THIN-PLY: EXPLORATION AND MANUFACTURING WITH AUTOMATED FIBER PLACEMENT

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ABSTRACT

Highly repeatable and nearly defect-free fabrication of composite parts is critical to the success and widespread acceptance of composite materials. Through optimization using thin-ply materials, composite parts can be manufactured to be lighter and tailored more specifically to anticipated design loads than with standard prepreg materials alone. However, defects arising from the thin-ply manufacturing process are not always similar to defects found with standard tows. These new defects warrant evaluation. At NASA Langley Research Center, the manufacturing process parameters associated with automated fiber placement (AFP), a slit tape-based composite manufacturing process, were optimized for the use of a thin-ply prepreg carbon-epoxy material. Carbon-epoxy tows with areal weights of 30 g/m^2 and 70 g/m^2 were used in these manufacturing trials. The AFP process parameters of heater output, compaction force, tow feed rate, and tow tension were adjusted and optimized for successful manufacturing. This article documents an exploration of thin-ply fabrication on both flat and complex-shaped surfaces. Ultimately, aerospace-quality laminates were made from the 70-g/m^2 material, but imperfections in the 30-g/m^2 material itself and the fact that the AFP machine was not designed for such a thin material meant that more research and trials are required to obtain flight-quality 30-g/m^2 laminates.

1. INTRODUCTION

As the demand for lighter, faster, and more fuel-efficient aircraft increases, manufacturers are seeking state-of-the-art materials and processes to cost-efficiently produce composite parts. The high specific strength and stiffness of carbon fiber composite materials make them an ideal substitute for many metal components in aeronautical and space applications. A basic composite material comprises a matrix, such as an epoxy, in combination with a fiber reinforcement. The resulting inherent directional dependency of the material allows engineers to tailor their designs with greater specificity to the loads, and thereby reduce overall weight [1] [2].

As is the case across almost all industries, composites manufacturers are moving to faster manufacturing methods, which frequently use automated processes as a more cost-effective option compared to traditional hand layup. One cost- and time-effective approach is automated fiber placement (AFP), which uses a robotic or gantry system to additively manufacture a part using slit composite prepreg tapes, also known as "tows". The process of laying tows and consolidating "plies", or layers of thermoset prepreg, with various fiber orientation angles is performed by the AFP system before the part is cured in an autoclave. As a result, fabrication is faster than with traditional hand layup, and the overall quality and reproducibility of the part is improved. The tows typically used in AFP have widths ranging from 3.175 mm to 12.7 mm (0.125 in. to 0.5 in.), which can reduce material waste and match the part boundary more closely than with many other automated processes such as automated tape laying.

At the NASA Langley Research Center (LaRC), AFP is conducted with the Integrated Structural Assembly of Advanced Composites (ISAAC) robotic system. Through research at LaRC with ISAAC, the boundaries of AFP capabilities are constantly being tested, including in the areas of new material forms and the steering of tows for variable stiffness designs. One new material form currently being studied is thin-ply prepreg material, which has less than half the areal weight of standard-ply material. By manufacturing composite parts with thinner plies, the performance could be improved and the weight reduced compared to parts built with only standard thickness plies. The use of thinner plies for selected structures widens the design space and provides opportunities for structural tailoring to specific design loads beyond what can be achieved with standard thickness materials alone.

In addition to the production of lighter parts and expansion of possible laminate designs, the use of thin-ply layers can also provide mechanical advantages such as a delay in the onset of damage and higher ultimate strength values. However, thin-ply fabrication has thus far been largely limited to hand layup, and there has been no literature encountered in the literature review on implementing thin-ply material in an AFP process. New manufacturing-related AFP thin-ply research activities at the LaRC are documented in this paper.

2. LITERATURE REVIEW

With the advent of composite tow spreading technologies, thin-ply material is becoming increasingly commercially available, and has already been implemented in high-performance and weight-sensitive applications such as solar planes and racing catamarans [3]. In comparison to standard prepreg material, thin-ply has a significantly lower fiber areal weight ranging from 15 g/m^2 to 70 g/m^2 compared to the typical 140 g/m^2 to 170 g/m^2. This lower fiber areal weight leads to opportunities in both design and mechanical properties.

Thinner plies permit the design and manufacturing of lighter composite parts and permit the inclusion of a greater number of fiber orientation angles within a given thickness. Composite engineers can propose more optimal laminates by using thinner plies compared to standard-thickness plies. Additionally, hybrid laminates can be created that utilize standard plies along the principal stress directions and thin plies to suppress delamination. Thin plies can also lead to smoother, more gradual laminate thickness changes.

Using thinner plies can increase some laminate mechanical properties compared to using standard-thickness plies. This thin-ply effect can be achieved by varying the laminate laying sequence while keeping the stacking sequence, fiber orientation angles, and fiber volume fraction constant. Laminates can be created with either ply-block stacking, where each fiber orientation angle is repeated "n" times as in $[+45_n/90_n/-45_n/0_n]_s$, or sublaminate stacking, where the sublaminate ply sequence is repeated n times as in $[+45/90/-45/0]_{ns}$. Amacher et. al., was one of the first research groups to observe this thin-ply effect by using a single fiber-resin system, but using a wide range of ply thicknesses, including standard plies, ply-block stacking, and sublaminate stacking [4]. Tsai et al., demonstrated a 10% increase in ultimate strength in unnotched tension of quasi-isotropic thin-ply laminates compared to those with thicker plies [5]. Lovejoy and Scotti [6] showed that combining thin and standard plies in a hybrid laminate can yield weight-savings for aircraft structure while having a reduced impact on manufacturing time.

The failure in composites typically begins with transverse microcracking before leading to catastrophic failure through delamination and possible fiber breakage. Delamination frequently occurs due to interlaminar stresses concentrated near the free edge of the laminate. Kim and Soni showed that the onset of delamination damage increases as the number of plies increases but is dependent on the fiber orientation grouping of plies [7]. The exact cause of the improved mechanical qualities is unknown, but may be attributed to a statistically greater number of defects in thicker plies in comparison to thin-plies that causes them to probabilistically fail at a lower stress, as well as the constraining effect of surrounding plies on intralaminar crack propagation [8].

