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Title: The Effect of Process Parameters on First Ply Deposition in Automated Fibre Placement

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ABSTRACT

Automated Fibre Placement (AFP) is widely recognised as one of the most advanced processes for manufacturing structural composite components. Understanding the process remains at the forefront of academic/industrial investigation due to the myriad of parameters that affect the quality of the deposited tape. A novel AFP testbench, which included a heated glass tool, was developed to aid in the investigation of the material behaviour underneath the roller during compaction. The material behaviour was captured by using a camera directed at the compaction region, where the data was subsequently analysed using a vision analysis technique during a post-processing step. The results indicate that the use of a glass tool can help in quantifying the tape spreading when subjected to varying process temperatures as well as identifying various defects and features that can arise in a typical AFP manufacturing cycle.

INTRODUCTION

Composite materials are becoming an increasingly popular choice for the next generation of structural components. Their inherent design flexibility allows engineers to target a diverse range of applications within multiple sectors (aerospace, automotive, energy, etc.) through a variety of manufacturing techniques. Among these techniques, Automated Fibre Placement (AFP) is widely recognised as one of the most advanced processes for manufacturing structural composite components [1]. In comparison to manual processes, it can offer significantly higher repeatability, productivity, and is ideally suited for large parts with simple geometry. Despite the advances in recent years, understanding the manufacturing process remains at the forefront of academic and industrial investigation due to the myriad of parameters (such as head inclination, speed, pressure, temperature) that affect the quality of the deposited tape [2][3].

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Successfully depositing the first ply remains a challenge and the resulting quality will carry through lay-up. In particular, the conditions at the nip point, being a region where access is typically limited to just fore and aft of it, are vital in determining how a deposited tape behaves throughout the processing cycle, as this is the moment in which the tape is expected experience the most deformation.

In this study, a lab-scale AFP testbench was designed and constructed to enable safe, quick and simple manufacturing experiments for a variety of materials and process parameters, utilising modular subsystem equipment that can be easily installed to reproduce the environment native to an industrial AFP cell. The novelty of this testbench is the inclusion of a heated glass tool (Figure 1), which not only allows for direct heating of the material but also for new methods to be employed when investigating the deposition process – as previously unobservable regions due to the opaque nature of traditional tools are now accessible.

**METHODOLOGY**

**AFP TESTBENCH DESIGN**

A bespoke laboratory testbench, initially designed and constructed to enable on-the-fly process control in AFP [4], was used for the research presented in this study. Figure 1 highlights the main subsystems of the rig. The head (mounted on the gantry) contains the compaction unit and heat lamp, which runs along two parallel linear rails fixed to the frame. This allows for simple x-direction tape depositions, where the movement of the rig is controlled via a CNC motion controller. The modular design of the rig allows for easy installation, adjustment, and modification of components such that a variety of manufacturing process conditions can be recreated. The compaction unit features a PID controller such that the user can specify a set force to act on the tape material during deposition. In addition to this, the IR (Infra-Red) lamp (Krelus G3-6-5mm) is also designed to be controlled through a PID controller to ensure a constant temperature at the point of interest (measured by a Optris® CS infrared pyrometer, supplied by Optris GmbH).

Figure 1. (a) CAD model of AFP testbench showing key subsystems. (b) Diagram of setup for capturing the tape material behaviour under the roller.
One of the key features of this testbench is the inclusion of a heated glass tool, which allows for the material behaviour underneath the roller to be captured via the use of a camera (Manta G-917 supplied by Allied Vision), a mirror (inclined at 45° to the horizontal) and an LED lighting arrangement. Figure 2. The tool is constructed from two layers of engineering glass which sandwich a network of nichrome wires suspended in an optical-grade silicone resin. This design allows for the tool to heat up when a current is passed through the nichrome wires (due to resistance heating). Figure 3 depicts the key features of the glass tool. The temperature of the tool was checked by using a FLIR E60 infrared camera (as shown in Figure 4) and a K-type thermocouple placed on the surface of the tool with a small quantity of thermal paste to ensure good thermal contact. It should be noted that the AFP testbench is designed to accommodate interchangeable tools. As such, a second aluminium tool (with embedded heating elements) was designed and constructed to provide further data should a more standard tooling option be desired for future deposition tests.

Figure 2. (a) Close up view of tape material (post-deposition) on glass tool and (b) camera, mirror, and light setup underneath the glass tool.

Figure 3. Cross section view of heated glass tool used in this study.
DEPOSITION EXPERIMENTS

For each experiment, 400mm of tape material (½” IM7/M91 prepreg slit tape supplied by Hexcel), was deposited onto the glass tool. Prior to each test, the tool was cleaned with acetone and the test parameters were set according to Table I. The images from the camera under the tool were captured at a rate of 10Hz and stored for subsequent processing. The nominal values for the deposition speed and compaction force were 1200 mm/min and 50 N respectively.

