CHARACTERIZING REFLECTANCE PATTERNS OF UD CF/PAEK COMPOSITES FOR LASER ASSISTED FIBRE PLACEMENT

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ABSTRACT

In-situ consolidation during laser assisted fibre placement (LAFP) has the potential to provide a fast and cost-effective manufacturing solution, that can be used for manufacturing large scale aerospace components. The processing temperature plays a vital role in obtaining consistent consolidation quality and interlaminar bond strength when manufacturing parts with in-situ consolidation. The heat flux distribution may be influenced by the reflection patterns of a composite surface, and therefore accurate descriptions of these patterns are important to obtain a good prediction of the thermal response during processing. The present study proposes a fast methodology to characterize the reflective patterns of a composite surface subjected to near-infrared laser light under a shallow incidence angle, using a technique based on high dynamic range imaging. It is observed that, in line with other studies, the reflection pattern of a CF/LM-PAEK composite tape changes considerably with fibre orientation. Moreover, the radiance maps of the reflected patterns showed a 15% decrease in the light received on the screen for a composite under 45° fibre orientation in comparison to same light shone on a sample with 0° fibre orientation.

1 INTRODUCTION

The application of thermoplastic composites (TPCs) in the aerospace industry is increasing due to the need for more sustainable and lightweight solutions. As such, the range of applications for thermoplastic composite materials is expanding towards large scale structures with increased geometrical complexity. This trend is made possible due to the emergence of automated manufacturing techniques, such as laser assisted fibre placement (LAFP) and laser assisted tape winding. The potential of this technology for large and complex structures is recently showcased in the STUNNING project [1,2], which featured an 8.5 m long fibre-placed fuselage section.

For in-situ consolidation during LAFP, the processing temperature plays a vital role in obtaining consistent consolidation quality [3]. In the case of laser assisted fibre placement, the material is heated to the desired processing temperature by means of high-intensity near-infrared (NIR) light. The resulting heat flux distribution on the tape and substrate during the LAFP process can be estimated by means of a ray-tracing approach, which for high accuracy should account for the anisotropic reflection patterns of a composite tape [4,5].

Several studies have already proven the dependence of the fibre orientation on the reflection profile of thermoplastic composite tapes [4-6]. The laser light does not simply reflect off of a composite surface in a specular manner, but instead scatters in multiple directions due to the orientation and shape of the carbon fibres embedded in the matrix. This effect, where the light scatters of a cylindrical fibre, is schematically shown in Figure 1, and is one of the important aspects when understanding the source for the differences in the processing temperature for substrates with various fibre orientations.

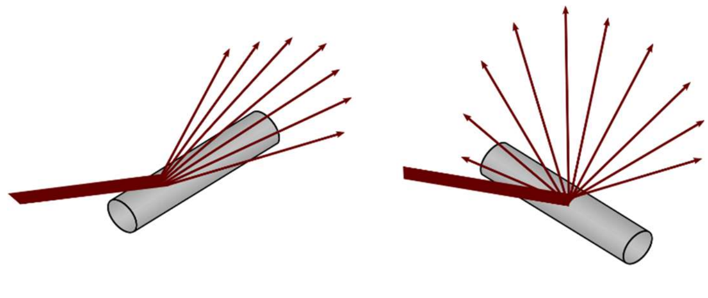


Figure 1: Scattering of light from a carbon fibre, with the laser oriented parallel to the fibre orientation (left, α=0°) and perpendicular to the fibre orientation (right, α=90°).

With the scattering mechanism explained here, characterizing the anisotropic reflection patterns of a unidirectional thermoplastic composite will help to support the optical-thermal process simulations for LAFP, allowing for better predictions of the thermal response. Using gonio-reflectometers and integrating spheres [5] it is possible to establish the necessary numerical values. However, the procedure using such a gonio-reflectometer to measure the reflectance distribution of a composite tape may take up to three hours for a single location in a specimen [5], and provides information on the reflection distribution for the entire hemisphere.

