INVESTIGATION OF THE TEMPERATURE INFLUENCE IN THE CONTEXT OF AUTOMATED FIBER PLACEMENT LAYUP ON DOUBLY CURVED TOOLS

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ABSTRACT

This study aims to investigate the induced effects on the temperature requirements due to the use of a complex geometry, while also gathering data for two types of materials supplied by Toray Industries. Automated Fiber Placement (AFP) has been sweeping the composites manufacturing industry due to its ability to manufacture parts with high speed, repeatability, and process quality. As a result of the advancement of the machines' capabilities, it is being used to manufacture parts with higher degrees of complexity. The effect of the shape's complexity on process parameters, namely temperature, is not well understood. Experiments consists of using zero- and ninety-degree constant angle layups on a complex tool to thoroughly examine the effect of curvature on the AFP process. Results show that material selection is vital to ensure high quality parts because of the difficulties with adhesion to the complex surface. Repeated layups indicate that an increase in temperature is necessary in concave areas to overcome bridging and steering defects. Heater deviation can also vary and will result in local increases and decreases in temperature. All of these effects must be accounted for when process planning, and should be monitored during AFP manufacturing to ensure high quality parts.

Keywords: Automated Fiber Placement, Process Parameters, Temperature Influence, Complex Tools
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DOI:

1. INTRODUCTION

Automated Fiber Placement (AFP) is an automated process that consists of a gantry/robotic system with an attached fiber placement head. The AFP head enables multiple strips, or tows, to be laid onto a tool surface to manufacture the laminate. Adhesion between the incoming tows and substrate at specified speeds is ensured by using appropriate process conditions such as heating, compaction, and tensioning systems. A series of tows forms a course, courses are then combined to create a ply, and multiple plies create a laminate. AFP has been consistently progressing the ability to manufacture composite parts with high speed, repeatability, and improved quality. This had led to more industries adopting and researching the technology. Flat, low curvature geometries, and cylinders have been the focus areas of research, but AFP in now being used on parts with increasing complexity. Moreover, AFP is also explored for small and medium parts, versus the traditional large structures. Previously complex parts had to be manufactured through manual lay-up which is a costly and time-consuming process – as well as having accuracy issues – where each composite layer is placed by hand. Although such a process allows for a wider range of applicable surface complexity, it is not feasible for larger structures and the adaptation of the AFP process is beneficial. The AFP machine enables the process to be fully automated with little machine stoppage and manual work. But when AFP defects occur, laying is put on hold and material has to be reworked. The complexity of the part has significant effects on the required AFP process parameters to prevent these defects. There is a difference between 1D, 2D, and 3D layups in terms of process parameters and defect occurrence [1]. 2D steered layups have changes of steering radius within a single ply, but 3D layups also have a change of tool curvature within a single course. This makes it difficult to find good process settings for an entire 3D layup. In order to achieve this, the process parameters must be understood as well as the parameters effect on defect occurrence and their inter-relation. The essential parameter to be considered in this study is temperature, although optimization of compaction, feed rate (head speed), and tow tension are also vital for high quality layups.

Temperature is a crucial factor to ensure proper adhesion of incoming tows to the substrate. Research has shown that proper process temperatures lead to increased adhesion and higher overall part quality [2]. The applied temperature must be in a certain processing window: high enough to ensure adequate material tackiness, but not so high that material degradation occurs. The importance of sufficient temperature is increased when laying up on complex tools with the combination of concave and convex curvatures. The extent of possible curvatures of a tool must be within a certain limit to prevent collisions with the machine being used [3]. Even with this limitation, the curvatures can be severe enough to warrant attention to the associated effects, however published research is limited on this topic. [4] presented a decomposition of the heating elements in AFP to enable better across the roller control of the heat received by the substrate. When placement is over complex parts, heat is received differently by the substrate due to differences in distance across the roller. There are multiple defects that can occur from improper adhesion, however the main defects due to tool curvature are bridging and steering induced defects such as wrinkles, puckers and angle deviation. A bridging defect occurs when a tow does not fully adhere to the concave surface, resulting in a gap between the tow and substrate [1]. Steering is induced by the projection of a constant fiber angle onto a curved surface, producing a tool path with in-plane curvature. Although the radius of the tool path is not significant compared to the minimum steering radius, it produces defects commonly seen in steering experiments. The notable defects of this study are folds, wrinkles, and further bridging. Tow pull up occurs due to the change in length between the inside and outside of the tow. This change in length causes tensile strains leading to the outer part of the tow losing its adherence to the substrate, and possibly bridging [5] [6]. The combination of the tool curvature and induced steering creates a challenging lay-up scenario.