Most of published thin-ply research at this point has focused on the mechanical properties of thin-ply material in comparison to standard-ply material based on hand layup. The use of AFP for standard thickness composite construction, however, has been well documented with widespread usage, *e.g.*, the Boeing 787 Dreamliner. Similar to the course of metal-working industrialization, AFP processes are based on multi-axis computer numerically controlled (CNC) machines with feeding mechanisms to build up a part layer-by-layer in an additive, rather than subtractive, manufacturing process [9]. Through controlled tow tension, compaction, heat, and tow feed rate, AFP places prepreg tows on a tool, or reverse mold of the intended part, and directly consolidates them with a compaction roller. A variety of resins can be used with AFP including most commonly used thermosets, which are then cured in an autoclave, and thermoplastics.

Although AFP is widely used, especially in the aircraft manufacturing industry, the process is not yet completely automated. The characteristics of the completed composite part are highly dependent upon tool geometry, environmental conditions, and in-coming material quality. Any modifications or fluctuations in the material or process can cause defects in the part to occur. These defects must subsequently be identified and repaired by hand. Such repairs can be quite time-consuming. Without repairs, defects can degrade the mechanical properties. The most common types of defects include gaps/overlaps, puckering, tow wandering, angle deviation, and wrinkles [10]. The presence of gaps decreases mechanical strength through the creation of resin-rich areas, while overlaps tend to locally increase the stiffness of the part [11], [12], [2]. Defects must be kept to a minimum in order to successfully manufacture consistent, high-quality composite parts. The ability to fabricate carbon-epoxy composites using thin-ply material in AFP would significantly expand its potential applications by providing a faster, more cost-effective, and reproducible method of manufacturing thin-ply composite parts.

3. AUTOMATED FIBER PLACEMENT WITH THIN-PLY

At LaRC, AFP research is conducted within the ISAAC facility. The ISAAC robot can be paired with a variety of end effectors, including an AFP head, is shown in Figure 1. Two additional degrees of freedom are provided by a 12.6-m long linear rail and a vertical rotator for the manufacturing of complex geometries [13].

Up to 16 6.35-mm (0.25-in) wide prepreg tows can be laid simultaneously by the AFP head. Following tape backing removal, prepreg tapes are redirected from spools located on the head into a feeding mechanism. The tows are fed onto the surface and cut to the appropriate length while being compacted by a 101.6-mm (4-in.) wide polytetrafluoroethylene-coated roller. Several tows placed at once comprise a course, which can be placed both uni- and bi-directionally. Multiple courses in one layer make up a ply, and several plies constitute the fully formed laminate. All aspects of the robotic system, as well as a 3.7-m by 1.8-m coupon table and additional end effectors, are located within the work cell. The entire system is located in a ISO 7 clean room to maintain control over environmental conditions and airborne particulates. In addition to an AFP end effector, ISAAC also has laser projection, non-destructive inspection (NDI), ultra-sonic cutting, and through-the-thickness stitching capabilities.

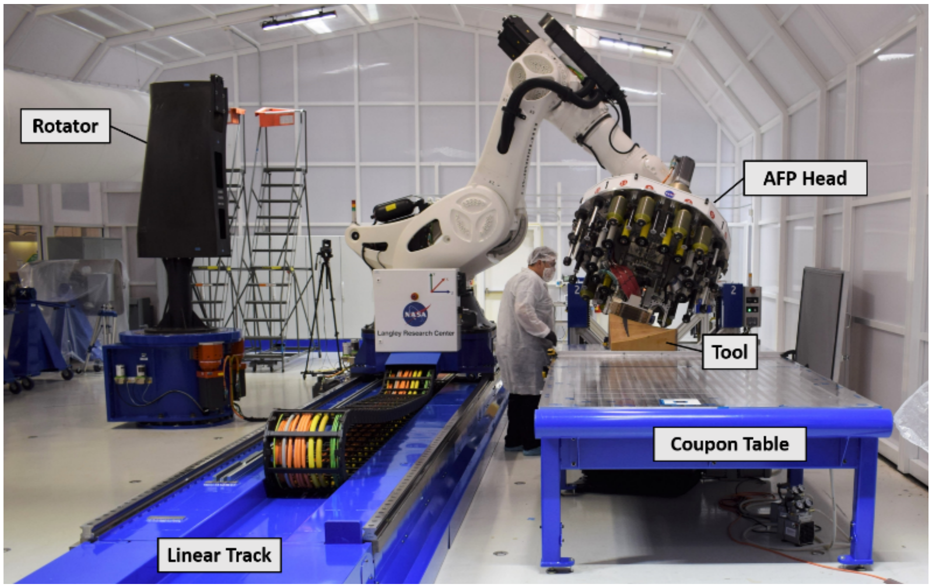


Figure 1. ISAAC robotic system.

The process of building a composite part with ISAAC requires a significant amount of project planning and is conducted in several phases as illustrated in Figure 2. A structural engineer initially designs the laminate and defines appropriate fiber orientation angles. A three-dimensional (3D) computer-aided design model is developed to simulate the tool upon which the tows will be laid. The layup design and numerical control (NC) code for ISAAC are created using the programming and simulation programs that can identify potential joint failures or collisions prior to running a program on the robot [14]. The NC code is then imported into ISAAC, and a dry run is conducted without placement of composite material. Upon successful completion of the dry run, the build is carried out. Throughout the build, the process may be halted to allow for inspection and defect repair as necessary. The fully-placed laminate is then vacuum-bagged and cured in an autoclave.

