AUTOMATED FIBER PLACEMENT OF COMPOSITE WIND TUNNEL BLADES: PROCESS PLANNING AND MANUFACTURING

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ABSTRACT

The ability to accurately manufacture large complex shapes in a consistent and repeatable manner has led to Automated Fiber Placement (AFP) being the predominant mode of manufacturing for large composite aerospace structures today. Currently, AFP is being considered for medium- and small-scale parts. Composite wind tunnel blades have traditionally been fabricated by hand layup for pre-impregnated or dry fabrics with resin infusion. Though well proven, the traditional fabrication method is laborious and tedious, and hence expensive. The project described in this paper used the Integral Structural Assembly of Advanced Composites (ISAAC) facility at the NASA Langley Research Center to build a manufacturing demonstration unit (MDU) with a shape representative of a wind tunnel blade. This MDU is used to discuss tooling, process planning, and fabrication. Additionally, details of the generic manufacturing workflow are presented.

1. INTRODUCTION

Wind tunnel blades are typically designed and fabricated to precise specifications to achieve the designed balance and shape. Such blades are frequently at risk for damage by high-velocity debris during tunnel operations. Currently, many blades are fabricated from fiberglass using a hand-layup process that results in a very high unit cost. If many blades are damaged in a wind tunnel accident, the tunnel may be out of operation for a long time as blades are rebuilt using this expensive and labor-intensive process. This paper documents the efforts undertaken to evaluate using Automated Fiber Placement (AFP) to manufacture blades which could replace the blades in an existing tunnel in a more cost-efficient manner than with traditional hand layup. While AFP is typical for the fabrication of large composite aerospace structures, it is now being considered for small and medium scale parts. As such, the use of AFP and associated technologies seems promising and is investigated.

Several process and physical parameters are typically investigated for any shape to be manufactured, material to be placed, and machine to be used for AFP. Selecting the best

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combination of these resources is process planning. Often, the unique characteristics of a manufacturing cell's established processes and physical parameters are required to enable complex manufacturing. The combination of machine, materials, and design in the context of using AFP to manufacture wind tunnel blades is described in this paper.

In AFP, slit prepreg tapes are placed on a flat or complex-shaped surface and consolidated to build a composite part. To further illustrate, we present first the concept of tows and courses. Material is initially produced in large tape and cut to ¼-in., ½-in., and several other preset width dimensions, identified as tows. For each layer of material building the laminate, several tows are delivered through a feeding mechanism and deposited on the tool surface to form a single course Typically, several courses are placed to create a ply. Each ply usually contains fibers oriented in one direction, such as 0° or 45°. Plies of several orientations are placed to create a laminate. Figure 1 shows the Integrated Structural Assembly of Advanced Composites (ISAAC) robotic system at the NASA Langley Research Center [1]. ISAAC is an ElectroImpact AFP machine with the capacity to simultaneously layup 16 tows to manufacture composite parts. Figure 1 shows the robotic arm mounted on a robotic rail while the AFP head is placing material on the tool.

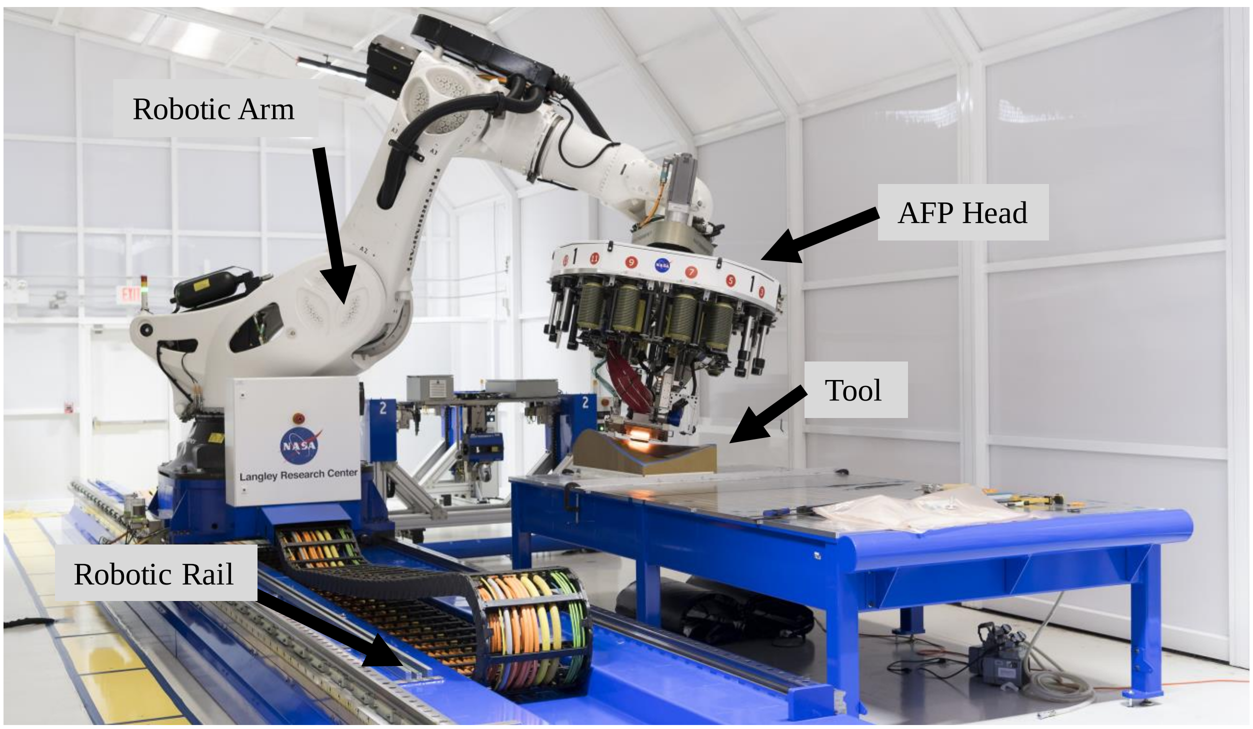

Figure 1. ISAAC at NASA Langley.

