MANUFACTURE OF SUBSTRUCTURE BY AUTOMATED FIBER PLACEMENT

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ABSTRACT

Automated Fiber Placement is maturing as a technology for building large-scale composite aero structures. As a result, productivity and quality benefits from AFP are becoming more attractive for composite sub-structure parts that historically had only been possible to build by hand. Optimized equipment and processes are needed to address the particular challenges of sub-structure AFP.

1. INTRODUCTION

Spirit AeroSystems has multiple large composite aircraft programs employing AFP to build a variety of major components and sub-assemblies. As experience grows on these programs and production approaches steady rates, AFP processes similarly begin to stabilize. Learning curves for various facets of production such as Operations, NC Programming, and Inspection develop best practices and improvements that drive production rates to a nominal level. As a result, significant improvements in cost and flow time become more difficult to introduce as equipment, tooling, and processes have largely been determined and improved beyond the developmental phase.

New AFP processes may still offer gains in productivity and quality to these programs. Aside from primary structure, smaller components such as frames, stringers, and other parts may suggest weight and cost benefits from migration to composite materials and automated processes. Spirit AeroSystems has investigated the feasibility of substructure components for production by AFP and has collaborated with Electroimpact of Mukilteo, WA for simulation and machine concept development. From these efforts, a concept for right-sized, purpose built equipment, tooling, and processes has emerged. Multiple real-world tests have been performed and proof-of-concept articles have been built. Further simulation shows additional opportunity for capable, productive processes. As a result, solid ground has been layed for AFP of substructure, with equipment and processes that can benefit existing programs, new programs, and new work packages for the foreseeable future.

1.1 Application problems for Substructure AFP

AFP technology is in use on various existing production programs as the preferred method to build Primary Structure. However, most installed AFP machines are at or near capacity so when assessing new production opportunities, new capital equipment may be required.

Much of the existing equipment is also sized for producing large structure, such as one-piece barrels, fuselage panels, or wing spars and is not optimal for production of smaller parts with complex and compact geometries. Accelerations for these machines are relatively low but linear speeds can be high, and large layups with long fiber tow paths benefit from high linear speeds. AFP times for gradual curvatures, as on a fuselage panel or barrel, are much more sensitive to linear velocity than to acceleration, and do not require high accelerations to keep the AFP head oriented to the tool surface.

In contrast, small parts are built within a smaller envelope and may have a high number of direction changes and high-complexity rotary motions over very small spans. In these applications, higher linear speeds are never achieved due to a combination of machine sizing and complex part geometry. Small corner radii, high part curvature, and compound contours can challenge the capability of AFP machines. Further, the sizing of existing machines can limit physical access to a tool with concave geometry.

In addition to these various machine-related challenges, a greater understanding of process constraints on AFP is emerging. Inspection times, machine reliability, and machine motion may each be optimized with smart planning and purpose-built equipment and processes. Any of these improvements may be marginal when individually implemented, but a comprehensive approach to automation for a particular application can drastically improve the efficiency of the substructure fabrication process as compared to standard AFP production paradigms.

1.2 Equipment development

Spirit has collaborated with Electroimpact in Mukilteo, WA to develop production concepts, tool loading methods, and machine simulations based on equipment they have developed for purpose-built fabrication of sub-structure. Our best scenarios for substructure fabrication utilize high-acceleration equipment that has the tight-clearance capability required for substructure fabrication. In addition, our mutual experience with AFP over a broad scope of applications recognizes the flexibility of AFP equipment beyond single-shape specialization. Demonstration of multiple tool geometries has been shown on a single machine and improvement in the production rates of these parts may be achieved by optimization of machinery as shown in simulations.

2. EXPERIMENTATION

2.1 Case Study: One-piece frames

In 2011, Spirit AeroSystems R&D built several one-piece c-shaped parts with high curvature by AFP using our Electroimpact AFP equipment. The primary goal of this testing was to demonstrate capability for substructure with difficult geometries – specifically frames, small spars, and door surrounds. Machine performance and process time were not specifically considered but AFP process capability and part quality were assessed. Follow-up testing was performed at Electroimpact in Mukilteo, WA with a second machine using the same tooling.

2.1.1 AFP layup by Spirit AeroSystems

The first challenge in building a demonstration frame on Spirit's R&D AFP equipment was simply loading and probing the tool. Due to the size and axis configuration of the machine, there were physical constraints in accessing the tool surface.

Spirit's R&D AFP has a Cprime axis, which allows A, B, and C axes to be rotated together along a secondary C axis. This allows the A axis carriage to be aligned for best clearance to the tool, and can improve A axis range of motion. Even with this configuration, the motion of the Spirit AeroSystems machine required the tool to be set at a height which was non-ergonomic to avoid machine collision with the floor.