Preventing the aforementioned defects is important to ensure optimal part quality and performance. This study will delve into the required temperatures for proper adhesion along a doubly curved tool. The effects will be quantitatively examined to observe the trend of the necessary temperatures, and a lay-up of all courses will validate experimentation. The knowledge gained will assist in increasing the quality of complex parts produced by AFP machines, therefore expanding its applicability. The remainder of the report will consist of 4 sections. Section 2 will explain the experimental setup and procedures used during experimentation. Section 3 will present the results of trials with single courses and entire ply layups. Section 4 will discuss the findings and their significance. Lastly, Section 5 will consist of a summary of our work and suggestions for future research.

2. EXPERIMENTAL PROCEDURES

2.1 Experimental Setup

These experiments were carried out using an Ingersoll Machine Tools Lynx AFP machine and a doubly curved tool made out of aluminum, both of which can be seen in Figure 1 and Figure 2. This tool allows for experimentation on a doubly curved surface with varying curvature in the zero direction. Heat was applied using the humm3® [7] head attachment seen in Figure 2 (b). This heating source is a flash lamp with rapid heating capabilities along with a small head that makes it beneficial for complex tools. The shape of the crystal allows for focused heating on the substrate and prevents heating of incoming tows. It is known that the temperature is directly related to the power of the heater, and the power is dependent on three variables: voltage, frequency, and pulse time [8]. By setting the frequency and pulse time at 60 Hz and 2000 ms respectively, we can obtain increments of power by controlling the voltage. The lowest voltage used was 100 V while the highest used was 220 V. Head cooling was also used to ensure the tows inside the AFP head remained cool to prevent them from getting tacky and sticking inside the head. The head cooling temperature was set to be 6-8 °C.

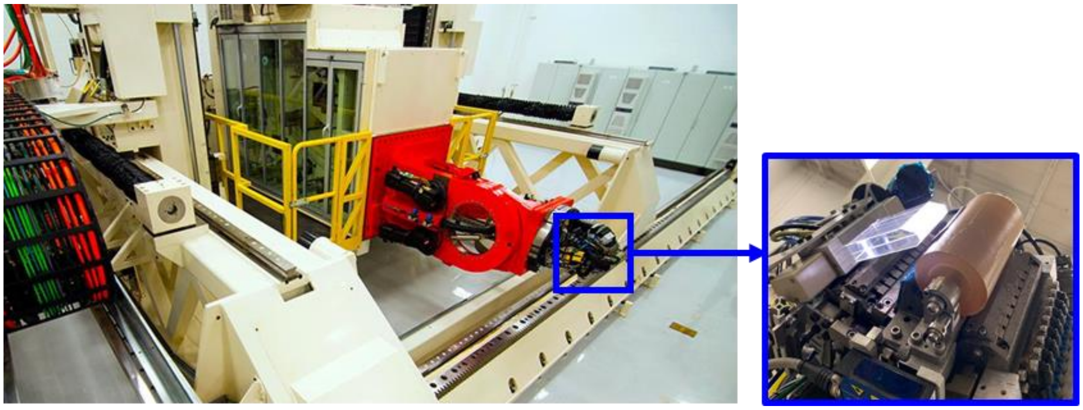

(a) (b)

