2021-01-0043

High Speed AFP Processing of Thermoplastics

Michael Assadi
Electroimpact Inc.

Abstract

Today, large aircraft components rely on automated fiber placement (AFP) processing followed by an autoclave cure. High-speed AFP processing has proven very effective for insitu layup using thermoset materials on latest generation AFP equipment. There remains, however, a substantial opportunity to utilize thermoplastic pre-impregnated (prepregs) for large structural components in commercial aircraft.

Thermoplastics have an advantage with the elimination of uncured resin build-up. The build-up limits AFP reliability and productivity. This advantage hasn't been realized because most thermoplastic research has centered around full insitu consolidation intending to eliminate post-processing for curing. The main restriction of full insitu consolidation is on the speed (and productivity) of the AFP process, which is limited by the physics or chemistry of thermoplastic materials. This method places all the demands of final part quality (low porosity, proper crystallinity and autohesion) on the AFP process. In addition, the insitu consolidated AFP process is further complicated by being sensitive to the quality of the raw material, which can vary greatly from supplier to supplier and for each material matrix.

Current advances in materials, AFP technology and post processing can greatly increase the productivity of thermoplastics for large structural components. Toray Advanced Composites' CF/PEEK TC1200 is a well-established material in the industry, providing a large material property baseline for reference and comparison. TC1200 was used in the high-speed trials with success. CF/LMPAEK (TC1225) is the latest slit tape that provides a lower viscosity, and lower processing temperature, that will enable even faster AFP speeds and part complexity.

The advances in AFP technology, such as the new, Variable Spot Size (VSS) laser, have enabled the AFP processing of thermoplastics with individual tow heating. There are new Out-of-Autoclave (OoA) post-processing methods that can achieve the proper crystallinity and autohesion. By implementing these advances together with high speed AFP processing, the advantages of thermoplastic materials can be realized for large structural part.

Introduction

Large structural components of current commercial aircraft are constructed using AFP processing of thermoset materials followed by an autoclave curing process. AFP processing has been replacing many Automated Tape Laying (ATL) systems because they can reduce waste with individual (narrower) tows used in the AFP process to deposit near net material. The autoclave curing process is used for proper consolidation and autohesion required to attain the desired mechanical properties.

In the continual pursuit of cost and production time reductions, the efforts to optimize these processes have focused on increasing AFP cell utilization by increasing AFP reliability, reducing inspection time and reducing cure time. Advances in higher processing reliability [1] and automated in-process inspection methods [2] continue to increase AFP cell productivity with regards to thermoset materials. Combining these latest improvements and by blurring the lines between customer and supplier responsibilities, the overall system utilization has been increased dramatically for AFP systems with AFP4.0 [3]. All of the advances in AFP technology can be applied to both thermoset and thermoplastic materials.

There are also opportunities to reduce curing times by replacing the autoclave cure with Out of Autoclave (OoA) processing. This includes using dry fiber AFP processing (DFP) [4] followed by resin infusion using thermoset resins [5]. Dry fiber materials increase reliability by eliminating the issue of resin build-up, a known reliability issue for the AFP process; however, thermoset prepregs are mostly in use today.

In any case, thermoplastic materials do offer a great advantage over thermoset prepreg and dry fiber materials: Thermoplastic parts can be welded together which can potentially eliminate or reduce fastening of aircraft structures. This would have the effect of reducing downstream production processes. For this advantage to be realized, thermoplastics must better compete with thermoset prepreg production for large structural parts in aviation.

Insitu Consolidation

Typically, when thermoplastics are applied with AFP for large structural parts, the goal is to completely consolidate the material directly on a tool. This method attempts to achieve final part contour and quality during AFP layup (full insitu consolidation). As the material is dispensed by the machine, a compaction roller presses the material onto the previous layers while melting both the incoming material and previous layers (substrate). Applying pressure while the material is at the melting point removes voids (measured by material porosity) to achieve the desired part strength. If porosity is too high (>2%) the strength would not compete with thermoset materials. Further, crystallization throughout the laminate is required to facilitate welding. Finally, interlayer bonding, or autohesion, is required to achieve the desired strength as well. Proper melting temperature, pressure and dwell must always be maintained to achieve the required autohesion. To achieve the required properties during layup, the AFP process must be slowed to meet the material needs. It is the feeling of the author that trying to achieve all three qualities (porosity, crystallinity and autohesion) during lamination is the main reason why AFP insitu consolidation of thermoplastics has not made a business case for large structural parts when compared to existing methods.

However, there remains a substantial opportunity for using thermoplastic materials in a high-speed AFP process combined with OoA curing. This paper will focus on the improvements necessary for high speed AFP processing of thermoplastic materials to meet or exceed the productivity of thermoset materials.

Heating Systems for Thermoplastics

Thermoset materials require relatively low AFP processing temperatures. Traditional production systems use IR filament bulb heating [6] attaining processing temperatures of 32°C – 50°C. The heaters are aimed at the substrate material, warming enough of the substrate to allow the incoming material to (lightly) bond to the substrate material. The lamination is also easy to repair.

