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Automated fiber placement: A review of history, current technologies, and future paths forward

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A R T I C L E I N F O

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A B S T R A C T

Automated fiber placement (AFP) is a composite manufacturing technique used to fabricate complex advanced air vehicle structures that are lightweight with superior qualities. The AFP process is intricate and complex with various phases of design, process planning, manufacturing, and inspection. An understanding of each of these phases is necessary to achieve the highest possible manufacturing quality. This literature review aims to summarize the entire AFP process from the design of the structure through inspection of the manufactured part to generate an overall understanding of the lifecycle of AFP manufacturing. The review culminates with highlighting the challenges and future directions for AFP with the goal of achieving a closed loop AFP process.

Introduction

Background

Carbon fiber materials became available for commercial use in 1966 [1] stemming from research done by Watt et al. [2] at the Royal Aircraft Establishment. Soon after its appearance, it became clear that the manufacturing process was extensive, and automation would be advantageous. Two of the cornerstone automated processes to appear were automated tape laying (ATL) and automated fiber placement (AFP), with the latter being the focus here. The ATL process replicates the manual layup of unidirectional (UD) tape (75 – 300 mm wide [3]) but can be done at higher speeds, on larger parts, with greater control, and over slightly curved surfaces [4,5]. The AFP process consists of a gantry/robotic system with an attached fiber placement head. The AFP head enables multiple strips of composite material, or tows, to be laid onto a tool surface. Adhesion between the incoming tows and substrate is ensured by using appropriate process conditions such as heating, compaction, and tensioning systems. A series of tows forms a course, courses are then combined to create a ply, and multiple plies create a laminate.

Nearly 10 years ago, Lukaszewicz et al. presented a highly detailed review of automated prepreg layup [3]. Since this time, there has been an enormous amount of progress in this field. However, the authors are not aware of such an in-depth review detailing the most recent advancements and opportunities in the field of AFP. The presented state-of-the-art will build on the previous review with the newest information and technology while also presenting a novel methodology for a closed loop AFP process (Fig. 1). Since the inception of AFP, the entire process has been made up of several isolated pillars: (1) Design, (2) Process Planning, (3) Manufacturing, and (4) Inspection. The personnel and data from each of these pillars is often siloed, with little interaction to optimize the process. This flow of data originates from concepts within the manufacturing sector of "Industry 4.0" where technologies are continually improving creating a race to integrate them. The data flow ensures that design is no longer a starting point, but rather a trade in a continuous improvement cycle that integrates process planning, manufacturing, and inspection. To achieve such a workflow as the one presented, many challenges remain within the AFP industry and the composites domain as a whole.

The authors have broad interdisciplinary backgrounds and each author approaches AFP from a distinct perspective. Close quarters and frequent collaboration between them have convinced the authors that the full flow of available information should be used to enhance the AFP manufacturing cycle. Lessons from inspection on parts has revealed characteristics relevant to determining optimal processing parameters and design considerations. Process planning can inform machine motion and path planning. Physics and geometric modeling of material behavior directly feeds into process planning tools. In other words, the sum of each discipline of AFP is far greater than the respective parts.

This implies two distinct recommendations that will be highlighted and reinforced throughout this paper: (1) that individuals from

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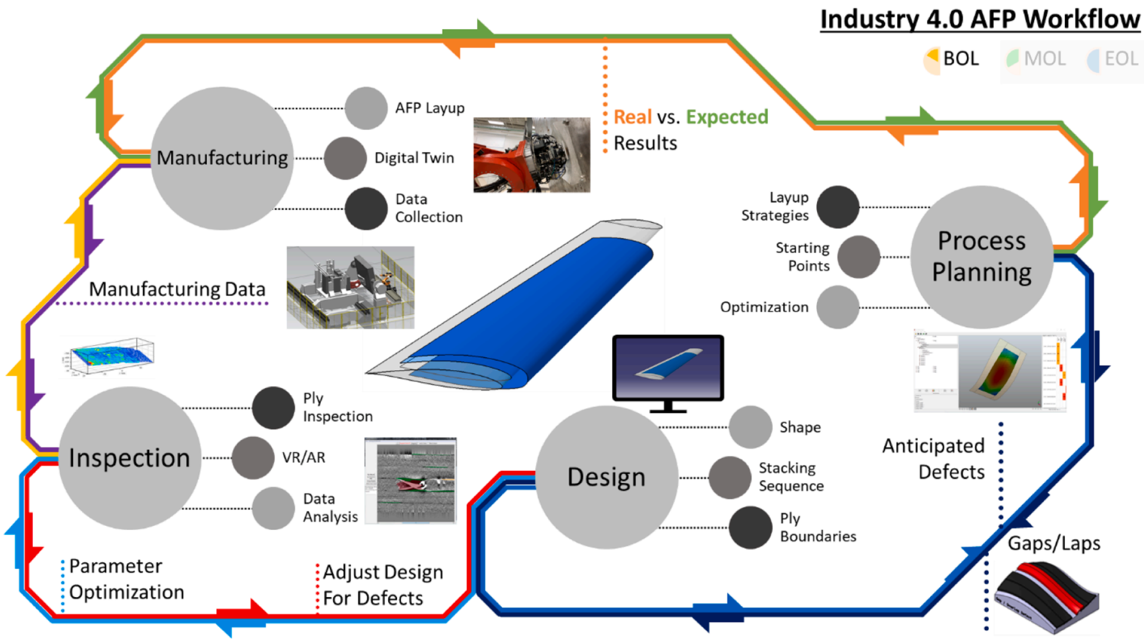

Fig. 1. Graphical representation of closed loop AFP workflow [6].

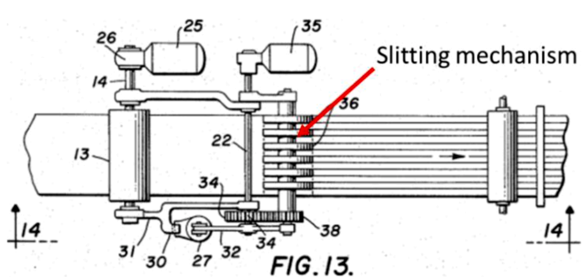

Fig. 2. Schematic of the patent utilizing slitting to form tows [7].

designers to machine programmers should be in constant communication with one another for the production of a given part, and similarly (2) that systems should be established for transfer, integration, and analysis of multi-domain data from each phase of manufacturing. This constant integration of new data from outside domains allows for the manufacturing process to be iteratively improved throughout the production of a part and contributes to the generalization of approaches for new parts.

The following will provide a state-of-the-art review of AFP starting with a brief history of AFP and its major advancements since its inception. This will be followed by a detailed review of the AFP process including current state-of-the-art in materials, machines, design, process planning, manufacturing, and inspection. Finally, current and future research opportunities will be presented culminating with an investigation into how the presented closed loop flow can be achieved.

History of AFP developments

Before AFP technologies were created, composite production of large structures was largely accomplished with ATL and filament winding. The earliest documented account of the concept of using tows instead of tapes was in 1974 [7]. This invention utilized a splitting mechanism (Fig. 2) on an ATL head that slit 3-inch-wide tapes into 24 individual strands, now referred to as tows. The use of tows allowed for layup on increasingly complex parts that were not previously possible with wider tapes. The use of such a slitting mechanism led the way for future developments leading up to the AFP machine.

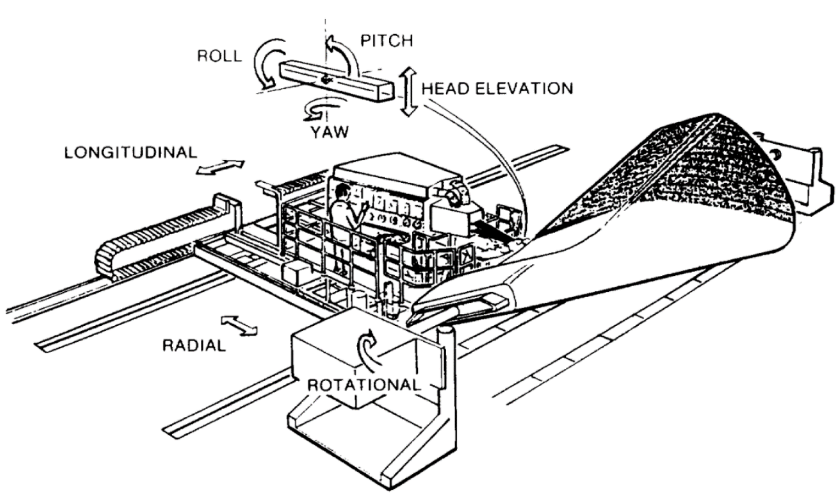

Fig. 3. Drawing of early AFP machine created by Hercules [10].