This paper is used to describe the process planning approach with a wind tunnel blade as the example manufacturing element. The long-term goal of the project is to fabricate replicates of this blade using automated processing alone or a hybrid of automated processing and hand layup instead of the slow and expensive hand layup process previously used.

The concept of process planning in AFP and the associated terminologies are presented in section 2 and are not specific to wind tunnel blades. The methodology used to create the starting geometry for a selected wind tunnel blade is presented in section 3. This step is necessary when no appropriate Computer Aided Design (CAD) model is available for the part to be manufactured. The active process planning steps and associated recommendations and analysis are presented in section 4, including an example of the development of a tool to be used for AFP. The manufacturing of the composite wind tunnel blade manufacturing demonstration unit (MDU) is described in section 5 and conclusions for this study are presented in section 6.

2. PROCESS PLANNING CONCEPTS

The sequence of manufacturing encompasses: specifications, design, process planning, toolpath generation, computer aided manufacturing, prototyping, and manufacturing. Often the step of process planning is ill-defined, which can lead to un-manufacturable designs and manufacturing problems that could be avoided with more consideration of manufacturing needs and restrictions at the beginning of the process [2,3]. The goal of this section is to highlight the need for selecting the appropriate combination between the design, material, and manufacturing resources to ensure manufacturability.

The translation of a design to a fabricated structure requires a thorough understanding of both the anticipated behavior of the material during manufacturing and the controllable process parameters associated with the manufacturing platform itself. In the context of AFP, the most difficult element is the AFP head's ability to kinematically reach and place the material. Additionally, material placement for a specific complex design can be a time-consuming and expensive endeavor. Even when AFP is used, the complex shape may slow the robotic placement process and human inspections are typically required after each ply. Although the initially defined placement may be achieved within the constraints of a particular machine, slow layup leads to added expense and an evaluation of the placement methodology could lead to a more efficient process. Four parameters can typically be altered to attain the optimal process for placing material and ensuring proper tackiness for a particular part. These parameters are heat, pressure, material placement rate, and tow tension. Heat intensity is the amount of heat applied to the underlying substrate layer during placement. Pressure is the compaction force applied to attach the new material to the underlying layer. Material placement rate defines the layup speed and is often a balance between production needs and layup quality. Finally, tow tension is the force individual tows are subjected to along the fiber direction during placement [4].

Material process parameters can be configured and modified without consideration of damaging the manufacturing apparatus. Improperly accounting for accessibility, however, runs the risk of damaging the AFP machine. Commanding the AFP head, especially the heater/roller area, into a concave area, can damage the machine severely enough to cause a work stoppage. This potential problem creates an additional burden in the process planning stage of fabrication that requires virtual verification of the toolpath collisions, dry runs of the placement program on the manufacturing platforms without contact to validate the toolpath, and possibly modifying certain elements (such as approach and retract operations). Sometimes, toolpath changes are not sufficient to manufacture a particular design, in which case design alterations and/or machine alterations must be considered. If design alterations are not possible, process planners may recommend physical alterations of the manufacturing apparatus. The latter can involve selecting an alternate manufacturing method, a different machine, or to performing major alterations to the original machine system, such as replacing the heating system with a more compact one.

In conclusion, process planning is a matchmaking stage that attempts to connect design with manufacturing while taking material and geometrical requirements into account. It is often the most difficult aspect of manufacturing and requires a substantial amount of time to ensure design requirements are matched with appropriate manufacturing methodologies.

3. BLADE REVERSE ENGINEERING AND MODEL CONSTRUCTION

The wind tunnel blade selected for this study is from the NASA Ames Research Center 11-by 11-ft Transonic Tunnel (11-Foot TWT) [5] and is shown in Figure 2. Unfortunately, no computer model was available for this blade, so a CAD representation of the blade's outer surface geometry was created. Reverse engineering of the wind tunnel blade consisted of two steps: (1) Acquiring a series of points from the outer surface, and (2) Model construction. This development is shown in the following sections. First, a CAD model construction is discussed in section 3.1, followed by modifications to this model to ensure MDU manufacturablilty using the existing AFP machine without any machine hardware alterations.

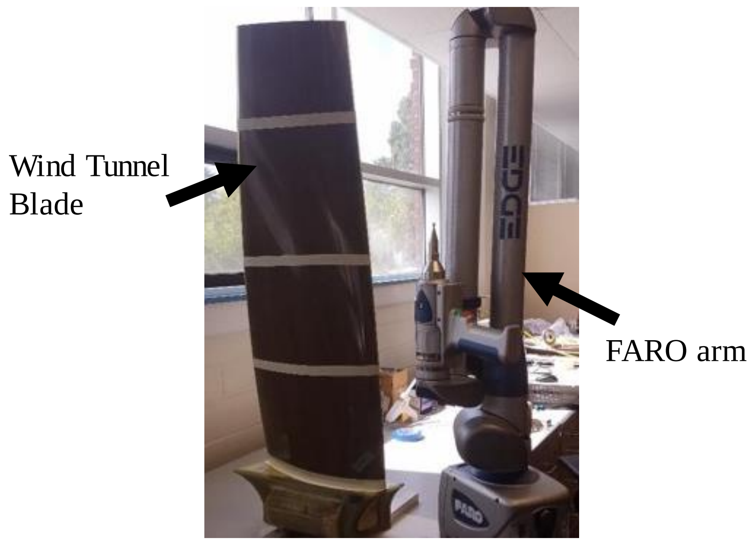

Figure 2. Ames wind tunnel blade and FARO arm.