This research proposes a fast methodology for experimental characterization of reflection patterns of unidirectional TPC tapes, for which the pattern projected on to a 2D plane can be obtained in a few minutes. The approach is based on high dynamic range (HDR) imaging, leading to information about both the reflection pattern as well as the light intensity distribution of a thermoplastic composite material suitable for fibre placement. This framework may help to understand possible fluctuations in the processing temperature originating from variations in the optical behaviour of TPCs.

2 MATERIALS AND METHOD

2.1 Unidirectional thermoplastic composite tapes

A unidirectional carbon fibre reinforced LM-PAEK composite (Toray, Cetex TC1225) was considered for this research. The tape has a thickness of approximately 0.14 mm, and was slit to a width of 6.35 mm. The fibres in the pre-impregnated tapes are of type T700G, with a fibre volume fraction (V_f) of around 60% and a fibre areal weight (FAW) of 145 g/m^2.

The slit tapes are wound up on a spool, where the outward facing surface is taken as the top surface of the tape. Only the light scattered from the top surface is presented in this study. However, differences between the top and bottom surface may be noteworthy for future investigations.

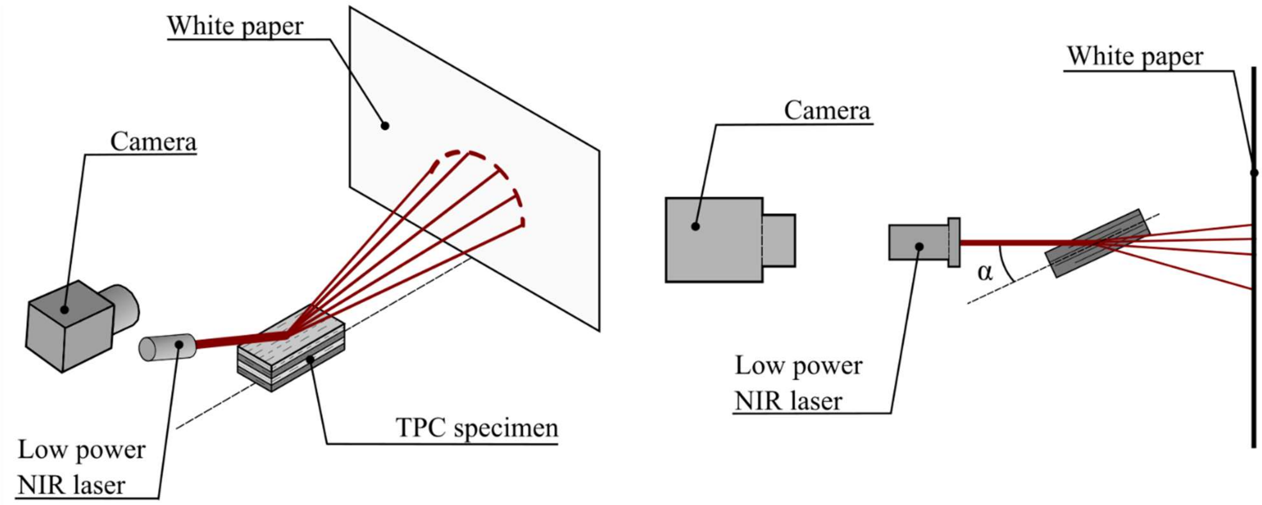
Given the thickness of the tape, it is assumed that the CF/LM-PAEK tape does not transmit any light through the tape. The reason for this assumption is that light is either reflected or absorbed within the top layers of carbon fibres in the tape specimen [4].

2.2 Experimental setup for image acquisition

The reflection characterization setup consists of a camera, near-infrared laser and white paper reflection screen. All components are placed inside a dark enclosure to prevent ambient light from disturbing the measured reflection pattern, as shown schematically in Figure 2.

