COMPOSITE PANEL DEMONSTRATOR MADE BY AUTOMATED DRY FIBER PLACEMENT AND RESIN INFUSION

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ABSTRACT

This paper targets the development of the Automated Dry Fiber Placement (ADFP) process in combination with resin infusion, which allows producing high-performance aerostructures (i.e., fuselage panels, etc.) at a reduced cost in comparison with conventional Automated Fiber Placement (AFP)-autoclave techniques. However, several scientific challenges need to be addressed here, including mechanical behaviors of laminates made by ADFP-infusion, geometrical stability of the preform made by ADFP, preform thickness spring back over time, and binder effects on preform architecture and performance, etc. This paper discusses different process parameters for depositing material using ADFP and different infusion setups and studies the impact of these parameters on the laminate quality. Challenges in both ADFP and infusion processes, including the formation of various defects, are identified, and solutions to overcome them are reviewed. Finally, a procedure is defined to analyze the quality of obtained laminate by this process. In this work, four 76 cm by 76 cm (30-by-30-inch) fuselage panels were fabricated using ADFP and resin infusion.

1 INTRODUCTION

Rising needs for composite structures in different industries such as aerospace, automotive, biomedical and energy make automated manufacturing techniques attractive. This high demand for polymer-matrix composites (PMC) advocates the development of automated manufacturing techniques for different applications. In particular, the Automated Fiber Placement (AFP) process can be addressed as a new approach for manufacturing large-scale complex composite structures and is used by most aerospace companies, such as wing skins and spars for Airbus A350 XWB[1]. Compared to traditional techniques, it has many advantages, such as reducing material waste, increasing the production rate, and reducing costs. Although AFP requires lower technician times than conventional methods like hand layup, the materials used for the AFP process can increase costs.

Typically, the aviation industry chooses fibers pre-impregnated with resin (prepreg)[2], expensive materials with a limited working/shelf life that need autoclave curing, making it significantly more energy-consuming than oven curing. Taking advantage of dry fibers could lead the industry to a method that saves material cost and energy consumption. Automated Dry Fiber Placement (ADFP) can fabricate complex performs such as preforms with cut-outs and fiber steering around them, which is more accessible than prepreg due to the lack of matrix inside the microstructure.

Dry fiber preforms made by ADFP can be impregnated by resin transfer molding (RTM) process such as vacuum-assisted resin infusion (VARI), as an out-of-autoclave process, without requiring high investment for equipment and training technicians[3]. Unlike pre-impregnated materials (prepreg), dry fiber materials have no matrix inside their structures; however, they can consist of substances to keep the fibers together and increase resin infiltrating in infusion[4]. In this work, developing a process combining automated dry fiber placement (ADFP) with vacuum-assisted resin infusion (VARI) provides a door to a method that can fabricate high-performance structures competing with conventional hand layup and prepreg autoclave systems.

2 Material

2.1 Dry Fiber

Unlike pre-impregnated materials (prepreg) widely used for the AFP process in the aerospace industry, dry fiber materials are recently introduced to this field. These materials have no matrix inside their structures; however, they consist of a substance called binder (see Figure 1), which holds the dry fibers together[5]. Also, some of the available dry fibers contain a veil layer that provides channels for resin infiltrating; in other words, it improves permeability for infusion. Using these materials can help the manufacturer reduce energy consumption since the autoclave is removed from this process. Also, the production cost is lower than prepreg material due to the lack of a matrix layer. Currently, there are several suppliers for this type of material. Table 1 shows some dry fiber tapes currently available for the ADFP process.

Figure 1. PRISM TX110 dry fiber tape cross-section [6]

Table 1. Dry fiber Materials

No.	Supplier	Material name	Nominal fiber density, g/cm^3	Nominal areal weight, g/m^2 [7]	Nominal tape width, mm(in)	Binder type [7]
1	Hexcel	Hitape IMA/IM7	1.79	140	6.35(1/4)	Epoxy-based
2	Cytec Solvay	TX 1100 IMS65	1.78	196	6.35(1/4)	Epoxy-based
3	Teijin	Tenax E HTS40 X030	1.76	126	6.35(1/4)	Thermoplastic based

To define the mechanism of dry fiber's substances, dry fiber tapes are examined using a 3D microscope (VHX 5000 Keyence). Based on the obtained photographs from Solvay dry tape, we can understand the difference between veil and binder in terms of permeability and processability, as shown in Figure 2.