3.1 CAD Model Reconstruction

To create the CAD model, first a reconstruction of the outer surface shape was created through profile sweeping. To gather the geometrical data in digital form, five equally spaced cross sections, including the root and tip, were marked. Then a FARO Edge arm [6], shown in Figure 2, was used to obtain a series of points from the surface of the part. These points shown in

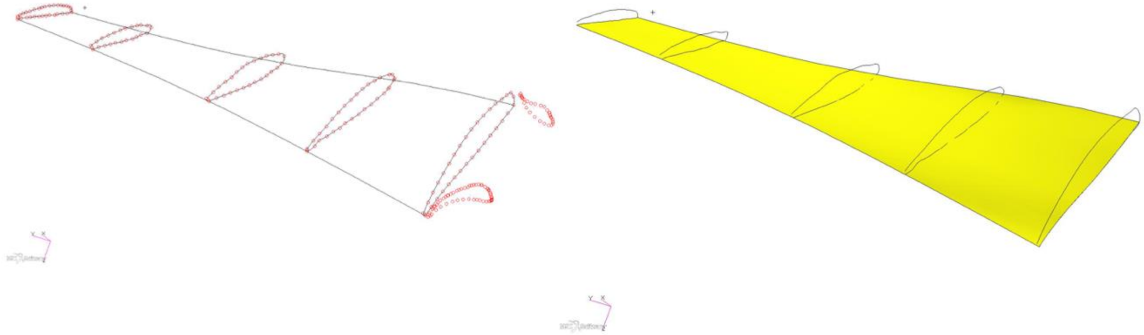

Figure 3 (a) were obtained through a continuous scanning technique, where the FARO arm's tip was moved along the defined cross sections and the software automatically collected points with 5 mm spacing.

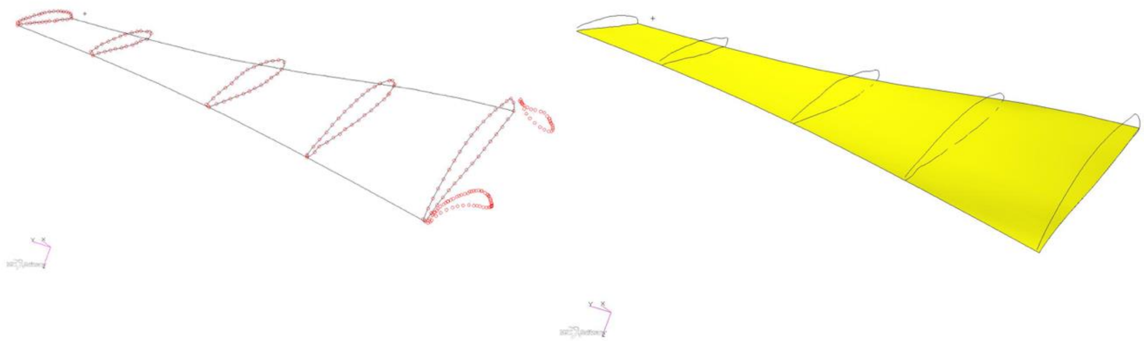

Figure 3. (a) Measured points (b) Closed loop cross-sections and surface.

Following the acquisition stage, the points, shown in

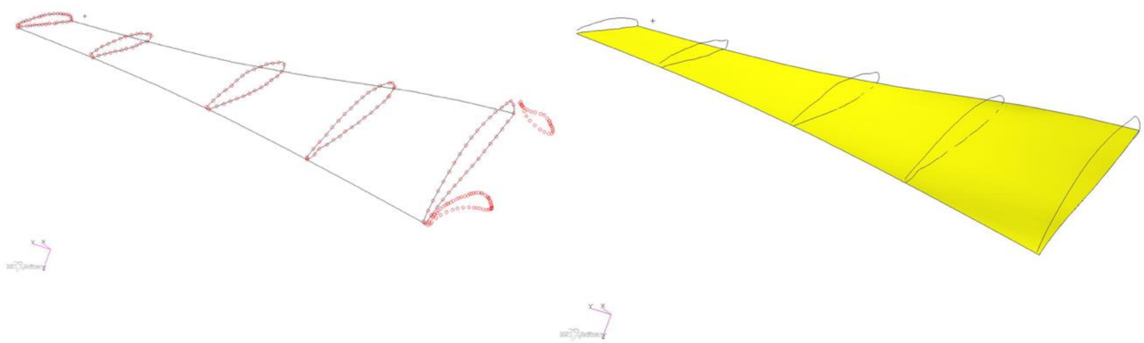

Figure 3 (a), were imported to Creo® [7] in order to create the tool surfaces. For each cross section, a spline fit through the captured points, as shown in

