

DEVELOPMENT OF A “DIGITAL TWIN” OF THE AUTOMATED FIBRE PLACEMENT (AFP) LAYUP OF LM-PAEK THERMOPLASTIC MATERIAL USING A PULSED XENON FLASHLAMP HEAT SOURCE

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Abstract: *Xenon flashlamps have emerged as an alternative heat source to the laser in Automated Fiber Deposition (AFP) of thermoplastics. A Xenon Flashlamp system, consisting of a flashlamp, reflector and light guide, has been shown to reach the temperatures required to process thermoplastic composites in a similar response time to a laser with reduced safety burden. To quickly determine good process parameters for TC1225 LM-PAEK, an opto-thermal simulation model has been created. Two simulation techniques optical ray tracing and finite element analysis (FEA) were used to characterize the flashlamp source and predict the resultant processing temperature respectively. Using these simulation tools, pulse parameters can be chosen more quickly to achieve a desired processing temperature without a significant number of physical trials.*

Keywords: Automated Fiber Deposition; digital twin; pulsed Xenon flashlamp; ray tracing; FEA

1. Introduction

An optical-thermal simulation tool for predicting AFP processing or “nip point” temperature for pulsed xenon flashlamp systems with heated tooling has been developed for end users. This tool allows the prediction of nip point temperature from system parameters before starting layup. This will allow the system user to more quickly determine the most optimal system parameters, reducing setup time and maximizing the time available for laying-up good-quality thermoplastic material. There are a lot of constituent material parameters and validation experiments required to reach a point where the simulation tool is at a point where the end user can use the tool with confidence.

Goniometric, optical materials and surface models, as well as energy level validation work was covered in a previous publication [1]. This paper covers the follow up work namely validation of the irradiance distribution, measurement of thermal parameters, comparison of the initial version of the “digital twin” with AFP layup experiments and investigations into radiative heating effects originating from the quartz light guide.

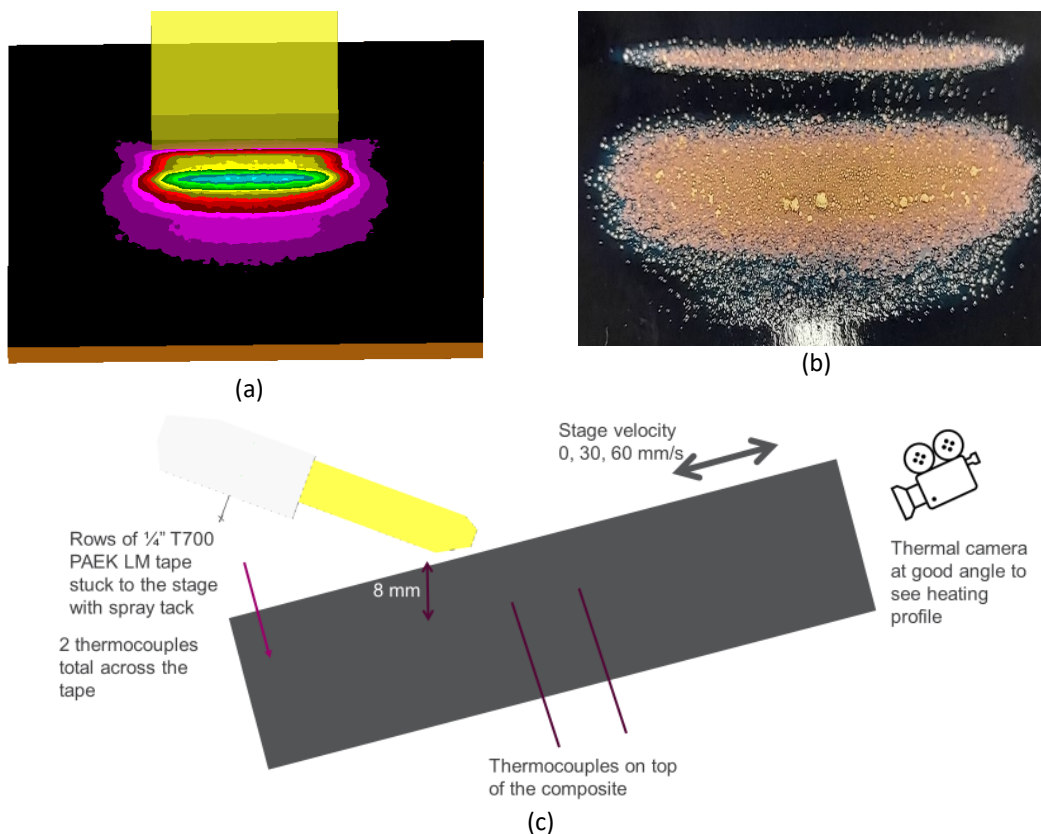
2. Experimental Validation of the Irradiance Distribution