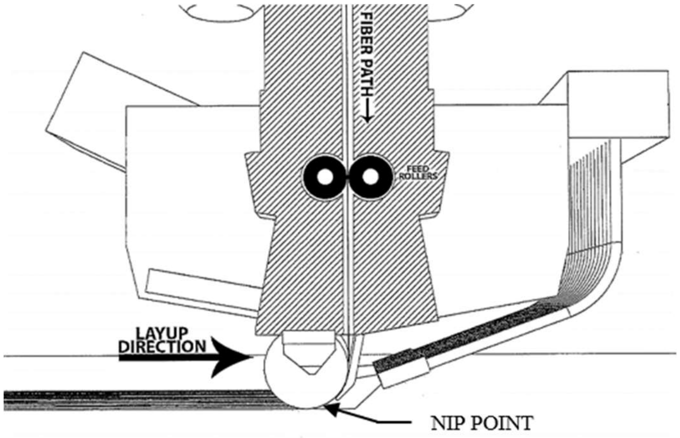

Figure 1. Laser beams aimed at the nip point of the AFP processing head in front of the incoming material.

Thermoplastic AFP processing temperatures are much higher (300°C – 400°C) and the heating spot must be aimed directly into the nip point where the incoming material meets the substrate (Figure 1). Lasers and flash lamp technologies have been used to reach these higher temperatures, but existing systems only offer a fixed heating spot size (Figure 2).

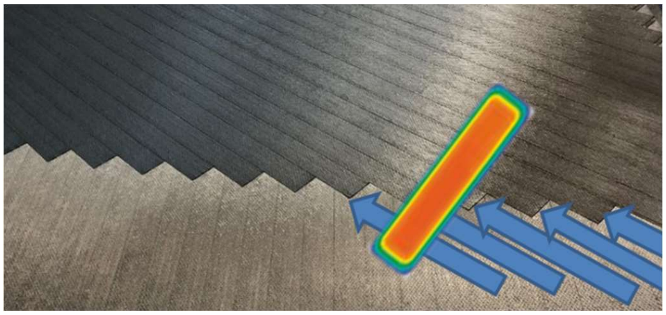

Figure 2. Fixed Spot Size Laser does not accommodate variable number tows.

Laser heating can provide a very reliable, distinct spot resulting in precise control of the placement of heat versus flash lamp heating. The laser spot can be aimed precisely to heat only the target area and eliminate residual heat in the area surrounding the compaction roller and outside of the nip point or material course. The spot can also be aimed to heat proportional amounts of the incoming and substrate materials with the proportion adjustable to accommodate contoured, three-dimensional parts.

Most production parts, however, contain features like pad-ups, ramps, core fillers and penetrations (doors, windows, etc.). Consequently, tow ends (or “drops”) are contained within the flying parts or within the engineering edge of parts (EEOP) (Figure 3). To accommodate these features, the process requires an individual spot for each tow lane to adequately take advantage of the AFP process.

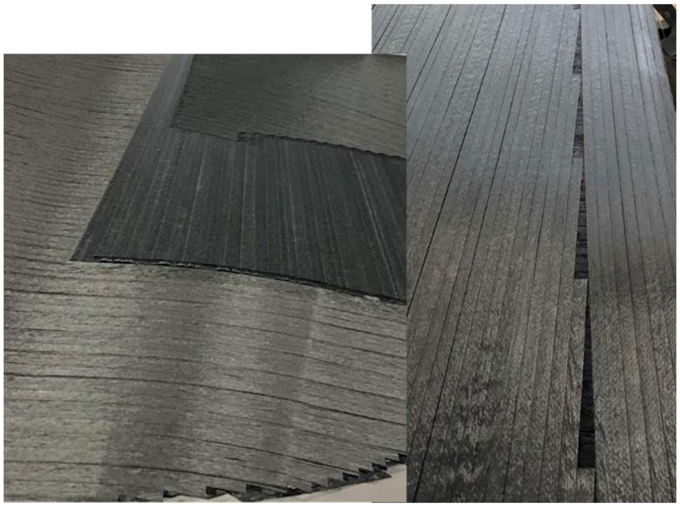

Figure 3. Part lamination features (pad-ups to the left and convergent zones to the right) that contain interior tow ends or drops.

A laser has been developed to provide individual heat spot for each lane of material (tow) which will be described in detail in this paper.

Variable Spot Size (VSS) Laser Heating System

There are many good examples of laser heaters with fixed spot sizes available in the industry today but nothing that can produce individual heat for ¼” pitch or ½” pitch AFP tows that could fit onto an AFP processing head. A laser, with a variable spot size, matched to the AFP tows, would enable AFP processing on production parts with tow drops contained within the (EEOP).

A Variable Spot Size (VSS) laser was developed and produced using individual heaters for each tow. The first design has a spot sized for ½” wide tows and 16 lanes (Figure 4) and provides 560Watts/inch of power targeting thermoset materials (VSS-LP-H16). Each spot measures 12mm wide by 12 mm long and delivers 280W for a total of 4,480Watts of power. Optics were designed to achieve a precise spot size with distinct edges to prevent overlaps or gaps in the power delivery.