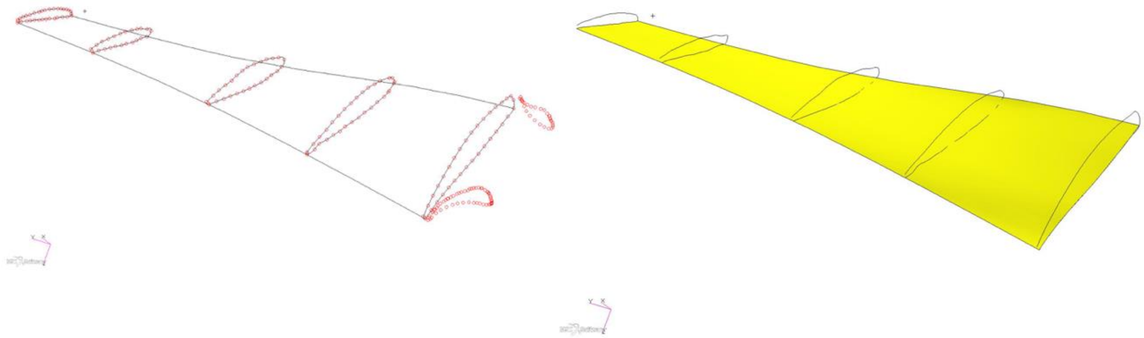

Figure 3 (a) and Figure 3 (b) was used to create a closed loop. A swept blend was performed, connecting the spline developed for each cross section, to create the final solid representation of the blade, as shown by the yellow surface in Figure 3 (b). Absolute accuracy was not necessary for the verification stage of the project, a model which captured the approximate geometry of the blade was sufficient. Once the geometry of the blade was developed, the outer mold line of the upper surface of the blade was used to create the surface for placement of material. In AFP terminology, the term “tool” is used for the surface on which the fiber placement will take place. Often referred to as the “mold” in traditional manufacturing processes, the tool needs to withstand the compaction loads by the AFP machine, as well as the temperature and pressure environment required by the curing cycle. After developing the outer surface of the part, the tool design was finalized by adding thickness to the model. The final result is shown in Figure 4, where the runout and subsection regions are depicted. The runout is the area where the AFP roller contacts the tool prior to and after the material layup. The subsection region is the blade portion selected for further investigation.

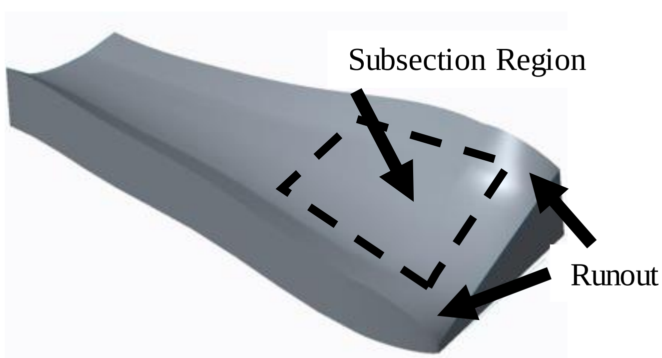

Figure 4. Solid tool.

3.2 Modifications for Process Planning

The CAD geometry described in the previous section and shown in Figure 4 required further processing to prepare the file for subsequent stages. Because the goal of this study was to explore the adoption of AFP for the manufacturing of the wind tunnel blades, only a portion of the blade, shown as the subsection region in Figure 4, was evaluated for the feasibility study. Figure 5 shows the ply boundaries on the selected sub-region of the blade, highlighted in Figure 4. Fabrication-specific elements such as ply boundaries and model extension are then created to account for machine travel and robot flexibility. The blue curve in Figure 5 shows the ply boundaries. The region between the blue curve and the edges of the tool represent the runout region.

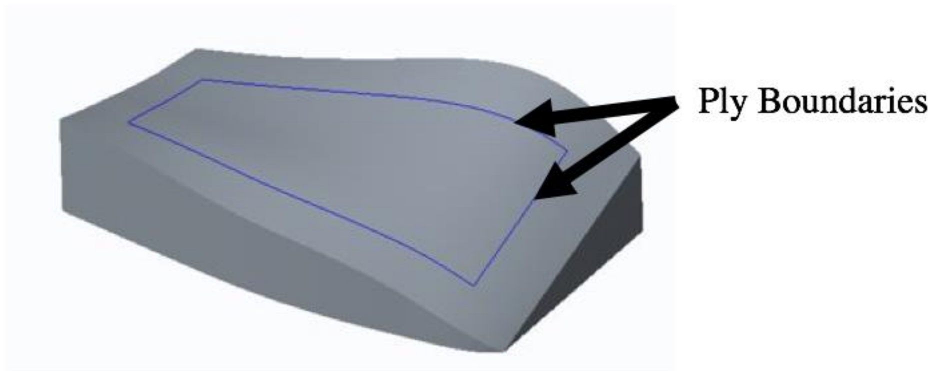

Figure 5. Selected section of blade.

3.3 Manufacturing Process

The previously outlined feasibility study followed the manufacturing flowchart shown in Figure 6. Following the design assessments, process planning, which is presented in Section 4, and toolform manufacturing, which is presented in Sections 5.1 and 5.2, are conducted. These two steps are followed with the AFP validation process where air runs and dry runs are performed. Air runs are used to validate the numerical control (NC) code and are conducted without the toolform in place. Air runs are primarily conducted to validate the process planning stage to identify any robotic joint errors. Dry runs consist of running a physical simulation on the toolform but without actually placing material. Dry runs ensure that there will be no collisions between any portion of the robot and the tool or other hardware in the cell during fiber placement. Once both the air run stage and the dry run stage are validated, fiber placement takes place and is detailed in section 5.3. Following the layup process illustrated in Figure 6, the final results are presentented in section 5.4.