Figure 1: Image of the AFP machine and fiber placement head

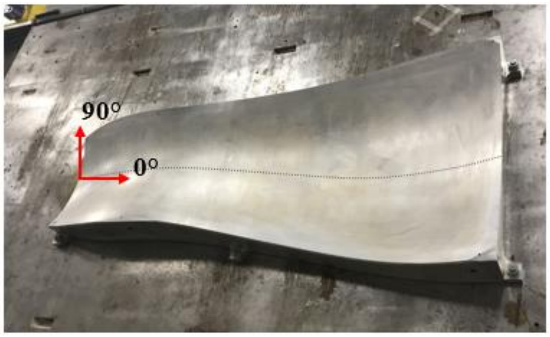


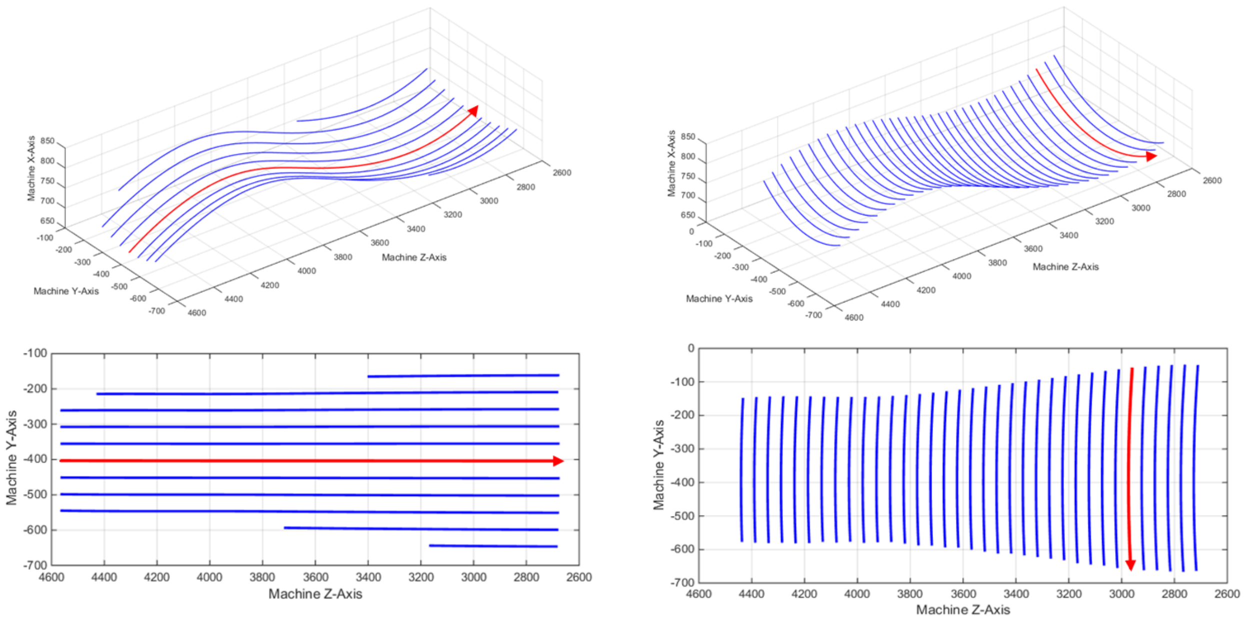
Figure 2: Image of the doubly curved tool used during experimentation

Furthermore, the experimentation used two materials supplied by Toray Industries: material A and material B. Both materials had a tow width of 6.35 mm (0.25 in), and 8 tows were used to create the courses. Different materials were used to ensure that the results were valid between materials with varying properties.

Programming of the AFP machine was performed using the Ingersoll Composite Programming System (iCPS). Careful consideration was taken through simulations and dry runs to ensure that any possible collisions were avoided. After ensuring there were no collisions, courses were ran to determine the highest speed that could be achieved while also remaining constant. This was determined to be 10 m/min. Similar to the speed, the other process parameters remained constant to explore only effects on temperature. The compaction was set at 445 N (100 lbs) and was applied using a roller with a width of 5.5 cm (2.2 in). Lastly, the tow tension was set at 3 N (0.67 lbs).