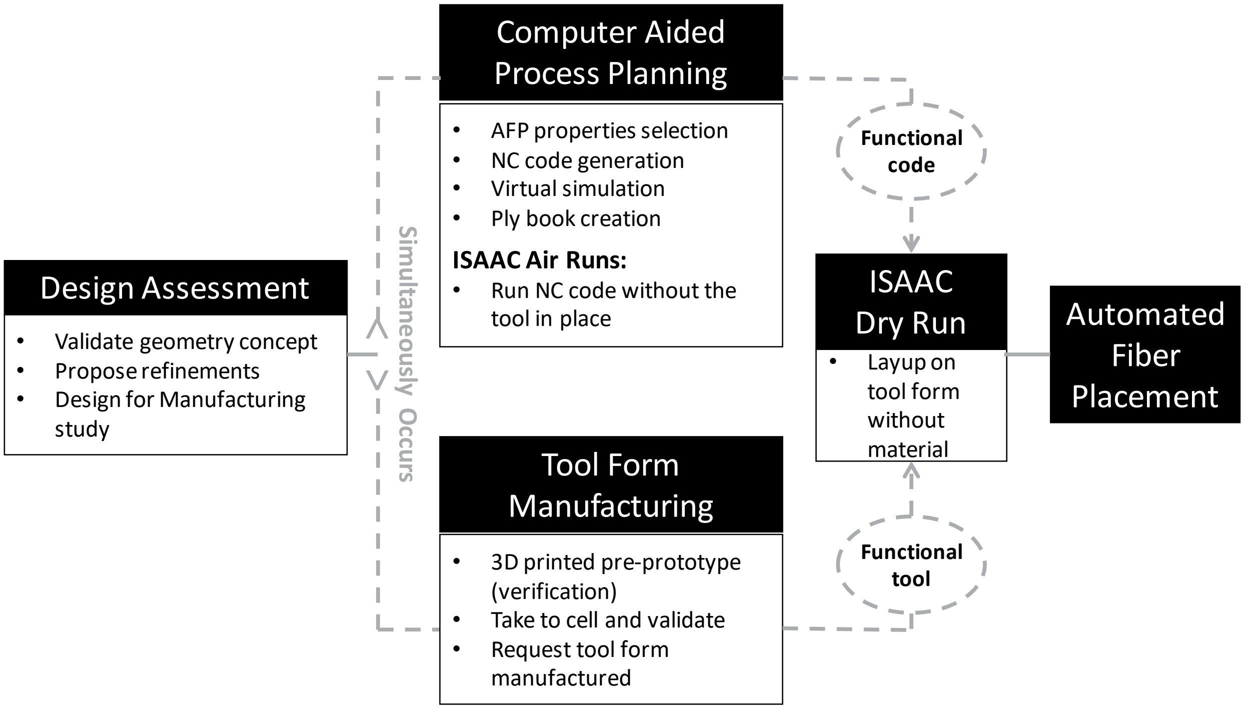


Figure 2. ISAAC manufacturing flowchart [15].

Although the programming controls the majority of the settings, and these settings are established prior to placing material, the operator has real-time control over some manufacturing parameters including tow tension, compaction force, tow feed rate, and heater output during the course of the build. The choice of the values for these parameters are highly dependent on the material system being used and the AFP head orientation relative to the tool geometry. The ideal value of these parameters can vary from one part to another. Therefore, exploration trials must be carried out prior to the manufacturing of a composite part in order to predetermine the manufacturing settings without compromising time or material during the fabrication of the final part.

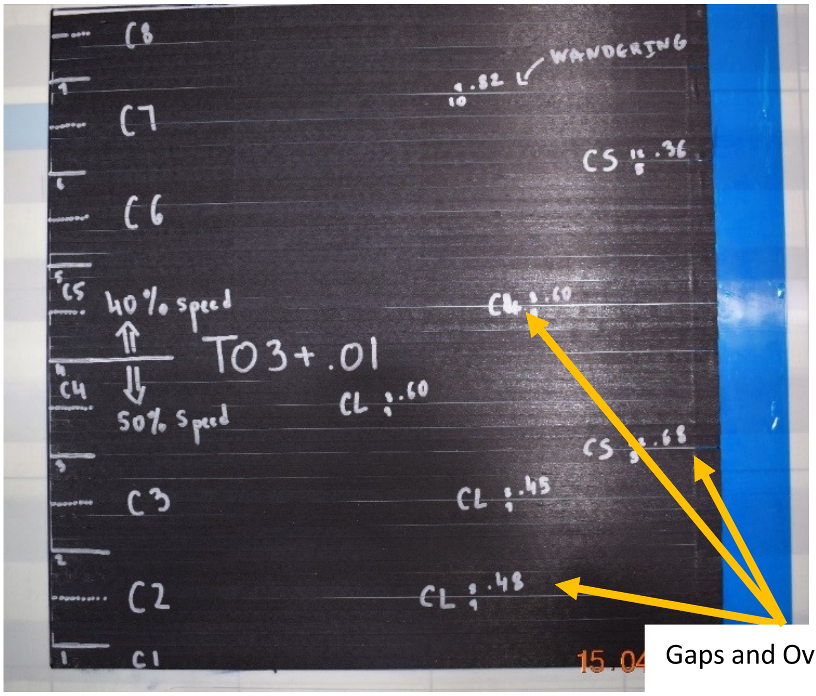
Identification of appropriate values for process parameters is determined through a qualitative analysis of defects at various fiber orientation angle placements. Ideally, the placement should entail a minimal number of defects while the part is fabricated with a high feed rate. Certain types of defects can be correlated or attributed to a specific process parameter, which can be consequently adjusted. In the thin-ply trials discussed herein, the manufacturing process parameters were determined in order to successfully place plies with areal weights of 30 g/m^2 and 70 g/m^2 material on flat and complex tool surfaces. Parameters were systematically varied individually between trials, which typically consisted of several courses within a ply. Once a ply was laid, trials progressed to full ply placement, and eventually to full laminate manufacturing.

4. THIN-PLY LAYUP OF A FLAT PANEL WITH 70 G/M^2

The goal of these studies was to understand the robot configuration and process parameters necessary to lay plies and manufacture a part with the minimum number of defects requiring manual repair. Thin-ply AFP trials began using the Toray 3900-2/T800S fiber-resin system with tow widths of 6.35 mm (0.25 in.) and an areal weight of 70 g/m^2. Before starting 70 g/m^2 trials, the coupon table surface was cleaned and covered with a Mylar sheet that extended at least 101.6 mm (4 in.) around the perimeter of the two 355.6 mm (14 in.) by 355.6 mm (14 in.) panels intended for both 70 g/m^2 and 30 g/m^2 trials. The edges of the sheet were secured with flash tape, and vacuum was applied to keep the surface flat against the table. Preliminary exploratory trials were conducted. These initial trials were followed by manufacturing trials.

4.1 Exploratory Trials

The initial design of experiments included variations in fiber orientation angles, temperature (heater output), pressure (compaction force), tow tension, and tow feed rate. Parameters were adjusted in succession to facilitate observation of effects on part quality. After each trial, the process was paused, and the ply was qualitatively observed for defects. The fully-laid ply was then removed prior to the next trial. Feed rate is a percentage of the maximum allowable speed, which in this case is 25.4 m/min (1000 inches/min (ipm)). Heater output is proportional to the feed rate. The inverse relationship between heater output and feed rate causes heater output to decrease as feed rate increases. Ten trials were conducted by each placing three courses as shown in Figure 3.



Gaps and Overlaps

Figure 3. Effect of feed rate on ply quality at 40% feed rate (upper half of panel) and 50% feed rate (lower half of panel).