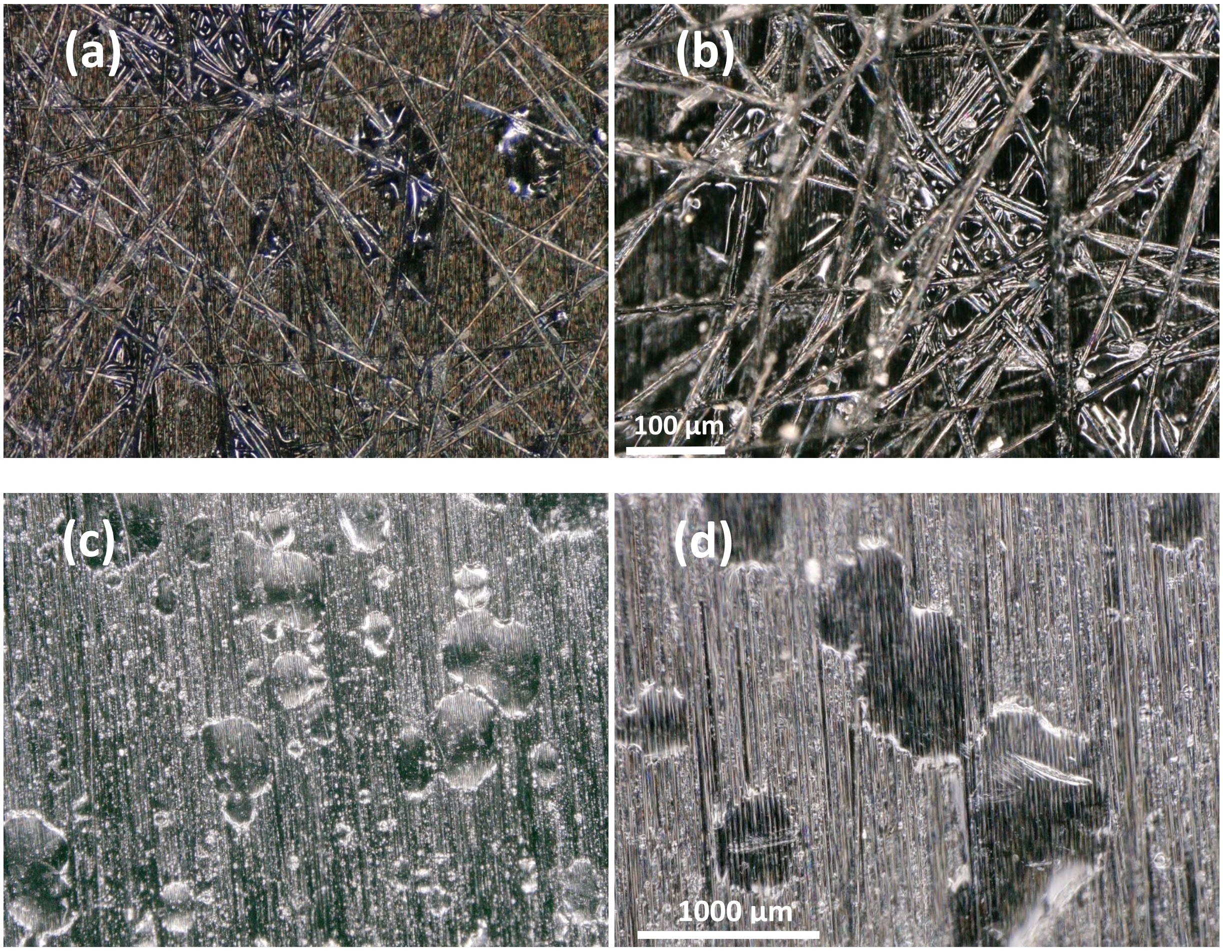


Figure 2. Veil layer on Solvay (a) 200x; (b) 300x - binder spots on Solvay (c) 200x; (d) 500x

2.2 Epoxy Resin

In this work, both room temperature and hot infusion, one at 25°C and another at high temperature (120 °C), were employed to study the difference in impregnation and processability. In terms of room temperature, Araldite®LY 8601 (Resin) / Aradur® 8602 (Hardener), a two-component, low-viscosity epoxy system, was used.