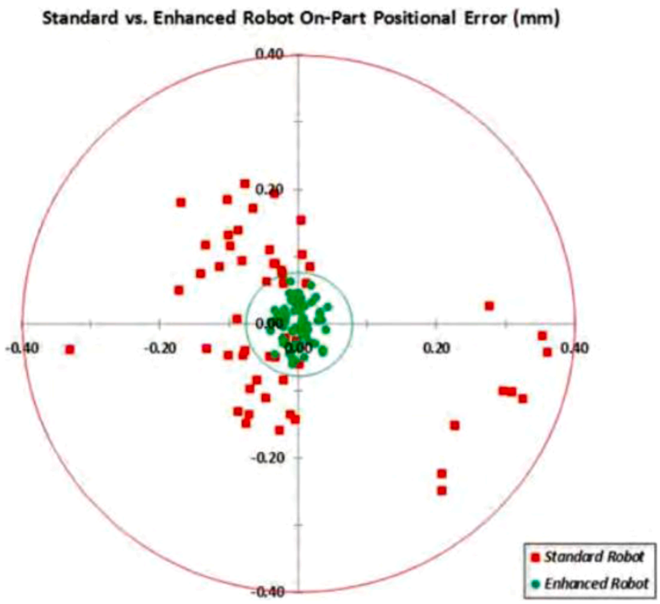

Fig. 4. On-part positional error of standard and highly accurate robots [23].

Hercules began development of AFP machines in 1980, and they became commercially available later that decade, being implemented by aerospace companies such as Boeing, Lockheed, and Northrop [8]. A depiction of an early machine created by Hercules is presented in Fig. 3. The machines were a combination of the differential payout capability of filament winding and the compaction and cut-restart capabilities of ATL. Developments of roller design, material guiding, and material heating from ATL were also directly applied to the AFP process. The AFP system had the capability to vary layup speed, pressure, temperature, and tow tension. Bullock [9] added to this capability by demonstrating an offline programming system that would benefit the machine's production time. The offline system allowed the programming to be done independently and then uploaded to the machine for execution.ss

A report by Grant and Benson [11] in 1993 presented the implementation of a refrigerated creel system to minimize issues within the creel, prolong material life, and allow for clean unspooling. Research in the 1990's was also focused on improving productivity of the AFP process. This began with a system that could deliver up to 24 tows at once [12]. With this system a layup rate of up to 30 m/min was reported, corresponding to a productivity of 1.9 kg/h, more than doubling the productivity associated with manual layup. Productivity continued to enhance through reliability [13]. Reliability over complex geometries was improved by delivering tows along a curvilinear path, otherwise known as steering. An application of this development showed a 450% improvement in productivity, a reduced material wastage from 62 to 6%, and a cost reduction of 43% [14,15] when compared with using a combination of filament winding and hand layup. These improvements in AFP also coincided with the development of thermoplastic composites for aerospace structural applications. The use of these materials allowed for *in-situ* consolidation during layup, but higher placement temperatures and pressures are required [16]. Research on thermoplastic layups became a necessity due to the large size of the composite structures exceeding the size of the autoclaves needed for curing [17].

Starting in the 2000's a great deal of research was focused on improving process reliability and productivity. Boeing [18] and Electroimpact (EI) [19] have performed studies on the amount of time delegated to manual inspection and rework of AFP layups. Boeing showed that layup inspection and rework comprised 63% of the total time, more than 2.5 times as long as the layup process. EI found that inspection and repair consumed 32% of the total time, while machine layup time was 27%. A 2006 patent produced by Engelbart et al. [20] was the first to describe an automated detection system. The system would electronically access positional data to define a defect location, and then the machine would automatically return to that location. EI also made a major contribution to the productivity of AFP machine with the development of a high-speed system capable of 2000 in/min (50.8 m/min) with interchangeable heads and reduced tow-path length [21].

Research by Flynn et al. [22] published in 2010 presented efficient simultaneous use of a multiple machine cell as well as modular AFP heads. The modular head offered advantages of 360° positioning, multiplicity of tow widths, short tow path, and offline maintenance. This was further enhanced with a report in 2013 with highly accurate robots demonstrating a 3-sigma accuracy of +/- 0.08 mm (Fig. 4) [23].

The most recent industry relevant AFP research topics consist of high throughput AFP, minimal defect layups, and *in-situ* thermoplastic layups. High throughput AFP and minimal defect layups are focused on improving the overall quality and efficiency of AFP manufactured structures. *In-situ* thermoplastic layups are focused on combining layup

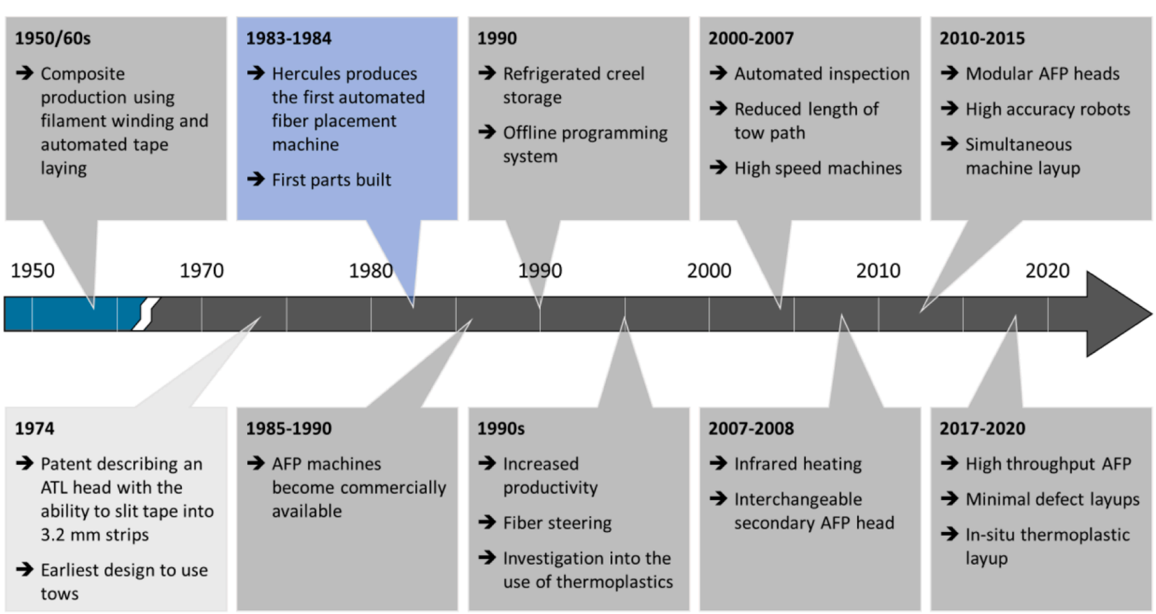

Fig. 5. Timeline of AFP developments [24].

Table 1
Characteristics of each material type.

Material	Processing Temperature	Material Storage	Curing
Thermoset	Low	Frozen	Autoclave/Oven
Thermoplastic	High	Room Temp	*In-situ*/Autoclave
Dry Fiber	High	Room Temp	Infusion

and curing, preventing the need to perform a costly and size limiting curing step. All the advancements presented in this section are summarized below in Fig. 5.

Materials

Material choice can lead to adverse or beneficial effects on the manufacturing process along with the final overall quality. There are three main types of materials used for AFP manufacturing, those being thermoset, thermoplastic, and dry fibers. Thermosets and thermoplastics are referred to as "prepreg" because the fibers are already pre-impregnated with resin, while dry fiber is not. Each of these comes with its own processing range and technique which are explained in the latter. Table 1 below provides a summary with key characteristics of each material.

Thermoset

Thermoset prepregs utilize a combination of fibers and thermoset resins. Thermoset resins are polymer resins with a relatively low viscosity, and when cured form a rigid 3D lattice structure [25]. These materials are the most common AFP material used because they are the easiest to manufacture due to the comparatively low optimal processing temperature required for successful layup [26]. Since the processing temperature required to reach the gel or melt point of the material is close to room temperature, less heat is necessary leading to easier manufacturing. In addition, thermoset tapes require a secondary processing step, such as autoclave consolidation, increasing processing time and cost [27]. Typically thermoset processing temperatures should not exceed ≈70 °C in order to prevent initiation of the cure reaction within the resin [28]. Further, due to the thermoset resin within the material, it is required to keep the material frozen to slow the curing reaction.

Thermoplastic

Thermoplastic prepreg materials use a combination of fibers and thermoplastic resin. These types of resins have a high viscosity and do not chemically join, or cure, when heated meaning they can go through solid and fluid transformations many times [25]. Thermoplastics are beneficial as they have many advantages over thermosets including recyclability, rework ability, high temperature performance, high impact resistance, and long shelf life at room temperature [27]. Furthermore, these materials bring about the possibility of skipping a post consolidation step such as an autoclave, oven, or hot-press by using *in-situ* consolidation [29–31]. However they are difficult to layup due to higher required temperatures (typically around 400 °C [28]) and smaller operating processing window [32].

Dry fiber

Dry fiber materials, just as they sound, do not contain a resin matrix. Similar to thermoplastics, dry fiber layup requires higher temperatures and has a small operating window [32]. Dry fiber has a long shelf life at room temperature, and lends itself to steering application since it is easier to steer as there is no matrix confining the fibers, allowing the tow to bend or shear [33]. However, dry tows do not have tackiness so a vail (thin thermoplastic layer) is required to allow lay-up of the tows [34]. The lack of resin within the material has a benefit of reducing resin build-up in the machine head, resulting in longer maintenance intervals and greater reliability [35]. This material has a disadvantage in post-processing as well due to the need to infuse resin into the final part.

Table 2
Typical design practices for design of composite structures [36].