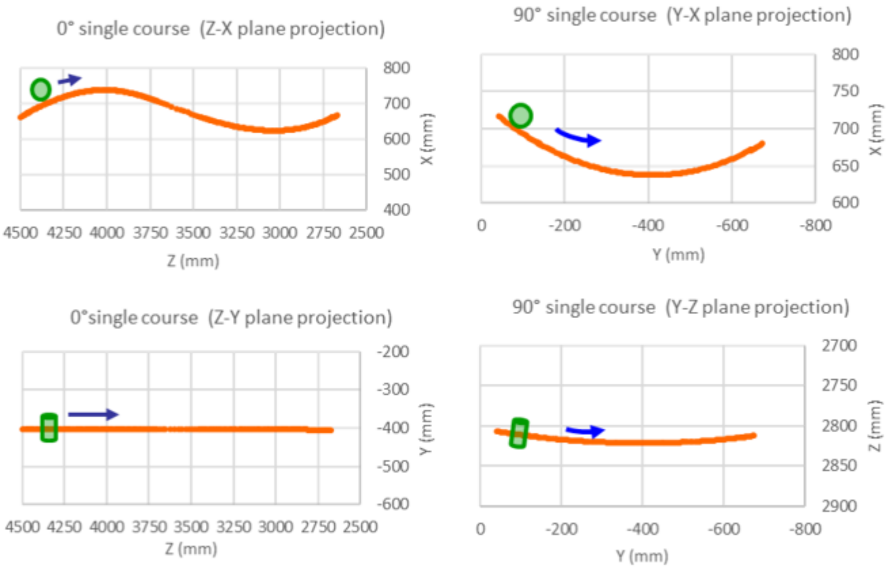
2.2 Experimental Procedures

A two-stage test plan was used to explore the effects that complex geometries have on required process temperatures. The first stage consisted of experimenting with a single model course in the zero- and ninety-degree directions. The experimental courses are highlighted in red in Figure 3. Four initial plies were laid before experimenting to eliminate variability and heat dissipation into the tool. The zero-degree courses are straight in the AFP roller travel direction, while the curvature of the tool varies significantly as illustrated in the x-z projection. Contrarily, the ninety-degree courses have a varying steering radius as illustrated in y-z projection, while the tool curvature is relatively constant as illustrated in y-x projection. The projections can be seen in Figure 4. This stage allowed for a detailed examination of the experimental courses to analyze any present defects, while also exploring the differing curvatures along the tool. The assessment of the defects was done visually and classified in two parts: (1) how well the incoming tows adhered to the substrate, and (2) how substantial the defects were. Using this assessment, the courses were categorized as either a fully tacked course, or a course that has defects. The fully tacked category includes courses that are fully adhered to the substrate with no large visible defects. The defects category includes courses that are partially or totally untacked from the substrate or have significant defects. Examples of each category can be seen in Figure 5. If a layup resulted in a course with defects, the temperature was incrementally increased until a fully tacked course was achieved. This data provides the lower bound of the materials processing window. The temperature measurements were acquired using a Graphtec data logger (GL980) and thermocouples placed onto the substrate material along the course. This allowed for measurements at various curvature values.



(a) (b)

Figure 3: (a) zero- and (b) ninety-degree courses



(a) (b)

Figure 4: (a) zero- and (b) ninety-degree courses with reference to roller direction

Stage two of the experiment was used to validate the results from stage one. In this stage, the layup was done for the entire surface to ensure that the required temperatures were valid across the part. Unlike stage one, this stage consisted of little intervention during the manufacturing process. Allowing the manufacturing to be completed ply-by-ply reflects the usual AFP process where each ply is laid and then inspected for defects.

3. RESULTS

3.1 Single Course Layup Trials

Figure 5 shows measured temperature and layup results with material A at multiple points along the zero-degree single course. Each point on the curved dotted line indicates measured substrate temperatures and inspection results at thermocouple locations along the single course. Temperatures are indicated on the y-axis of the graph, and visual inspection results are indicated by green circles (No defects) or red triangles (Defect occurrence). Red painted triangles represent defects such as lifted tows that occurred during layup, while hollow triangles represent defects of untacked tows that occurred at start of the layup. During the layup, machine feed rate (or head speed) and supplied voltage to the humm3® heater was constant. Therefore, the variation of material temperature might be due to the change of the distance between humm3® heater crystal and substrate material. However, in this case, maximum temperature difference was within 5 °C in single layup course.