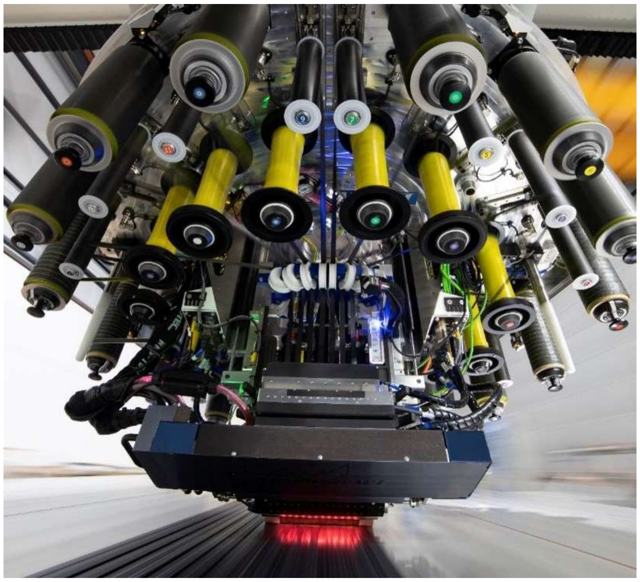

Figure 4. The Variable Spot Size (VSS) Laser. This example is a VSS-LP 16-tow x ½” lane 560W/inch laser targeting thermoset prepregs and dry fiber applications.

This VSS laser is fully integrated into a modular AFP head, eliminating an umbilical that could limit the travel of the machine.

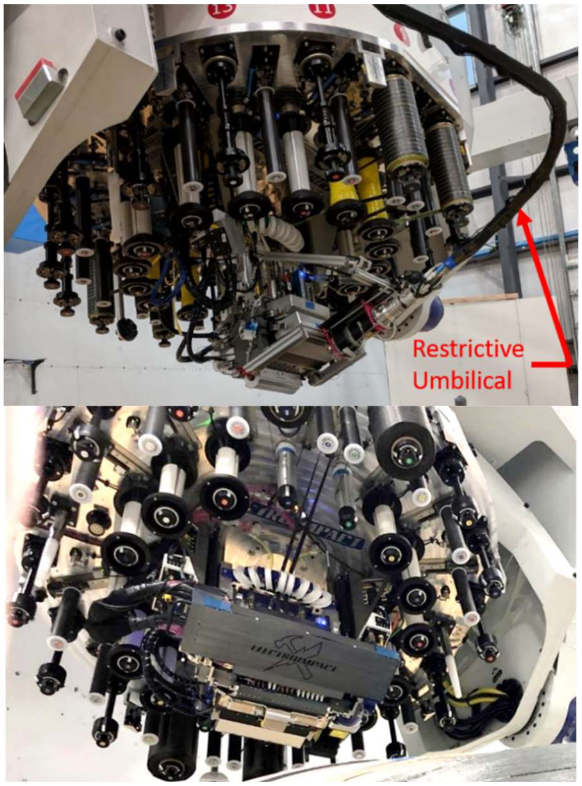

Figure 5. Fixed Spot Laser with umbilical (above and a Variable Spot Size (VSS) Laser integrated into a modular AFP head (below).

A high-powered model is needed for high speed processing of thermoplastic materials. The VSS-HP-Q16 would produce 1600W/inch and is currently in testing and expected delivery for customer operation in spring 2021. There are plans for another VSS-HP laser that will produce 2400W/inch in late 2021 or early 2022.

Each lane of the VSS laser is individually controlled to coincide with the course width and specific tow drops. The power level will also be independently programmable to support varied heating for individual lanes across a course to support steering or changes in geometry.

High Speed AFP Processing

Another recent advancement is an increase in AFP motion platform performance. Today, the AFP process is certified in production on thermoset parts operating at 100 m/min on several AFP gantry systems and up to 50 m/min on robot systems. The performance achieved on the gantry has reduced the number of cells initially required to meet production rates on an existing program. Important to note that top speed is not the only factor that contributed to this improvement, an increase in the dynamic response of the gantry machine was responsible for reducing the “off-part” time which can significantly increase processing time. For these high-performance systems, off-part motion can occur up to 150 m/min and acceleration/decelerations are up to 0.5g (4.9m/s). Robot systems do not have the same maximum speeds or dynamic response capabilities, so testing above 50 m/min was performed on the gantry machine.

Figure 6. High Performance AFP gantry machine.

Laser systems inherently have very quick response times to commands from the CNC control. Also, because the spot size is very precise, residual heat is minimized and warm-up and cooling dwell times are eliminated. When coupled with the VSS laser, a dynamically responsive machine can take advantage of this development and achieve high speeds for both on-part and off-part motions with reduced motion pauses for process control.

Power Curve Development and Controls

Processing thermoplastics at 100 m/min required extensive manipulation of the laser power curves to maintain a constant temperature at the nip point throughout the entire course. Material is processed with initial “add” speeds, accelerating up to maximum traverse speeds and then decelerating down to “cut” speeds. Laser power must be controlled to match the layup speeds throughout the course and any response lag resulted in large variations in temperature.

