A ROADMAP TO AUTOMATED COMPOSITES

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ABSTRACT

The transition from hand layup to automated composites manufacturing is difficult, time consuming, and costly endeavor with many barriers to make the switch. This paper seeks to make the benefits and considerations of the transitional process apparent and therefore easier to navigate. Through the outline of a business case for automation and considerations of machine type the reader will be well-equipped to determine the appropriateness of automation for their composites manufacturing. This paper attempts to provide knowledge of that evolution.

1. INTRODUCTION

The use of composite material in a manufacturing setting is a widely-accepted practice. In some industries (automotive and aerospace) composites not only represents an established process, but one that continues to mature. If a part contains sophisticated geometry or will not reach a high rate of production, manufacturers typically choose to exercise a hand layup process. This is the process of having skilled technicians place cut pieces of dry cloth or pre-impregnated material by hand. Staying with this manual method could inhibit future program production time, efficiency of the manufacturing facility, and ultimately contribute to loss of sales. Creating vast structures by hand simply cannot keep up with production rates and repeatability of automation. As a result, many progressive manufacturers like Boeing have turned towards an automated manufacturing approach for large composite structures such as spars, wing skins, and stringers [8].

Implementing automated composites requires a significant capital investment, alongside a steep learning curve. The expenditure in both cost and time inhibit many manufactures from instituting automation, despite the clear advantages. This paper will define important terminology, provide a business case for adopting automated composites, and point out considerations when deciding upon a machine. By shedding light onto these specific considerations, informed and successful steps can be taken to implement this constantly evolving technology.

1.1 Audience

Any manufacturing company considering expanding manufacturing from hand layup methods to those including the automated placement of composites material.

1.2 Overview

This paper will provide a detailed synopsis of the steps required in moving from traditional hand layup to automated composites manufacturing, all while placing a heavy focus on considerations upon making the transition. Topics discussed include the business case and rationale for making the transition to automation, cost and considerations, machine selection, impact to personnel and infrastructure.

1.3 Background and Terminology

When discussing automated composites manufacturing (ACM), several processes are referenced, typically in acronym-form that could easily confuse the uninitiated. The most prevalent and widely used forms of ACM are automated fiber placement (AFP) and automated tape laying (ATL). Additionally, composite tape winding (filament winding) is another process used for specific applications (pressure vessels, columns, etc.) but will not be discussed in-depth here.

ACM processes have been around for several decades, most prevalent in R&D settings, although there is a recent support for more widespread adoption in a rate production setting. AFP and ATL are proven processes both in government and commercial programs, allowing manufacturers the previously-unavailable possibility of creating massive composite components. With current machines ranging in size of 5’ to 140’ work cells, there are solutions from machine vendors to fit nearly every part. However, adoption of this technology outside of large Fortune 500 companies is scarce, partially contributed to the cost of purchasing hardware that can range from several hundred thousands of dollars to in excess of tens of millions. The other contributing factor in the slow adoption rate is that the knowledge base for ACM is similar but in some regards very different from traditional composites manufacturing methods. This knowledge must be hired from a small pool of talented individuals or trained directly from machine vendors. While not insignificant challenges, careful consideration and planning can overcome these to allow manufacturers to reap the benefits of automated composites processes.

Other key terms include the following:

- Add – The AFP process adds a tow to the form by feeding it out of the end effector and then cutting it, leaving it on the form. The process of adding the material to the form is called an “add.”

- Cut – The AFP process adds a tow to the form by feeding it out of the end effector and then cutting it, leaving it on the form. The process of cutting the tow to be added to the form is called a “cut.”

- Dropped tow – A process failure resulting in one tow not being placed on the form.

- FAT – “Final Article Testing” is a validation of machine capabilities with the machine installed at the customer site, testing in a setting identical to regular use.

- Feed rate – the speed which the part program is executed by the CNC. Typically quantified in distance per length, inches per minute or meter per minute.

- Layup – The process of adding material to the form, i.e. hand layup or AFP layup.

- MTB – “Machine Tool Builder” is the machine vendor.

- PAT – "Preliminary Article Testing" is a validation of machine capabilities with the machine installed at the vendor's facilities.

- Steering – Refers to the steering of a tow or multiple tows. A tow can be steered such that it gradually changes direction but still remains in contact with the layup surface and is free of defects. It is easier to steer narrow tows, while wider tows may not be steerable at all without producing laminate defects.