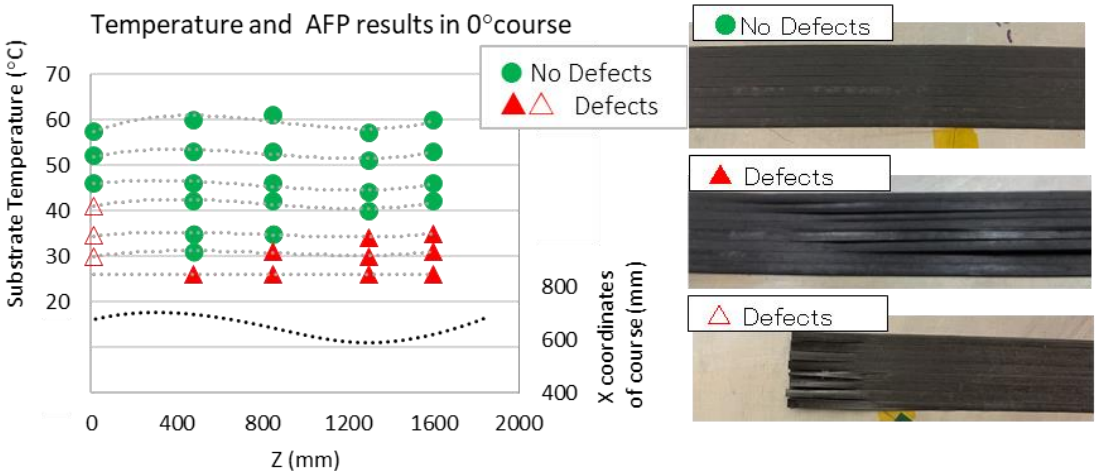


Figure 5: Measured temperature and inspection results for each layup settings with material A

As a whole, when materials were placed with higher temperature, it was more likely to adhere without defects. However, minimum temperature for proper adherence was different depending on the location along the course. The highest required temperature was needed at the beginning of the course, possibly caused by laying tows chilled inside AFP head with chilled roller, or just effect of tow edge's insufficient adhesion. Therefore, these abnormally high temperatures were not considered an effect of tool geometry. It should be noted that minimum temperature for tack was higher at the concave area by more than 5 °C compared to those at the convex area. Though there was not much difference (less than 5 °C) in material temperature throughout a single course, both proper adherence and defects appeared. This suggested that tow defects were caused by course shape.

The same experimentations, measurements and plotting were conducted for single ninety-degree courses with materials A and B. Minimum required temperature for every course and material were recorded and connected respectively to show a clear tendency of required temperature for adherence (Figure 6). Temperatures above the lines in the Figure 6 can be regarded as processing windows for each combination of material and course geometry. In zero-degree single course layup trials, both materials showed that concave areas needed higher temperatures than convex areas for proper adherence. Also, the start of each course required the highest temperature. Meanwhile, ninety-degree courses needed relatively higher temperature at all points along course than the zero-degree layup. These results strongly suggest concave areas generally require higher applied temperatures than convex areas. In addition, unlike the zero-degree results, ninety-degree courses showed almost the same, or slightly higher temperatures at all points along the course.