For hot infusion, the epoxy resin used was PRISM™ EP2400 resin system by Solvay. This liquid epoxy resin is a single part with low viscosity and 180°C (356°F) curing, ultimately leading to omitting post-processing like using an autoclave. The EP2400 viscosity was presented as a function of temperature in a range from 60 °C to 180 ◦C by the supplier, Solvay. In addition to viscosity, corresponding resin's pot life for different temperatures is also proposed in the material's datasheet [8].

3 Experiment

3.1 Automated Dry Fiber Placement (ADFP)

The experimental part is divided into two parts: First, automated dry fiber placement, and second vacuum assisted resin infusion. Although flat panels were not presented in this project, flat laminates with unidirectional and cross-ply layup were fabricated to find the process procedure and study the bottlenecks, illustrated in Figure 3. This project took advantage of the AFP machine at Concordia center for composite (CONCOM), which uses a hot gas torch (HGT) heating system for depositing fiber tows to fabricate the preforms.

Process parameters need to be determined after defining axes and offsets, tool geometry, and layup pattern for the machine regarding the automated dry fiber placement process. Generally, the operational parameters can be varied depending on the type of machine and heating system used in the process.

In our case, HGT temperature and flow rate are two crucial parameters to provide the necessary stickiness for the material to lay down on the tool. In addition to HGT parameters, the compaction force of the roller can significantly affect the depositing process. Usually, the compaction force presses the fiber to the substrate, increasing fiber content and infusion time. However, unlike prepreg, in which the matrix in their structures keeps them stiff, dry fibers have a bouncing effect that might cause peel-off in the substrate.

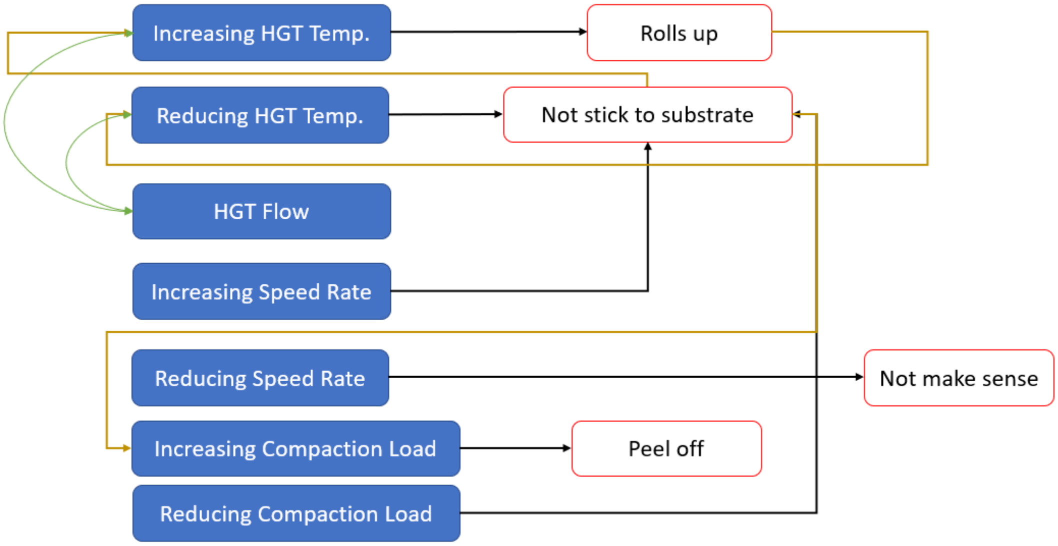


Figure 3. Relation between AFP parameters and possible depositing defects

In terms of defects, feeding tow may not stick to the substrate and create frays because of rolls up. Also, rolls up may appear due to the roller stickiness, which causes fibers to stick to the roller instead of the substrate. The possible solution is using Teflon shrinkage tapes on the roller (Figure 4) to make it slippery and non-sticky. Also, applying the optimized temperature and flow rate for the HGT can be the other solution. In some cases, edges start to lift after depositing more than six plies due to a lack of bonding at the edges. Although the tension in the roller is set at zero, there might be internal friction which causes tension in the depositing tow. Therefore, depositing more plies results in a softer substrate that may lead to edge lift-up. Clamping edges to hold the tows or staggering the layup can prevent this problem.