Low Speed Power Curves

Each type of the different thermoplastic matrices (PEEK, PEKK and LMPAEK) required individual temperature levels and power curves. It was also found that resin formulation varied between each supplier; so, PEEK matrices from one supplier required different settings for PEEK from another supplier. Further, the fiber/resin distribution varied greatly (Figure 7) resulting in a specific power curve for each supplier’s material.

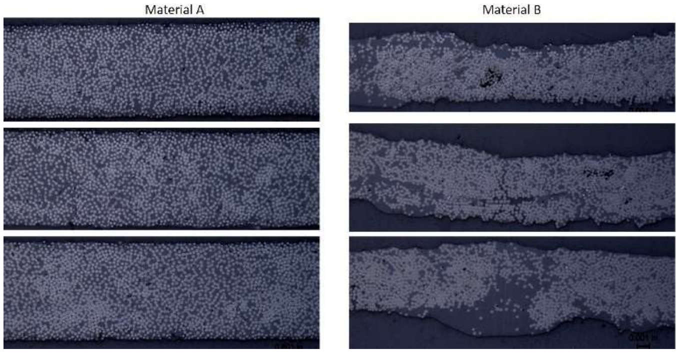

Figure 7. Resin and fiber distribution for the same material type varies between suppliers and even between various manufacturing plants from the same supplier. The Full Insitu Consolidation process was sensitive to these variations in attaining porosity and autohesion.

Different temperatures were also needed for the first few plies due to dissimilar material (i.e. Kapton) for the first layer as well as varying heat dissipation through the tool surface. After 3-5 plies, however, the required laser power levels became more consistent at reaching the appropriate temperatures for subsequent plies.

Laser power is clearly related to actual tool-point speed as well. For insitu consolidation trials, the tool-point command velocity was typically used as a trigger to program the amount of laser power delivered to the nip point. Typical insitu consolidation speeds range between 1 – 13 m/min (50 – 500 IPM). Speeds along the entire course were fairly constant. Once a target temperature is achieved for a particular speed, the power level was mapped to develop a curve for each material tested. Figure 8 depicts a power curve designed to maintain a constant temperature throughout a course for speeds up to 13 m/min (500 IPM). As shown, the relationship between speed and laser power is not linear and required a 2nd order equation for insitu consolidation speeds.

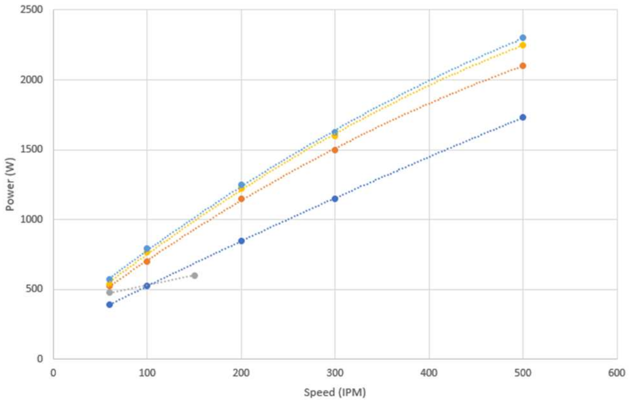

Figure 8. A typical 2nd order power curves for Insitu Consolidation processing with speeds between 1 m/min to 13 m/min (50 – 500 IPM).

High-Speed Power Curves

Transitioning from the insitu consolidation to high-speed processing exaggerated or exposed many relationships and anomalies with the layup. For these tests, the following speeds were used:

- Add Speed: 40 m/min (1600 IPM)
- Traverse speed: 100 m/min (4000 IPM)
- Cut speed: 50 m/min (2000 IPM)

Testing was completed on a flat tool (aluminum plate) with a mylar insulating layer topped, with a Kapton film vacuumed to the tool surface. The layup was a flat coupon laminate measuring 1m by 1m by 16 or 24 plies thick (Figure 9).

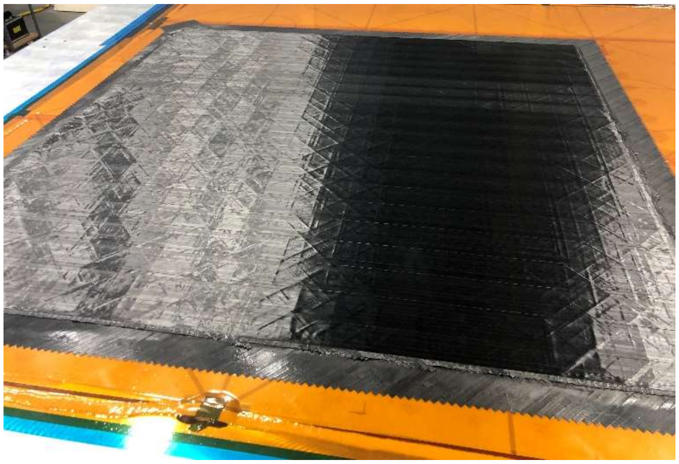

Figure 9. High Speed trials: 1m x 1m flat coupon on an aluminum tool with Kapton film, 16 or 24 plies thick.