Since previous work demonstrated the optical energy output of the simulation aligns with the integration sphere measurements [1], the distribution of energy exiting the block end modified for AFP from the simulation was subsequently experimentally validated. Figure 1 (a) shows the predicted energy distribution from the optical simulation and figure 1 (b) is an image of the

energy output estimated from photosensitive burn paper. The distributions look similar but required experimental measurement.

Measuring the energy distribution or surface irradiance was not straight forward with available equipment, but a method for estimating the irradiance was determined using a thermal camera and the test setup in figure 1 (c). A Micro Epsilon TIM640 thermal camera with a refresh rate of 133 Hz was used for the measurements. The high refresh rate was required to ensure that the temperature measurement was as close to the peak as possible. A single pulse from the xenon flashlamp system of 200 V and 2.5 ms duration was directed at the thermoplastic surface whilst the camera was recording. The thermoplastic sample was then left to cool for approximately one minute before another pulse was directed at the sample, with this process repeated until there were several decent pulse measurements available. Thermal image stills were captured immediately before and after each pulse, where figure 1 (d) captures a post-pulse image.

As can be seen in figure 1 (d), a line was plotted along roughly the center of the irradiated zone and was used to capture datasets of temperature measurements. For each pulse, the post-pulse temperature was subtracted from the pre-pulse temperature from the entire dataset along the line. These results for three pulses are plotted in figure 1 (e) and show that all the lines have the same reproduceable behavior, with deviations in ΔT due to the camera frame rate and pulse start time not being synchronized. The thermal plot in figure 1 (e) also shows evidence of five fringe artifacts, which help with the validation process.