Design Practice	Effect
Employ balanced and symmetric laminates	Minimizes elements in [B] and [D] matrices, avoids coupling between bending,, warping, and twisting effects
Maximum number of consecutive plies	Prevents delamination and residual stresses
Maximum and minimum ply angle jumps	Decrease inter-laminar stress and obtain dispersed laminates
±45° surface plies	Increases damage tolerance, buckling load of thin laminates, and protects load carrying plies from impacts
Add fabric as inner and outer layers	Absorbs impact damage and minimizes drilling "breakout"
Pair +45- and -45° plies	Minimizes inter-laminar shear and in-plane shear is carried in tension and compression in the 45° layers
Use larger fraction of +/- plies in shear regions	+/- piles are better at handling shear loads
Minimum steering radius	Prevents fiber buckling and minimize steering defects
Ply drops	Helps with laminate continuity

Design

Composite materials have the advantage of improved mechanical properties such as high specific stiffness and strength, corrosion resistance, enhanced fatigue life, and improved fracture toughness compared to traditional materials [36]. However, utilizing the benefits of composites requires careful design and optimization. Setoodeh et al. [37] provides two categories of design of a composite structure: (1) constant stiffness [38] and (2) variable stiffness [39,40]. A constant stiffness design uses the same stacking sequence over an entire structure where the goal of the design process is to optimize this sequence. Contrarily, a variable stiffness design utilizes changes in fiber angle and thickness across a structure, both of which are optimized for structural performance.

In industry, manufacturing of composites is still limited to conventional constant stiffness laminates with possible fiber angles restricted to 0, ±45, and 90° [41]. These fiber angles are often used in a way that creates a quasi-isotropic laminate. In addition to ply angle restrictions, laminate design guidelines have also been developed over time to guarantee the robustness of the laminate. These guidelines consist of having mid-plane symmetric laminates, balanced laminates, maximum number of consecutive plies, maximum and minimum ply angle jump, and ±45° surface plies [40]. Utilizing symmetric and balance laminates minimizes elements of [B] and [D] matrices in the ABD matrix, resulting in avoided coupling between bending, warping, and twisting effects. The maximum number of consecutive plies should be limited to 2–4 layers which decreases the chance of delamination. The maximum jump of ply angles between plies decreases the inter-laminar stresses. Minimum ply angle jumps are used to obtain dispersed laminates, helping to withstand impacts. Further, utilizing ±45° surface layers improve damage tolerance, buckling loads of thin laminates, and protects primary load carrying plies. Utilizing fabric plies as inner and outer layers can absorb more impact damage and can minimize drilling "breakout". Lastly, it is advisable to use a larger fraction of +/- plies for improved performance under shear loads.

Design flexibility of composite structures can be enlarged by properly utilizing the fiber steering capabilities of a fiber placement machine, creating more efficient composite structures [42]. The advantage of curvilinear fibers on structural performance has been extensively studied, accompanied by studies proposing optimal fiber paths for various applications. The authors in [43–46] investigated the design of variable

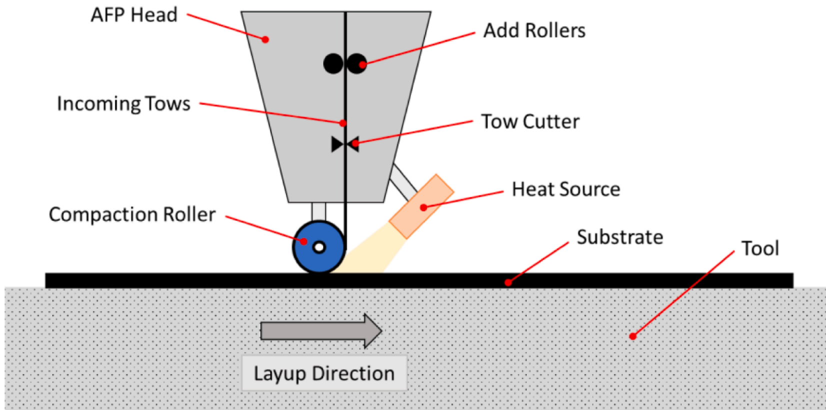

Fig. 6. Simplified representation of an AFP head.

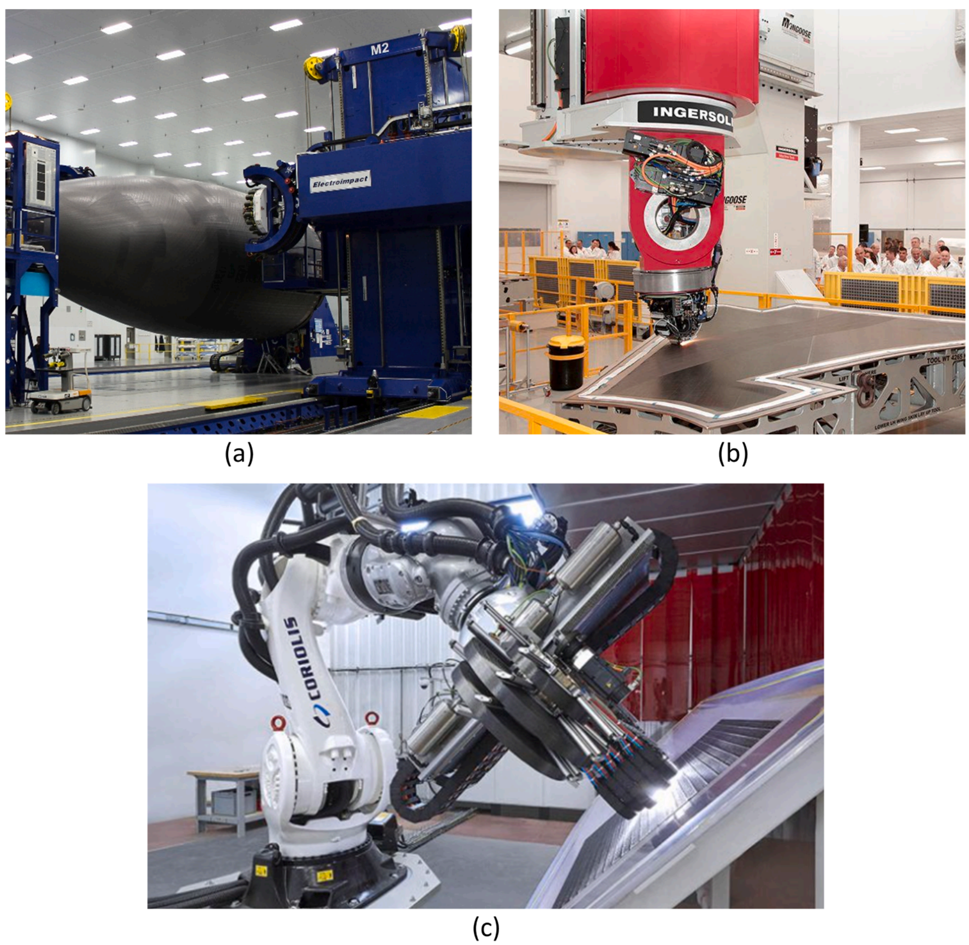

Fig. 7. Images of (a) horizontal gantry [50], (b) vertical gantry [51], and (c) robotic arm type AFP machines [52].

stiffness laminates that are enabled through the AFP process. These laminates utilized tow steering to optimize the performance by strategically creating fiber paths that exploit the greatest benefit of the composite material. Variable stiffness design utilizes the guidelines above, however the guidelines are applied locally at each point in a structure to maintain structural integrity. Another manufacturing constraint for variable stiffness laminates is the minimum turning radius of the fibers. This constraint is applied to prevent fiber buckling due to compressive forces within a tow when steering. Also, uniform load distribution within a structure is rare, leading to locations of a structure with high and low load requirements. This is accounted for with continuity constraints where ply drops are required to achieve continuity, also referred to as blending. Table 2 below, based on the information provided by Beckwith in [36] along with information gathered from Albazzan et al. in [40], summarizes the common design practices for composite structures. For more information regarding the advances and difficulties of variable stiffness laminates, the reader can refer to [37,39, 40,47–49].

AFP machine hardware

This section will discuss the types of AFP machines and review the

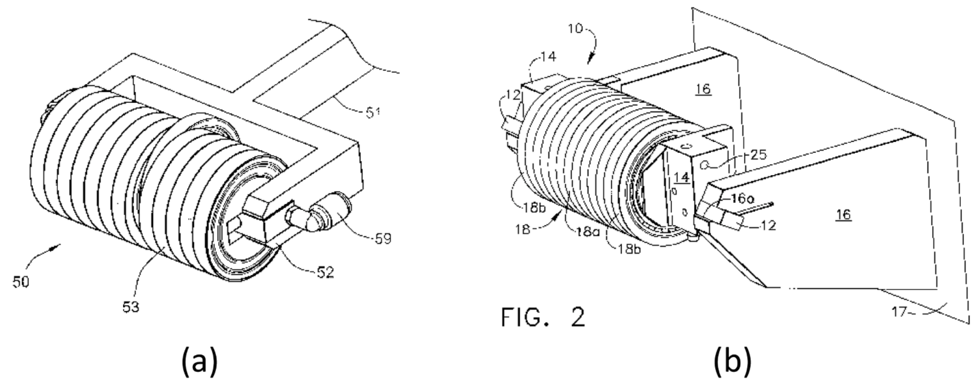

Fig. 8. Representations of segmented compaction rollers by Ingersoll Machine Tools [54] and Boeing [55].

main hardware. The hardware discussed will include major parts such as robotic platforms, compaction rollers, and heat sources. In order to ease explanation of the complex AFP head, a simplified representation is presented below (Fig. 6).