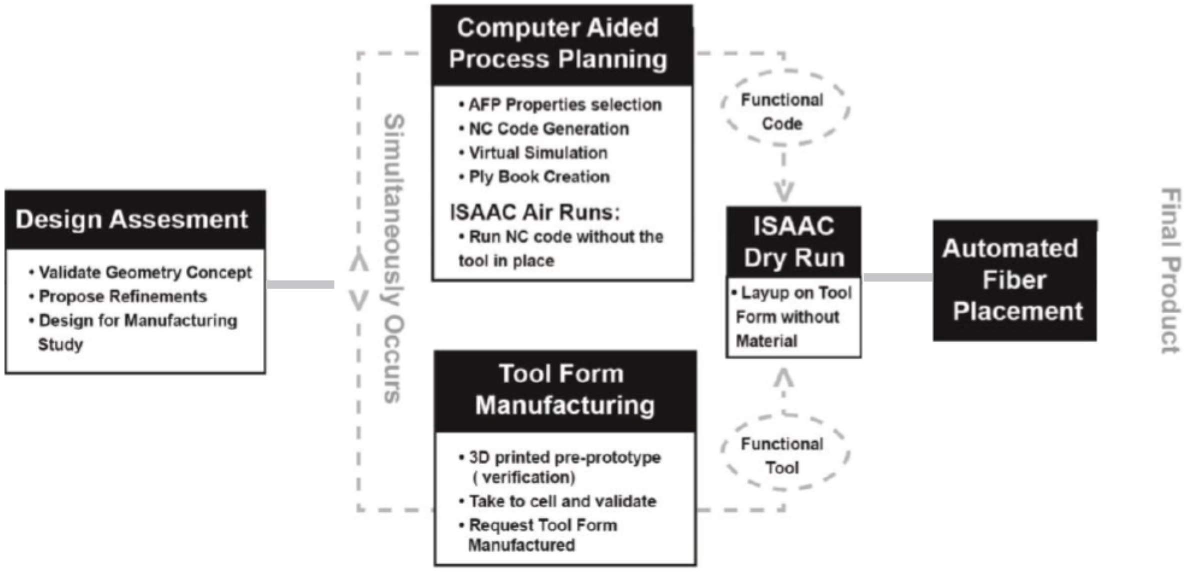

Figure 6. Manufacturing flowchart.

4. PROCESS PLANNING

This section details the process planning and toolpath generation for the fiber placement. First the NC code using Vericut Composite Programming (VCP) © by CGTech [8] is created as discussed in section 4.1. The most important considerations in this first step are the heater orientation correction and selection of layup strategy. Then the machine simulation is conducted to ensure accessibility as discussed in section 4.2. This simulation is conducted using Vericut Composite Simulation (VCS) © by CGTech.

4.1 Programming using VCP

Toolpath generation requires a detailed definition of the fiber placement strategy [9]. This definition includes numerous functions, detailed in [10], such as: boundary creation, starting point selection, fiber placement strategy, steering constraints, inter-band offset, stagger shifts, boundary coverage, and off-part motion. Process planning functions are split into layup strategy optimization and toolpath optimization. Programming the layup path is critical and complicated since each of the process planning functions are inter-connected. For example, selecting the optimal starting point is related to the layup strategy. Selecting the ideal combination of these functions minimizes the AFP-related defects [4]. For most applications, the primary defects to avoid are gaps between tows, overlap of adjacent tows, and angle deviations from the planned orientations. Part of this optimization includes angle deviation and tow steering constraints between the machine and surface.

In the context of this research work, because of the concave curvature of the surface, one of the goals was to identify a layup strategy that would avoid collisions between the heater and the tool surface. The heater orientation tool within VCP allows the user to import a CAD representation of the AFP heater assembly which is used to check for heater-tool surface collisions. An evaluation of potential collisions is depicted in Figure 7. The green cylinders in Figure 7 represent a series of locations of the roller during material placement. The heater is shown in red and the blue and yellow strips represent courses of material. After running an initial trial, the programming can sometimes be modified by changing the angle of the heater relative to the part surface to eliminate collisions. For tool surface regions where there are unavoidable collisions, it may be possible to shift the starting point of a course to move the heater away from problem areas. For areas where no collision-free configuration is possible, the course could be removed from the automated process and simulation and that course could be placed through hand layup.

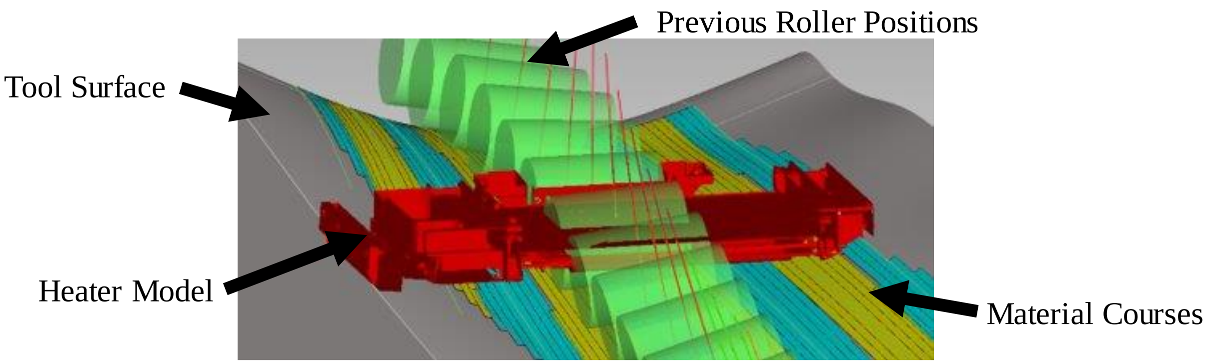

Figure 7. Heater orientation optimization.

4.2 Simulations using VCS

Simulating AFP enables rapid iteration between VCP and VCS. Joint limits, kinematic singularities, and work cell collisions are detectable, and allow the user to determine the best course of action. The user may have options including repositioning the tool on the layup table, modifying some joint configurations, and changing offsets used to generate the NC code. These steps are often followed with a machine dry run (i.e., running the program on the robot without material) with a small offset to ensure that the programmed path is actually realizable on the machine. The following section describes the investigation of joint limits and in-depth analysis of the heater collision element.