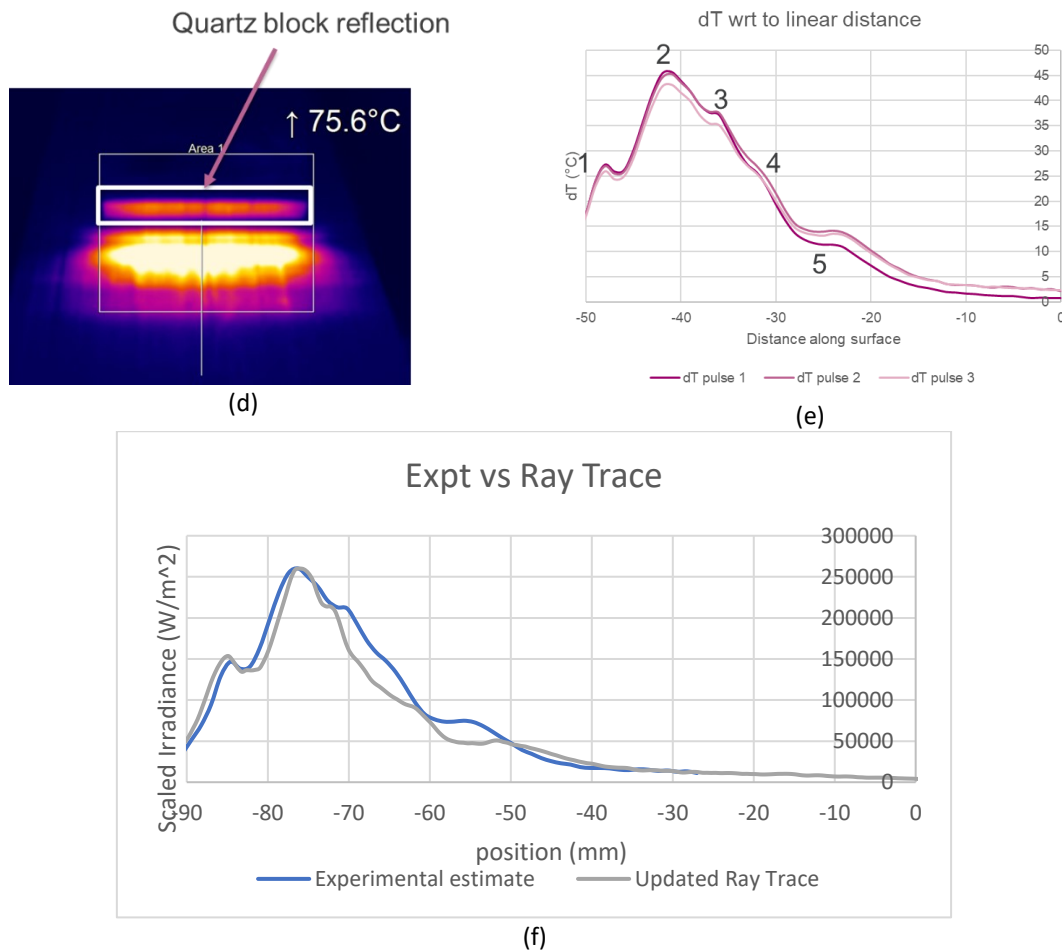


Figure 1: (a) image of ray tracing prediction of the validation experiment. (b) Burn paper capture of energy exiting the quartz block. (c) Schematic diagram of experimental test setup used to validate the optical simulation output. (d) Thermal camera still of TC1225 PAEK LM tape after a single pulse. (e) Change in temperature with respect to distance plot for a single pulse. (f) Comparison between experimental estimate of irradiance

The next part of the validation was to convert the dT plot data in figure 1 (e) into irradiance, q using a simplified version of Fourier's equation for surface boundaries shown in (1). Since the pulse duration is short and the experiment is static, both the convective and advective terms can be neglected. For the purposes of this estimation, the partial derivative in y can be approximated as the penetration depth as indicated in (2). The thermal diffusivity α is given in (3). The specific heat c , thermal conductivity λ , and thermal diffusivity α values are shown in figure 3.

$$\frac{\partial T}{\partial t} = -\frac{1}{\rho c} \frac{\partial q}{\partial y} \quad (1)$$

$$\frac{\partial}{\partial y} = \sqrt{\frac{\alpha}{\pi f}} \quad (2)$$

$$\alpha = \frac{\lambda}{\rho c} \quad (3)$$

The comparison between the simulation and experimental estimate of irradiance is shown in figure 1 (f) and agreement appears to be excellent with energy levels of the two peaks and fringe positions appearing to line up. This appears to validate the energy profile produced by the optical simulation. The key outcome is that the optical simulation gives an excellent representation of the actual optical output of the system.

3. Optical Simulation Output

For AFP layup systems, the geometry of the systems is important for the optical simulation because the irradiance received is proportional to the distance between the end of the light guide and the target surface. For the AFP system used in experimental trial, the geometry was as shown in figure 2 (a). Based upon the validated optical simulation from this work and [1], the simulated irradiance absorbed at maximum averaged energy for the substrate and tow tapes is given in figures 3 (b) and (c) respectively. These results were converted into pulsed heat flux boundary conditions that were read by an ANSYS transient thermal simulation.