Platforms

There are three main types of AFP machines: horizontal gantry, vertical gantry, and robotic arm. The type of machine to be used is dependent on the size and shape of the part. Large plate-like structures are good candidates for the gantry type of machine, especially the vertical gantry, because they do not require complex motion. Horizontal gantries are usually preferred when the tool has a large height or needs to be rotated because the gantry structure does not hinder the tool. However, the robotic arm type of machine will be beneficial for complex shapes because it has a wider range of motion to maneuver around higher curvatures.

Fig. 7 provides images of each type of AFP machine mentioned above from EI, Ingersoll Machine Tools, and Coriolis. In each case the tool can be rotating or stationary depending on the geometry of the part. The horizontal gantry style machine has 6° of freedom (DOF) associated with the robot with 3 being cartesian and 3 being rotational along with an additional external rotational axis for the mandrel/tool. The vertical gantry system performs in the same manor, except the AFP head performs the layup from the top of the tool and there is typically no rotating mandrel. The robotic arm machine has 6 rotational DOF associated with the robotic arm along with a linear axis. These can also be combined with a rotator that utilizes a rotational DOF to combine for a total of 8 DOF. This type of machine can layup on tools that are arranged vertically and horizontally, and on tools that rotate making it the most versatile option.

Compaction rollers

The primary function of the compaction roller is to place the tows, facilitate the development of required levels of tack, and reduce the voids between the tows [28]. The roller applies pressure to the incoming tows and substrate to ensure proper adhesion right after temperature has been applied from a heat source (Section 4.3). This adhesion plays an integral role in preventing manufacturing defects. Different types of compaction rollers are described below.

Solid compaction rollers

AFP heads that are used for small scale production generally use rollers that are solid or perforated. The hardness of these rollers is an important factor in which one to use. The hardness is measured through the durometer scale. This scale is the international standard for measuring the hardness of materials [53]. A higher durometer value corresponds to a harder material. Bakhshi and Hojjati [28] conducted an experiment that examined solid rollers with durometer values of 35, 60, 85, and a stainless-steel roller. The stiffness of the roller will determine how the compaction force is applied to the tows, and the area over which it is applied. The softer material will apply a lower pressure distributed over a larger area, while the harder material applied a large pressure on a very small area. It was determined that a softer material capable of providing the appropriate compaction is optimal due to the compaction being applied over a larger area.

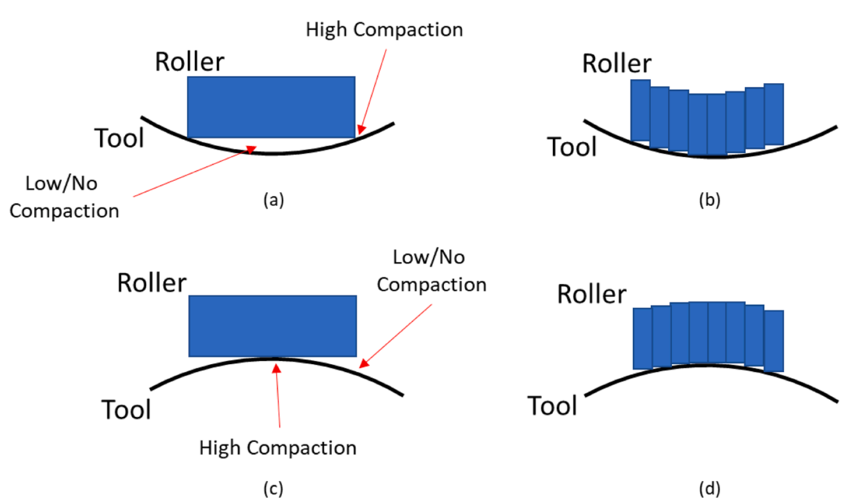

Fig. 9. Example of the conformability of a (a) solid and (b) segmented roller.

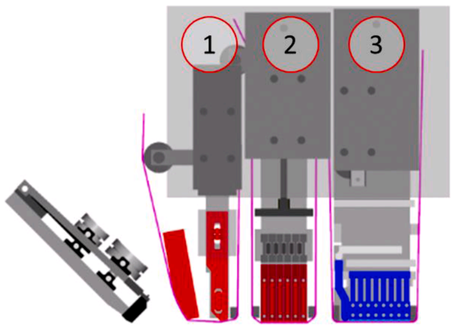

Fig. 10. Diagram of the *in-situ* thermoplastic compaction system [58].

Table 3
Summary of the characteristics of each heating system.

Heating System	Material	Controllability	Temperature
HGT	Thermoset/Thermoplastic	Low	Medium
IR	Thermoset	Medium	Low
Laser	Thermoplastic	High	High
Pulsed Light	Thermoset/Thermoplastic	High	Medium/High

Segmented compaction rollers

AFP machine that are used for industrial manufacturing often use segmented conformable rollers that are composed of multiple small rollers with the capability to move separately on the same shaft. Each of these rollers consists of a metal interior with a flexible cover. Images from the patents of some of these rollers are provide in Fig. 8.

These types of rollers are used for increased control of the compaction force across the entire course. It is important to have a uniform pressure distribution across the roller to ensure proper tow placement. This becomes especially important when using a large non-segmented roller on a curved surface such as aerospace stiffening structures. Inadequate conformity between the roller and tool can lead to reduced pressure applied to the tows [56]. The individual rollers of the segmented roller can adapt to more complex surfaces by utilizing the several height-adjustable rollers controlled by pneumatics or fluid filled bladders enabling individual compaction pressure [57]. This increased conformity is demonstrated graphically in Fig. 9.

Thermoplastic compaction

As discussed in Section 2.2, thermoplastic materials require extreme heat and cooling for proper processing. This has proven to be difficult to achieve in single passes with normal AFP head attachments; therefore, research has been done to integrate heating and cooling into the compaction system. The authors in [58] developed a system for out-of-autoclave (OOA) AFP layup that consisted of three conformable compactors that would heat and chill the composite. This system works as follows: (1) the first hot line compactor establishes initial intimate contact and healing, (2) the second hot area compactor maintains temperature to complete healing of the polymer chains, and (3) the third cold compactor chills the material and compresses the voids. A schematic of the whole system is shown in Fig. 10. Steel is often used in thermoplastic compaction rollers due to the need to sustain the high temperatures the mechanisms will be exposed to [28].

Heat sources

The application of heat is a key factor in ensuring proper adhesion between the substrate and incoming tows. The hardware that applies the necessary temperature is typically referred to as a “heater”. The heater is a device that is mounted to the AFP head that supplies heat during deposition to ensure adhesion of the incoming tows to the substrate [26]. The devices that will be covered below consists of hot gas torches (HGT), infrared (IR) heaters, lasers, and pulsed light heaters. These heating systems are summarized below in Table 3.

Hot gas torches

HGTs have been used for more than two decades and were used as heating mechanisms in ATL machines and in initial AFP machines [59]. This mechanism uses a hot gas, usually nitrogen, with the applied temperature being controlled by the gas flow rate [60]. Using a HGT is comparatively inexpensive, but the temperature is difficult to control [61]. The high temperatures that are possible with this heating device make it a candidate for thermoplastic layups [62]. In [63], it is noted that HGT heating of thermoplastics is not practical above about 150 mm/sec however, improvements in prepreg material have yielded improved performance up to 200 mm/sec. When comparing HGTs and laser heaters, HGTs have some advantages namely the lower safety concerns, provides more distributed heating, and heats both the polymers and fibers [64].

IR heaters

IR heaters are one of the most common heat sources seen in AFP manufacturing of thermoset materials. Heat transfer from the IR heater to the substrate is done through radiation [65]. Calawa and Nancarrow [66] developed a quartz lamp IR heater with the advantages of short response time, durability, and longest wavelength with high power output. When radiant energy hits an object some of that energy is absorbed, some is reflected away, and some is transmitted through. For this reason, a reflector is often incorporated to ensure most of the emitted energy is in a useful direction [66]. This heating system has a main disadvantage of inefficient heat transfer and non-uniform heating due to the wide dispersion of the heat [65]. Further, the heat generated by the IR heaters is not high enough for manufacturing with thermoplastic materials.

Laser heaters

Laser heaters are usually employed for thermoplastic layups, and have shown to be a better heating option [26,29,67]. The first concept of laser heaters was demonstrated by Beyeler et al. [68] in the 1980s. Lasers have become robust with lower costs, making them a commercially available process. Newer laser systems use a light wavelength that will heat the fibers instead of the matrix preventing damage to the material [69]. A laser system’s advantages consist of high energy density, more focused heating, faster processing rates, and better surface finish [64]. Experiments have also shown that laser-assisted AFP has comparatively better inter-laminar strength versus placement rate [70]. The main disadvantage of these systems is the necessary safety precautions that are required. Typically, laser shielding is required around the AFP cell along with personal protection equipment (PPE) to prevent any reflections from harming personnel. Further, laser heating cannot be used in some materials such as glass fibers due to the fact that glass fibers do not absorb the laser energy [64].