4.2.1 Joint Limits

The term joint limits indicate an invalid position, i.e., one where the robot has been requested to move beyond its programmed joint operational restrictions. Figure 8 (a) shows an error on axis 4. VCS indicates these errors by coloring the segment of the arm which has exceeded the joint limit. While placement is theoretically taking place on the tool, the robot is unable to reach this position due to either virtual or physical limitations. Virtual limitations are programmed in the VCS software that mimics the possible motion of the robot and restrictions necessary to avoid damage to the part or system.

4.2.2 Heater Collisions

Heater collisions occur in regions of tight curvature, where the head orientation has not been checked through VCP as shows in Figure 8 (b). To overcome collision problems, several tilt and lead angular positions were investigated, in line with Figure 7. For rapid prototyping, the long computation time for collision detection means that it is preferable to avoid VCP orientation corrections during the initial path planning iteration. Simulations through VCS with the un-optimized orientations help to identify which plies and/or tool surface regions necessitate the corrections for head orientation during subsequent iterations, reducing overall computation time.

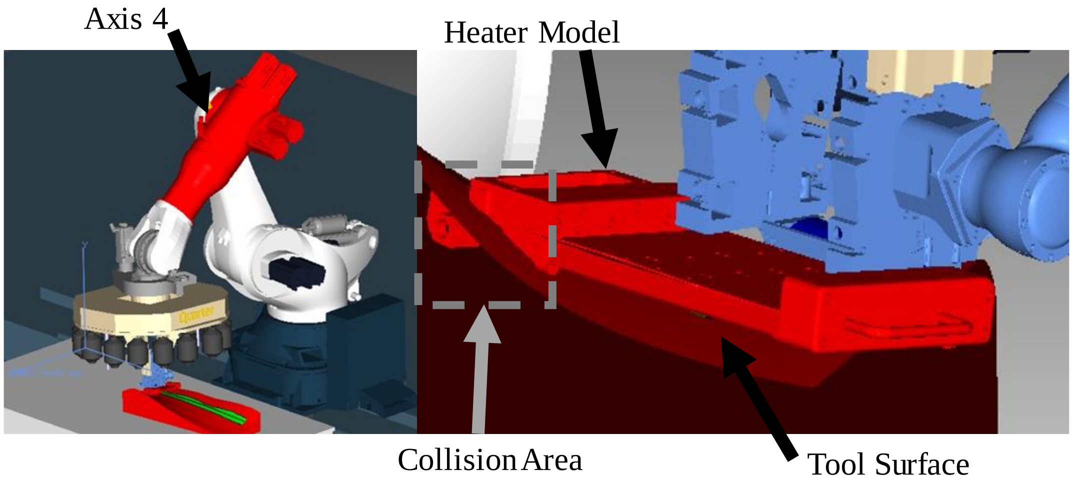

Figure 8. (a) Axis 4 joint limit error. (b) Heater collision with tool surface.

5. MANUFACTURING

This section outlines the details of the manufacturing process. Whereas this section is specific to the manufacturing of the wind tunnel blade segment, it provides a best practices procedure for manufacturing new shapes with AFP. First, the 3D printing of the prototype tool with a commercially available 3D printer is presented. Next, the 3D printing of the placement tool with material that could withstand both the AFP layup pressure and the autoclave cure cycle is described. Finally, the MDU is presented with details on the layup and the curing process.

5.1 3D Printing of Prototype Tool

Manufacturing tools for AFP are expensive, and while thorough and detailed shape analysis takes place during the process planning stage to ensure no heater collisions will occur, the use of an inexpensive 3D printed prototype of the final tool which could be quickly fabricated was valuable to use for offset dry runs without pressure and contact. This step identifies any other issues that might arise from differences between virtual machine limitations and actual ones.

The prototype tool, shown in Figure 9, was printed using polylactic acid (PLA) on a Gigabot 3+ 3D printer. The approximate manufacturing cost of the prototype tool was $300. The prototype tool was then placed on the layup table in the same location that the placement tool would be placed. ISAAC was manually positioned with different positions imitating the placement procedure. This step is used to provide feedback information and to update the location/positioning. Once the trials were performed, the tool design was confirmed and adequate confidence in the final tool shape was developed to complete manufacturing of the placement the tool and build the MDU.

Figure 9. 3D printed prototype tool.

5.2 Tool Manufacturing

Materials available for creating the AFP layup tool can range from invar metal, which is a nickel-iron alloy known for its invariance to temperature changes, to Ultem thermoplastic that can withstand a few repeated trials. The durability and precise geometrical requirements of the tool are determined by the anticipated number of parts to be fabricated and the dimensional tolerances of the final fabricated part. These requirements lead to the appropriate selection of the tool material and its associated cost. Invar tools are never justified for a feasibility study such as the one in this effort because of their high costs. In production of final hardware, using invar is highly desirable for thermoset prepreg layup since thermosets require curing cycles, and invar does not expand or contract significantly with temperature changes. In the case of fabricating many parts, the cost of invar tooling would be justified. In a feasibility study, 3D printing an Ultem tool for a few cycles was the best solution.

Prior to fabrication of the tool, a finite element analysis (FEA) was conducted to determine the required internal structure of the tool in preparation for its fabrication using 3D printing with Ultem material. Loads in the FEA were included to account for AFP compaction pressure, vacuum bagging pressure during cure, and composite curing temperature. The thicknesses of outer shell and the thickness and spacing of the tool internal structure were developed. The internal pattern is presented in Figure 10. The tool was then 3D printed on a Stratysys © 900 printer using Ultem. The tool was manufactured in two parts and later joined. Approximate manufacturing cost of the Ultem tool was $18,000. The final tool is shown in Figure 11. Further details about the tool manufacturing are presented in [11].

Figure 10. Internal structure of the placement tool.

Figure 11. Placement tool.