- Tow – a single strip of carbon fiber placed by an AFP machine. Tow widths can typically vary from one eighth of an inch to one inch.

2. BUSINESS CASE FOR COMPOSITES AUTOMATION

2.1 Expected benefits

One reason companies consider ACM is due to the impressive ability to lay down an extensive amount of pre-impregnated material on a form at a rapid rate. Thanks to rapidly-advancing ACM technologies, the possibilities for advanced composite parts appear endless. One of the most obvious reasons why Boeing choose to build the front and rear spars of the 777x wing with ACM instead of the hand layup process is the 236 foot wing span – a massive amount of material to place. By utilizing the strengths of AFP, Boeing designed and initiated efforts to accomplish that monumental feat. Boeing isn't the only company to understand that in the right setting, ACM is better and financially superior in the long term when compared to hand layup [8].

Another reason why manufacturers typically seek out ACM is for the same reasons anyone chooses automation: increased throughput, better quality, and reduction of labor cost. All of these benefits apply to ACM as well. However, the greatest advantage in choosing automation is part reproducibility. Reproducibility becomes a real concern for manual processes. When numerous technicians are expected to interpret engineering drawings, while placing material in the same exact location and direction – many times the process falls short. Automation virtually eliminates this difficult feat. The responsibility for interpreting engineering flag notes and ambiguous drawings no longer lies in the hand of the technician. Instead, the engineer dictates and analyzes pre-established machine paths before ever reaching the shop floor; thus eliminating potential waste of material and machine time. The same NC program can be executed as many times as needed with virtually no variability. With automation software such as CGTech's VERICUT Composites Programming, the manufacturing engineer possess the ability to control splice locations, ply staggers, and material orientation as designed. Simulation software such as VERICUT Composite Simulation allows engineers to simulate the part layup and machine motion in a virtual environment rather than wasting costly material and machine time. This creates a much more efficient and innovative method for creating composite parts.

2.2 Faster Manufacturing Rate

The speed at which material can be added to the form is one of the most apparent perceived benefits that exists within an ACM process, usually measured in material weight per time or material length per time. To that point, many (MTB's) advertise their machine's laydown rates (pounds per hour) as significant and distinguishing characteristics. Electroimpact, long known for their design and manufacturing of aerospace tooling and automation, has advertised feed rates of up to 660 pounds per hour for a given machine and part configuration. A reasonable rate for hand layup is two to three pounds per hour, less than one percent of the rate of Electroimpact's machine [5]. "660 pounds per hour is a number that our machines have achieved during customer machine PAT/FAT. That was on actual part geometry," said Brock Jahner, Automated Composites Project lead at Electroimpact [6].

The distinction, made here, of actual part geometry is vital. Unless specified like in this case, some ambiguousness to these quoted rates might exist. For instance, some MTB's of automated composites machinery don't qualify their speeds with part geometry or specifics, leaving out critical information. Twenty-four hundred inches per minute is possible on a flat surface, but many fabricated structural components feature significant curvature. Those laydown rates are dubious unless the MTB specifically states caveats and qualifiers for their numbers.

"The pounds per hour metric is kind of an interesting measure of productivity," Jahner went on to say. "We prefer to refer to this measurement as it factors in only the time that we as a manufacturer have control of. Taking into account all of the other activities (breaks, lunchtime, material loading, inspection etc.), the pounds per hour metric is significantly lower." This method of only factoring in time that the machine is running is often referred to as "A" rate and is defined as:

$$\text{“A” Rate; } (R_A) = \frac{W}{\text{Up Time}}$$

"W" is weight of the material placed and "Up Time" is qualified as "time within a ply during which the machine is occupied and fiber placing material in numerically controlled motion." "A" rate can be a good metric when differentiating between machines. However, other events contribute to the total process time in a real manufacturing setting. "C" rate, or called "floor-to-floor" rate is defined as:

$$\text{“C” Rate; } (R_C) = \frac{W}{(\text{Up Time} + \text{Down Time} + \text{Dead Time})}$$

"C" rate accommodates for daily events that affect every operation. "Down Time" refers to time which the "machine is occupied and capable of fiber placing material, but is not utilized" This refers to inspection, rework, material change, or lamination compaction. "Dead Time" encompasses time which the "machine is occupied but incapable of fiber placing material." Software or mechanical problems, loading or unloading tooling within the work cell, shift change, and breaks all contribute to dead time. "C" rate will most closely fit the actual constraints that affect a manufacturing timeline [1].