Heater output varied from 150% to 250%, feed rate from 30% to 100%, and compaction force from 222.41 N to 444.82N (50 lb to 100 lb) while tow tension remained constant at 4.45 N (1 lb). The parameter variations are shown in Table 1. Trials began with lower values of heater output and feed rate and increased as trials progressed, until courses began showing greater number of defects. When heat or feed rate became too high, adhesion to the underlying layer and wrapping of tows around the roller as a result of matrix melting became a common observation. As the AFP process with thin-ply is eventually optimized for manufacturing settings, the ideal process parameters will include the highest feed rate with minimum number of manual repairs necessary.

Table 1. Exploratory trials process parameters.

Trial*	Fiber Orientation Angle [°]	Heater Output [%]	Compaction Force [N (lb)]	Feed Rate [%]	Tension [N (lb)]
1.1	0	150	222.41 (50)	30	4.45 (1)
1.2	0	150	222.41 (50)	30	4.45 (1)
1.3	0	150	222.41 (50)	30	4.45 (1)
2.1	0	250	222.41 (50)	70	4.45 (1)
3.1	0	200	222.41 (50)	50	4.45 (1)
4.1	0	200	444.82 (100)	50	4.45 (1)
2.2	0	250	222.41 (50)	100	4.45 (1)
2.3	0	250	222.41 (50)	70	4.45 (1)
3.2 (C1-4)	0	200	222.41 (50)	50	4.45 (1)
3.2 (C5-8)	0	200	222.41 (50)	40	4.45 (1)

*C stands for course

The effect of feed rate on ply quality, while keeping all other parameters constant, can be observed in Figure 3 which corresponds to Trial 3.2 in Table 1. The upper half of the ply (courses 5-8) was manufactured with a feed rate of 40% and shows fewer tow gaps and less overall tow wandering compared to the lower half of the ply (courses 1-4) that was manufactured with a 50% feed rate. Recurring course gaps are due to material defects. After these initial trials were completed, the exploration progressed from trials based upon sets of three courses to full plies, where the selected variation of process parameters was dependent on the results of the initial trial. One ply was not removed prior to laying the next ply. Visible defects included gaps and overlaps angle deviation, and boundary errors. An initial ply was placed at 45°, as listed in Table 2. For the second ply at a 0° ply angle, the feed rate was kept the same for courses 1-3 at 40% feed rate, increased to 60% for courses 4-6, and then further increased to 70% for courses 7-8 (Figure 4). Some tow wandering was visible at the start of the ply as a result of defects from the underlying ply, as seen in Figure 4.

Table 2. Process parameters during manufacturing trials.

Trial	Fiber Orientation Angle [°]	Courses	Heater Output [%]	Compaction [N (lb)]	Feed Rate [%]	Tension [N (lb)]
1	+45	1-8	200	222.41 (50)	40	4.45 (1)
2.1	0	1-3	200	222.41 (50)	40	4.45 (1)
2.2	0	4-6	150	222.41 (50)	60	4.45 (1)
2.2	0	7-8	150	222.41 (50)	70	4.45 (1)

Based on these results, process parameters were identified to be used for future manufacturing trials with 70 g/m^2 material for this material system. These parameters were 200% heater output, 222.41 N (50 lb) of compaction force, and maximum feed rate values of 15.24 m/min (600 ipm) at all fiber orientation angles.

Figure 4. (a) Ply 2 with fiber angle 0°. (b) Tow wandering in ply start.

4.2 Manufacturing Trials

After completing the preliminary exploratory trials, a 35.56 cm by 35.56 cm (14 in. by 14 in.) composite panel with ply stacking sequence $[+45/0/-45/90]_{4S}$ and 8 tows per course was manufactured. Plies were not removed between runs (which make one trial). Courses were programmed at a constant angle with an approach angle of 5° and a unidirectional head movement. The approach angle is lifted from the surface and towards the tool placement. The process parameters for the initial plies were those identified as beneficial by the exploratory trials described in Section 4.1 including heater output of 200% and 222.41 N (50 lb) of compaction force. In the manufacturing trial, the feed rate varied from 7.62 m/min to 15.24 m/min (300 ipm to 600 ipm) to examine the influence of feed rate on tow wandering.

Plies 1-16 of the laminate required significant defect repair and were often subject to tow wandering and gaps/overlaps (Figure 5). Within the plies, tows were manually removed or relocated as necessary to the correct position by hand. Some tows experienced splitting, which may have been caused by the propensity of the material to separate in a resin-rich area (material defect), especially when the thin material was simultaneously subjected to compression by the roller and axial tension. Plies at ±45° required lower feed rates than 0° and 90° plies to obtain minimum-defect courses.

At the midplane of the laminate (between two 90° plies), flash tape was placed along the edges of the panel to facilitate removal of defective tows without damaging the underlying 90° layer. An observation was made that the ply placed over the tape was defect-free. This characteristic was attributed to the use of the flash tape, therefore, flash tape was then applied to just one side of the 45° ply, allowing for a direct comparison of the process with and without the tape, as seen in Figure 6. Since the presence of flash tape significantly reduced tow wandering near the beginning of the course, flash tape was applied to the edge of the preceding ply for all subsequent plies.

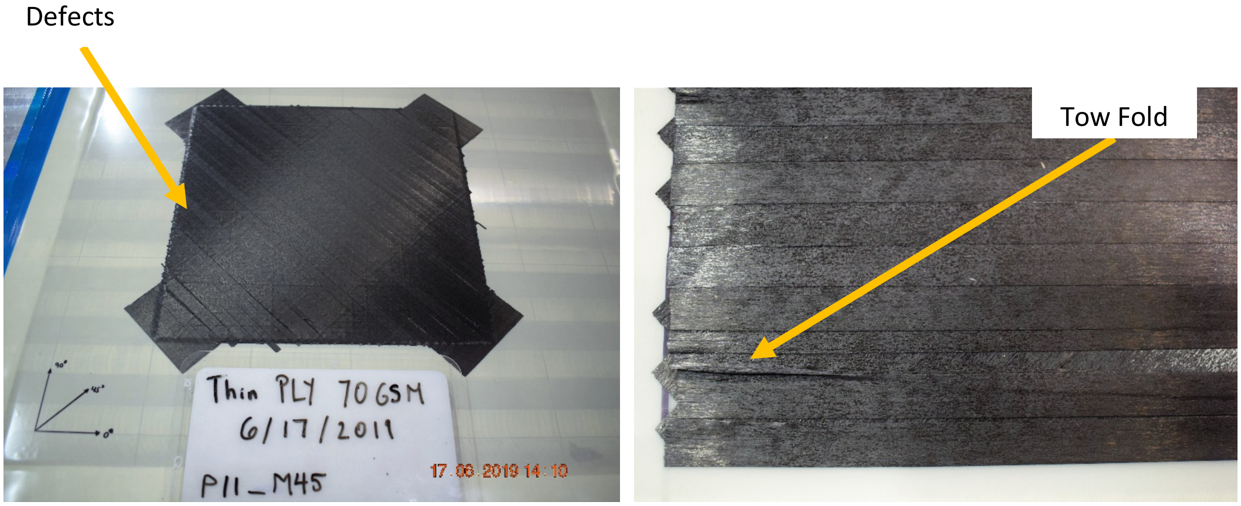


Figure 5. (a) Ply 11 (-45°) with tow wandering and angle deviation defects.