5.3 MDU Manufacturing

As described in Figure 6, dry runs were conducted to demonstrate that material placement would occur without collisions and without machine errors. This physical simulation step led to a placement process that only required defect inspection/correction typical for AFP. AFP layup was then performed with carbon epoxy composite on ISAAC. The MDU was fabricated by placement of Toray 3900-2C/T800 190 GSM 35% RW slit tape ¼-in. width tow onto the tool surface. Material placement is shown in Figure 12.

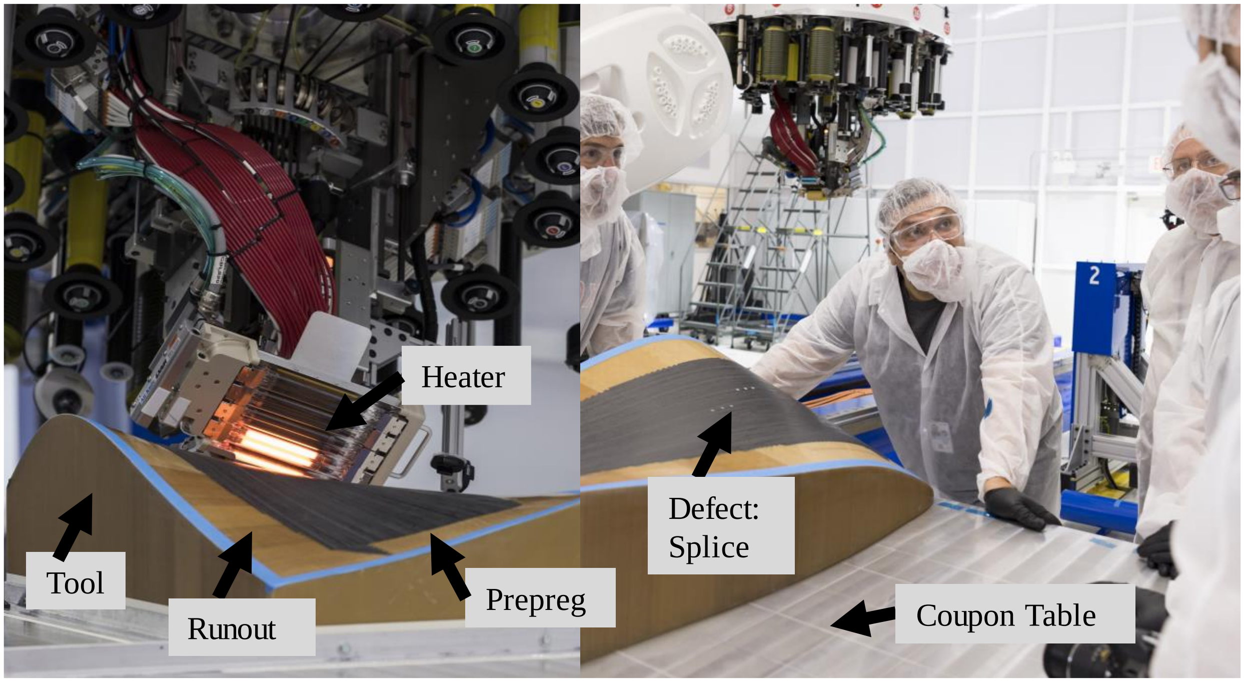

Figure 12. (a) Layup process. (b) Inspection, discussion and correction; layup shows splices (defect) whose tows will be replaced.

The complex-shaped MDU contained a 12-ply stacking sequence of $[30/0/\text{-}30/90/60/\text{-}60]_s$. For each ply, the environmental conditions in the clean room such as temperature and humidity, as well process parameters, were documented. Table 1 provides a sample of the data recorded in this documentation process. The full process details are documented in the NASA plybooks as shown in Figure 13 and Figure 14. The plybook provides a standardized method for documentation of the entire process during manufacturing and ensures traceability and quality control. During layup, each ply was inspected and tows were repaired or replaced as needed. Process parameters and repairs were documented for each ply. These parameters and the quality of the ply influenced the selection of the values for these parameters for the next ply.

Table 1. Sample environment and process parameters documentation.

Ply	Temperature (∘C)	Relative Humidity (%)	Heater (% power)	Compaction (N)	Feedrate (% programmed speed)
Ply 1	19.17	52	300	445	10
Ply 2	19.06	52	250	445	20

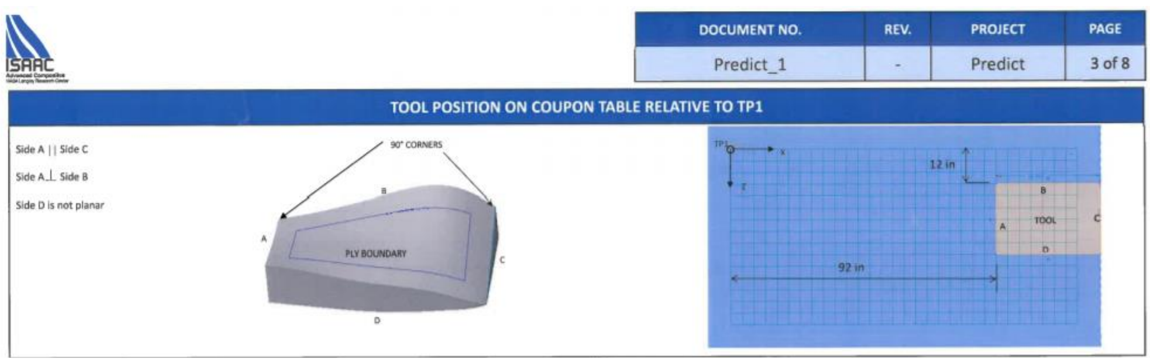

Figure 13. Sample page of NASA LaRC's plybook documentation process showing header portion with part details.

