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AFP Processing of Dry Fiber Carbon Materials (DFP) for Improved Rates and Reliability

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Abstract

Automated fiber placement of pre-impregnated (pre-preg), thermoset carbon materials has been industrialized for decades whereas dry-fiber carbon materials have only been produced at relatively low rates or volumes for large aerospace structures. This paper explores the differences found when processing dry-fiber, thermoset, carbon materials (DFP) as compared to processing pre-preg, thermoset materials with Automated Fiber Placement (AFP) equipment at high rates. Changes to the equipment are required when converting from pre-preg to dry fiber material processing. Specifically, the heating systems, head controls, and tow tension control all must be enhanced when transitioning to DFP processes. Although these new enhancements also require changes in safety measures, the changes are relatively small for high performance systems.

Processing dry fiber material requires a higher level of heating, tension control and added safety measures. However, once these are achieved, processing rates and reliability may be significantly improved for DFP versus traditional pre-preg AFP processing. Overall payout speeds as well as steering speeds can be increased for dry fiber resulting in increased laydown rates when using current AFP processing techniques. The lack of resin within the material greatly reduces resin build-up, which supports longer maintenance intervals and greater reliability by minimizing or eliminating the problems associated with resin build-up. The controlled emission area and fast response time of precision heating systems greatly reduce unwanted heat on surrounding areas and increase process performance. In addition to DFP, further developments in the heating system have also proved beneficial for thermoset as well as thermoplastic processing. All of these advantages increase the machine utilization as well as reliability when processing aerospace parts made from dry fiber materials with AFP equipment.

Introduction

Most large, structural components of commercial aircraft have been manufactured using aluminum or, more recently, pre-impregnated carbon reinforced plastics (pre-preg). The industrialization of commercial production using aluminum materials has occurred and optimized over the last 100 years. Industrialization of production using pre-pregs has occurred over the last 30 years in both military and commercial programs. Automatic placement (AFP) of pre-preg material continues to evolve with advances in the AFP process reliability and rate increases. Parallel to that effort, there has been a recent interest in utilizing dry fiber carbon reinforced plastics for large structural components in newer commercial aircraft programs.

Dry fiber carbon reinforced plastics may offer some of the same advantages that current pre-preg material has over aluminum and offer further advantages over pre-preg itself. It should also be noted that the optimization of processing pre-preg materials is still underway and has not reached full optimization, in the opinion of the authors.

This paper will focus on the processing differences between automatic placement of dry fiber, carbon reinforced plastics (DFP) compared to current automatic placement of pre-impregnated carbon reinforced plastics (AFP).

We will discuss the different enhancements necessary when reconfiguring an AFP process head to the DFP process, specifically on a *modular* process head. The modular head eliminates or reduces any effects of the positioning platform (machine tool or robot) and so the lay-up process is agnostic to the positioning platform. This is not true for equipment using a remote creel house, which has much more variability in tension control. Maintenance differences emerge when comparing DFP and AFP processes to the extent of enhancing production by increasing machine utilization and reliability.

Finally, DFP performance advantages experienced during test trials will be discussed for several part types, namely wing skins (covers), wing spars, as well as fuselage skins.

AFP Process with Modular Heads

Modern AFP equipment, using modular process heads, facilitate process changing on the same positioning platform (robot or machine tool) which includes different material formats such as ATL tape or 6.35 mm through 38.1 mm wide AFP tows as well as cutting and probing.

More importantly, modular heads offer more separation between the positioning platforms and the AFP process. Features, such as temperature and condensation control, tow tension control and fuzz collection points are contained solely on the process head. This, in turn, reduces effects of machine positioning or changes in part programming on the AFP process, allowing for better separation between production activities and process engineering activities.

For AFP pre-preg processing, the resin increases in tackiness with increases in surface temperature. Current AFP processing uses IR filament lamps to heat the impregnated resin to achieve the proper tackiness. The IR filament lamps are mounted on the AFP process head, aimed at the existing (substrate) material, broadcasting heat in the layup area. There is no distinctive heat spot size and temperatures are relatively low, reaching around 60°C on the substrate surface.