(b) Tow fold, tow wandering, and boundary placement defects in ply 2 (0°).

Figure 6. (a) Defect-free ply with application of flash tape.

(b) Ply with (left) and without (right) application of flash tape.

5. THIN-PLY LAYUP OF A FLAT PANEL WITH 30 G/M^2

The potential of 30 g/m^2 thin-ply material to be used in manufacturing was explored in subsequent trials. The material used in these trials was 6.35-mm (0.25-in.) wide prepreg tows from Hexcel with an IM7/8552 fiber-resin system. It is important to highlight that the material is not optimized for AFP, but was the less tacky hand-layup form of the material system. For 30 g/m^2 thin-ply material, the proposed process parameters to be optimized included variation in temperature (heater output), compaction force, tow tension, and tow feed rate, according to Table 2. Like the 70 g/m^2 study, a 35.56 cm by 35.56 cm (14 in. by14 in.) panel was built. A $[45/0/-45/90]_{4s}$ ply stacking sequence was again used, but 4 or 8 tows per course were placed instead of 16 tows. Like with the 70 g/m^2 material, courses were programmed according to the rosette rule with an approach angle of 5° and a unidirectional head movement. Unlike for the 70 g/m^2 material, a tackifier or double-sided tape was often applied prior to ply placement to increase adhesion of the beginning of a course to the substrate.

5.1 AFP Head Modification

A first backing tape layer had been applied to each 30 g/m^2 spool prior to slitting to support the tows during slitting, followed by the second layer of backing tape used to prevent tow self-adhesion within the spools. Therefore, in order to utilize 30 g/m^2 tows with the existing AFP head, some modification of the head was necessary to remove both layers of backing tape. A secondary take-up spool was designed and prototyped to be used in conjunction with the standard AFP setup. The secondary take-up spool was used to remove the first layer of backing tape that was removed from the tows closer to the feed shoot in order to stabilize the tows and prevent curling. The secondary take-up spools installed on the ISAAC AFP head is shown in Figure 7.

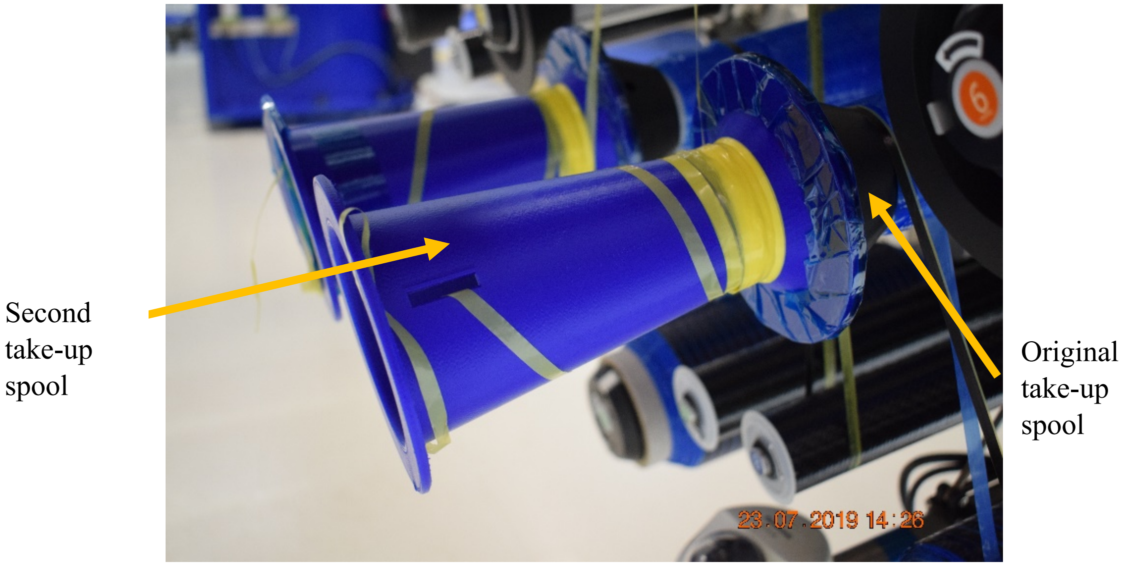


Figure 7: Secondary take-up spools on the ISAAC AFP head

Unfortunately, a noticeable inconsistent variance in tow width on the spools of the 30 g/m^2 material was identified, as shown in Figure 8. This variation led to defects in ply layups, particularly gaps between tows. As this is a material quality issue that may have been caused by a combination of the original material roll quality in combination with the slitting and winding process, this issue must be addressed by the manufacturer and slitter, and therefore cannot be optimized through control of AFP parameters.

Because thinner tows are more sensitive to temperature and mechanical stress during ply layup, lower amounts of heat and compaction force were applied in early trials to reduce the risk to tow jams. However, contrary to expectations, a low heater output and compaction force seemed conducive to causing tows to be pulled in and break within the feed guide chutes and active feed rollers, as seen in Figure 9. Small variations in hardware dimensions among passive guide rollers seemed to also facilitate more frequent jamming of tows in some locations than in others.