As engineers begin discussing details of machine envelope, capabilities, and rates with potential machine suppliers, one must be aware of any qualifiers to machine rate. Planning a part delivery schedule using an idealistic rate that doesn't take into account breaks, inspection, lunchtimes, etc. will result in impossible deadlines.

2.3 Decrease Production Time

Machine runtime is not the bottleneck of the ACM process. In fact, machine runtime accounts for at most one third of the actual time that a part spends in the cell. In order to have realistic expectations about the benefits that will come with automating a manufacturing process, what happens with the other two thirds of the time must be considered [9].

Once the machine completes the placement of a given sequence, the fabric needs inspection. Traditionally, QA inspectors with magnifying lenses, rulers, and other tools inspect for unintended overlaps, gaps, material defects, and other undesirable manufacturing outputs. This can take hours for large parts and represents a significant contribution to the time it takes to build the laminate. In fact, inspection accounts for the largest input in determining the total time a part is within an ACM work cell. In the case of the 787 fuselage barrel, this took two to three times as long as the material layup, as seen in Figure 1 [7].

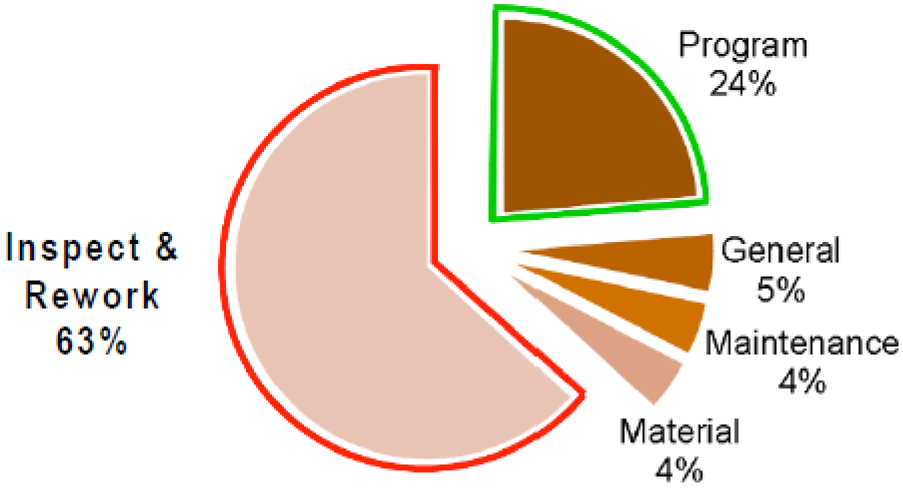

Figure 1. Breakdown of overall time spent on different processes during part fabrication for 787 fuselage barrel

Inspection assistant technologies exist to help mitigate the largest section of time spent on inspection and rework. One such tool is a long throw laser projector mounted in the work cell, or on the motion platform of the machine. By utilizing feedback from the CNC on events like dropped tows (an AFP process failure), the laser projector can project areas of possible rework to reduce the time spent by the inspector identifying them.

A scanning profilometer also helps reduce inspection time. Either mounted on the same motion platform as the end effector or another nearby motion platform that shares the same work cell, the part can be scanned either simultaneously to material being placed, or just after placement. Generated data is compared to the nominal layup and used to identify overlaps, gaps, bridging, twisted tape, splices and other defects. Should a discrepancy exist between the nominal and actual, it is identified on the part with a laser projector for an inspector to rework. Having this automated scanning assistant both directly reduces the time it takes to identify areas of rework as well as ceaselessly inspects the laminate for fault. A standard acceptable machine tolerance for dropped tows is one in three thousand. Given the diligence and effort required in manually finding approximately sixty process failures in 180,000 events, even highly skilled inspectors fail to catch every defect. By utilizing the joint benefits of automated inspection with automated manufacturing, as much as thirty percent of the time of the part build could be saved [9].

It is not enough to only reduce rework time, as any rework could be seen as a downstream symptom of a bigger problem: machine repeatability. In one example, recovery time after a process failure of a dropped tow was averaged to approximately nine minutes with a concurrent time of part rework estimated at fifteen minutes. Over the full three day part build, the summation of time spent recovering from these issues was tallied at fifteen hours [9]. Despite meeting industry reliability standards, rework and recovery after a dropped tow can significantly impact the project timeline which is one reason why a push for more stringent reliability standards is being made. Todd Rudberg of Electroimpact stated that “In a production-setting, our machine reliability is one process failure in approximately 6000 add/cut events,” but that they were making improvements to reach a goal of one in 10,000. “The key is maintenance,” Todd added. “We can achieve as high as one failure in 16,000 events during Final Article Testing and with a clean machine” [10].