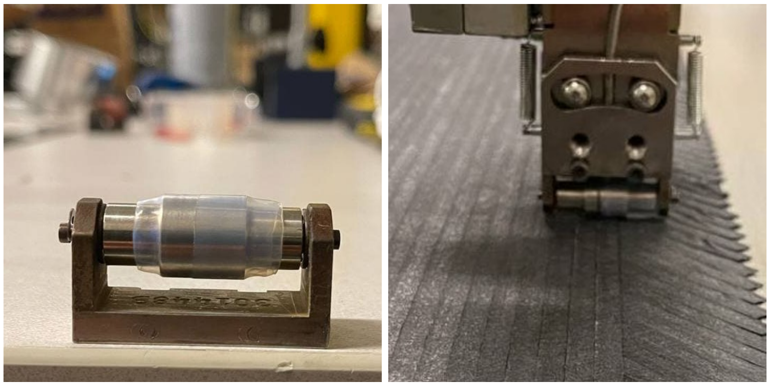


Figure 4. Teflon shrinkage tapes on the roller

3.2 Vacuum Assisted Resin Infusion (VARI)

Resin transfer molding (RTM) has been proposed to the aerospace industry to manufacture complex components with high quality, lower costs, and inexpensive equipment [9]. Among all kinds of RTM methods, vacuum-assisted resin infusion (VARI) is considered one of the cheap and easy to operate methods that can prevent mold manufacturing and high injection pressure. Different developed VARI types provide a pressurized chamber to compact the stack up under the vacuum bag and flow the resin inside the structure [10].

Two infusion setups were employed for the two epoxy systems used samples in this work. First, Seeman's composite resin infusion process (SCRIMP) for room temperature curing, see Figure 5; second, vacuum-assisted process with the membrane (VAP) for high-temperature curing, see Figure 6. On the one hand, in SCRIMP, one vacuum chamber is introduced to setup, which consists of a layer of distribution media to accelerate the in-plane flow front to achieve a shorter infusion time. Since the setup configuration is simple and the operational temperature is lower, it does not require much equipment and has a faster preparation time. On the other hand, the VAP membrane provides two different chambers, the outer for applying pressure and extracting gas and the inner for resin infusion, by adding a membrane layer. Generally, a membrane is an air-permeable layer that acts as a filter and lets air and gas pass through it; however, it is a resin barrier and contains the resin inside the chamber[11].

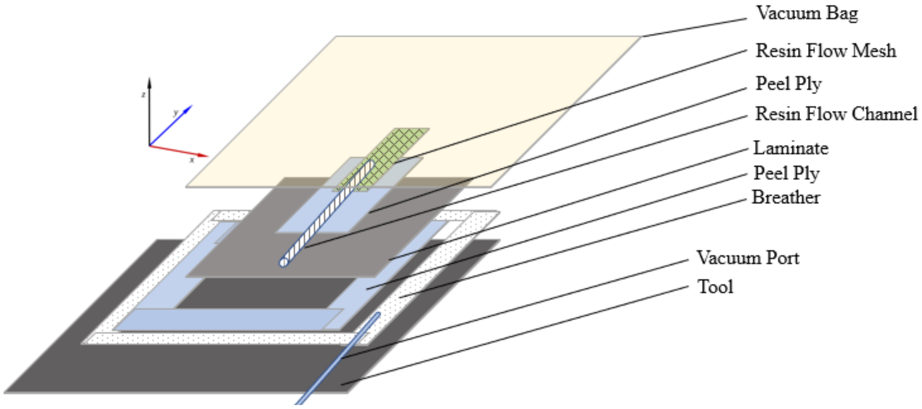


Figure 5. Explosive view of SCRIMP setup

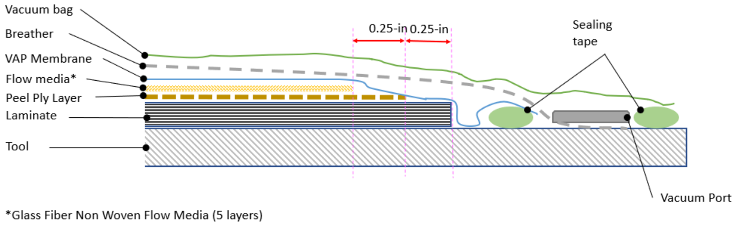


Figure 6. VAP membrane setup

In VARI, the most critical parameters affecting the process are stack-up permeability and resin viscosity. One of the many advantages of using AFP on manual hand layup is allowing the manufacturer to deposit or steer the fibers in complex geometry. However, due to compaction loads applied on preform by AFP, impregnation time increases relatively compared to manual hand layup[4].