The laser used in this setup is a 5 mW NIR diode laser with a wavelength of 980 nm (CPS980, Thorlabs Inc.). This wavelength is similar to that of the laser heating system used on actual LAFP equipment. The difference with an actual LAFP laser is that in this case the laser intensity is significantly lower, and therefore the tape specimen does not heat up when placed in the setup. Moreover, the spot size of the laser in an LAFP system is often a rectangular shape, whereas for the test setup the laser spot is circular or slightly elliptical.

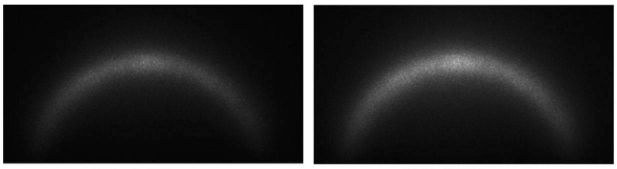
The spot size of the 5 mW laser in the setup was set to 2 mm in diameter by means of a diaphragm. For this investigation, the laser angle was set to 19 degrees with respect to the surface. Consequently, the projected laser spot on the composite surface for this incidence angle is an ellipse, with is semi-major axis measuring almost 6.2 mm, and the semi-minor axis of the projected spot still measuring 2 mm. This setting for the laser spot size was chosen, such that edge effects can be avoided when projecting the laser over the width direction of the slit composite tape (i.e. when α=90°, in the most extreme case).



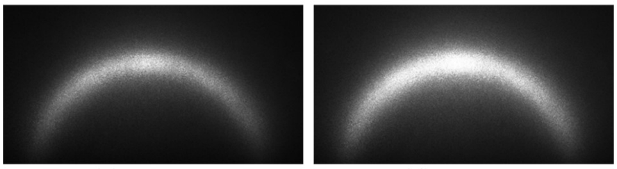
(a) (b)

Figure 2: Schematic representation of the developed setup to characterize the reflection patterns of thermoplastic composite tapes, placed inside a dark enclosure to reduce ambient noise.
(a) isometric view, (b) top view

The camera used in the test setup is sensitive to light in the near-infrared range as well as the visible spectrum, equipped with a monochromatic CMOS sensor and a 10 MP resolution (UI-5490SE, IDS Imaging Development Systems GmbH). The camera is controlled via a Python interface (based on the package *pyueye*) to acquire an image series at different exposure settings. An example of the images acquired using the described procedure is shown in Figure 3.



(a) 100 ms (b) 200 ms



(c) 400 ms (d) 800 ms

Figure 3: Illustrative example of images acquired at varying exposure times, at α=0°.

The anisotropic reflection profiles contain regions with both high as well as low light intensities. By acquiring a series of images at different exposure or shutter times, both ends of this intensity profile can be captured. The obtained image series at varying exposure times can be combined into a single image with the same unit, thereby providing a radiance map. The final radiance maps presented in the results were obtained based on a series of 8 images for each radiance map, with the exposure times ranging from 50 ms to 1800 ms. The utilized exposure time range can be seen in Figure 4.

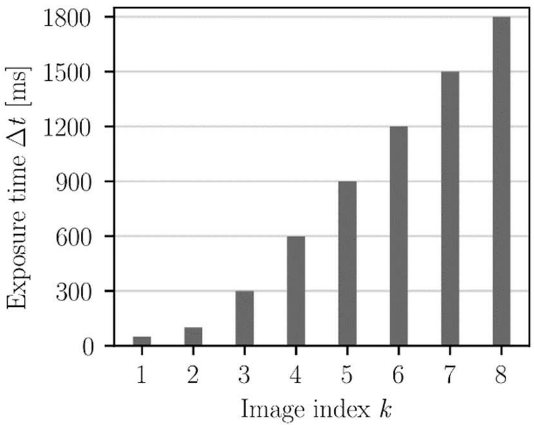


Figure 4: Plot of the exposure times used for a full image series, used for computing the final radiance maps

2.3 Image processing: radiance map computation

The acquired images were processed to obtain a radiance map covering the high and low intensity regions in the pattern. This procedure was done by using a simplified version of high dynamic range (HDR) imaging, sometimes also referred to as exposure fusion. This exposure fusion technique is based on the assumption of reciprocity in the camera sensor, as also explained by Debevec and Malik [7]. The concept states that for an imaging system, the optical density is only a product of its irradiance and exposure time Δt. Therefore, doubling the scene irradiance and halving the exposure time will lead to the same optical density on the film or sensor.