Pulsed light heaters

The pulsed light heaters are a recent development that provides AFP manufacturers with another choice of heat source outside of the conventional hot gas, IR, and lasers. An example of such a heating system is Humm3® developed by Heraeus [71]. The heat is delivered by a Xenon flashlamp using three programmable pulse parameters: voltage, pulse duration, and pulse frequency. The light is directed onto the substrate through a crystal enabling focused heating on the substrate. These systems deliver rapid heating with heating time and temperature comparable to a laser system.

Modular AFP Heads

The more recent AFP machines that have been developed utilize a modular AFP head which has demonstrated high rate and high quality in

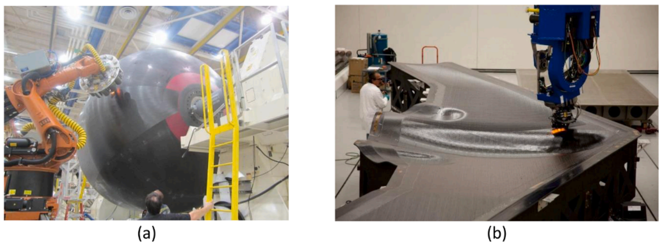

Fig. 11. AFP machines laying up skins for a (a) cryogenic tank [78] and (b) blended wing body [79].

commercial aircraft production [23]. The development of a modular head came from the desire to use multiple tow widths and enable offline maintenance [72]. This head offers advantages such as multiplicity of tow widths, very short tow path, and rapid head change [22]. All the characteristics and advantages listed lead to decreased downtime of the machine and higher throughput of manufactured parts.

Toolform manufacturing

The term "tool" is used in AFP to represent the surface that the material is being laid onto and it represents the shape that the final structure will take. The tools can be made to manufacture structural components for aircraft [73], space vehicles [74], and marine vehicles [75]. Depending on the structure that is being built, the geometry of the tool can vary greatly. Understanding what geometry is being used and how it affects the AFP process is vital for high quality manufacturing.

Types of tool geometries

The tool geometries discussed will be focused on production style tooling, as types of research-based tooling are too variable to account for in this paper. Tooling geometries can be split into the three basic categories of flat, singly curved, and complex or doubly curved. Completely flat tooling is not a common shape for industrial AFP production because it lends itself to other composite manufacturing techniques such as ATL or hand layup. However, sections of more complex tooling can be flat. Singly curved tooling is usually used for components such as wings or sections of a fuselage [76]. Singly curved tooling can also be distinguished into open contour and closed contour surfaces. Closed contour surface, such as cylinders, must be mounted on a rotating mandrel which may not be required for the open contoured surface. Lastly, complex tooling can be used to manufacture structures such as wind tunnel blades [77] and blended wing bodies. A couple of examples of the manufacturing of these structures are presented in Fig. 11.

Effects of tool geometry

The effects of different tool geometries on the AFP process are not prevalent in literature but are mainly learned through manufacturing experience. The quality of the layup can be severely impaired by the complexity of the part [80]. Harik et al. [81] provided some basic knowledge on anticipating defects such as gaps, overlaps, bridging, and twist due to layups on complex geometries. Chu et al. [82] demonstrated that a decrease in pressure uniformity across the compaction roller is seen when using complex tools. Wehbe et al. [83] provide a method for geometrically predicting wrinkling based on tool curvature and path geometry.

Manufacturing experience will provide knowledge such as collision avoidance, temperature dependencies, compaction requirements, and induced steering. It is important to do extensive simulations and dry runs on highly curved geometries to ensure there are no collisions between the AFP machine and the tool. Severe curvatures may result in sections of the tool being impossible to reach depending on the machine and the hardware attached.

Process planning

Preparation for AFP layup usually begins with a process planning phase. This phase consists of creating a plan of how the layup will be completed. A review of layup strategies and process parameters is provided below. Lastly an overview of process modeling is provided to demonstrate the necessity of understanding the behavior of the AFP process before manufacturing. Each of the aspects of process planning plays its own role in the creation of an efficient and quality manufacturing plan.

Layup strategies

The choice of layup strategy is responsible for determining starting points, reference curves, and coverage across the surface. Each of these choices can enhance or diminish the layup quality. The following will provide a brief description of the available process planning techniques. A detailed review can be found in [84].

Reference curves

Before the entire tool surface can be covered with toolpaths, a reference or guide curve is needed. Using various types of reference curves can greatly impact the outcome of the layup. The strategies for creating reference curves are fixed angle, geodesic, and variable angle. A fixed angle strategy creates a curve from a given starting point that has a constant angle from a given axis or direction along the entire surface. The reader can refer to Refs. [85–88] for further details.

The geodesic curve method can be used to avoid steering because the curvature along a geodesic path is null. A geodesic is the shortest possible path between two points on a curved surface, resulting in a straight line on a flat plate [89,90]. The path can be obtained either by specifying a start point and a direction of travel or a start and end point and the curve will follow the natural path of the surface [84].

Variable angle guide curves vary the fiber orientation along the curve to create variable stiffness laminates [68,69]. Although there has been recent research in optimizing variable angle paths [40], the calculations and optimizations are more difficult than the other techniques. There are 3 main strategies for defining these reference curves: (1) constant curvature [61, 71,72], (2) linear variation [73–75], and (3) nonlinear variation [91].Each of these strategies uses a slightly different method to define the points and curves for layup trajectories.

Coverage strategies

Various coverage strategies are used to create the course centerlines across the tool surface. There are three strategies that can be used, those being independent curves, offset curves, and shifted curves [84]. The independent curve method uses independently drawn curves to cover the surface. This method is often used on highly complex tool surfaces where it is possible to draw the courses staggered, with a constant length, and different directions [87]. Favaloro and Hauber [86] used this method to create many short courses to limit gaps and overlaps on a conical surface. While this method can limit gaps and overlaps, it is very time consuming and not often used for conventional surfaces.

The offset or parallel curves strategy is the most common one used for path planning [84]. In this strategy adjacent curves are computed from the reference curve to cover the entire surface. The two approaches to define the adjacent curves are a parametrical approach and a mesh approach [45,87,88,92]. The parametrical approach solves a system of equations numerically to define the equations of each successive line. The mesh approach starts from a random reference curve on the meshed surface and uses the Fast Marching Method [93] to propagate this curve, creating the other courses. The advantage computing parallel curves is that they are equidistant which prevents gaps and overlaps between courses. However, when considering a complex surface, the fiber directions of the offset curves can vary from the reference curve. Also, if the initial reference curve has curvature, the neighboring paths will have increased curvature therefore decreasing the steering radius. If the critical steering radius is exceeded, this will cause further defects.

Lastly, the shifted curve strategy [34,46,90,94] simply shifts the reference curve by applying a translation is its perpendicular direction. The main advantage in using this method is the simplicity in covering the surface with course centerlines. Kim et al. [34] showed that the fiber directions of the shifted paths are not guaranteed on complex surfaces, and an increase in gaps and overlaps can arise.

Path optimization

The authors in [91,95–97] developed methods to optimize the placement of fiber paths onto the tool surface. Jiang et al. [95] reported a 63.4% to 69% path error reduction using the maximum, mean, and variance of a path error distribution model and optimizing the roller's path. Blom et al. [91] developed a method to optimize course locations based on user requirements of thickness variation in a variable stiffness laminate. The authors in [96,97] investigated the kinematics of the AFP machine's motion leading to a method of optimization of tool paths based on machine limitation.

Process parameters

The parameters used for any specific part are chosen by compromising between layup quality and high layup speeds demanded by industry [98]. Using adequate process parameters is crucial in determining the quality of the layup, and can impact the resulting mechanical properties of the composite part [99,100]. The main parameters and their effects are summarized in the following.

Speed

Various layup velocities show alterations in layup quality and required processing parameters [101,102]. Lower speeds result in longer thermal exposure which results in improved polymer healing up until the applied temperature results in degradation of the material [103]. An increase in layup speed will result in less time that the compaction force and temperature are applied to the material leading to weak cohesive forces [104].

Pressure

Compaction pressure is one of the major parameters associated with final part quality [105]. The main concept of applying compaction pressure is to adhere the incoming tows to the substrate and remove voids [106]. The pressure is the critical parameter to develop intimate contact between plies however excessive compaction can lead to material degradation [56]. For the case of thicker laminates, the compaction pressure's influence decreases significantly [107].

Temperature

For thermoplastic materials, temperature is the main parameter responsible for the development of interlaminar strength due to it creating the optimal interface between the incoming tows and the substrate [29]. The applied temperature heats the material above the melting temperature and is then consolidated by applying pressure, and solidifies as it cools [108,109]. It is imperative not to use a processing temperature significantly above the material's melting temperature because it can lead to material degradation [110,111]. Further, the temperature parameter can lead to many side effects that can reduce part quality. For example, deviation in temperatures across the part lead to non-uniform cooling rates resulting in residual stresses and part deformation [112]. The authors in [111,113] showed that cooling rates are also essential with thermoplastics because it affects the degree of crystallinity, hence affecting the mechanical properties. Other factors such as void dynamics [111,114,115], material healing [116], and intimate contact [59] are highly dependent on temperature.