4 Results and Discussion

Benefiting from placing dry fiber with AFP on a curved mold and infusing preforms made by ADFP with VARI, a 76 cm by 76 cm (30-by-30-inch) fuselage panel with symmetric quasi-isotropic layup [(90/45/0/-45)]s was fabricated, as it is shown in Figure 7. Three different curved panels had been manufactured before to obtain a high-quality demonstrator. A procedure was defined to analyze fabricated laminates' quality, as described in Figure 8.

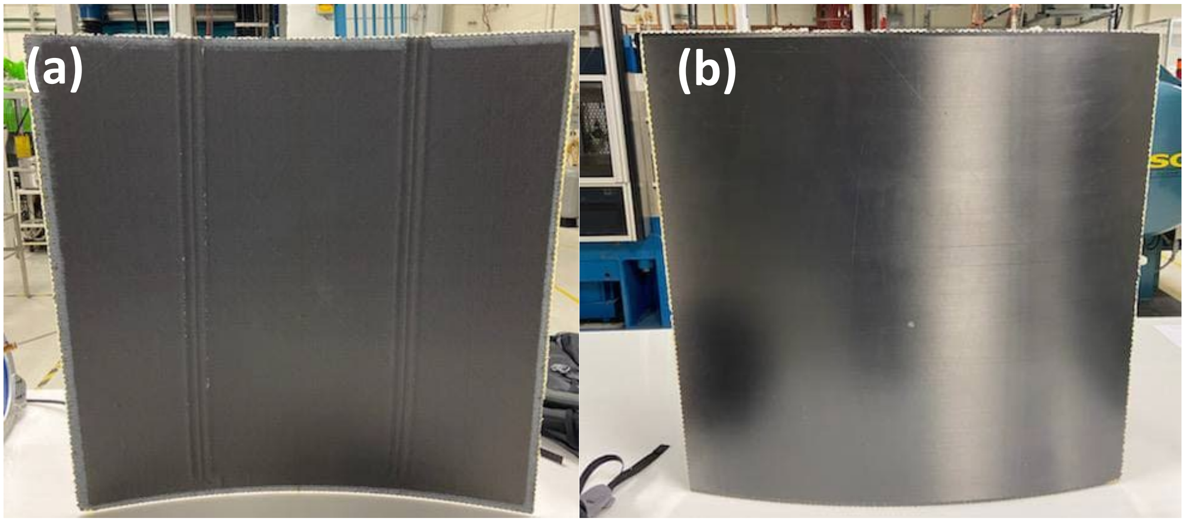
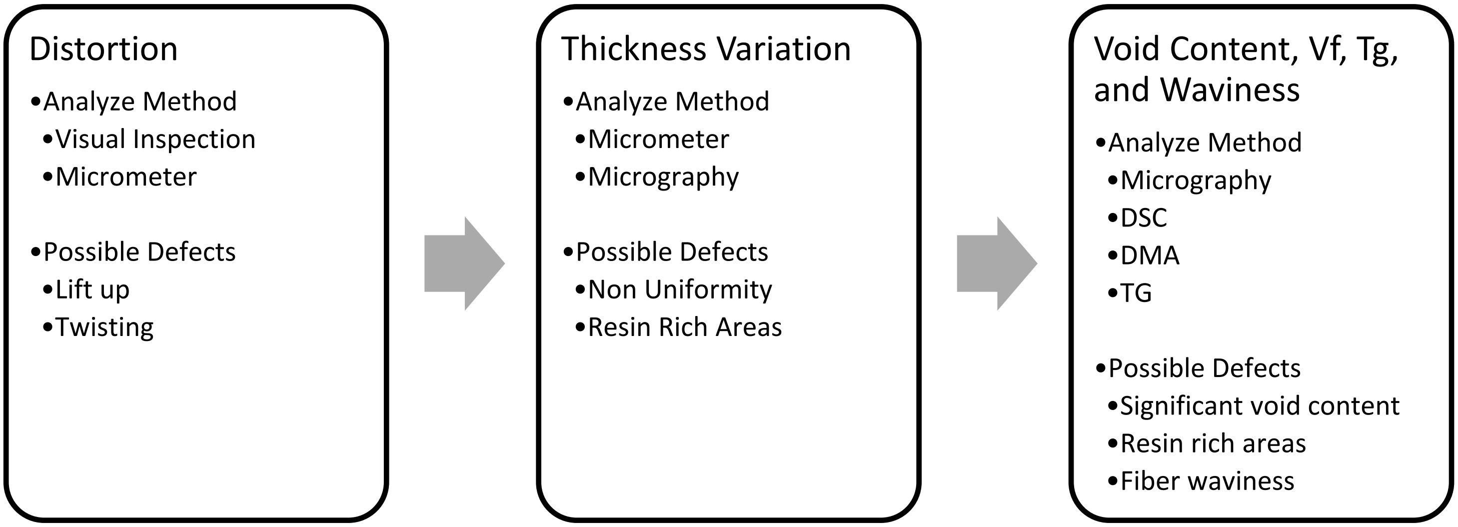