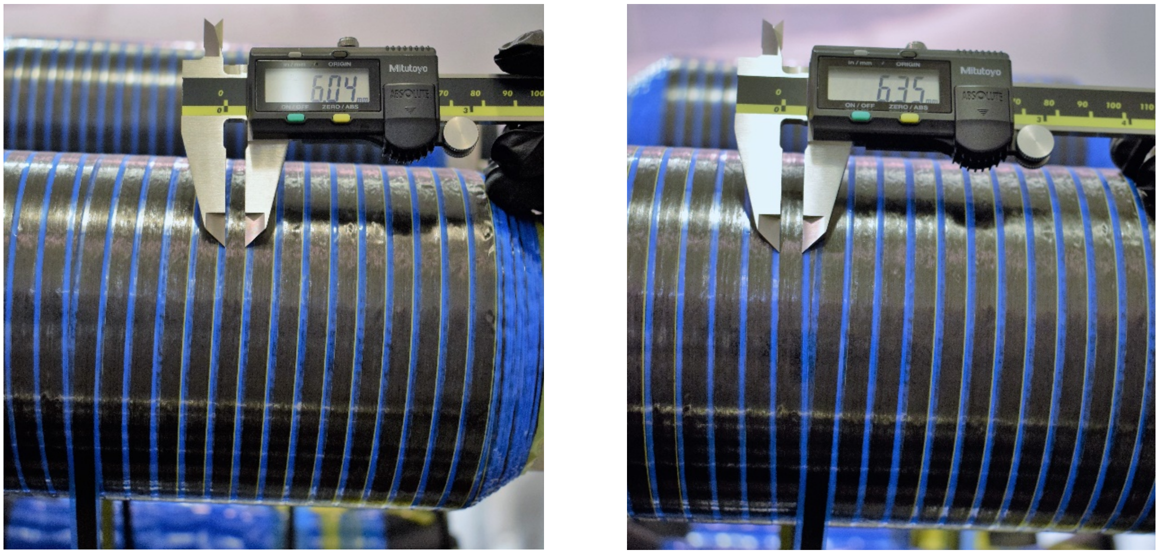


Figure 8. (a) Material width of 6.04 mm (0.2378 in) / narrow.

(b) Material width of 6.35 mm (0.2500 in) standard.

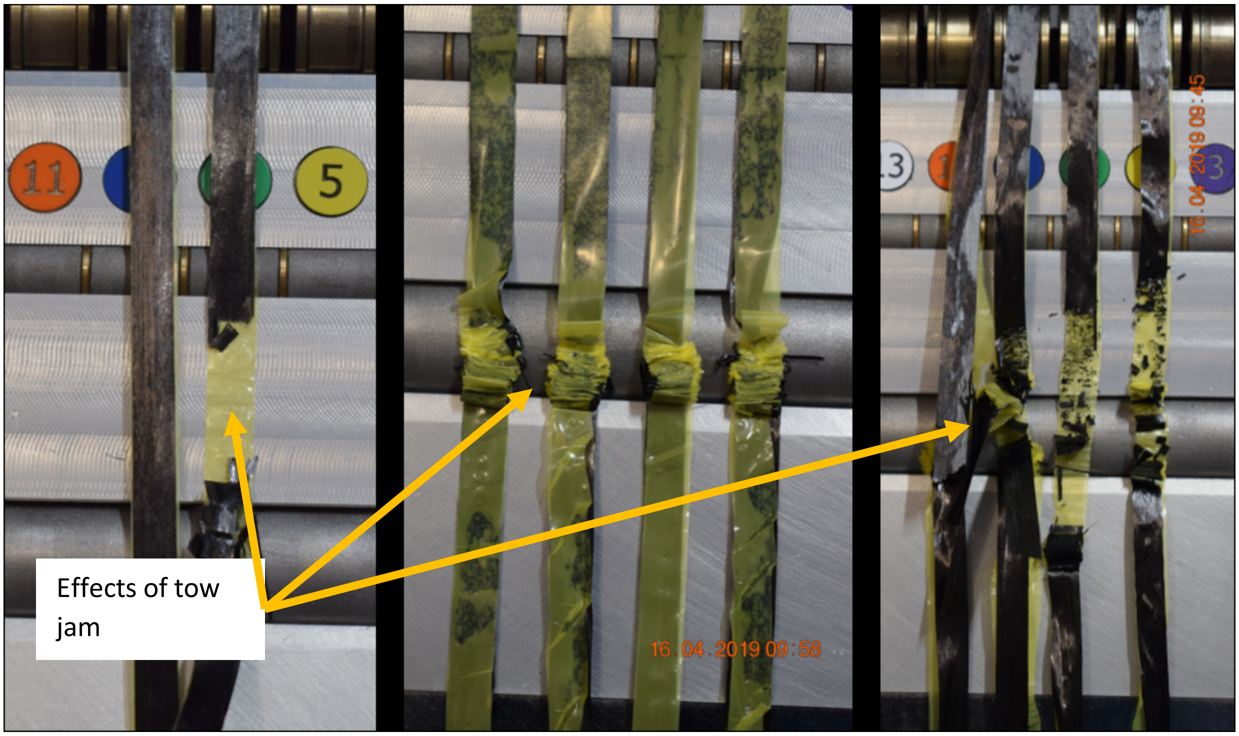


Figure 9. Tow jams in feed guide rollers.

5.2 Manufacturing Trials

In subsequent trials, compaction, heater output, and tow tension were increased in an effort to better support the tows as they moved through the guide chutes, and the feed rate was varied per course. As shown in Figure 10, the courses with 20% feed rate had the highest quality of layup. However, gaps and tow folds appeared for all feed rates.

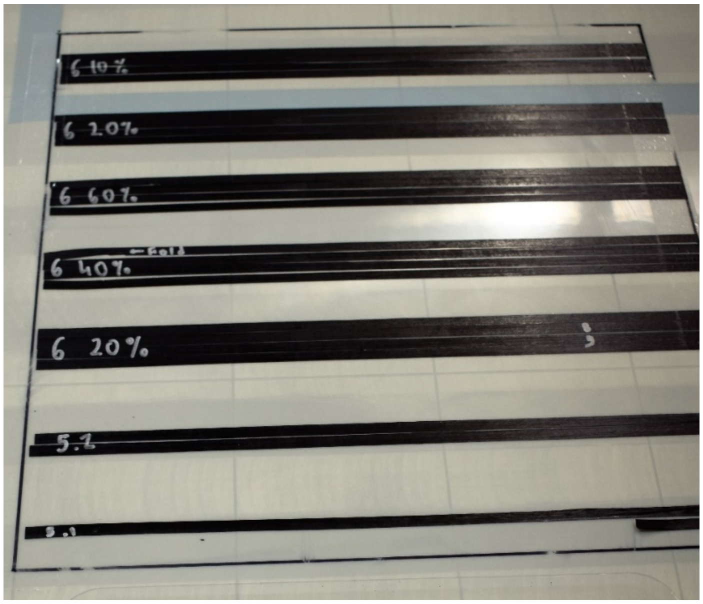


Figure 10. Trial 6, 30 g/m^2 with various feed rates between 10% and 60%.