In terms of heating of thermoset materials, the goal is not to reach the melting point but to achieve an appropriate level of tackiness. Appropriate degree of tack is the key mechanism in the formation of most layup defects and is most influenced by layup temperature [117–119]. Higher tack is considered favorable to hold the prepreg on the tool surface as well as ensuring adhesion to subsequent plies [120]. Like thermoplastic heating, excessive temperatures lead to material degradation. Finding the appropriate temperatures for either case is often determined through trial and error [121]. However, tack characterization can provide an adequate starting point for proper applied temperatures [122].

Tow tension

Research on fiber tension during the AFP process is limited in the literature. The centralized idea is that tow tension assists in the placement of tows [123]. Excessively high tow tension leads to tow slips due to the tension force overcoming the adherence [35]. Rudberg et al. [124] developed a Modular-Servo-Creel head to address the issue of tension control, leading to increased part quality.

Parameter optimization

A large area of research is the optimization of process parameters with the aim to improve manufacturing quality with proper processing parameters. Aized and Shirinzadeh [125] researched the relationship of process parameters and part quality using the response surface method. Through analyzing gas torch temperature, head speed, and compaction force, each parameter was correlated to its effect on process quality. Han et al. [126] developed a multiscale collaborative optimization method for high speed AFP layup in terms of mechanical characteristics of the prepreg tows. Wehbe et al. [127] was able to use numerical techniques to find optimum path curvatures and process parameters for fiber steering on a cylinder. Baz Radwan et al. used a design of experiment to determine the optimal processing window for a high and low tack prepreg material [128].

Process modeling

Another important factor when process planning is modeling the various processes where possible. Computational models using software tools such as ABAQUS to simulate the deformed tow after fiber placement have been shown to have sufficient agreement with physical measurements. Bakhsi and Hojjati [129] showed a very good agreement between simulation and experimental results through modeling the whole prepreg deposition process. Rajan et al. [130] used a similar technique to model bonding of slit tape to the substrate to predict wrinkle formation and showed excellent agreement for a 6.35 mm prepreg tow. Hutten utilized a physics-based framework to study the sensitivity of simulation setups and its effect on defect predictions [131]. Work has also been done regarding the simulation of roller deformation and compaction pressure and its effect on tow placement [28,132,133]. These models have the capability to predict many aspects of the AFP process, however they are time consuming to build and run, and are not widely applicable to a range of input conditions.

Material properties models are also an effective method for understanding the materials behavior during the AFP process. Rajan demonstrated the effect of tow stiffness properties (longitudinal, transverse, shear stiffnesses, and others) on defect formation, as well as viscoelastic effects of resin dominant stiffnesses [134]. Another key characteristic for material in the AFP process is its tackiness and adhesion properties. The authors in [118,119,122,135] investigated tackiness and adhesion models including the effect of temperature, contact time, and compaction on the bond strength between the tow and the substrate. It is also necessary to understand how a material will behave under various temperature during AFP manufacturing and during the cure process. Yassin and Hojjati [136] has presented a detailed review on temperature and heat transfer models, including prediction of peak temperatures as

Table 4
Effectiveness of various inspection techniques.

Technique	Gap	Overlap	Wrinkle	Twist	Missing	Pucker	Fold	Bridging	Splice
Profilometry	✓	✓	✓	✓	✓	✓	✓	*	✓
Thermography	✓	✓	✓	✓	✓	✓	✓	✓	✓
Eddy Current	—	—	*	✓	✓	*	*	*	✓

✓- Can detect well
*- Can detect but not distinguish from other defects
—- Can detect depending on size

well as transient effects and variable temperature profiles along the path. Belnoue demonstrated cure models that predict the deformation of the fibers and the resin flow during cure processes, and the obtained final shape of defects [137].

Geometrical models predicting wrinkling based geometrical quantities such as the tow path, width and tool geometry have been shown in [83,138,139]. These types of models have demonstrated an accurate analysis for wrinkle locations within a given layup. The authors in [140–144] have developed analytical models predicting the limiting critical steering radius for wrinkle formations. The models can approximate a measure for a critical radius below which defects start to form. However, the mechanics models tend to oversimplify the problem to get a closed form or rapid solution. This often leads to neglecting the interaction of different defect formations and the effect of the process parameters.

Process data collection

Inspection techniques

The quality control during AFP processes is either manually done by visual inspection of the operator [145] or by using various types of automated inspection methods. Due to the low contrast between the substrate and incoming tows, visual identification of defects has proven to be difficult. However, thermal imaging, laser profiling, eddy current inspection [146] and other non-destructive testing (NDT) techniques have been employed to ease the difficulty of inspection. The development of abilities to rapidly monitor and inspect AFP manufactured plies is a top priority in improving manufacturing efficiency [124]. Current industry standard for inspection is primarily visual/manual. While frequently accurate, manual inspection is typically very time intensive, requires expert knowledge, and reduces traceability in determining the quality of layup. The time cost of manual inspection is significant [18,19,147], with estimates placing percentage of machine time dedicated to laydown being as low as 24%. This is almost entirely due to manual inspection and rework, with inspection time growing with the size of each part. This makes producing large scale composites increasingly time and cost prohibitive. Table 4 below summarizes the effectiveness of defect detection with popular inspection techniques (profilometry, thermography, and eddy current).

Thermography

Thermographic monitoring is based on a thermal camera combined with (process depending) image processing that can analyze the visible temperature difference between the laid tow and the substrate [148]. The temperature difference in the tow is triggered by the propagation of heat through the laminate. Accurately measuring the temperature profiles requires the thermal camera to be mounted onto the AFP head to measure the temperatures directly after the compaction roller. This information can be used to derive and store both tow position and process relevant defects. Gregory and Juarez [149] demonstrated that the changes in temperature profiles seen in *in-situ* thermographic monitoring are sufficient for identifying all types of defects. Schmidt et al. [150] also used this technique combined with an edge detection algorithm to localize tows and detect temperature discrepancies. Juarez and

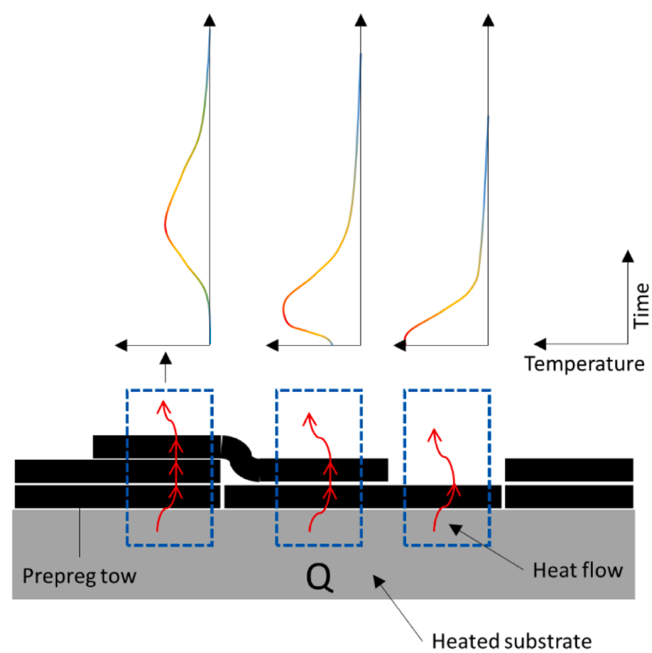

Fig. 12. A depiction of the effect of defects on the temperature profile [151].

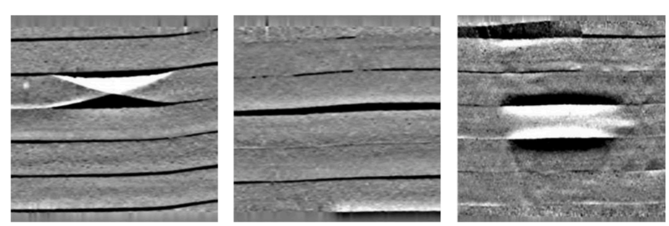

Fig. 13. Visualization of profilometry data [153].

Gregory [151] provides a depiction (Fig. 12) of how defects contribute to the temperature profile. The temperature measurement from a gap is higher due to a smaller substrate thickness to absorb the heat, and vice versa for an overlap. Various other defects such as twists, splices, and folds can be deduced from the temperature profiles.