<table>
<thead>
<tr>
<th>Test case</th>
<th>Tool temperature (°C)</th>
<th>Heat lamp temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>RT (room temperature)</td>
<td>RT</td>
</tr>
<tr>
<td>B</td>
<td>35</td>
<td>RT</td>
</tr>
<tr>
<td>C</td>
<td>RT</td>
<td>50</td>
</tr>
<tr>
<td>D</td>
<td>35</td>
<td>50</td>
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</tbody>
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VISION ANALYSIS TECHNIQUE

A script was developed in the NI (National Instruments) Vision Assistant environment to extract the tape width dimension under the roller. The image is initially calibrated (based on the 10mm spacing between the nichrome wires along the length of the glass tool- as this is a known dimension) and a grayscale dilation is applied to remove the pixels that occupy the nichrome wires. This aids in the calculation of the tape width measurements, which is carried out by using the “detect edge” function, where the transition between the dark tape and the brighter roller can be distinguished. From this, the “calliper” function provides the distance between the two previously identified edge points – thus returning the measured tape width. Batch processing is employed to automate these series of steps for the entire image collection for each experimental test run, so that the tape width can be captured as a function of time.
RESULTS AND DISCUSSION

TAPE WIDTH DURING COMPACTION

The average width of the tape under the roller during compaction throughout the tape deposition, as computed by the NI Vision Assistant software, was seen to generally increase for the temperature-assisted deposition experiments, as shown in Figure 5. This trend is understandable given that unidirectional materials tend to spread in the direction transverse to the fibres under compaction loading at temperature, explaining why the values across all cases are higher than the nominal as-supplied tape width of 12.7 mm. This behaviour is seen to be more noticeable at higher temperatures due to the reduced material viscosity which enables greater material deformation.

Though the “High” set temperature of the heat lamp (50 °C) was greater in magnitude than the “High” setpoint of the glass tool (35 °C), the greatest tape spreading was measured in the deposition experiments which had the tool as the heat source. This could be due to the fact that the tool temperature was more stable due to its constant temperature and large heat capacity as opposed to the fluctuating temperature recorded by the pyrometer during the experiments – whose effect is partially diminished once the tape exits the heated area and enters the compaction zone. This fluctuating temperature in the material due to the heat lamp can occur if the pyrometer moves slightly off the tape target point and onto the roller, which sees thermal cycling after each revolution – potentially explaining the larger error bars (standard deviation) for this test case.

Figure 5. Plots of averaged tape width dimension in the compaction region across the entire deposition length. Black dotted line represents nominal as-supplied tape width. Error bars indicate standard deviation.
TAPE WIDTH AFTER COMPACTION

A second set of points (located 32 mm after the compaction region along the tape length, labelled as Aft-roller zone width as Seen in Figure 6) for each test image was captured in the Vision Assistant script. This enabled for the tape width to be captured after the material had undergone compaction and to check if it had deformed. The data shows that only minor changes in width were seen across cases B, C and D – corresponding to width reductions of 0.160 mm, 0.073 mm, and 0.178 mm respectively. Case A did not see any change in tape width between the compaction zone and the aft-roller region. This suggests that the material is dimensionally stable and very little occurs in terms of the lateral shrinkage once it has been deposited.

Figure 6. Photograph of tape material being deposited, showing locations for width measurements at both the “compaction zone” and “aft-roller zone”.

GENERAL OBSERVATIONS

In addition to the calculation of key tape dimensions, other data such as compaction area size, tool adhesion quality, and fibre waviness (though not extensively explored in this study) could be inferred from the test image data. Figure 7 illustrates a single image for both cases A and D, where a slight pucker can be seen just forward of the compaction region in case D. This feature eventually gets flattened out and the data shows no further indication of a defected tape, though it can be assumed that a different combination of processing conditions (whether it be process parameters, tape steering, material systems, etc.) can generate more profound defects which would be able to be tracked and analysed using this novel experimental setup. The ability to investigate this previously unobservable region opens a realm of possibilities for machine vision techniques to help the user understand the fundamental
material behaviour throughout the AFP manufacturing cycle. This can become extremely useful when particular material systems need to be characterised or when a processing window requires development for the introduction of a new material system.

Figure 7. Photographs of tape material underneath roller for conditions Case A and Case D.

CONCLUSIONS

A novel testbench, which included a heated glass tool, was developed to aid in the investigation of the material behaviour underneath the roller during automated deposition processes. This was achieved by using a camera directed at the compaction region (via a mirror) to capture images of the deposition experiments for subsequent post-processing. This was done such that the tape width could be captured at the moment the material enters the compaction zone as well as just aft of the roller. Four test cases (each with varying levels of temperature from both the IR heat lamp and the heated glass tool) were carried out to investigate the influence of these process parameters on the tape behaviour. Overall, it was shown that the tape material remains dimensionally stable as evidenced by the minor tape spreading captured in the compaction region. Other qualitative features such as fibre waviness and tape defects, though not analysed, were discussed for subsequent research opportunities, given that flat and straight deposition experiments are not likely to yield major defects in the material. This would require for the vision analysis algorithms to be further developed in order to capture these features.

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