Because the fiber orientation angle, as well the presence of underlying plies, can have an effect on the number and type of defects, several trials were conducted on overlapping plies at 0°, 90° and +45°. The square area outlined in Figure 11 was relatively free of visible defects, indicating the need for a "lead-in" area during an actual build.

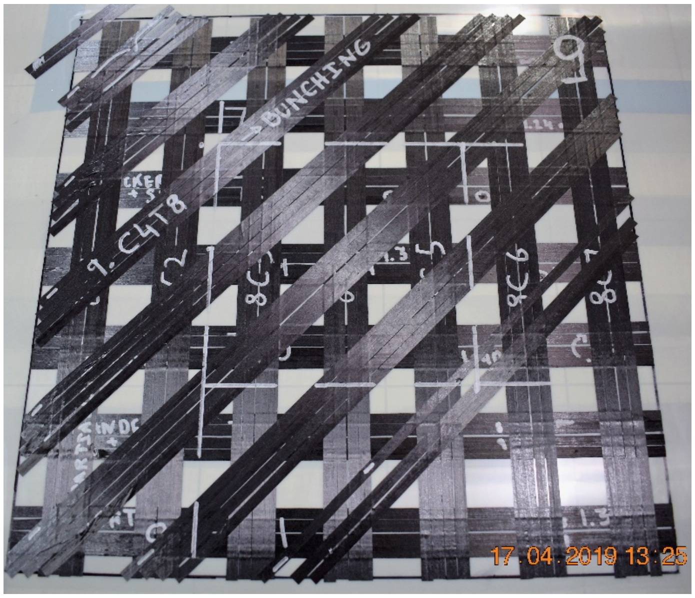


Figure 11. Overlapping trials at various fiber orientation angles.

The process parameters determined to be appropriate for 30 g/m^2 during this study were 200% heater output, 444.82 N (100 lb) of compaction force, 4.45 N (1 lb) of tow tension, and a relatively low feed rate of 5.08 m/min (200 ipm). Using the results from the prior exploration, two overlapping full plies with fiber orientation angles of 0° and 90° were successfully manufactured, as seen in Figure 12. The plies were also relatively defect-free, though some gaps and overlaps between the tows were still present, which could have resulted from the material defects mentioned previously.

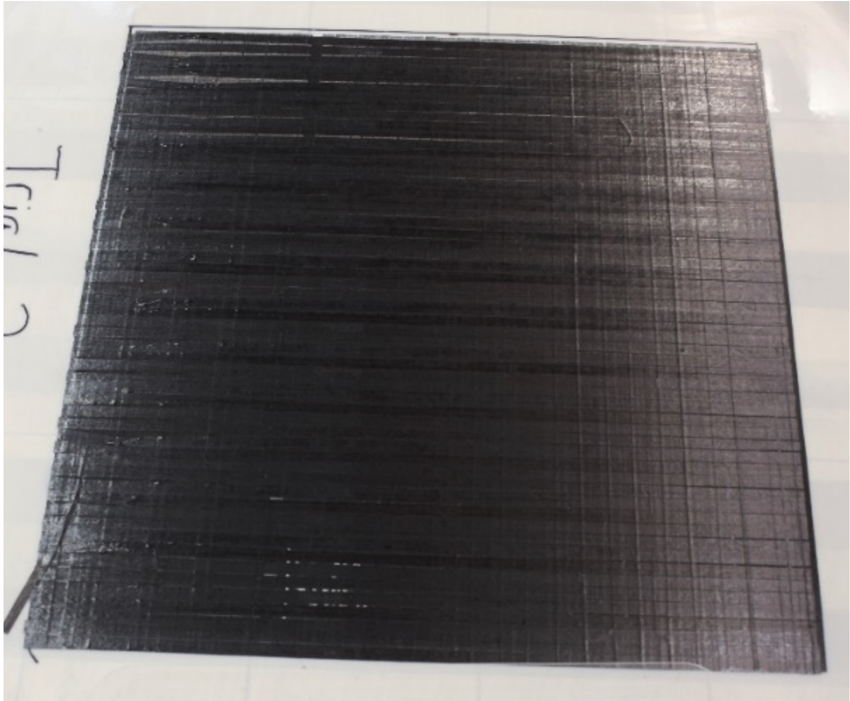


Figure 12. Successful placement of 0° and 90° plies.

6. THIN-PLY LAYUP OF A COMPLEX SURFACE WITH 70 G/M^2

After successfully manufacturing a flat panel with 70 g/m^2 Toray 3900-2/T800S fiber-resin material system, an evaluation of placing this same material on a complex-shaped tool surface was conducted as shown in Figure 13. This complex shape contained concave regions that posed a particular challenge to placement. This complex-shaped tool was originally used for placement of standard thickness plies in the study described in [15].

6.1 Exploratory Trials

Four plies of 70 g/m^2 material were sequentially laid up on the complex tool with orientations of 0°, 30°, -60°, and 90°. The processing parameters used in this trial ranged from 200% to 250% heater output, 222.41 N to 444.82 N (50 lb to 100 lb) of compaction force, and a feed rate from 5.08 m/min to 10.16 m/min (200 ipm to 400 ipm). The double convexity of the tool presented an additional challenge, particularly in obtaining sufficient compaction of the plies. Defects were identified between plies, marked, and photographed for documentation in order to examine the effects of defects on subsequent plies. Because this trial was focused on exploration, defects were not repaired.

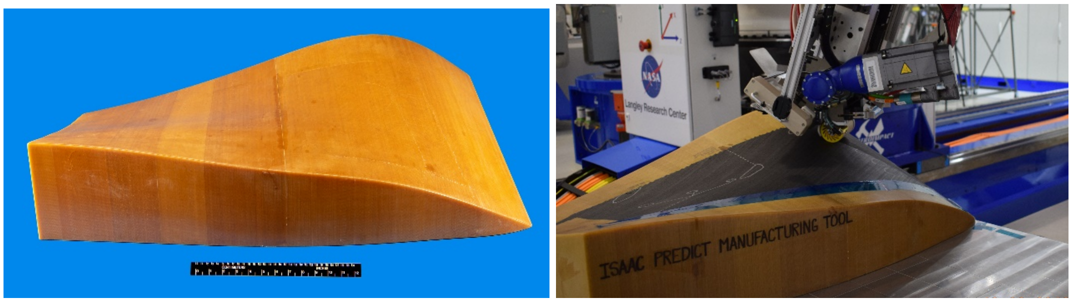


Figure 13. (a) Tool with complex curvature. (b) Layup with ISAAC on complex tool.