When transitioning between lower and higher speeds, 3rd order equations became necessary even for flat coupons (**Error! Reference source not found.**). Different curves were established for each of the first 5 plies.

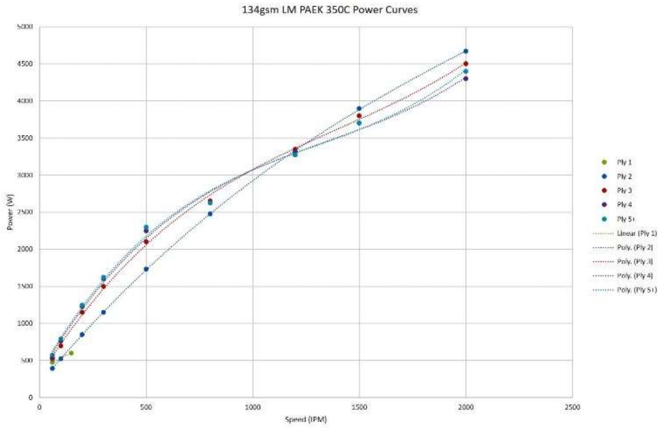

Figure 10. Power curves required 3rd order equations in the control system when transitioning between lower speeds to higher speeds. Power curves were refined for each specific material matrix.

During initial trials, laser power was linked to the tool-point command velocity, however, temperature control was relatively inconsistent at higher accelerations. Maintaining a constant temperature during add speed, accelerating to traverse speed and then decelerating to cut speeds with accelerations of 0.5g resulted in erratic temperature readings (Figure 11).

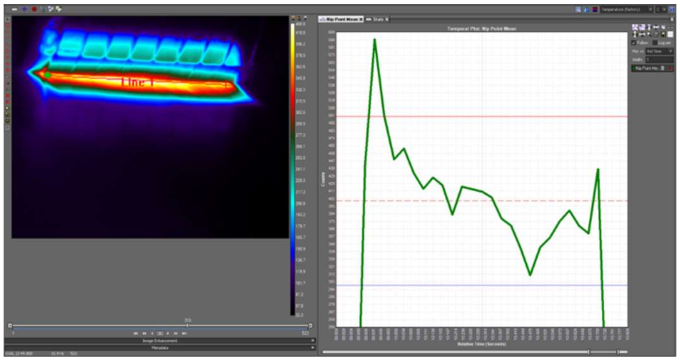

Figure 11. Temperature at the tool-point as measured by a FLIR thermal camera.

The erratic temperature results were plotted against laser power and the tool-point command velocity. In the graph below, the orange curve represents the tool-point command velocity, the blue curve is the laser power and the gray curves are the tool-point temperature as measured by a FLIR thermal camera.

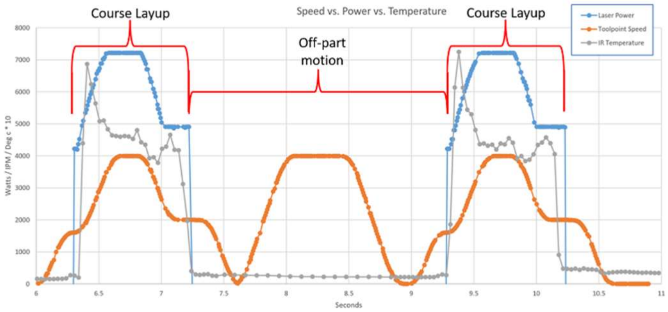

Figure 12. Power curves based on commanded tool-point velocity alone were not able to control nip point temperature.

In both the gantry system and robot AFP systems, secondary feedback is used on every axis to measure the actual velocity for each. Also, the gains for each axis are set for quick dynamic response so the location of the nip point is instantaneously known. Position error compensations further complicate nip point velocity but the triggers that determine true position were used, instead to program the laser power. Implementing these changes resulted in greatly improved temperature control at the nip point in real time for both systems, achieving +/-20°C.

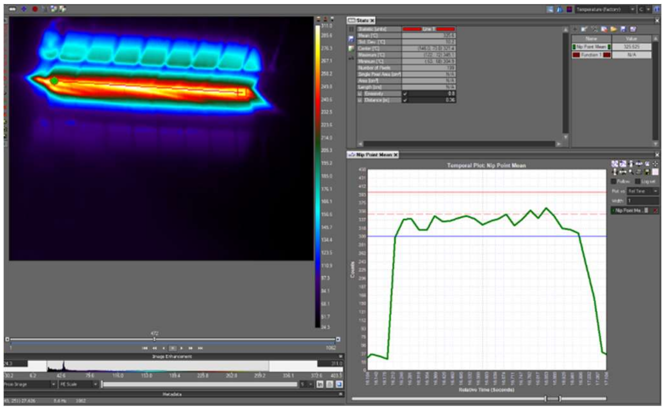

Figure 13. Temperature control at high speeds. (Add speed = 40 m/min, traverse 100 m/min and cut 50 m/min, 0.5g acceleration) after adjustments.