Additionally, the exposure fusion can be simplified further since both the camera and scene to be captured are kept stationary and fixed, such that any motion compensation is ignored. The exposure fusion approach currently implemented is done under the assumption that the response of the CMOS sensor is linear with respect to the light intensity in the scene.

Based on the aforementioned assumptions, the image sequence is fused into a single radiance map, based on equation (1), which gives the radiance E for each pixel i as:

$$E_i = \left(\frac{1}{N}\right) \sum_{k=1}^{k=N} \frac{Z_i^k}{\Delta t_k} \tag{1}$$

Where, Z_i^k is the pixel brightness of the ith pixel of image k, given a series of N images, while $\Delta t_k$is the exposure time of the k^{th} image. Note that the obtained radiance value E_i is in pixel radiance unit, and can be converted to a physical unit, such as W/m^2, upon calibrating with known values. For the presented results no calibration is performed.

Implementing the described procedure based on the example image series shown previously in Figure 3, leads to the resulting radiance map as presented in Figure 5.

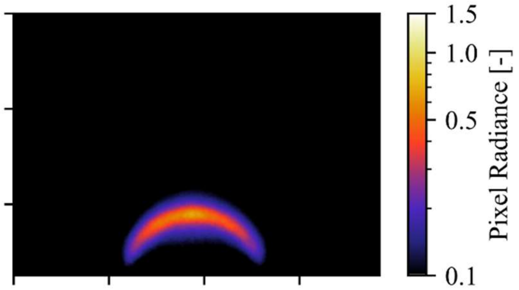


Figure 5: Computed radiance map based on the illustrative example series of four images as presented in Figure 3.

Based on the radiance map, it is possible to derive several other quantities, such as a total scene irradiance. The total scene irradiance can be computed by summing the radiance values of all pixel locations, E_i. In future work, other parameters related to the shape of the pattern will considered as well, allowing to quantify slight deviations and variations in the pattern. In that case, the parameters could be defined based on the theoretical bi-directional reflectance distribution functions (BRDFs) as presented by Pharr [8].

3 RESULTS

3.1 Radiance maps for varying fibre orientations

A single CF/LM-PAEK tape specimen was tested under different fibre orientations, ranging from 0° to 45°, in steps of 15°. The radiance maps corresponding to these fibre orientations are shown in Figures 6a to 6d respectively. Qualitatively, a large difference can be noted in the shape of the pattern, similar to the findings by Stokes-Griffin et al. [4]. The reflection pattern features a crescent shape under 0° fibre orientation (as observed in Figure 6a), that widens and opens up on one side as the fibre orientation (α) is increased.

In line with the findings from earlier studies, the observed effect is likely due to the light reflecting off the carbon fibres. A further proof on this hypothesis would be to show that the matrix is partly transparent for light in the NIR wavelength range.

Lastly, the reflection pattern for the 0° fibre orientation could help to deduce effects related to asymmetries in the tape. When closely observing the tails of the left end and right end of the crescent shape, it is possible to note the differences in light intensities between both ends. Whether this is truly related to a slight asymmetry in the fibre morphology in the specimen, or whether there is a small misalignment in the developed setup, should be studied further.