Profilometry

Profilometry utilizes laser projections onto a surface to infer surface features from pattern deviations [152]. This method enables rapid profiling of a surface without considering the surface contrast (Fig. 13) [153]. However, material type can have a direct effect on the quality of data gathered and therefore the accuracy of defect identification and classification [154]. Cemenska et al. [155] showed that profilometers can detect gaps, overlaps, foreign object debris (FOD), bridging, puckering, delamination, and tow twist given sufficient size. The feature recognition necessary for detecting these defects requires processing the raw data with custom algorithms that can be highly complex requiring

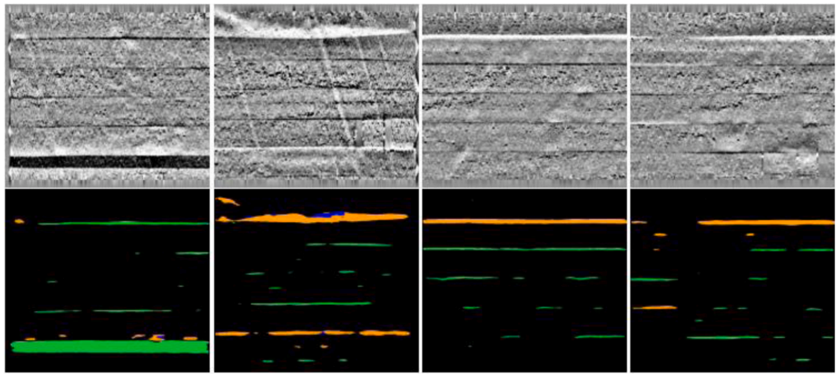

Fig. 14. ML segmentation of an AFP part scan for defect identification [172].

high performance computing for higher feed rates. It should be noted that when properly optimized, profilometry offers unrivaled surface detail, allowing for more accurate analysis and the identification of a broader range of defects. Two recent industrial *in-situ* inspection systems offered from Coriolis and EI are both profilometry based [156,157]. However, variation in the optical properties across materials makes this difficult.

In-situ inspection

A major distinction that must be made in the inspection and quality monitoring of AFP parts is between inspection systems that are ply-by-ply and inspection systems that are *in-situ*. Ply-by-ply or static systems wait until the layup process or a part of it is complete, then inspects while the AFP machine is inactive. *In-situ* methods are capable of inspecting while AFP machine is performing layup. This maximizes machine usage and reduces the amount of necessary machine downtime, therefore contributing to higher process throughput. The advantages of *in-situ* systems are driving the majority of the development in AFP inspection towards this area.

The thermographic approaches to inspection mentioned previously in this chapter are all implemented as *in-situ* systems, using the heat emanating from the layup process as a way to produce images. In addition, companies such as Flightware [158] have developed *in-situ* AFP inspection systems based off of profilometry and laser line scanning. EI's RIPITx system has recently become an industrially available inspection option for profilometry-based *in-situ* inspection [157].

Automated defect identification

Once the data acquisition component of an AFP system is created, it is also often advantageous to marry it to a data analysis system to automatically identify defects through the data. Approaches to data analysis vary across application, but a consistent class of algorithms has coalesced under the branch of computer vision and deep learning. Nearly all of the data acquisition systems that have been developed present their data in a visual manner. This design choice allows engineers to leverage advances in computer vision to perform automated defect identification.

In particular, the advent of Deep Learning image processing algorithms spurred on by the success of convolutional neural networks [159] has allowed for significant improvements in the performance of industrial inspection systems [160,161]. Iteration on neural network architectures for computer vision has produced a number of models that achieve human or near human levels of performance [162].

A considerable drawback to these approaches has been the large amounts of data required to properly train one of these deep object detection algorithms. New areas of emphasis are on brining this barrier to a more accessible point by utilizing principles such as transfer learning [163,164], whereby lower level features learned on one dataset are preserved and reused on a similar dataset. In the area of AFP inspection, this may present a potential path forward for training a model to detect across multiple material types or with multiple sensors as input.

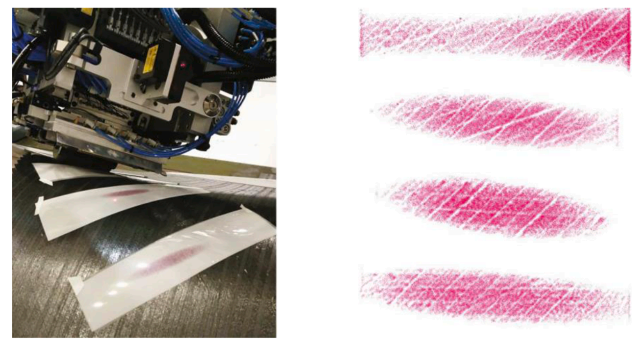

Fig. 15. Determining compaction pressure during Layup in Jiang et al. [178].

To perform a prediction or training cycle with these models, it is important to leverage many of the modern advances in computer hardware that allow for massive parallelization of neural networks. Computer hardware such as Graphical Processing Units (GPUs) [159, 165] and Field Programmable Gate Arrays (FPGAs) [166–170] utilize parallel processing to massively increase the speed at which many neural networks run. In the case of FPGAs, this is the result of writing dedicated hardware in silicon to perform operations rather than relying on standard general-purpose processors.

Some work has begun to combine these principles to create automated detection algorithms for AFP defects. Several studies by the authors have leveraged machine learning, integrated systems, and advanced computer hardware to create a computer vision system for learning and identifying AFP defects [154,171–173]. Fig. 14 shows the results of an intelligent segmentation algorithm that is capable of identifying narrow gaps and overlaps in profilometry scans of a layup.

Parameter monitoring

Compaction monitoring

Monitoring compaction is crucial for understanding the loading of green material and has a direct effect on part quality. Fiber Bragg sensors [174–176] have been embedded into AFP tows prior to deposition on a tool and used to monitor the compaction pressure on a given tow. In terms of AFP, the layup conditions are monitored by measuring the reflected wavelengths which are then related to parameters such as pressure and temperature [177]. Results from experimentation done by Oromiehie et al. [62] proved that simultaneous measurements of strain

Table 5
List of defect types and their associated category [81].

Defect	Category	Causes	Significance
Gap/overlap	1	Fiber steering, Layup over complex surfaces	Site for failure initiation, Resin rich areas, Site for wrinkling
Twist	1	Initiated by folding, Rotation during bi-directional layups	Increase/decrease in local thickness
Missing tow	1	Discontinued material feeding, Insufficient tack adhesion	Local thickness variations, Resin rich pockets
Boundary coverage	1	Material cannot perfectly meet at edge of part	Affects shape of part, Failure points if not trimmed
Angle deviation	1	Incorrect roller coverage, Small steering radii	Causes overlaps, Leads to resin rich areas
Wandering tow	1	Unsupported portions of tow between roller and cutter	Leads to gaps and overlaps
Position error	1	Obstruction of tow during feeding, Incorrect machine reference, Machine control issues	Results in gap, Site for failure initiation, More pronounced influence since close to boundary
Fold	2	Tensioner errors, Long or complex tow paths, Steered paths	Substantial influence on local fiber volume fraction, Creates resin rich areas
Pucker	2	Excess tow feeding	Significant loss of strength
Wrinkle	2	Tow placement at small steering radii	Causes gaps and folded tows, Loss of strength
Bridging	2	Too much tow tension, Insufficient tack adhesion	Resin rich areas, Delamination
Loose tow	2	Length of tow is shorter than length between roller and cutters	Results in gaps/overlaps and missing tows
Splice	3	Two tows joined end to end during the slitting process	Local thickness change, Site for failure initiation especially under compressive loads
FOD	4	Resin or fiber fuzz collects on head, Other debris from production area	Improper adherence of next ply

and temperature in the AFP process can be derived using wavelengths from the sensors. In addition, acoustic emissions from matrix cracks and fiber breakage can be identified using the embedded sensors post-cure.

Compaction pressure can also be determined through the application of "smart films" that change color as compaction is applied. Jiang et al. [178] used such a film from the FUJIFILM Corporation to show the compaction pressure applied by the roller in a dry run over a previously laid-up ply. Fig. 15 demonstrates how this material is used in determining compaction pressure on the material during the AFP process.

Machine motion

Machine motion data, including feedrate can be determined through the extraction of machine motion data from the controller [127]. Various approaches to motion capture have demonstrated effectiveness in other areas of robotics and could be adapted to work with AFP systems [179].

Temperature monitoring

Temperature is a critical feature for the assurance of part quality in the AFP process. Variations in temperature can have a significant effect on properties such as material tack [121,135,180,181]. One of the more common ways to get nip point temperature for AFP is to perform an initial set of runs at various heater settings and use thermocouples to determine an empirical relationship between the values [127]. However, this requires additional material and manufacturing time that does not go towards the production of the overall structure. For *in-situ* temperature monitoring, thermographic cameras can be used, with cameras watching from behind the roller and observing heat transfer through the entire thickness of the material [148,150]. The live monitoring of nip point temperature can also aide in the development of computational [182] or empirical models [145] showing how process affects temperature.

AFP defects

Due to the inherent complexity of the AFP process, defect occurrence is inevitable throughout the layup. These manufacturing defects can have a significant negative influence on a structure's performance [183, 184], thus it is vital to understand the creation and effect of each defect. A majority of defects are a side effect of tool geometry, fiber steering, and material imperfections [81]. All defects can be broken down into 4 main categories: (1) positioning defects, (2) bonding defects, (3) tow defects, and (4) foreign bodies [148]. A comprehensive list of all defect types and their category is given in Table 5 below. Harik et al. [81] provides in depth information on the anticipation, existence, significance and progression of each defect, and Brasington et al. [185] accompanies this with visual models of each defect type presented in Table 5 that can be 3D printed to aid in learning the defects' geometrical aspects. The following will provide a discussion on the types of defects with images of each gathered from Brasington et al. [185].

Research opportunities

The authors propose that the next 20 years of AFP development will be centered on a single word: "*Democratization*". In essence, the primary thrust of AFP development will be similar to other previous manufacturing processes (i.e., 3D printing), namely reducing barriers to entry for new adopters of the technology and streamlining the operations of machines for larger entities. This will likely manifest in a number of ways, but in particular we believe that it will focus on the augmenting of expert knowledge through the development of expert systems, the continued development of small modular flexible machines, and a reduction in production time and equipment cost through the adoption of OOA processes and materials.