More modifications to the power curves were needed depending on the previous substrate material (previous ply) layup direction.

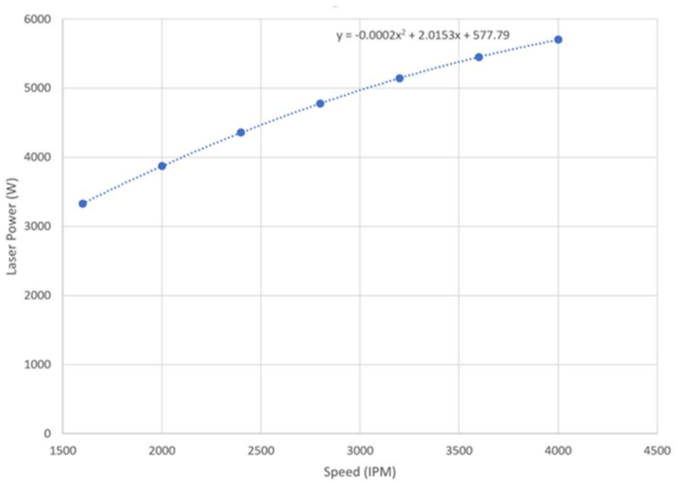

Figure 14. Power curve developed for processing thermoplastic material between 40 m/min and 100 m/min.

Material Types

Toray Advanced Composites provided CF/PEEK (TC1200) material used in these trials. Toray Advanced Composites has a range of aerospace grade CETEX® slit tape materials that include reinforced polyphenylene sulfide (PPS), polyetherketoneketone (PEKK), polyetheretherketone (PEEK), and the low melt/high flow polyaryletherketone (LMPAEK); all reinforced with carbon fibers and some with fiberglass. CF/PEEK (TC1200) is a well established material in the industry and provides a large material property baseline for reference and comparison.

CF/LMPAEK (TC1225) is the latest slit tape that provides a lower viscosity, and lower processing temperature, that will enable even faster AFP speeds and part complexity. An NCAMP database for UD T700G/TC1225 hand layup and press consolidation is available as a material database reference point for transitioning to AFP. All of these materials are used for their combination of thermo-mechanical performance, inherent good fire, smoke and toxicity properties and inherent chemical resistance to a wide variety of fluids.

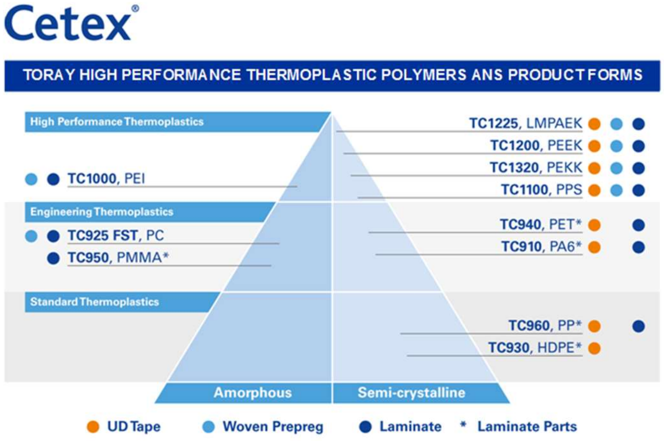

Figure 15. Toray Advanced Composites has a range of aerospace grade CETEX® slit tape materials.

The lower viscosity of LMPAEK compared to PEKK or PEEK should give an advantage in the elimination of voids during AFP. There are three void evacuation mechanisms: diffusion through the thickness, in-plane air evacuation and void filling. Lower viscosity will allow for easier flow into void areas of a laminate that can occur at ply drops or at tow gaps. In terms of speed of AFP laydown, lower viscosity means the polymer can flow into these void areas more quickly before the compaction head passes over a feature and the LMPAEK solidifies, thereby allowing for higher speeds to fill a given void.

Further Refinements for High-Speed Layup

At slower speeds typical for insitu consolidation, a quilting pattern emerges as the plies or layers build up coupon thickness (Figure 16). The effect is exaggerated as layup speeds exceed 60 m/min and is greatly exaggerated at 100 m/min.

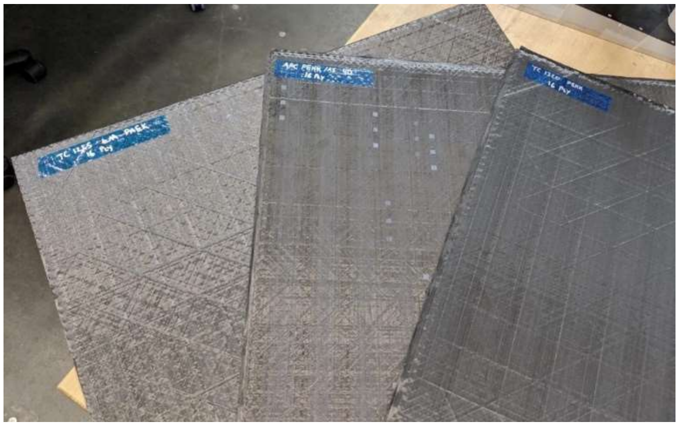

Figure 16. Quilting patterns emerge as more plies are laid down. The effect is exaggerated to unacceptable levels at high speeds.