Figure 7. Demolded demonstrator after infusion a. bag side b. tool side

Firstly, the free edges of laminate under the vacuum bag might lift after demolding the part due to spring back effects and causes residual stress, resulting in deformation[12]. Therefore, to analyze the quality of laminate, deformation should be measured.

Secondly, the variation of chamber pressure on preform under the vacuum bag influences the thickness variation; thereby, it is critical to measure the thickness variation of laminate. In addition to having local low pressure, bag bridging also creates resin-rich areas that end in non-uniform laminate with major mechanical properties problems.

In liquid composite molding, voids could appear due to gas released from the chemical reaction of epoxy and air trap through resin flow[13]. Additionally, local resin-rich areas in the laminate structure could also reduce the fiber content and result in mechanical properties. Finally, laminate made by this developed process should satisfy the standards of the aviation industry in terms of fiber volume fraction, void content and degree of cure.



Distortion
- Analyze Method
  - Visual Inspection
  - Micrometer
- Possible Defects
  - Lift up
  - Twisting

Thickness Variation
- Analyze Method
  - Micrometer
  - Micrography
- Possible Defects
  - Non Uniformity
  - Resin Rich Areas

Void Content, Vf, Tg, and Waviness
- Analyze Method
  - Micrography
  - DSC
  - DMA
  - TG
- Possible Defects
  - Significant void content
  - Resin rich areas
  - Fiber waviness

Figure 8. Schematic of quality analysis procedure for laminate med

In the first step, the thickness of 40 points was measured using a micrometer with a precision of 0.001 mm to evaluate thickness uniformity, and the average thickness is reported in Table 2.

Table 2. Thickness variation of the demonstrator laminate

Average Thickness	CV %	Maximum Thickness	Minimum Thickness
1.503 ± 0.025 mm	1.503	1.595 mm	1.473 mm

4.1 Microscopic Analysis

Optical microscopy analysis was performed by taking samples from the demonstrator (Figure 9),1- to measure the thickness variation and void content, and 2- to evaluate the microstructure of the preform. The average void volume fraction was 0.311 %. Accordingly, it can demonstrate that using a membrane layer provides uniform vacuum pressure on the preform, resulting in higher impregnation.