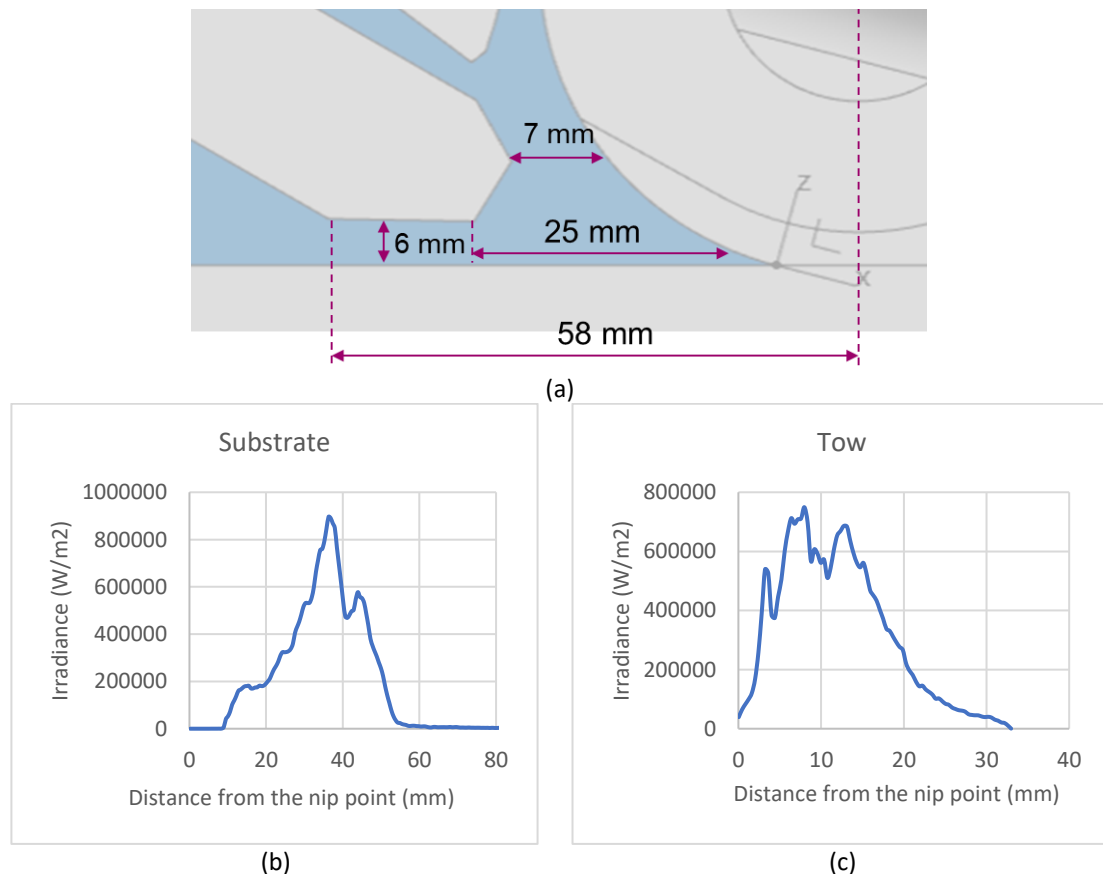


Figure 2 (a) CAD schematic of AFP layup system used for trials. Optical simulation irradiance outputs along the central axis of the source at maximum averaged power for (b) substrate and (c) tow in AFP trials arrangement.

4. Development of Transient Thermal FE Model and Comparison between initial Opto-Thermal Simulation and AFP layup trials

Samples of TC1225 PAEK LM tape were sent to external laboratories for external characterization by laser flash analysis (LFA) and differential scanning calorimetry (DSC). LFA directly measures the through-plane thermal conductivity and thermal diffusivity of a material, and the specific heat was directly measured by DSC. Using these measurements and the relationship between the quantities given in (3), a full thermal model of the thermoplastic composite was built. One point of uncertainty is that the thermal conductivity measurements were performed on fully consolidated samples and materials processed by AFP only are likely to be partially consolidated, meaning the effective through-plane thermal conductivity of the substrate tape will likely be lower than the values indicated here for cases greater than one ply thick.