Figure 1 Tool Loading at Spirit AeroSystems

The second challenge was utilizing a Cprime rotation during the traverse across the tool. The A axis for this machine does not have sufficient travel to accommodate a 180º move (required for this test) without also engaging Cprime. Since the axis of the tool surface is not linear, this creates additional complexity that required post-processor modifications by Electroimpact to facilitate a combined A and Cprime move.

The convex shape of the tool results in close clearances with the AFP head. In addition to convex curvature, the tool corner radius is small: approximately 6 mm with a tool width of approximately 10 cm. In order to traverse the tool from flange to flange across both tool radii, the AFP head must be articulated through 180º of rotation on multiple axes within a short distance. After this move is completed, the head must then be rotated on another axis by 180º, and the traversing motion with rotations is repeated. This is a challenging and highly repetitive motion driven by the application. While the AFP equipment was capable for this geometry, it was noted how crucial machine acceleration and rotary velocity is on a compact part such as this frame.

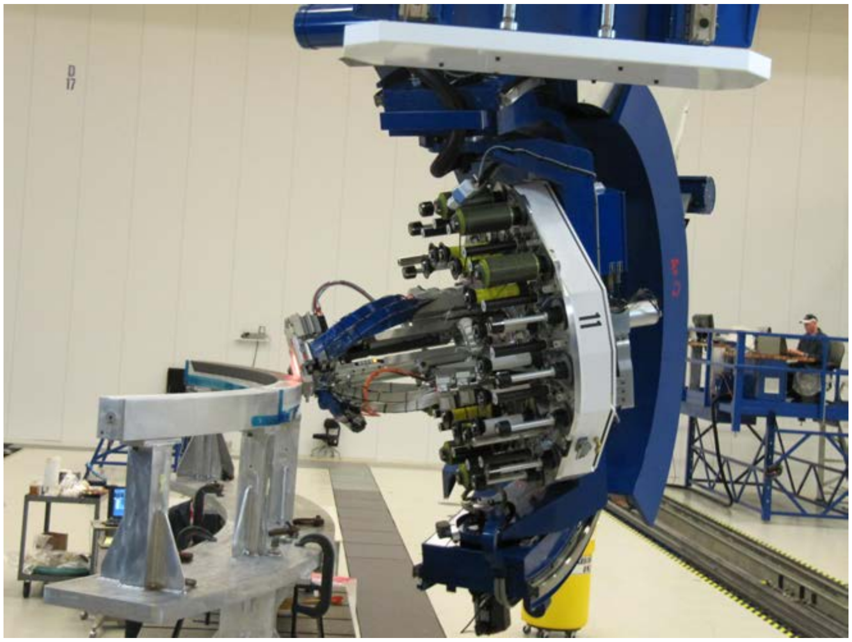

Figure 2 Cprime rotation during laydown

After the tool loading and machine motion issues were addressed, two test frames were completed successfully. Ply quality was in-line with typical AFP processes, and the equipment handled the geometry well.

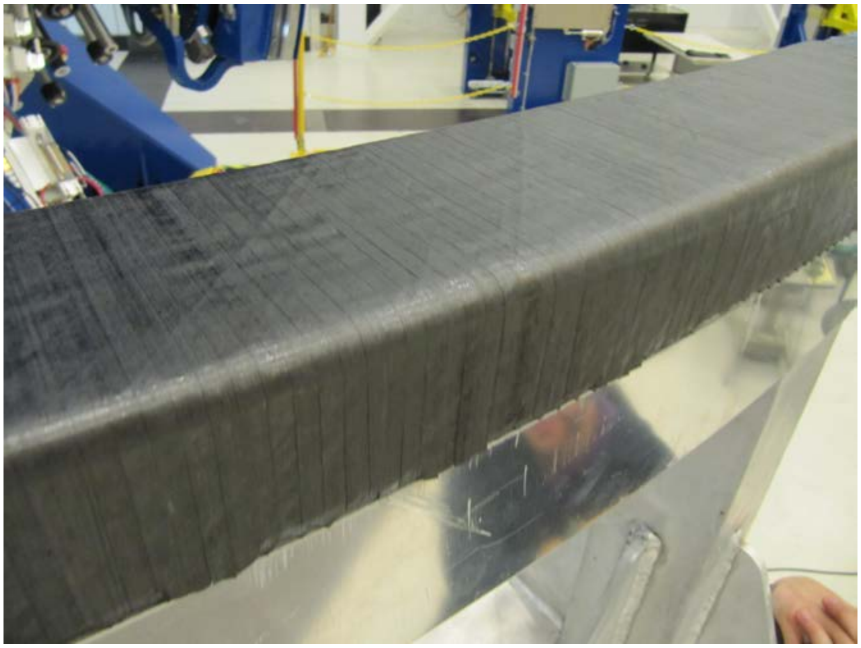

Figure 3 Typical ply quality

Completed frames were assessed for part quality and then utilized for other process development, including Composite NDE and Composite Milling.

