamp system, it may be apparent that the flashlamp system can reach six times the speed of the IR-heaters. Best adhesion is reached at the highest processing temperatures. Such temperatures could not be achieved with IR-heaters – which are limited in power at the available space on the end-effector - at reasonable process speeds. For flashlamps, by contrast, there remains further potential for higher speeds with increased energy transmission at a reduced distance to the nip point, which is especially promising for nylon-based binder activation. Therefore, an optimized flashlamp setup is superior to IR-heaters when it comes to lay-up speed. Additionally, other characteristics found in this study have greater impact on the process.

The main advantage of the flashlamp is to be found in its advanced controllability. With IR-lamps the beginning of the heating is delayed. This causes poor adhesion at each beginning of the track.

Ultimately this can lead to peeled off tapes in production. Further, the delay is not reproducible and greatly depends on the residual temperature of the IR-heaters. This impairs a stable process. The flashlamp showed a reproducible behaviour and good adhesion right from the start of each track. Additionally, the internal energy control based on the current lay-up speed works well. This is seen in the consistent mean temperature over the length of the tape and eliminates the need for a closed-loop controller to regulate the temperature. The IR-heaters produce a consistent temperature over the length once the heat-up is finished but also overheat in the end due to residual heat.

Adhesion is generally better for the first layer using a flashlamp. This cannot be said for the second layer, since peel forces were comparable when using IR- and flashlamp heating. A higher temperature was required for flashlamp activation of the second layer. This may be explained by the higher speeds and the resulting shorter time of exposure, compression and cool down. Nevertheless, the interrelationship between activation temperature and activation of the binder at higher speeds needs further investigation. This might be highly dependent on the type of binder used.

4 CONCLUSION

Flashlamp heating shows great potential for DFP and is superior to IR-heating in terms of controllability and reproducibility. Therefore, it poses a viable alternative to IR-heating for DFP in open production environments. The achievable lay-up speeds and consequentially production rates are higher. However, this research did not focus on the achievable maximum speed due to the speed limit of the end-effector. More significant advantages of flashlamp heating that arise from the results are a direct energy transfer into the material, enhanced heat guidance and much better adhesion in the beginning of the tracks. If flashlamps are approved for operation without safety housing they are a promising alternative to lasers and are potentially capable to reach similar production rates for DFP processes.

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