Design for manufacturing

Design of composite materials continues to be a heavily studied and researched domain that can be extremely complex depending on the application. However, the ever-increasing complexity is transferred to the manufacturing sector when the design is ready to be produced. In order to create a structure that is designed for manufacturability, in depth communication between personnel within design, process planning, and manufacturing is required. The designer must understand the intricacies of the AFP process such as the unavoidable defects along with understanding how to mitigate them.

Hardware challenges

AFP machine hardware needs to continue to grow in two principal ways: (1) hardware must continue to evolve to address the expansion of material selection beyond thermosets, specifically to materials that can be used in OOA processes, and (2) hardware should be smart in the sense that hardware components can be continuously monitored and used for data collection during layup. Some progress has been made in both areas over the past 5 years, but significant progress has yet to be made in such a way that these advancements have not left the research lab.

Adjusting to new material types in an attempt to develop OOA processes has led to considerable interest in thermoplastic materials. The high processing temperatures necessitate a change in the way AFP machine components are constructed. Some of this has been accomplished through the development of new heating elements such as laser heaters that can quickly get material up to temperature and is more controllable than hot gas heaters. But other changes are required before many of the more exotic thermoplastics of interest to the aerospace community can be used. Common elastomers found in rollers do not permit the nip point temperatures, sometimes in excess of 500 °C, required to melt thermoplastics for layup. A common substitute is to either chill the roller or substitute an elastomer roller for a steel one. The first solution is only a viable option for small components where the chilled roller is not subject to prolonged heating. The second drastically limits the design space to flat panels and can have adverse effects on the layup quality. Similarly, other components to the AFP machine in direct exposure to heating must also become hardy to high temperatures. These include scoops, bearings close to the roller, pneumatic and mechanical systems on the head, and sensors for data collection.

AFP machine hardware continually advances with a multitude of patents each year. However, the developed hardware is rarely, if ever, in line with the most recent industry 4.0 capabilities. In order to constantly monitor the AFP process, the hardware must be able to provide useful data at a high speed. This data must be combined with a high speed and volume data collection system. The most difficult part of achieving this is development of the algorithms that can utilize the data to make changes and predict future problems.

The next generation of the AFP process should also include digital twins that incorporate the entire process. This requires that the hardware on the AFP machine must be able to communicate from the physical to the digital environment. Kirkpatrick et al. began the development of a digital twin with create a digital AFP cell include the AFP machine and a secondary inspection robot [186]. The hardware on the AFP machine still needs to be connected in order to utilize the data.

Tooling challenges

The development and creation of tooling for AFP is an expensive process. The tooling is usually made as large metal structures, typically invar, capable of continually surviving the curing process with minimal thermal expansion. However, creating new "one-off" tools is difficult due to economic limitations. The cost of tooling is justified with the amount of use it will receive, making justification of unique tooling difficult. Harik et al. performed some investigation of using a 3D printed a tool with Ultem, and showed manufacturing success [187].

Tool-less manufacturing is an attempt to prevent the need for expensive tooling. This process often uses two robotic systems that collaborate to create composite parts without the need for tools. This process is a new one, and still needs development to create industry level structures. Mikrosam has created such a system, and it is thought that the technology can lead to industry scale manufacturing [188].

Process planning challenges

Process planning should develop efficient code that can be run by the AFP platform to manufacture the intended part. Inefficiencies arise when superfluous machine motions are performed or when manual rework is required for placement defects, which may arise from a combination of improper processing parameters and fiber layup paths. Proactive and reactive approaches may be taken to counter these inefficiencies, and these will represent the core of future developments within process planning. These approaches for process planning will rely on detailed characterizations of the material properties of the selected composite and designated machine platform. Through the in depth understanding of these properties, defects arising from fiber paths and processing parameters will be simpler to predict, and the methods for developing machine code can be augmented to account for these predictions and adjust paths and parameters to mitigate the defects. Additionally, the characterization and improvements in simulation techniques will enable detailed virtualization of the layup process and facilitate accurate simulation of fiber placement and the effects of processing parameters. These enhanced defect prediction and mitigation techniques can even reach back to the composite design phase and communicate regions of the structure with high defect probability allowing alterations of design to improve manufacturability [189,190], eventually developing a tool which has direct feedback to composite design.

Inspection challenges

Inspection has the potential to act as a linchpin for AFP manufacturing systems, affording the ability to dynamically update machine performance and provide insight into the functioning of specific machines or processes. Therefore, it is of critical importance that inspection continues to grow in capabilities. Future development will likely proceed in several directions: (1) the continuation of pushing for higher accuracy and a wider range of defects, (2) the creation of sensor fusion systems leveraging multiple data collection techniques, and (3) integrating inspection systems with other platforms to develop defect databases that can be used for process development.

Increasing detection accuracy

Improving accuracy and widening detectable defect classes will always be a point of emphasis in the inspection arena. Many of the recent advances in machine learning and computer vision will likely play a major role. Developments in machine learning models, both in architecture and components have continued to push what is possible in object detection, localization, and segmentation. The mechanisms behind many of the large language models, such as transformers, are filtering into computer vision applications [191,192]. There will be an emphasis on deep learning and computer vision models that are able to have acceptable prediction accuracies with a minimal amount of labeled training data. Weakly supervised learning systems [193,194], and potentially even unsupervised learning systems [195–197] may have the best long term outlook given that generating by running AFP experiments is both expensive and time intensive. It is also important that where the trained machine vision algorithm lacks in accuracy, performance is skewed towards a high false positive rate than a high false negative rate.

Sensor fusion

Increasing the field of defects that a given inspection system can identify may be a result of expanding the space of input features available to be processed. By incorporating multiple sensors, the available features may improve data quality and allow for a more complete analysis of a part. High fidelity surface scanning provided by profilometry may be effectively augmented with the fusion of eddy current inspection data to provide subsurface data that may be able to better distinguish between certain types of defects. This sensor fusion approach has been used successfully in civil [198], aerospace [199], and environmental [200] applications.

Integration and influence on manufacturing

AFP is an intricate process with many influencing factors. Attempts to explicitly model AFP layup quality from first principles is a challenge, with numerous attempts but few widely adopted industry tools. AFP layup requires a multi-physics approach that combines micromechanics, cure kinetics, viscous flow, fracture mechanics, and heat transfer, etc. The most popular quality evaluation tools are those that are restricted to simply predicting gaps and overlaps through geometric arguments, such as Vericut VCP [201].

It is therefore critical to have integrated inspection systems such that inspection data can be reincorporated into the manufacturing process for process improvement. This means that future inspection systems should have an eye towards how their data will be used further downstream. How inspection data is processed, represented, and made available to external parties can be critical in determining the success of an inspection system. In the case of machine learning systems, there

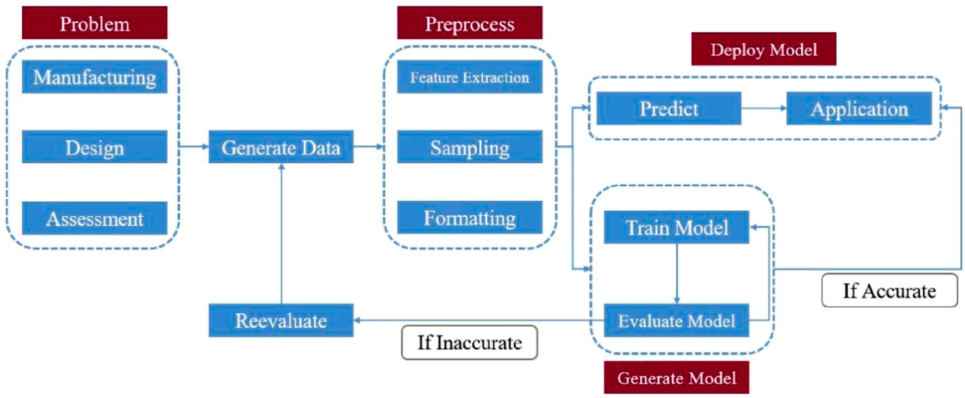

Fig. 16. A system for online machine learning systems as demonstrated by Sacco et al. [171].

should also be consideration to how data security, continuity, and availability is integrated such that systems can be dynamically retrained (Fig. 16).

Summary

Since AFP's industrial start in the 1980's, it has continually advanced to become a leading manufacturing technique for large composite structures. Early advancements in the realms of process reliability and productivity lead the way for the adoption of this technique within many aerospace companies. With review of the intricacies of each pillar of the AFP process, it is evident that progress has not stalled. Expertise ranging from composite design through inspection provides a deep understanding of the AFP process. This knowledge has produced the state-of-the-art technologies that are presented here. Overall productivity and reliability are still on the rise as AFP enters the realm of future manufacturing.

With the leap into Industry 4.0, we believe that the focus of AFP research must be on the augmenting of expert knowledge through the development of expert systems, the continued development of small modular flexible machines, and a reduction in production time and equipment cost through the adoption of OOA processes and materials. This presents a series of research opportunities culminating in a closed loop AFP process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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