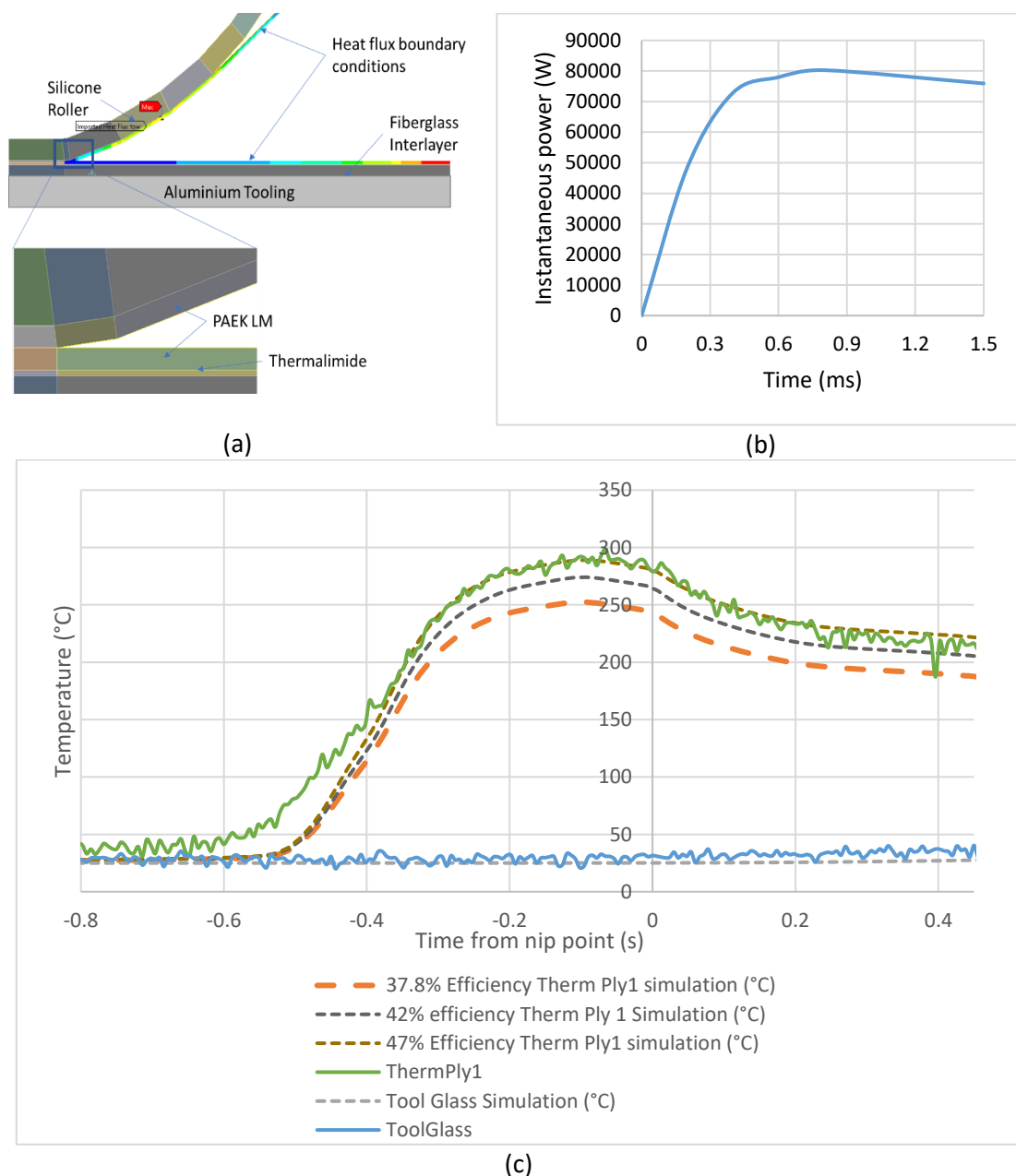
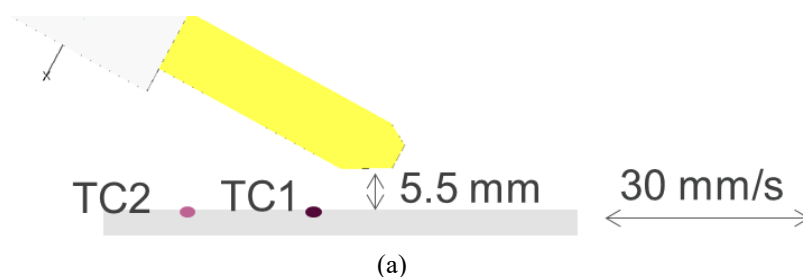


Figure 3 (a) Schematic of transient thermal FE simulation with constituent materials. (b) Oscilloscope measurement of instantaneous electrical power for a single pulse with same parameters as that used in the AFP trial. (c) Comparison between thermocouple measurements and the digital twin from the initial trials for a two-ply quasi-isotropic (QISO) layup on an ambient tool with pulse parameters of 250V 90 Hz 1.5 ms 75 mm/s.