The incoming material is applied to the previously layer of substrate material via a compaction roller, which presses the incoming material onto the warm substrate with the intention of adhering the layers or *plies* together. This forms a joint similar to a "cold solder joint" between the plies allowing more plies to be applied to build up part thickness. In the current AFP process, little or no heat is applied to the incoming material to avoid warming the process head and increasing resin build-up.

The modular head tow path starts with a creel that supports bobbins or *spools,* variable in number, typically 4, 8, 16, or 24 spools. Each tape or *tow* of material is routed from the spool, past a spring tensioner, through feed and cut modules, and then out to a compaction roller that presses the material to a form or tool surface. Just outside of the compaction roller is a heating element

The resin, when combined with a broadcast heat source, creates the problem of depositing resin along the tow path within the process head. As the resin builds up in the tow path, resistance is created and tension control is affected. The resulting process degrades over time, in large part, due to resin build up causing equipment downtime, part repair and decreasing equipment utilization between 25% and 30%.

FIGURE 1 AFP Modular Process Head - ½″ × 16 tows (Electroimpact Inc.).

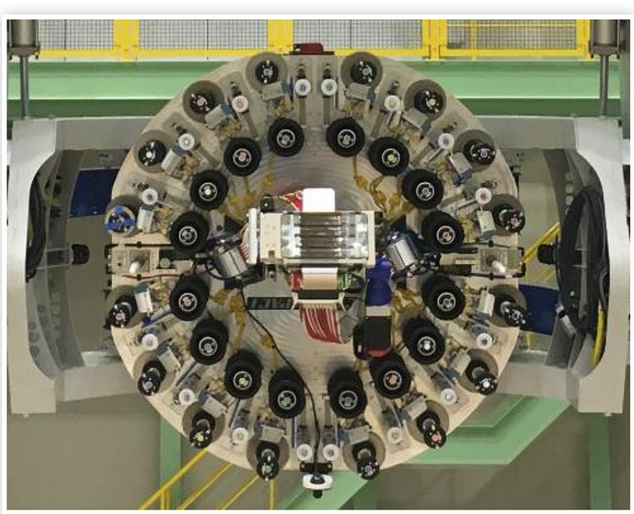


FIGURE 2 AFP IR Filament Lamp heating layout (Electroimpact Inc.).

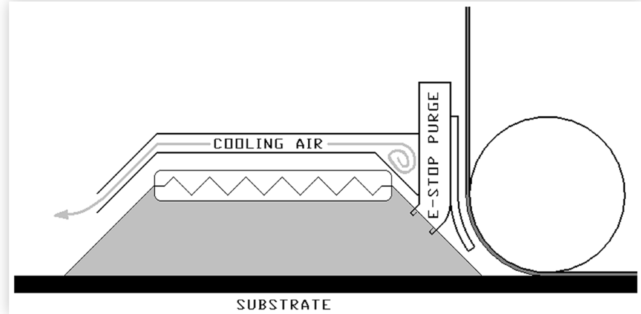
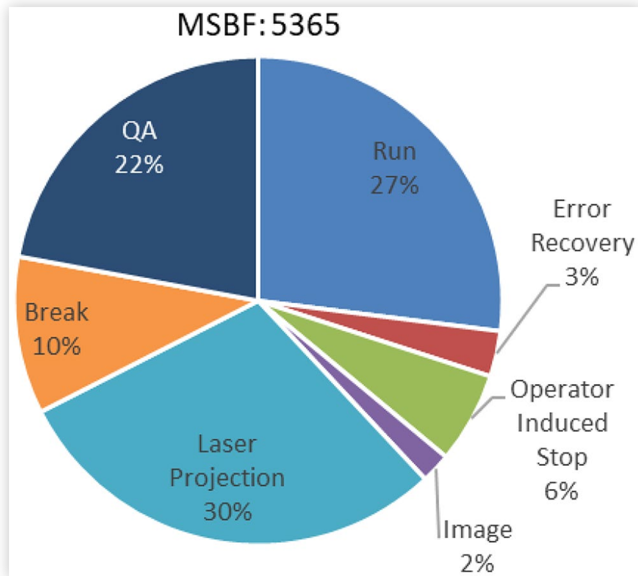