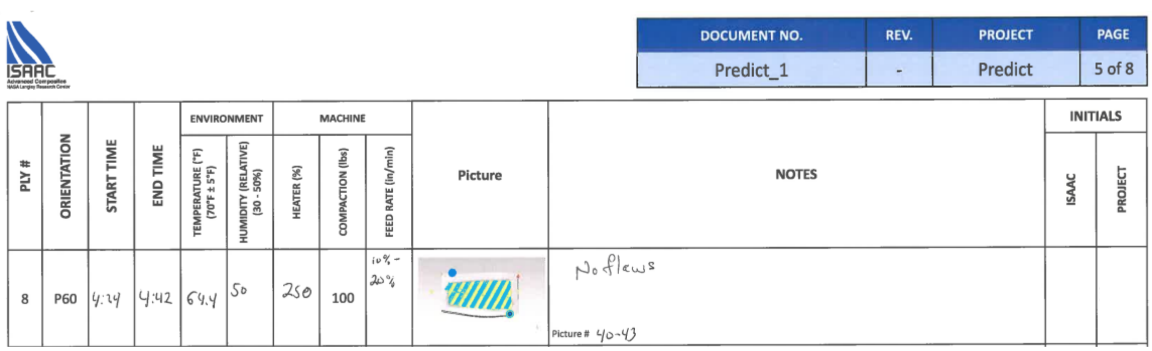

Figure 14. Sample page of NASA LaRC's plybook documentation process showing data recording header and sample data.

5.4 Cured MDU

Following fiber placement, the MDU was vacuum bagged and prepared for the curing cycle. The cure cycle used a combination of pressure and temperature to achieve full cure. Acceptable cure cycles are dependent on the resin system of the prepreg. Afterwards, the MDU was removed from the autoclave, unwrapped, and visually inspected. The MDU geometry maintained the shape of the tool and no surface defects were visible. No further evaluation was conducted. Figure 15 and Figure 16 show the MDU where the complexity of its geometry, being a doubly-curved shell, is clear.

Figure 15. Cured MDU (side view).

Figure 16. Cured MDU, side view demonstrating complexity of the part.

6. CONCLUDING REMARKS

A composite MDU in the shape of a wind tunnel blade was manufactured using AFP to evaluate the applicability of AFP to such complex shapes. The design and fabrication of this MDU provided an example to explain some best practices and process planning for AFP applied to complex-shaped parts. Process planning step that connects design with manufacturing while taking material and geometrical requirements into account. Process planning is often the most difficult aspect of manufacturing and requires a substantial amount of time to ensure design requirements are matched with appropriate manufacturing methodologies. The process planning steps were presented herein, as well as the overall workflow of AFP manufacturing. This project demonstrated that some areas of the selected blade are manufacturable with the current ISAAC system configuration.

In the context of the optimal AFP workflow process, the steps needed to achieve a rapid AFP prototyping cycle using 3D printing of tools that can withstand a typical autoclave cure cycle and are sufficient for concept validation were identified. These tasks included the reverse engineering of an existing wind tunnel blade, heater viability assessment as related to the desired surface geometry. The tool positioning taking into account both robot kinematics and cell safe zones were introduced as well. The workflow with discussions on needed air-runs, dry-runs and the actual placement process were presented.

7. ACKNOWLEDGMENT

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8. REFERENCES

1. NASA ISAAC Fact Sheet, FS-2016-12-273-LaRC, 2016.
2. Sabido, A., Bahamonde, L., Harik, R., & van Tooren, M., "Maturity Assessment of the Laminate Variable Stiffness Design Process," *Composite Structures 160* (2017): 804-812. https://doi.org/10.1016/j.compstruct.2016.10.081
3. Albazzan, M., Harik, R., Tatting, B., & Gürdal, Z., "Efficient Design Optimization of Nonconventional Laminated Composites using Lamination Parameters: A State of the Art," *Composite Structures 209* (2018): 362-374. https://doi.org/10.1016/j.compstruct.2018.10.095
4. Harik, R., Saidy, C., Williams, S., Gurdal, Z., and Grimsley, B. "Automated Fiber Placement Defect Identity Cards: Cause, Anticipation, Existence, Significance, and Progression". *Proceedings of SAMPE 2018 Conference & Exhibition*, Long Beach, California, 21 – 24 May 2018, Society for the Advancement of Material and Process Engineering.
5. https://www.nasa.gov/centers/ames/orgs/aeronautics/windtunnels/11x11-wind-tunnel.html Accessed 2/14/2019
6. FARO, 12 February 2019, <https://www.faro.com>
7. PTC, 8 February 2019, <https://www.ptc.com>
8. CGTech, 8 February 2019, <https://www.cgtech.com>

9. Rousseau, G., Wehbe, R., Halbritter, J., & Harik, R., "Automated Fiber Placement Path Planning: A state-of-the-art review," *Computer-Aided Design and Applications* 16(2) (2019): 172-203. https://doi.org/10.14733/cadaps.2019.172-203

10. Halbritter, J., Harik, R., Saidy, C., Noevere, A., and Grimsley, B., "Automation of AFP Process Planning Functions: Importance and Ranking". *Proceedings of SAMPE 2019 Conference & Exhibition*, Charlotte, North Carolina, May 20-23, 2019, Society for the Advancement of Material and Process Engineering.

11. Grenoble, R., Harik, R., Munden, D., Halbritter, J., Jegley, D., Mason, B., "Assessment of Automated Fiber Placement for the Fabrication of Composite Wind Tunnel Blades". *Proceedings of SAMPE 2019 Conference & Exhibition*, Charlotte, North Carolina, May 20-23, 2019, Society for the Advancement of Material and Process Engineering.