Since the optical aspect of the simulation is valid and the key thermal diffusivity parameters measured, a finite element (FE) simulation was built within ANSYS Mechanical with supplemental ADPL scripts using the methodology described in [2]. The simulation is Eulerian with an advective term added to the heat flow equation as shown in (4) and solved as a transient thermal problem over a period of 1.5s to ensure a quasi-equilibrium state. The validated optical simulation output results shown in figure 2 were imported into the FE simulation as pulsed heat flux boundary conditions as shown in figure 3 (a), with the LFA and DSC measurements used to describe the PAEK LM film. The IV behavior of individual pulses was measured using a Tektronix MDO 3024 oscilloscope, as shown in figure 3 (b), giving an electrical pulse energy and this was converted to an optical pulse energy using the 37.6% efficiency value determined in [1].

In parallel to the development of the thermal simulation, AFP layup trials were performed using a commercial 6kW pulsed Xenon flashlamp system built by Heraeus attached to a Coriolis C1 robot. Layup was performed on an aluminium table with a 1 mm thick fiberglass interlayer and a 0.05 mm thermalimide film, below the first ply of PAEK LM material. Layup was performed in QISO orientation and system parameters of 250V 90 Hz 1.5 ms 75 mm/s were used to perform the AFP process. Thermocouples were placed between the thermalimide and first ply of PAEK LM film and the tooling and fiberglass, providing reliable thermal measurements. The data from the thermocouple measurements, as well as predictions from the thermal simulations are plotted together in figure 3 (b). As figure 3 (b) demonstrates, the initial thermal simulation appears to closely match the shape of the heating curve: but the overall result is conservative. A further simulation runs at both 42% and 47% assumed conversion efficiency suggests that the tape is starting to heat earlier than predicted and there is an additional heating effect that heats samples before the main Xenon flashlamp heating process commences.