The quilting does affect layup quality by making it difficult to achieve the desired porosity and autohesion. The uneven surface texture, or ridges, contribute to temperature variations by creating small hot spots and shadows, affecting the melting pool of the substrate material.

As the quilting effect was investigated, it was determined that there are two main causes of the quilting effect:

1. Lapping and gapping of each individual tow within a single course of the incoming material.
2. A spread of the total course as the incoming material melts and is compacted.

Lap/GAP Control

The lap/gap issue is related to the inherent stiffness of the incoming material and how it moves through the tow path before and right up to melting during the layup process. First, the straightness of the material varies based on material quality and from batch to batch. Next, how the material interacts with the compaction roller varies as well before its final placement on the laminate. After some modifications to a standard thermoset AFP head, the aiming of the material was controlled to deal with the material stiffness. Scoops and tow pathways were redesigned specifically for thermoplastic materials to optimize feeding and placement. Laps and gaps were reduced after these modifications were completed.

Course Spread Control

A compaction roller provides the force to bond the incoming material with the previous material (substrate). The compaction roller material must be compliant to accommodate contoured surfaces and ramps, while accommodating the high processing temperatures (>400°C). However, as the thermoplastic material is melted and compacted, the course (made up of 8 tows in this case) spreads over the nominal course width due to the compliant roller deformation. The individual tows all move apart stemming from the center of the roller. Although programming purposeful course gaps can minimize the overlapping that occurs at the edge of the course, variations in the compaction force can exaggerate this effect. For contoured surfaces and/or high-speed processing, these variations can be significant or unacceptable and can result in increased laps/gaps.

To address this issue, a compaction roller that is compliant radially, but not axially, was required. A compaction roller was developed with a sleeve or casing to prevent axial deformation but was compliant radially and yet withstands the high processing temperatures. Even with variations in compaction force, the axially stiff material reduces and limits the amount of course spread and, consequently, lapping/gapping during layup.

Once these two root causes of quilting were corrected, the resulting laminates exhibited greatly reduced quilting, even revealing splices several layers deep (Figure 17).

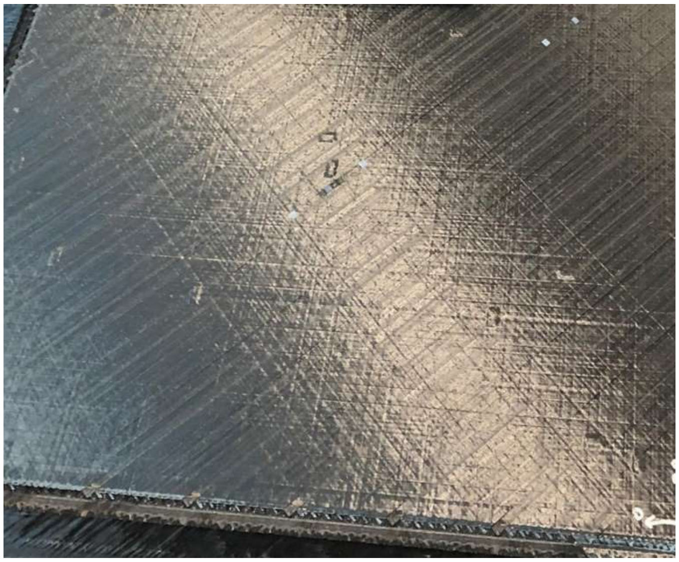

Figure 17. Using a specialized compaction roller design, the quilting effects were greatly minimized revealing tow splices several layers deep.

For high-speed layups, these improvements create a smoother surface resulting in better temperature control because there are less ridges to interfere with the laser beam, also reducing or eliminating hot flashes and temperature variations along the entire course. These improvements also increase the uniformity of part thickness resulting in higher quality laminates and possibly enabling certain OoA curing methods.

Repairability

Full insitu consolidation requires the complete bonding of the incoming material to the substrate layers to achieve final part quality and properties. These laminates are not repairable during the lamination process, or at least not repairable quickly enough to support competitive productivity.

However, once consistent temperature control was achieved in these high-speed tests, there was a relatively large temperature range for producing a lightly bonded, moderately bonded or fully bonded (unrepairable) laminate. The level of bonding will prove to be more important for heavily contoured parts while still maintaining the ability to repair the lay up during production as can be done today with thermoset prepreg laminates.

When using high-speed processing followed by a curing process, the bonding required is only enough to ensure part contour is maintained, even after handling to support the desired curing method. On a flat coupon, temperatures were empirically determined to achieve light bonding, moderate bonding and heavy bonding. The criteria for bonding was repairability versus tacking level. Moderate bonding was achieved when the laminate was well tacked, but removing an individual tow after layup was still possible without damaging the laminate. Once a moderate level of tacking was achieved, the temperatures were then varied to achieve light tack, while still holding securely enough to lay subsequent layers but easily repairable and a heavy tack where the layers were bonded and not repairable. The range was determined to be between 300°C and 400°C in 50°C increments below the control tolerance of +/-20°C (Table 1).