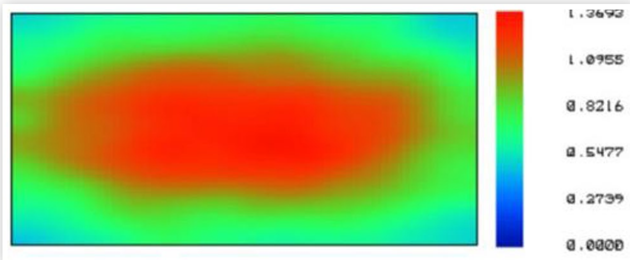
FIGURE 3 Example AFP Machine Utilization (Electroimpact Inc.).



DFP versus AFP Processing

For the DFP process, resin is not present in the dry fiber material to provide tackiness required for layup. Instead, there is a thin veil of thermoplastic added to the tows to achieve the proper tackiness required for AFP layup. The melt

FIGURE 4 IR Filament Bulb heat spot (Electroimpact Inc.).



temperature of the thermoplastic is relatively high, closer to 175°C. However, burning the sizing, which happens at a higher temperature, must be avoided for proper infusion processing. In addition, due to the small amount of thermoplastic material, both the substrate material and the incoming material must be heated where they meet, the nip point, to ensure a proper bond during layup.

IR filament lamps are not sufficient to achieve the higher temperatures at higher rates. The large, undefined spot size of the IR filament lamp has a tendency to under heat the nip point while overheating the surrounding area, including the substrate and equipment. This results in burning some of the binder within the substrate material or under heating the incoming material during layup. The effect is exaggerated during the layup of more complex geometries, such as wing spars. The IR bulb requires a warm-up and cool-down period which affects layup quality and processing time. Flash lamp and laser technologies have also been trialed for increased power levels required for the DFP process, however, this paper focuses on a Variable Spot Size (VSS) Laser as the heat source for reasons stated below.

DFP processing is a relatively low tack process when compared to AFP process; therefore, tension control has a greater effect on part build. Because the modular head contains the entire tow path, extra friction along the tow path is eliminated and this increases tow tension control capability, especially at high speeds. However, a servo-creel was developed to obtain very low or zero load tension control.

Finally, the lack of resin in dry fiber materials eliminates the reliability issues related to resin build-up. DFP contamination issues are limited to fuzz build-up and this varies based on material selection. Slit material yield more fuzz as compared to non-slit materials. Regardless, resin elimination greatly affects reliability, downtime and maintenance intervals due to fuzz build up.

High Temperature Heating with Variable Spot Size (VSS) Laser

For initial DFP testing, IR filament lamps and flash lamps were used to process 12.7 mm and 38.1 mm wide tapes. For the IR filament lamps, speeds were reduced to less than 50 m/min (2000 in/min) and achieved minimal tacking due to the lack of power. Both of these heating systems produced a non-distinct heat spot, although the flash lamp did produce a slightly more distinct spot. Both of these heat sources exhibited some lag in responsiveness, requiring complex programming to accommodate aggressive geometries or at the start and end of tows. Residual heat was difficult to control. IR filament lamps have been used in AFP production for decades but the flash lamp technology is still in development. The HUMM3 flash lamp system from Heraeus was used for these initial trials and proved to be more powerful than IR filament lamps. However, the indistinct spot, slow response time and power degradation were reasons to move towards diode laser technology.

FIGURE 5 DFP Test Bench with Fixed Spot Diode Laser (Electroimpact Inc.).

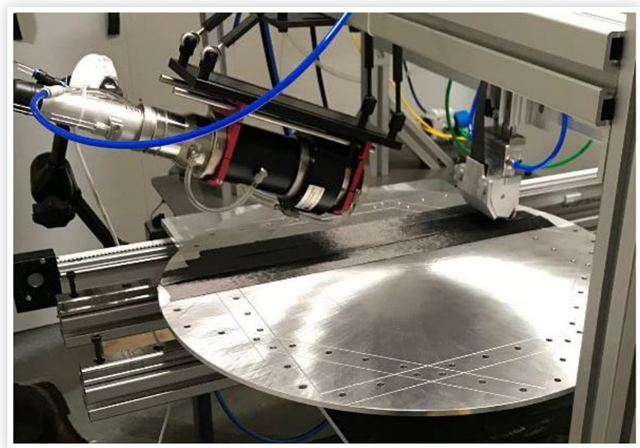


FIGURE 6 Fixed Spot produced by Diode Laser system from Laserline GmbH.