5. Investigation into Radiative Heating Effects



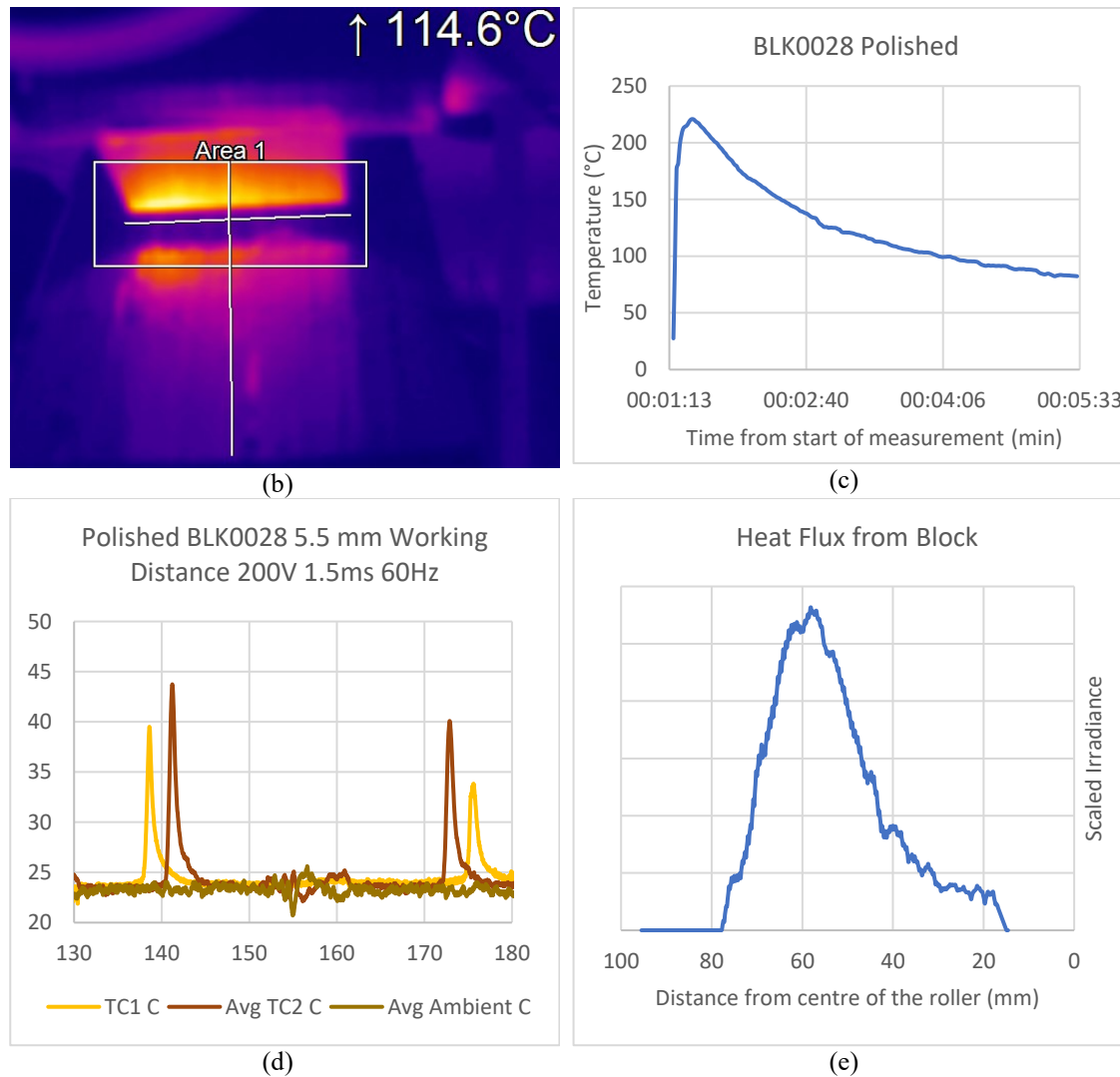


Figure 4: (a) Schematic of experiment designed to prove existence of radiative heating of the substrate tape from the light guide. (b) Thermal camera still capturing the heating of the quartz block after 60s of operation at 200V 1.5 ms 60 Hz for a 6 kW system. (c) Thermocouple measurement of a block cooling after operating in the same conditions as (b). (d) Thermocouple measurements on the surface of the PAEK LM material after pulsing was completed, confirming radiative heat transfer. (e) Estimated heat flux from block heating deduced by running the thermal simulation in “reverse”.

Further analysis showed that an additional radiative heating process originates from the quartz block, which functions as a light guide, heating up whilst the system is powered and this heat transferring to the composite tapes via radiation. This requires characterization so that the thermal model is less conservative. A schematic of the test sample is shown in figure 4 (a) and to characterize the additional radiative heating effect, a 6kW pulsed xenon flashlamp system ran at 200 V 1.5 ms 60 Hz for one minute under observation of a thermal camera. Once pulsing was completed, a thermocouple was placed on the surface of the quartz block and sample of PAEK LM composite material with two thermocouples on the surface was run under the system at 30 mm/s with the end of the light guide being 5.5 mm above the thermoplastic sample. As the

thermal camera and thermocouple measurements of the block show in figures 15 (b, c), it can reach several hundred degrees on the surface and can potentially be locally hotter on the surface close to the back facet interface that appears to be a heating source. Cutting the quartz will cause surface imperfections at facet edges, preventing a small amount of energy escaping as light. This energy will be converted into heat at this edge, providing the mechanism for heating the block and subsequent radiative heat transfer. Figure 4 (d) contains the sample surface thermocouple results and shows that the heating effect will heat the tapes even if the system has finished pulsing. This shows that this effect will need to be accounted for in any simulation tool, unless the block heating can be minimized via surface finish or AR coatings.

Finally, by running the thermal simulation in reverse, it was possible to obtain an estimate for the surface irradiance from the radiative block heating as shown in figure 4 (e) and this looks reasonable based on solutions with an additional heat flux boundary condition. 3D radiation simulations built in ANSYS Mechanical with the same geometry, with a thermal heating boundary condition up to a maximum of 1000°C show similar curves to figure 4 (e). This suggests that with careful thermal characterization of the quartz light guide during operation, an integrated simulation tool with a 3D thermal radiation simulation can be used to provide accurate estimates of nip point temperature.

6. Conclusion

Presently, a conservative “digital twin” has been produced to describe the AFP process with a pulsed Xenon flashlamp system. The reason why the simulation under-predicts “nip point” temperature is understood and is the result of IR radiation originating from the quartz light guide, used to direct optical energy, as it heats up during processing. Current effort is going into characterizing this effect so that it can be understood, possibly mitigated against, and included in an already good digital twin and improve its accuracy further.

7. Acknowledgements

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 886549.

8. References

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