Figure 4 Completed test frame

2.2 AFP testing by Electroimpact

After proof-of-concept frames were completed at Spirit AeroSystems, test plies (on the same tool) were performed at Electroimpact using a similar machine with a different axis configuration. This machine was designed for flexibility across a variety of geometries.

Figure 5 – Electroimpact seven axis AFP machine with swing-through head

Like the Spirit AeroSystems R&D AFP machine, the machine depicted above has the same axis order: Cprime, A, B, C. In this case however, the A axis was designed to achieve greater than 180º of motion. This requires much less Cprime rotation as well as allowed for tool loading at an ergonomic height and for greatly simplified machine motion. Because this machine was designed for the slighter tapers of spars and not for the curvature of the frame tool, the B Axis carriage on this machine prevents access to the entire length of the tool. In a full-length ply, one of the B Axis motors would interfere with the tool.

During this test, 45º plies were run with 4 tows, 6 tows, 8 tows and 10 tows. Ply quality remained consistent from 4 to 8 tows. 10 tows showed excessive pucker on the outer two tows. This test indicated that the "ideal" AFP head for this part would be an 8 tow head. Electroimpact has since developed this head. The head has 8 tows and a flipper arrangement. The flipper allows the head to feed tow in two directions eliminating the need to spin the head to reverse course. This head is currently slated to begin testing during the summer of 2013.

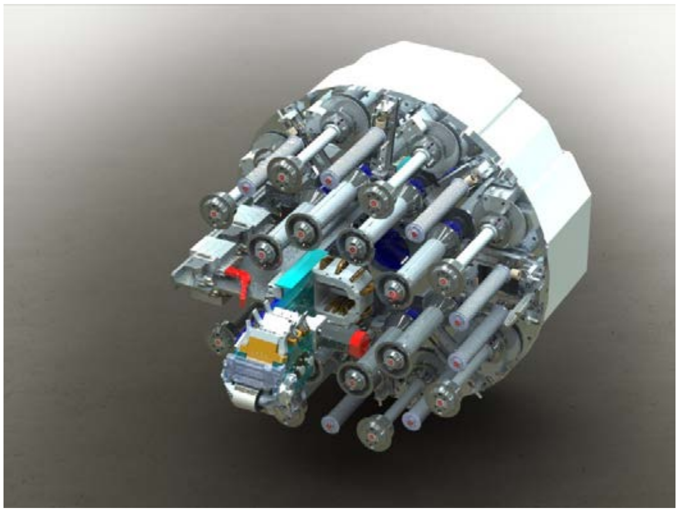

Figure 6 – Rendering of 8 tow head

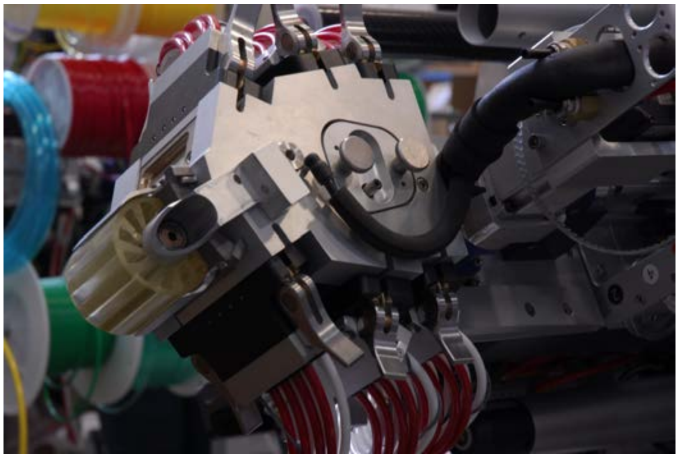

Figure 7 – Actual business end of 8 tow head

Ply quality and machine capability were comparable to the testing at Spirit AeroSystems, although the higher acceleration capability of this machine showed significant improvement to ply times, particularly on 90º and 45 º orientations where repetitive motion is high. This lead Electroimpact to generate additional machine simulations for equipment sized to this geometry with lower mass and correspondingly higher accelerations.

3. RESULTS

Machine motion and associated ply times were simulated for two configurations. The first was the machine used during testing at Electroimpact in Mukilteo, WA. The second was a light-weight conceptual machine scaled for AFP of frames and designed for high accelerations.