6.2 Discussion

A variety of defects were observed in the laminate including puckering, tow wandering, folds, split tows, and boundary errors. The splitting of tows seemed to be caused by resin-rich areas within the tows and was particularly noticeable at the onset of the ply and in the concave area of the tool, which may have been exacerbated by roller compaction or head angle deviations. Puckering was also observed where plies overlaid silver permanent pen markings on previous plies.

The need for a smaller roller (e.g. a roller designed for eight tows and only 5.08-cm (2-in.) wide became evident due to consistent "picking up" of tows by the 10.16-cm (4-in.) wide roller from previously laid courses (Figure 14). Additionally, a build-up of excess resin, as shown in Figure 14, caused several tows to jam, which was resolved by more frequent cleaning of the AFP head. Some tows displayed boundary error defects, showing that the excess resin buildup caused additional dulling of the cutting blades. Both observations indicated a need for more frequent cleaning of the AFP head when working with this thin-ply material system, mostly due to a combination of the fact that this resin system is not AFP optimized as well as that it is thin material.

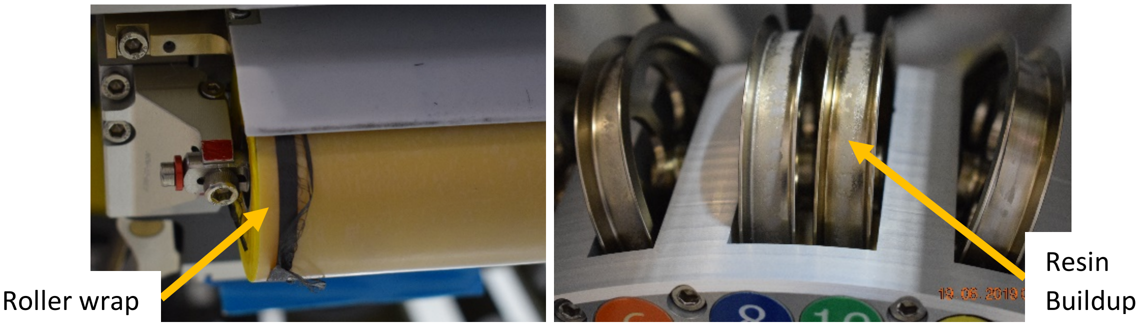


Figure 14. (a) Roller wrap due to high feed rate or heat. (b) Resin buildup on redirect rollers.

The final processing parameters in order to make fully formed and relatively defect-free plies using the 70 g/m^2 Toray 3900-2/T800S fiber-resin system on a complex-shaped tool were determined to be 200% heater output, 222.41 N (50 lb) of compaction force, and 10.16 m/min (400 ipm). With minimal AFP hardware modification, the ISAAC AFP system could be employed to manufacture this complex geometry with 70 g/m^2 thin-ply material.

7. RESULTS AND DISCUSSION

The results of these trials indicate that both 30 g/m^2 and 70 g/m^2 thin-ply materials have potential for application in relatively defect-free manufacturing once the appropriate process parameters have been identified. During all trials described herein, parameters including tow tension, compaction force, heater output, and tow feed rate were systematically adjusted until the placed plies showed minimal defects. The recommended processing parameter values are shown in Table 3.

Table 3. Final process parameters for all builds.

Material System	Toray 3900-2/T800S			Hexply IM7/8552-1
Areal Weight [g/m^2]	70			30
Build Type	Flat panel	Flat panel	Complex	Flat panel
Ply Orientation [°]	0, ±45, 90	+/-45	all	all
Heater Output [%]	200	200	200	200
Compaction [N (lb)]	444.82 (100)	222.41 (50)	222.41 (50)	444.82 (100)
Feed Rate [m/min (ipm)]	5.08 (200)	10.16 (400)	10.16 (400)	5.08 (200
Tow Tension [N (lb)]	4.45 (1)	4.45 (1)	4.45 (1)	4.45 (1)

A method of eliminating tow wandering was identified for 70 g/m^2 thin-ply material, that allowed the production of a 32-ply panel with minimal defect repair. Upon application of the flash tape along the edge of the ply start, all tow wandering and almost all other defects were eliminated in the ply. This result could be caused by a decrease in friction and roughness within the tow/substrate system as tows were applied in each new ply. The epoxy/epoxy interface of new tows sliding past the edges of previously laid tows exhibited a higher coefficient of friction in comparison to a tow on the smooth polyester flash tape. In AFP, because the tows are cantilevered from the guide tray along the scoop at the beginning of a course placement and before reaching the nip point, they have some freedom to move or change orientation slightly. The increased friction and roughness causes a tow to stick slightly before the nip point, which can introduce an angle deviation of the tow with respect to the nip point that is corrected when movement of the head causes the tows to align. With the flash tape present, the tows are less likely to stick to the underlying surface before the nip point, and therefore, are more likely to achieve the correct orientation through the feed guide.

Orientation sequences that allow for greater contact with underlying tow edges, such placing a 45° ply over a 90° ply, could also increase apparent roughness of the underlying substrate and promote angle deviation. This deviation would cause the 45° ply to have greater tow wandering, as has been previously seen.

The extreme thinness of 30 g/m^2 material introduced a greater sensitivity to the process parameters used in the ISAAC facility and was less compatible with dimensions of AFP head hardware, such as guide feed depth. Similar process parameters were implemented using 30 g/m^2 material but with lower tow feed rates relative to 70 g/m^2 material. Hardware modification to the AFP head was required due to the presence of an extra backing tape provided with the prepreg material. Overlapping plies at various fiber orientation angles were also successfully manufactured with 30 g/m^2, though further adjustment of hardware and optimization of material quality is required before commencing with full-scale manufacturing or complex geometries.

8. CONCLUDING REMARKS

The use of 30 g/m^2 and 70 g/m^2 thin-ply materials was examined using the AFP robotic system at LaRC. The results of these trials indicate that both these material forms have potential for application in relatively defect-free manufacturing once the appropriate process parameters have been identified. During all trials described herein, parameters including tow tension, compaction force, heater output, and tow feed rate were systematically adjusted until the placed plies showed minimal defects. The recommended processing parameter values were determined for Toray 3900-2/T800S and Hexcel IM7/8552 materials through placement of +45°, 90°, -45°, and 0° plies. The use of thin-ply materials is extremely promising as a weight-saving and cost-efficient method to produce novel and high-performance composite parts with minimal time and labor investments.

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