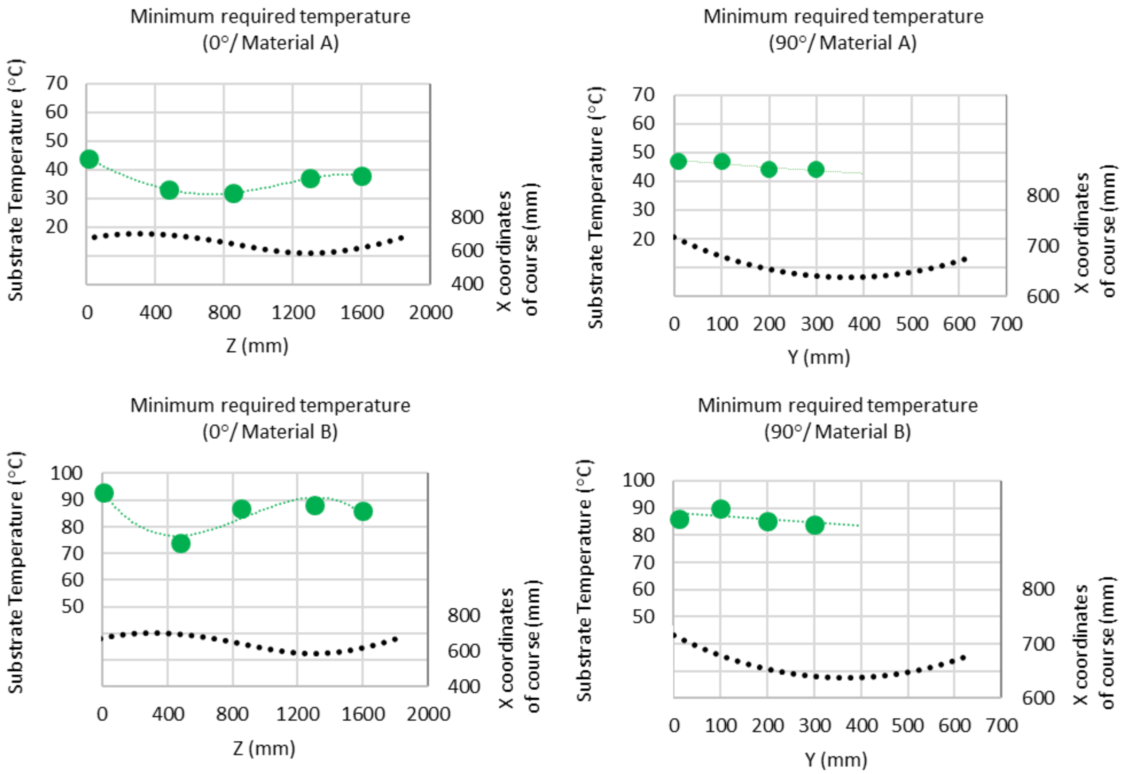
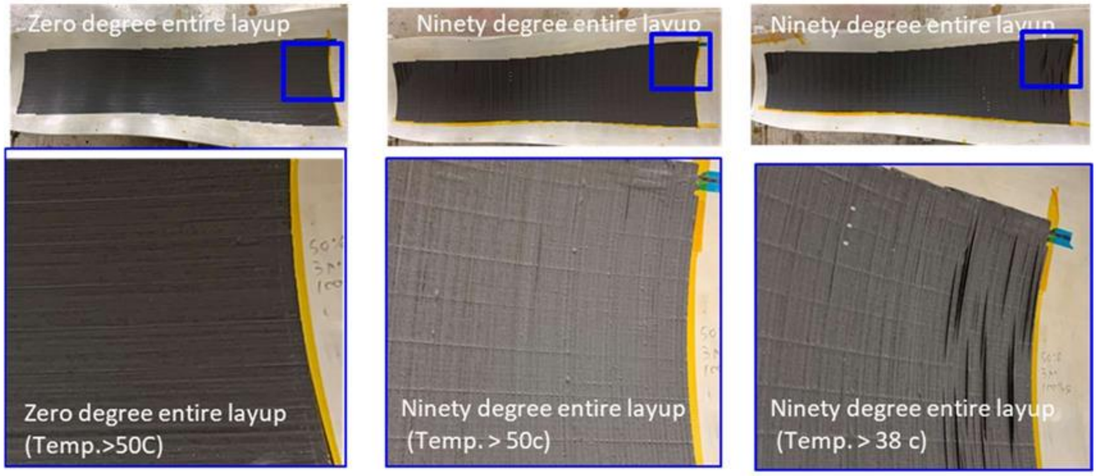


Figure 6: Minimum required temperature trend for adhesion in zero and ninety single course with material A and B

3.2 Surface Layup Trials

The series of results for entire ply layup are shown in Figure 7. There were no bridging defects during the zero-degree layup with material A when tows were laid down with an applied temperature above 50 °C. There were also no significant bridging defects when ninety-degree surface layups were laid with temperatures above 50 °C. Therefore, the AFP process did not have to be paused due to re-work defects during the layup of these plies. On the other hand, ninety-degree surface layups with temperatures above 38 °C brought many defects at the right-most area of the concave portion of the tool. This is in good agreement with the results obtained in first stage of experiments. However, significant defects did not occur after 8th course of the ply. These tendencies were the same when laying up with material B, though the temperature values were over 30 °C higher than those with material A. Therefore, the processing windows for each material obtained from the first stage experiments were well validated, and actual ply manufacturing was successfully demonstrated.



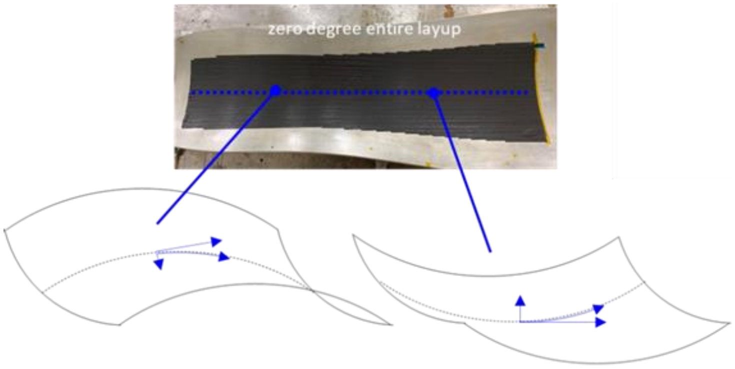
(a) (b) (c)