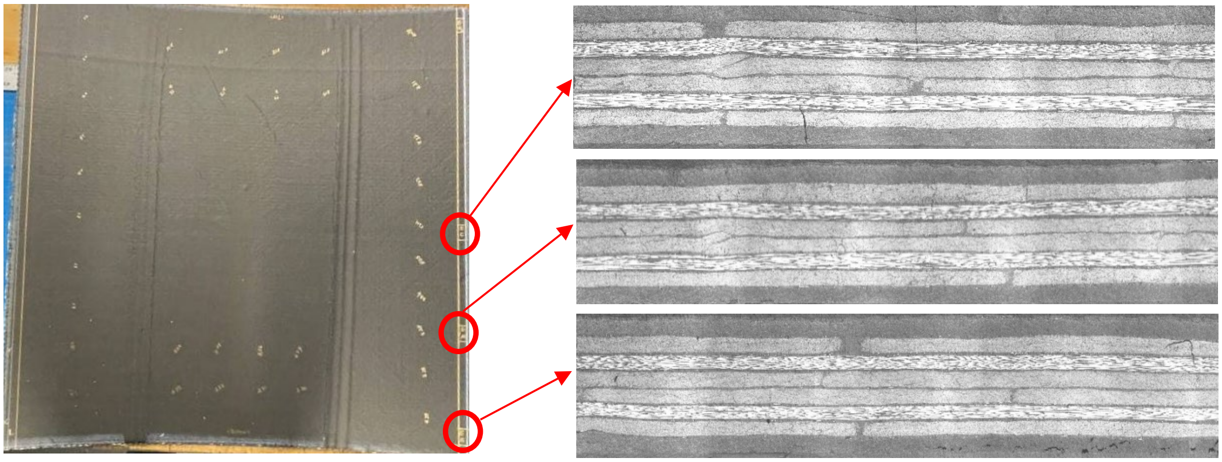


Figure 9. Micrographics for the demonstrator laminate

AFP machines can introduce gaps, overlap and different patterns like AP-PLY [13,14] between tows, changing the preform permeability. Although introducing gaps reduces the fiber content, considering an optimized gap pattern can result in high permeability and increase the epoxy impregnation.

In addition to introducing gaps to increase transverse permeability, adding more distribution media in the infusion setup can increase the in-plane permeability. As a result, it is seen that resin travelled further in-plane in the 4th panel by increasing layers of flow media from 2 to 5 in comparison to the 3rd panel. Although void content 25 cm from the edge of the 3rd panel was 1.713 %, the void content of the 4th panel's edge was noticeably lower than 0.5 %.

4.2 Fiber Content Measurement

Two methods were used to analyze the fiber content; 1- thermogravimetric analyzer test was used, and 2- microscopic images of samples taken from laminate. Thermogravimetric analyzer test (TGA) was run with ramp cycle up to 600 °C followed by isothermal for 10 minutes. According to the TGA test result (Figure 11), the sample weight loss is 23.17 %, and it can be estimated that 76.83 % of the sample weight is fiber. Moreover, either acid digestion test or microscopic analysis can verify this result, which microscopic analysis was chosen due to digestion's high hazardous effects.

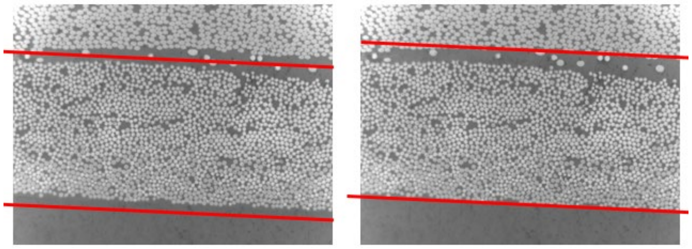


Figure 10. Microscopic measurement of the fiber content for the demonstrator laminate

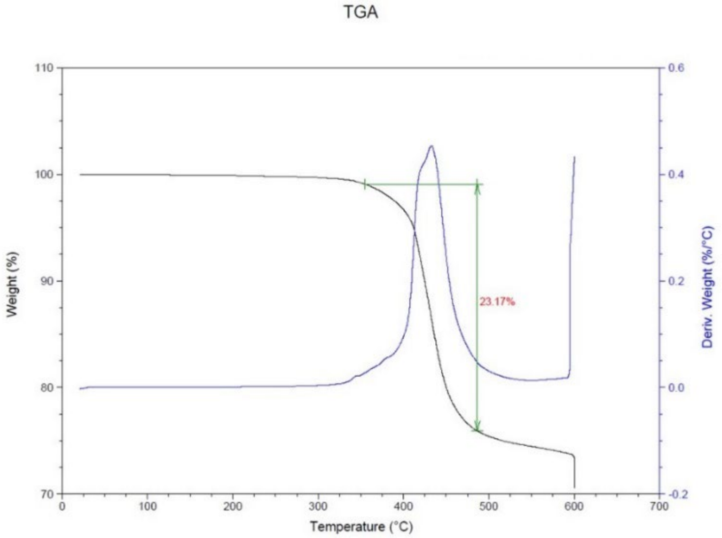


Figure 11. TGA result for the demonstrator laminate

As the layup sequence is symmetric quasi-isotropic with eight layers, cross-sections of taken samples are visible in the first and last layers, the 90° layers. Based on computing the fiber content for different regions in these two layers, the average fiber content is 60.02 ± 2.8 % which is 16.81 % lower than the TGA result. Mainly, two reasons could result in this difference between fiber content calculated by micrographs and TGA. First, epoxy might not burn completely in the TGA test, and second, fiber volume content might be different in other layers as only two layers were considered for calculations.