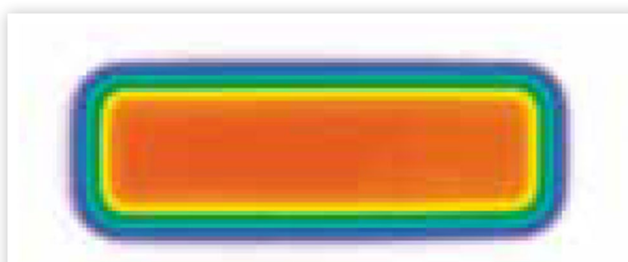


FIGURE 7 Slight global contour with several joggles and ramps require rapid changes in velocity and heating (Electroimpact Inc.).

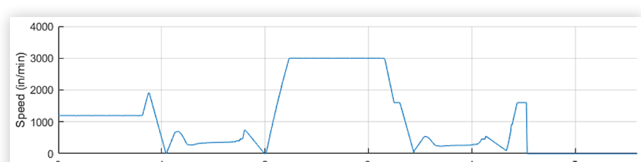


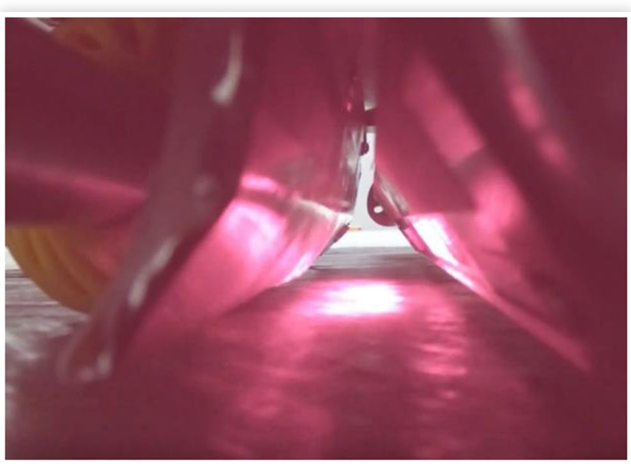
FIGURE 8 Variable Spot Size (VSS) Laser (Electroimpact Inc.).

A fixed spot Laser Diode heating was used to achieve the higher temperatures needed for higher speeds and better adhesion between plies. The particular laser system used was a 16 kW, fiber-coupled, diode laser from Laserline GmbH. The optics were mounted in close proximity to the compaction roller on the AFP head and the laser beam was transmitted via a 1 mm fiber optic cable. This laser provides a very reliable, distinct spot resulting in precise control of the placement of the heat. The spot was aimed directly at the nip point, to provide the proper tacking, similar to welding, by melting the thermoplastic on both the incoming and substrate materials.

The responsiveness of the system was nearly instantaneous, providing precise control of timing to ensure excellent tacking while avoiding overheating of the surrounding area. DFP layup speeds were tested from 20 m/min up to 300 m/min (12000 in/min) on the test bench.

Instantaneous responsiveness is a major heat source advantage, especially for complex geometries or tow paths. The power is precisely controllable while the tool point moves around small radii or joggles and rapidly changes velocity. The laser power closely follows the velocity resulting in excellent bonds throughout both low and high contour regions at higher speeds. The graph below shows that even on a relatively flat parts (i.e. spar), any joggles and ramps still require rapid changes in velocity. A responsive heat source maintains proper heating throughout these motion profiles.

FIGURE 9 Variable Spot of the VSS Laser (Electroimpact Inc.).



The rapid response times have led to improvements for off part motion as well, especially for the lead-in or approach. Without the warm up period required on the incandescent heat sources, lead-in distance is solely driven by part geometry. Steering speeds are also increased with laser heating because the proper intensity can be achieved without residual heat. The laser has proven to be a very effective and efficient heat source.