Table 1. Temperature range for lightly tacked and heavily tacked laminates indicate that repairability is possible while maintaining contours in parts.

Temperature	Bonding level	Reparability
300°C	Light	Easy
350°C	Moderate	Fairly easy
400°C	Heavy	Sometimes not possible

This indicates that a well-formed laminate can be achieved while still being repairable. Severe contours or steep ramps may push these limits but from a production standpoint, however, the temperature ranges seem to be large enough to be robust and support a production environment.

Summary/Conclusions

In summary, recent advances in AFP processing described here, and as well in the reference documents listed below, will help increase AFP cell performance and productivity.

- High-Performance Motion Platform
- High reliability AFP heads (>10,000:1)
- Maintenance interval planning
- In-process inspection
- Automated inspection

New technologies, specifically targeting thermoplastic materials, open the door for high-speed processing for large structural components if followed by a post cure.

- Variable Spot Size Laser heating
- Adaptive Power Curve controls
- High-Speed Lap/Gap control
- Specialized Compaction Roller Design
- Temperature control for repairability

Once these advances were implemented on an AFP gantry and the modifications/adjustments were made specifically for thermoplastic materials, producing high speed AFP coupons was controllable and repeatable. The resulting test coupons exhibited very consistent bonding of all plies within a laminate. Responsiveness of the motion platform and the heating system produced processing speeds which matched those achieved by the best production systems currently processing thermoset materials.

Tow drops that are contained within a part exhibited no overheated or underheated regions due to the individualized heating for each tow. Steering of thermoplastic materials can be accommodated with the individual lane control of the VSS laser.

Smoother surfaces, or elimination of surface quilting, helps maintain consistent temperature control during the processing yielding more consistent lamination thickness, potentially facilitating new and existing OoA curing methods.

Adaptable power curve control schemes will facilitate contoured parts at high-speed. The stability of the temperature control at the nip point produced a wide range of operating temperatures that will support high contours and repairability.

These improvements are enabling technologies that open the doors for thermoplastic materials by making them more competitive with existing thermoset prepreg and dry fiber materials for large structural parts.

References

1. Rudberg, T., Cemenska, J., and Sherrard, E., "A Process for Delivering Extreme AFP Head Reliability" SAE Technical Paper 2019-01-1349, 2019, doi:10.4271/2019-01-1349.
2. Cemenska, J., Rudberg, T., Henscheid, M., Lauletta, A. et al., "AFP Automated Inspection System Performance and Expectations," SAE Technical Paper 2017-01-2150, 2017, doi:10.4271/2017-01-2150.
3. Sloan, J., "Evolving AFP for the next generation", *Composites World*, June 27, 2019, https://www.compositesworld.com/articles/evolving-afp-for-the-next-generation.
4. Assadi, M. and Field, T., "AFP Processing of Dry Fiber Carbon Materials (DFP) for Improved Rates and Reliability," SAE Technical Paper 2020-01-0030, 2020, doi:10.4271/2020-01-0030.
5. Sloan, J., "Large, high-volume, infused composite structures on the aerospace horizon," *Composites World*, June 4, 2019, https://www.compositesworld.com/articles/large-high-volume-infused-composite-structures-on-the-aerospace-horizon
6. Calawa, R. and Nancarrow, J., "Medium Wave Infrared Heater for High-Speed Fiber Placement," SAE Technical Paper 2007-01-3842, doi:10.4271/2007-01-3842.
7.

Contact Information

Michael D. Assadi, Director of Thermoplastic Research,
Electroimpact Incorporated, mikea@electroimpact.com

Todd Rudberg, AFP Director,
Electroimpact Incorporated, Toddr@electroimpact.com

Ryan Jordan, Process Engineer,
Electroimpact Incorporated, ryanjo@electroimpact.com

Definitions/Abbreviations

AFP	Automated Fiber Placement, in 3.18mm, 6.35mm, 12.7mm and 38.1mm widths
ATL	Automated Tape Laying in 75mm or greater widths
CNC	Computerized Numerical Control.
crystallization	Resin restructuring or reordering within a part laminate.
DFP	Dry Fiber Placement
EEOP	Engineering Edge of Part defining the actual edge of a completed part.
laminate	A build-up of layers created using the AFP process.
nip point	Located where incoming material meets substrate material under the compaction roller in the AFP process.
ply or plies	Individual layers of carbon tows laid on a tool to build up a part.
porosity	A measure of the voids within a laminate.
prepreg	Resin pre-impregnated carbon fiber material.
spot size	The projection of a laser beam or other radiating heat source onto a part.
substrate	Material laid done on a previous ply.
tow	A tape of carbon reinforced plastic usually ¼” or ½” wide and ~0.007 thick used in the AFP process.
tow path	The path of a single tow starting from a bobbin and ending at the compaction roller.
VSS Laser	Variable spot size laser
VSS-HP Laser	Variable spot size, high power laser