4.3 Glass Transition Temperature

This study used differential scanning calorimetry test (DSC) and dynamic mechanical analyzer (DMA) to estimate the epoxy system's glass transition temperature and degree of cure. In each of these tests, the glass transition temperature is derived by measuring changes in specific material properties, specifically, heat capacity in DSC and mechanical strength in DMA. Based on the DSC test result, the unreacted portion in the above DSC curve is 0.2071 J/g which describes the residual heat of the reaction. Using Equation (1) and kinetic parameters for the PRISM EP 2400 resin, obtained from Ref [15], the degree of cure is above 99.5 %, considered cured.

$$\alpha = \frac{H_t}{H_T} = 1 - \frac{H_{res}}{H_T} \, [16,17]$$

$\alpha: The\ degree\ of\ cure$

$H_t: Heat\ generated\ up\ to\ a\ certain\ time\ t\ (\frac{J}{g})$ (1)

$H_T: Total\ heat\ generated\ at\ complete\ cure\ (\frac{J}{g})$

$H_{res}: Residual\ heat\ of\ reaction\ (unreacted\ portion)(\frac{J}{g})$

As shown in Figure 12, the DSC test approach was heating, cooling, and heating with a rate of 10°C/min. Consequently, the average glass transition temperature obtained from several samples is approximately 145°C. Using the DMA test and measuring the loss modulus and peak temperature, the average Tg was computed at 160.25 °C, which is very close to the epoxy Tg in the datasheet.

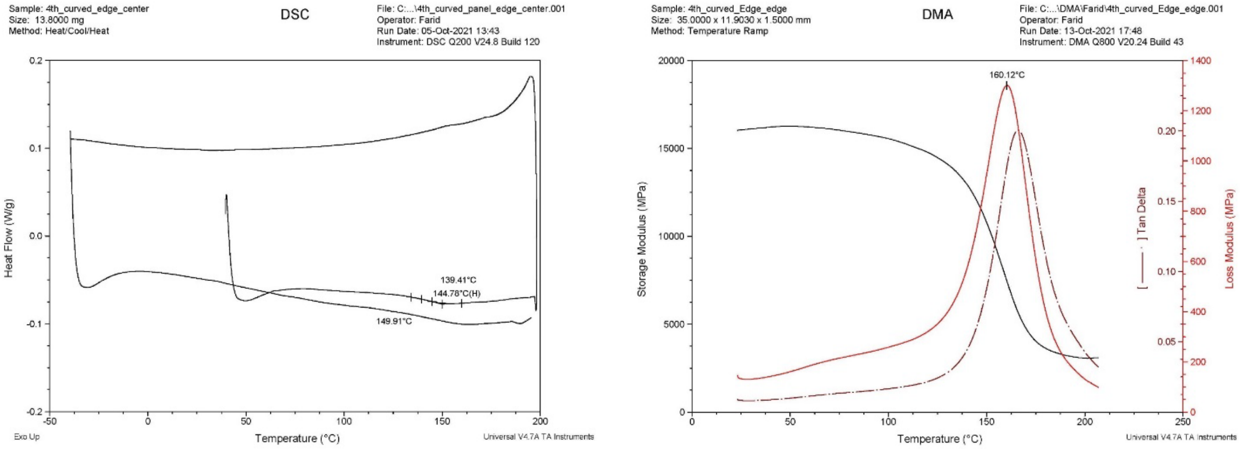


Figure 12. DSC and DMA results for the demonstrator laminate

5 Conclusion

The study presented here is a step to develop an alternative fabrication process for industries using automated dry fiber placement (ADFP) preforms impregnated with vacuum-assisted resin infusion (VARI). This paper targets the development of this process by fabricating a sizable demonstrator that reaches high standards in terms of thickness uniformity, void content, and degree of cure.

Firstly, the structure of dry fiber materials was studied to find the difference among available materials. Secondly, process parameters and the relation between ADFP and VARI were analyzed to study the processability of this method. Thirdly, possible defects were discussed to understand the effect of parameters on the result. As a result, the fabricated demonstrator panel with [(90/45/0/-45)]s layup has a uniform thickness of 1.503 ± 0.025 mm, low void content of 0.311%, and degree of cure above 99.5 %. This research can be continued by developing this method for steering in complex geometries for different cutout patterns. Also, comparing this method's mechanical performance and cost and energy saving to prepreg-autoclave is considered the next step in this study.

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