It is very common to lay down staggered tows or variation on the number of tows during most parts. However, the fixed spot size does not accommodate the variable number of tows deposited at a given time. In addition, the fiber optic cable required an umbilical tethered to the AFP head, which limits machine motion and speed. Therefore, Electroimpact developed a **Variable Spot Size (VSS) Diode Laser** heating system.

The VSS laser is mounted directly on the AFP process head in close proximity to the compaction roller. Multiple diodes are used and independently controlled to heat each individual tow. The first model targets 12.7 mm (1/2″) wide tows on a 16 tow head called the H16VSS laser. The H16VSS laser provides 16 spots measuring 12.7 mm × 12.7 mm and eliminates the need for an umbilical.

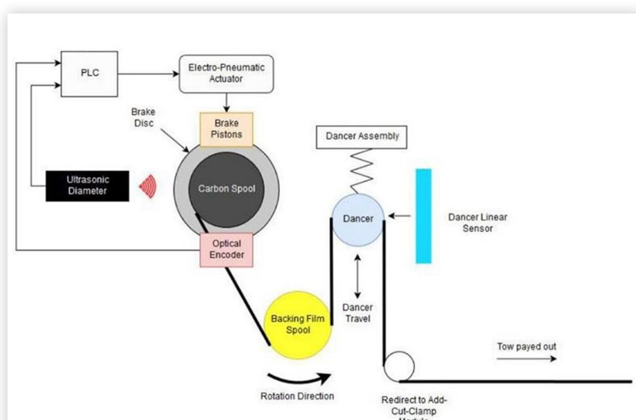
The VSS laser spots are aligned to each tow location, limiting the heat spot to each individual tow. The combined individual spot control, instantaneous timing and lack of any umbilical supports high rate and high quality lay ups for DFP processing.

Tension Control with Servo-Creel

Servo-Pneumatic Creel

On the previous generation of Electroimpact modular AFP heads, a pneumatic braking system was used in order to control the tension of the tow. Tow is paid out by using a servo

FIGURE 10 Servo-Pneumatic Creel (Electroimpact Inc.).



motor and pneumatic roller to pinch the tow and feed out at a controlled rate. Initially, the carbon spool is stationary and accelerated by the tension generated from spring force. The braking system can then decrease the rate of material unspooling in order to change the dancer displacement during operation. Due to the nature of varying inertias, and diameters as well as using sliding friction to control the rate of payout from the spool, tuning this system is a complex task.

A disadvantage of this system is that the dancer spring must generate relatively high force in order to create sufficient acceleration in the spool. In addition, if rapid acceleration cycles are present in the part program, it is possible that the dancer set point will creep upwards and, since the braking system cannot unwind the spool actively, this displacement will continue to build up until it over-travels. This high tension system can also cause large tow slips during high-speed tow add events. Another disadvantage is that to maintain a low tension, the dancer is only displaced a small amount. During high speed cuts, the dancer can completely stroke out causing slack tow.

Servo-Servo Creel

A servo-servo creel was developed for better tension control and sensing to support high speed layups and finer tension control. The main changes include replacing the brake disc with a servo/controller and gearbox combination. This allows the tensioning system to be completely controlled by the motor controller instead of the PLC. This is to offload sensor filtering to the PLC in order to get a more reliable diameter signal.

The servo-servo creel has a better sensitivity to tension and can react quickly to support lower operating tension and higher speeds. Lower tension is important for DFP because the material has no resin holding the fibers together. High tow tension during layup can result in shearing and unwanted movement of the fibers in the substrate.