Other methods of improving machine reliability are being made on the software front through feed rate optimization and programming strategies. Process failures are often focused in areas of a part layup where multiple material cuts and adds take place repeatedly. The VERICUT Composite Programming (VCP) software package identifies these and other key zones to help optimize machine feed rates by only slowing down when needed. This approach achieves both added machine repeatability and utilizing the maximum machine feedrate as often as possible. Also, part programmers can lengthen or join multiple small pieces of material to eliminate so many repeated material cuts and adds.

These caveats do not indicate that ACM is not a mature or reliable process, simply that there are additional considerations for manufacturers who want to take full advantage of every benefit that ACM offers. Reliability of the machine plays a large part in the overall efficiency of the machine, and as such, should be thoroughly understood. Failure rates of material add and cut events are good starts to understanding reliability, such as MTorres’ one failed add every 8,000 material adds and one failed cut every 40,000 material cuts, according to MTorres AFP project manager Manu Casado [2]. Given that a realistic rate of hand layup is hardly greater than two and a half pounds per hour, while even modest ACM machines can output ten times that at a reliable consistency, it’s easy to see the potential for time cost savings, especially on very large parts [5] [11].

2.4 Costs and considerations

As already discussed, the adoption of ACM can be a costly and challenging exercise. Along with the new manufacturing process comes new tooling, logistics operations, learning curves, training, and more. In addition, consideration has to be given to either modifying an existing facility’s layout or constructing a new building to house the new large machinery. Furthermore, there is a steep learning curve in part design and machine operation that either must be addressed by existing experienced personnel, or additional training which takes time and experience. This experience will not be gained without loss of productivity and scrap material, both of which must be accounted for. Lastly, part production volume must be taken into account when evaluating the appropriateness of ACM.

Each one of the aforementioned considerations equates to an added cost on top of the already expensive hardware of the machine. For this reason, any decision to adopt ACM must include an in-depth analysis of the realistic costs related to this new manufacturing implementation. Without careful documentation of the costs associated with the implementation, a realistic return on investment (ROI) cannot be made. “For all of the capabilities of ATL and AFP, every processor must evaluate the structures on which the technology will be used, taking into consideration the part's size, volume, complexity and application as well as ply requirements and other variables that influence process selection” [11].

A full account of expected costs, in addition to information from the MTB about realistic part rates, can help aid potential ACM adopters in determining if ACM is financially beneficial for them as well as aid in the calculation of meaningful ROI estimates. Understanding the considerations and assumptions that go into these expected costs ensures that they are well thought out.

3. MACHINE TYPE CONSIDERATIONS

Two of the most prevalent categories that ACM machines fall into are AFP and ATL. This distinction directly affects the parts producible based on layup surface curvature: AFP uses more narrow material which is able to be steered over surface curvature, whereas ATL uses wider material such that it cannot be steered over a surface without producing defects in the laminate. The tradeoff of ATL is a much higher volume of material placement, requiring a form with little to no curvature. Rarely is an ACM machine sought after without having a specific part and program in mind. Consideration of the demands and characteristics of the part in question will help in the decision between AFP and ATL.

Beyond the choice between AFP and ATL, the next step in determining which machine solution would best fit the process is addressing which motion platform would be best suited for your part. Given an exceptionally large part (for example, with dimensions in a given direction of greater than fifteen feet) an overhead gantry would be the best solution, as seen in Figure 2 [4]. Typical configurations include linear X, Y, and Z axes with a C, on B, on A rotational axes mounted on the Z axis. Additional axes such as a second C axis are beneficial in certain circumstances. Unique solutions can come about if the part is very large, such as the Electroimpact machine used to fabricate the Boeing 787 fuselage, which utilizes two towers and two end effectors working in synchronization to apply material to opposite sides of the tool at the same time. If the footprint of the part is not as immense, then a robot arm on a floor gantry is a common solution and seen in Figure 3 [12]. The robot configuration contains several advantages to the overhead gantry including cost. In most cases, robot arms require less floor space and infrastructure to operate compared to large gantry machines. While stereotyped as less accurate than gantries, MTB’s using robot arm motion platforms overcome this by replacing the stock internal gearing with in-house developed systems, as well as add additional motion control feedback on the joints, as is the case with Electroimpact robot arms.