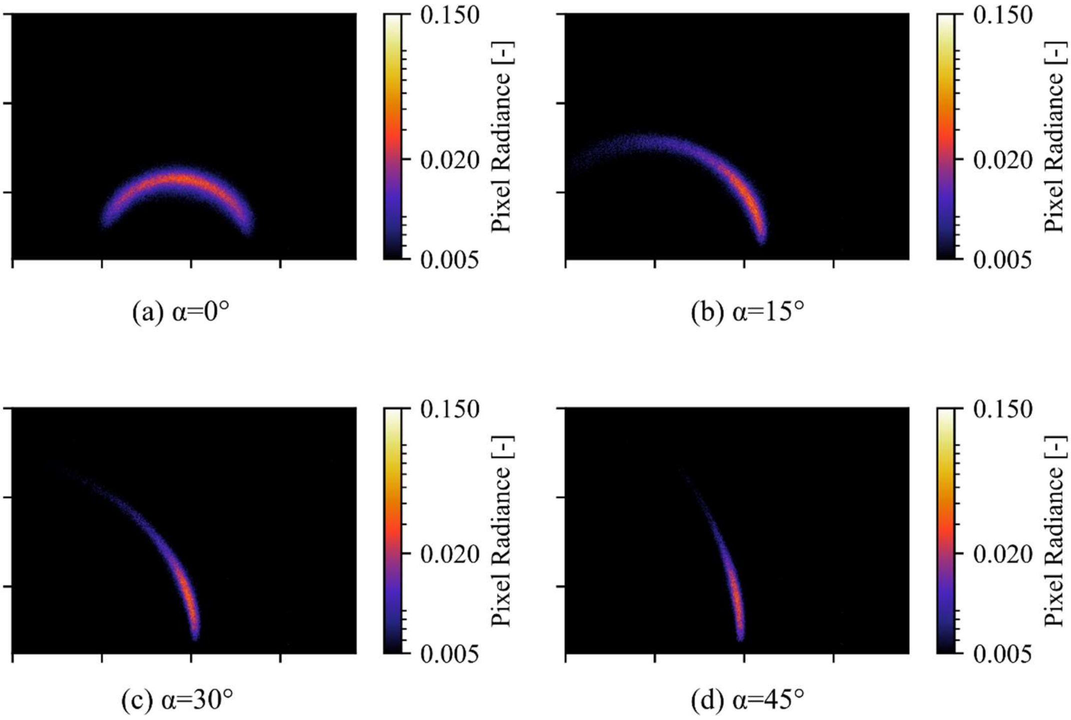


Figure 6: Radiance maps of a CF/LM-PAEK tape in as-received state, for the fibre orientations α as indicated.

3.2 Computation of total reflected light intensity for varying fibre orientations

Due to the change in reflection pattern under different fibre orientations, the total amount of reflected light is likely to differ as well. Based on the radiance maps presented in Figure 6, as well as additional intermediate specimen fibre orientations, the total scene irradiance was computed by summing over the pixel radiance values in each radiance map. The resulting normalized scene irradiances as a function of the specimen fibre orientation are shown in Figure 7.

It is important to note that with this method, only the light captured on the screen is accounted for. The amount of reflected light that falls outside of the field of view of the camera cannot be estimated using the current method, and therefore influences any conclusions based on these results.

Despite the limitation on the field of view of the camera, the total scene irradiance provides a relative measure for the total amount of reflected light. The graph in Figure 7 shows that for higher fibre angles (up to 50 degrees), roughly 15% less light is captured in the radiance map. Consequently, this may relate to a lower Fresnel reflectance factor R, but the trend shown in Figure 7 is likely less extreme when one could consider the light reflected in the entire hemisphere above the surface. Possible deviations of this method can be quantified by performing a validation measurement of the same sample using, for example, an integrating sphere

The possibility for higher absorption at off-axis fibre orientations can be explained based on the effect of self-shadowing. As such, light that is scattered off in several directions (as was shown before graphically in Figure 1) may be blocked by neighbouring fibres and partially absorbed again.