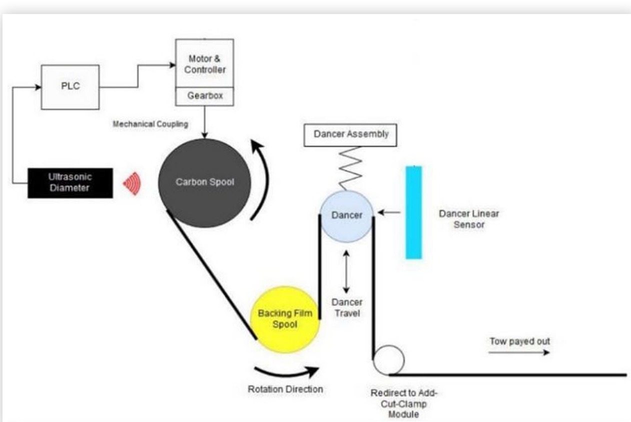
By utilizing internal sensors, the servo-servo creel has the added benefit of measuring slipped tows, add/cut error detection as well as tow-end placement. We call this technology RIPIT for Real-time In-Process Inspection Technology. Tow slip detection is crucial information when understanding tow behavior as it is placed on the part. Causes of tow slip are incorrect normality of part program to actual part surface or dirty rolling elements in the feed module.

RIPIT has the potential of replacing external, out-of-process inspection systems which would significantly increase AFP equipment utilization. RIPIT performance today can detect tow placement to the following tolerances:

1. Detect Tow Slips >.050″
2. Detect Add Placement ±.050″
3. Detect Cut Placement ±.050″

This system would benefit DFP or AFP processes.

FIGURE 11 Servo-Servo Creel (Electroimpact Inc.).



DFP Processing Advantages and Disadvantages

Machine utilization competes with part loading, inspection, repair and maintenance activities. Resin build-up that occurs during pre-preg AFP processing is a source of downtime and part repair due to failed add/cuts, reduced tension control and fuzz build-up. With the lack of resin within dry fiber material, downtime events and repair times are significantly reduced for DFP processing versus AFP processing. The resulting potential is a 15-30% increase in utilization. Please note that fuzz development for slit dry fiber material can be excessive, resulting in some FOD creation.

Servo Creel tension control supports higher quality layups with more consistent tension control. This is more noticeable on thicker parts or parts with complex geometries such as spars or local joggles with DFP processing. Higher DFP laydown speeds are also supported above 100 m/min (4000 in/min) due to the absence of resin and increased tension control.

Servo Creel tension control also supports Real-Time In Process Inspection Technology (RIPIT) which measures slipped tow detection, add/cut error detection and offers better end placement accuracy, all in real time. RIPIT inspection of tow end placement has the potential of reducing or eliminating inspection time. This greatly increases AFP or DFP equipment utilization. Overall floor to floor rates are improving on equipment utilizing RIPIT and this technology should be certified early 2020.

DFP processing requires higher temperature heating and finer tension control when converting equipment from pre-preg AFP processing. The VSS Laser required to achieve the higher temperatures benefits both DFP and AFP processing. The precision control provides instantaneous heat commands reducing or eliminating hot and cold spots, resin build-up in the head, and increased steering speeds and radii. The variable spot contains heating to the active tows only. This prevents overheating and roller wraps during layup. The laser also decreases off part motion typically used for broadcast heat sources by eliminating warm-up or cool-down events.

While the VSS laser offers production and quality improvements, the design includes a class 4 laser requiring the appropriate safety measures. The relatively low power required for DFP processing allows the use of divergent laser light. For high speed equipment, this means that the safety fencing remains in the same location but the fence opacity must block the laser light. Each installation has different requirements and the second generation of lasers will be designed with the goal of reducing the safety measures for DFP or AFP processing.

DFP also produces laminates with lower tacking. This can make the parts more fragile and produces challenges on thicker layups. Preforms can delaminate or flare up at the part edges so processing methods should account for this.

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Definitions/Abbreviations

AFP - Automated Fiber Placement, in 3.18 mm, 6.35 mm, 12.7 mm and 38.1 mm widths

ATL - Automated Tape Laying in 75 mm or greater widths

creel - A rack holding bobbins or spools.

DFP - Dry Fiber Placement

FOD - Foreign Object Debris

fuzz - Debris created during the DFP process comprised of carbon fibers

gsm - Grams per square meter

IR - Infra-red spectrum light source

ply or plies - Individual layers of carbon tows laid on a tool to build up a part.

pre-preg - Resin pre-impregnated carbon fiber material.

tow path - The path of a single tow starting from a bobbin and ending at the compaction roller.

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