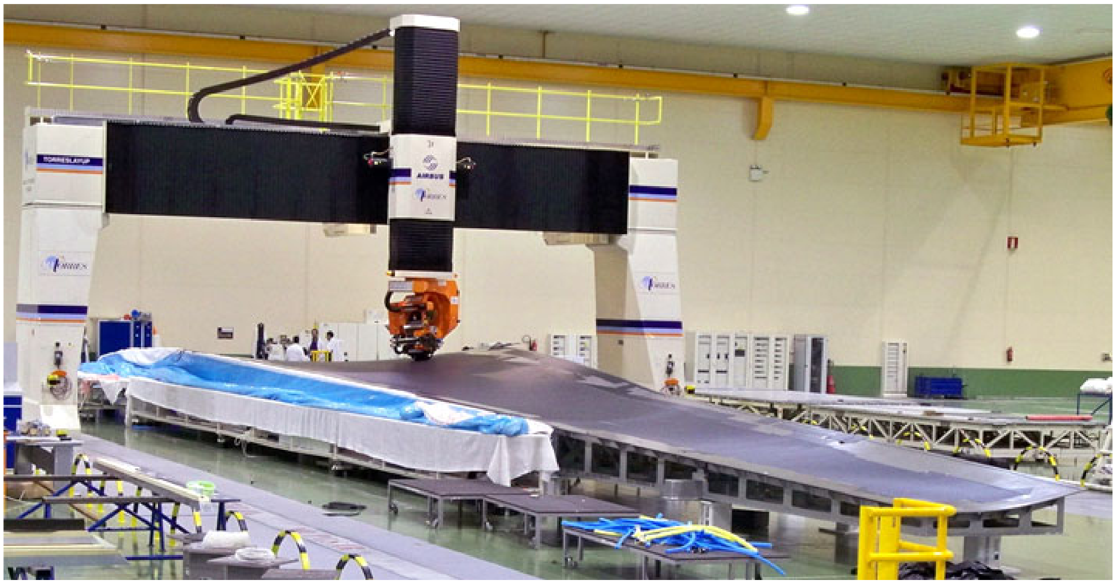

Figure 2. MTorres overhead gantry ATL machine

Figure 3. Electroimpact end effector on a robot arm

Other concerns to machine type include supplemental machine feature such as rotators, laser projectors, and probes. For parts that are circular or cylindrical, the use of a rotator or rotisserie is necessary. Depending on the mass of the tool to be rotated, it may be suitable to begin rotation in a direction and continue rotating in that direction for the duration of the layup. Other, lighter tools might benefit from rotating one direction, then rotating the opposite direction, essentially rocking back and forth. However, as rotators are extremely expensive, only those applications that need them should use them, as varying layouts of machine axes can potentially eliminate the requirement for a rotator. As has been described above, there is considerable benefit in the use of a laser projector to help with inspection and rework. Further, the ability to probe the layup tool with a probe mounted on the motion platform is invaluable in determining exact tool placement and increasing laminate quality.

4. CONCLUSION

Progressive companies from all of the world already reap the rewards that ACM offers. By adopting these new processes, these businesses prove to understand not only the benefits that automation brings for the future, but also how their current processes can be improved upon. The transition from non-automated composites manufacturing to automated processes is not trivial. However, manufacturers that can realize the benefits that AFP or ATL can leverage those tools to reduce manufacturing time on existing programs and open up the possibility of many other future programs. Complementing the automated manufacturing process with other automated processes like inspection, further compounds the advantages inherent to automation. Having realistic expectations about not just machine rate, but machine implementation is key at all organizational levels in order to create achievable timelines and delivery schedules.

Implementing automated composites requires a significant capital investment, alongside a steep learning curve. The information contained here sheds insight into what specific considerations should be taken before implementing this up-and-coming technology. Topics discussed include the business case and rationale for making the transition to automation, cost and considerations, machine selection, and impact to personnel and infrastructure.

As additional processes mature that complement ACM, the benefits of automation will increase and more companies will be willing to adopt it. Through complete understanding of the interconnections between these synergistic systems, vital benefits and strategic advantages can be realized.

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