3.1 Simulation of various AFP equipment scenarios

Provided in the table below is the actual runtime capability of a part manufactured at the Electroimpact facility. Next, a baseline simulation was run using the equipment tested at Electroimpact. Then, a simulation was run using a conceptual design scaled for AFP of small parts. Ply times were simulated for 0º, 45º, and 90º ply orientations, which are representative of a production application. Parameters and results for simulations are as follows:

	Ply orientation (º)	Feed Rate (m/min)	Linear Acceleration (G)	Rotary Acceleration (º/s/s)	Rotary Feedrate (º/s)	Rate (kg/hr)	Rate improvement
Large Gantry Actual	0	30.48	.2	750	45	9.62[1]	-
	45	15.24	.2	750	45	1.63[1]	-
	90	15.24	.2	750	45	2.2[2]	-
Large Gantry Simulation	0	30.48	0.2	750	60	15.01	-
	45	15.24	0.2	750	60	2.27	-
	90	15.24	0.2	750	60	1.77	-
Concept Machine Simulation	0	30.48	0.7	750	180	19.50	30%
	45	30.48	0.7	750	180	4.26	88%
	90	30.48	0.7	750	180	3.54	101%

Laydown rates were drastically different in this case, particularly for 45º and 90º orientations where rotary motion is high. For a representative part with the same tool geometry used in testing, and in quasi-isotropic configuration (equal quantity of 0º, 45º, 90º, and 135º orientations) this creates a gain in productivity for each orientation equal to the values above and a corresponding overall reduction in AFP time of 88% (layup only).

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[1] Smaller plies, lower rotary axis speeds were used during the actual part build. This accounts for the lower laydown rates. Later, higher rotary axis speeds were achieved as well as some part program execution improvements and these improvements are reflected in the Large Gantry Simulation.

[2] For this test, we ran 16 tows. This accounts for the higher rate than found in our simulation.

4. CONCLUSIONS

Although both Large-Scale machines used in testing were designed for flexible capability across a range of part geometries, the sizing of the machines was clearly not optimal for this application. This is an example of the limitations that may be imposed on a process when a machine, tool, or other configuration is not part of comprehensive process planning. AFP equipment may be highly capable and flexible and represent the state-of-the-art machine motion, but particular applications may have particular requirements. In order to ensure success for a given process, all such considerations must be anticipated.

4.1 "Ultimate" Concept for One Piece Frame AFP

Testing and simulation has lead to a mature concept for a complete AFP cell to produce this type of product. In addition to optimal equipment sizing for speed and acceleration, purpose-built hardware can reduce or even eliminate certain machine motions. For example, shorter AFP heads can reduce arc length of rotary motions and reduce move times and Spirit holds patents on bi-directional AFP heads which can apply material in two directions, and can eliminate repetitive rotary motions. Modular heads can reduce repair and head cleaning times.

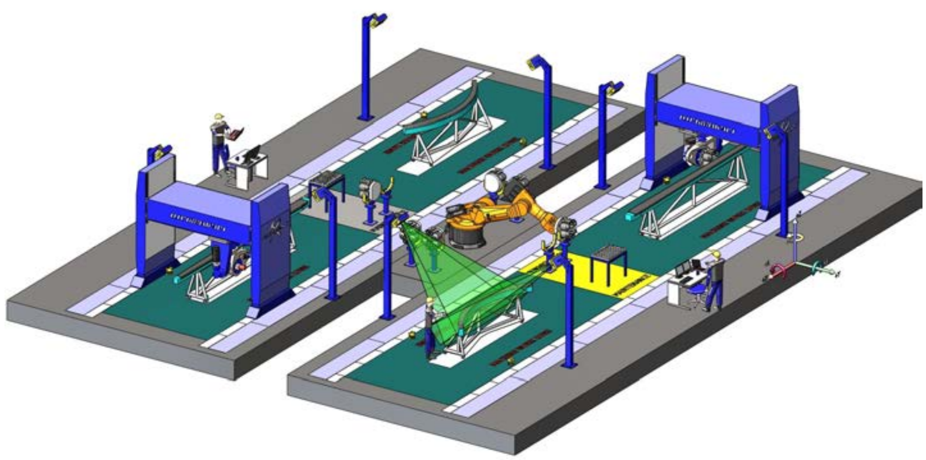

Figure 8 Conceptual AFP Cell for frames or small spars

Smart planning for tool turn times, inspection, and material handling will be part of a lean, productive process. All of this must be anticipated when assessing a new application.

4.2 Ensuring Success

It is only through complete process planning that the greatest gains can be realized. Understanding the constraints on the process, the requirements of the part geometry, and the technology capability of your company and suppliers will dictate the path to success. Clearly, intelligent machine design plays a key role in the successful utilization of AFP to produce substructure.

Based on testing, subsequent simulation, and developed concepts, Spirit AeroSystems has tools to assess work packages for existing and emergent programs and to offer productive and profitable solutions. In addition, Electroimpact is prepared to provide flexible and capable solutions for AFP, and particularly for AFP of substructure.

5. REFERENCES

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