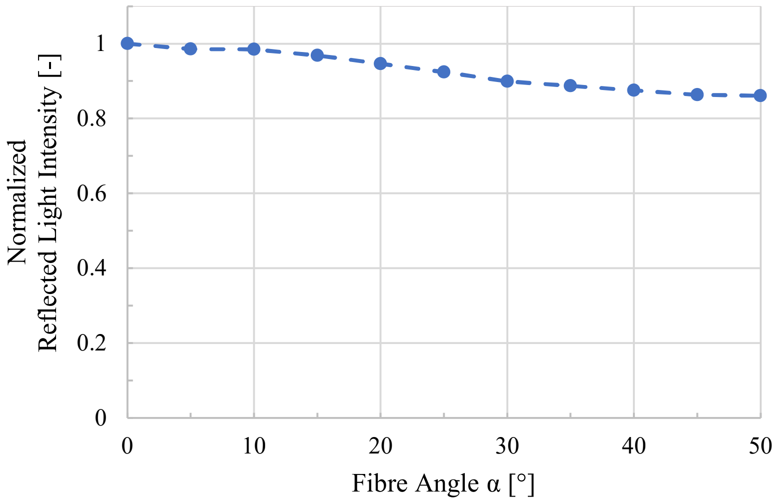


Figure 7: Graph showing the effect of fibre angle on the overall measured reflected light intensity, computed based on the radiance maps (normalized w.r.t. α=0°)

Lastly, calibration with a known physical value was not performed yet, and therefore the computed value is expressed as a digital number or pixel irradiance value. For this reason the graph in Figure 7 is normalized with respect to the value computed at 0° fibre orientation.

3.3 Discussion: Effect of reflection patterns in the LAFP process

With regards to the LAFP process, the results from Figure 6 as well as the trend in the reduction of the reflected light intensity in Figure 7 would indicate that different processing parameters are required depending on the fibre orientation in the substrate's surface. Since the thermoplastic composite tapes in an LAFP process are heated using a laser, the effect of differing fibre orientations, and hence changing reflectance, causes the heat flux distribution on the composite surface to change [6]. As a result, the nip-point processing temperature will be affected, leading to a decreased in-situ consolidation quality as the processing temperature deviates from the optimum. Reichardt et al. [9] have shown using an optical-thermal simulation study that a change in the reflective properties, as for instance an effect of changing the substrate fibre orientation, can lead to a considerable difference in the predicted nip-point processing temperature. This underlines the need for fast characterization method to obtain the appropriate numerical inputs that define the reflectance behaviour of a composite material.

Next to the importance of temperature predictions for LAFP using optical-thermal modelling, it is also worth to note that the reflective behaviour is likely affected by placement process itself, as another study already showed that the asperities on the tape surface may be flattened by the compaction roller [10]. Moreover, the distribution of fibres and matrix on the surface of the composite would subsequently be affected by the compaction force as well. As such, the results found in current study on the as-received composite tapes may differ from the reflection behaviour during the actual LAFP process.

4 CONCLUSIONS AND FUTURE WORK

This study proposed a fast methodology for characterizing the anisotropic reflection patterns of thermoplastic composite tapes subjected to NIR laser light. The acquired patterns, expressed as a radiance map, were shown for a unidirectional CF/LM-PAEK composite with fibre orientations from 0° to 45°. A large dependency of the fibre orientation was observed, likely due to the scattering from the cylindrical shape of the carbon fibre.

The current radiance maps, which were obtained in a matter of minutes, could already be used to provide qualitative insights between different material systems, batches and consolidation states of the material (i.e. before or after LAFP processing). To further correlate the obtained values to physical units, a calibration process would be required with a scene of known light intensity. To ultimately link the patterns to input parameters that can be used for optical-thermal modelling, a parametrization of the radiance maps is needed in terms of parameters of a bi-directional reflectance distribution function (BRDF). Furthermore, it may be useful to further detail the contributions of the fibres and matrix on the reflection pattern separately, to link the patterns with the tape morphology. Moreover, the influence of the laser assisted fibre placement process on these patterns is important as well, by testing tapes after placement, to improve the understanding of the current findings.

With regards to improvements in the image acquisition setup, it is possible to further investigate the linearity of the CMOS sensor. In more practical HDR imaging applications, a camera response function is often estimated and used to account for any nonlinearities introduced in the process of signal conversion.

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