Figure 7: Entire surface layup with temperatures above and below the processing window for(a) 0 and (b)(c) 90 degree with material A. (Equivalent results were obtained with material B)

4. DISCUSSION

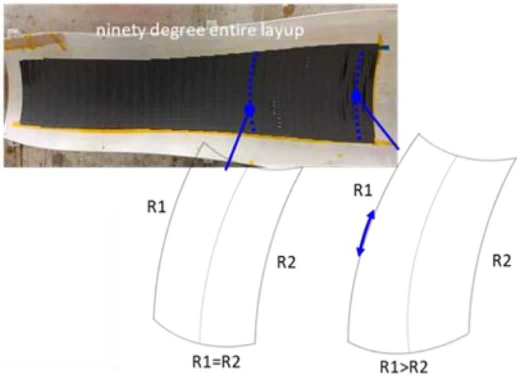
From the experiment, it became clear that concave areas are prone to bridging defects, even though processing temperatures were equivalent to the ones in the convex area. This is assumed to be due to the tow tension and tensile strain based on tow draping. Figure 8 and Figure 9 show schematic images of tows being laid along each course. Figure 8 (a) and (b) represent tows on different area of the zero-degree course. Both tows are exposed to effect of curvature, however the tensile vector component faces toward substrate in Figure 8 (a), but faces the opposite direction in Figure 8 (b). The tensile vector in the direction away from the substrate forces tows to lift up or bridge.

Ninety-degree course experiments brought similar results in terms of required temperature values in the concave area. However, the defects in these courses were characteristic of those shown in Figure 7 (c). The defects of tow lift up occurred at the outside of the course, and particularly only occurred on courses 1-6. Even though the steering radius in any single course was as large as 4500 mm measured from y-z projection of Figure 3, these defects are obviously caused by steering. This partial insufficient adhesion was contributed to tensile strain at the outer edge of the curved tows caused by the change in length between the outside and inside of the course (Figure 9 (b)). These effects should be taken into account to avoid bridging defects when tows are placed onto curved tool surface in both travel and width direction of layup motion.



(a) (b)

Figure 8: Schematic image of tow strain caused by curvature and steering: (a) convex and (b) concave for 0-degree course



(a) (b)

Figure 9: Schematic image of tow strain caused by curvature and steering: (a) constant and (b) varying steering radius for 90-degree course

5. CONCLUSION

In this work, accurate evaluation of processing temperatures and materials defects through experimental measurement and visual inspection of layups on a double curved tool were achieved. Tool complexity and AFP course shape was analyzed, and its effect on defect occurrence was investigated into detail. The results showed tow-lift and bridging defects on the complex tool occurred not due to heating deviation, but course shape geometry itself. It made it quantitatively clear that concave areas with lower curvature radii need higher temperature for tow placement without defect occurrence. Also, these defects are more likely to occur when tows were placed with steering on curved surfaces. The defects occurrence was contributed to the tensile strain in the tow while being placed on a curved path and a curved tool. This was considered to lead to insufficient adhesion between the tows and the substrate. Additionally, our understanding of the defects and material process parameters was validated through demonstration of entire ply layup with less defect occurrence or machine stoppages. The acquired quantitative information will help to perform 3D fiber placement on complex parts and can give useful insight to solve defects which could occur during 3D layups.

This research can be seen as a basis for future experimentation into how AFP heating can be affected. Firstly, more fiber angles should be explored (±45°), including non-conventional angles (15°, 30°, 60°). These experiments focused on zero- and ninety-degree fiber angles, but structures can have a wider variety than this. Also, more significant steering radii could be explored to examine how the required temperature may change. Applications of AFP layup on complex shapes also need to be explored. This can include things such as doublers, blended wing bodies, as well as smaller complex parts within a structure. Research also needs to consider how the other process parameters can affect the minimum required temperatures, as this will play an important role in determining the overall optimal processing conditions. Furthermore, this study has potential to be expanded to simulate layup on three dimensional tools and predict defects occurrence by combining layup course geometry analysis and actual experimental data. If the simulation is developed and it can predict how to resolve defect occurrence, and it would enable the AFP process to perform better on complex geometries.

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