Automated manufacturing of composites

Van Suong Hoa*

Concordia Center for Composites (CONCOM)
Department of Mechanical, Industrial and Aerospace Engineering
Concordia University, Canada

Received 13 September 2017; accepted 26 January 2018

Abstract:

Long fibre reinforced polymer composite materials have found many applications in many industries, such as aerospace, automotive, marine, wind turbine, and sports. Techniques for the manufacturing of structures used in these industries have been mainly Hand Lay Up (HLU), and Liquid Composite Moulding. While there are a few automated methods of manufacturing, such as Filament Winding and Pultrusion, these techniques are restricted to make structures that consist of surfaces of revolution, or fibres that are aligned only along one direction. The conventional methods of manufacturing of composites are therefore very restricted, either in slow rate of production, or in the shapes of structures that can be made. The advent of Automated fibre Placement (AFP) machines and automated tape lay up machines have brought forward new capabilities where structures of different shapes may be manufactured at relatively higher speeds. This paper presents an overview of the applications of AFP for the processing of structures made from thermoset matrix and thermoplastic matrix composites. Advantages and disadvantages, along with issues associated with the use of this new technique in the processing of each type of material will be discussed.

Keywords: ***Automated fibre Placement, automated tape lay up, automation, composite materials, composite structures, manufacturing, thermoplastic matrix composites, thermoset matrix composites.***

Classification number: ***2.3***

Introduction

Previous manufacturing methods

A common method for the manufacturing of composites is HLU. The stacks of the thermoset matrix composite materials deposited by HLU are cured either at room temperature (for the case of glass/polyester composites) or in an autoclave (for the case of carbon/epoxy composites). Other techniques, with some degree of automation, include Filament Winding, Pultrusion, Liquid Composite Moulding, and Compression Moulding. These techniques have been used to make important engineering structures. Their limitations include the shape of the article (cylindrical or spherical shape in the case of Filament Winding, fibres in only one direction in the case of Pultrusion, somewhat slower rate in the case of Liquid Composite Moulding, and small sized parts in the case of Compression Moulding). The increasing use of composites in larger structures (such as large airplane fuselage, large wind turbine blades) has given rise to the need for more automation. The two most commonly used machines for this automation are the automated tape laying (ATL) machine and the AFP. These two types of machines have many similarities in which they both can deposit composite material layers at high speed. They differ mainly in the width of the laid down material. ATL can deposit wider tapes [from 1/2 inch (12.7 mm) to 12 inches (304.8 mm) wide], while AFP delivers narrower tape [from 1/8 inch (3.18 mm) to 1/2 inch (12.7 mm)]. AFP can make up for the difference by using multi-tow courses. ATL is usually used for thermoset matrix composites, while AFP can be used for both thermoset matrix and thermoplastic matrix composites. In what follows, for the sake of brevity, AFP is described but many aspects of the description also apply to ATL.

Description of the AFP machine

For industrial applications, AFP machines can be very large. These machines can be used to make composite structures that are tens of meters long. They can deposit composite tows at the rate of hundreds of millimetres (or even metres) per second. Many companies in the aerospace industries have utilized these machines to make large composite structures over the past decades. A few examples are the fuselage of Boeing 787, and of the Airbus 380. The work done on AFP at the university

*Email:hoasuon@alcor.concordia.ca

level is relatively later than the activities in the industry. This is due to the high cost of the machine, the high demand for space to house the machine, and the high cost for its operation. However, due to the need to understand the mechanisms responsible for the performance of composite structures made using the technique, a few universities have invested in machines to study this technology, Concordia university included. Fig. 1 shows a photo of this machine at Concordia. The machine was manufactured by Automated Dynamics in New York (USA). It has 6 degrees of freedom. It can process both thermoset composites and thermoplastic composites. It uses a hot gas torch as the source of heating. Even though this machine is much smaller than the industrial type of machine, it has all the necessary features of a typical AFP machine. Fig. 2 shows a schematic of the device for tape deposition.

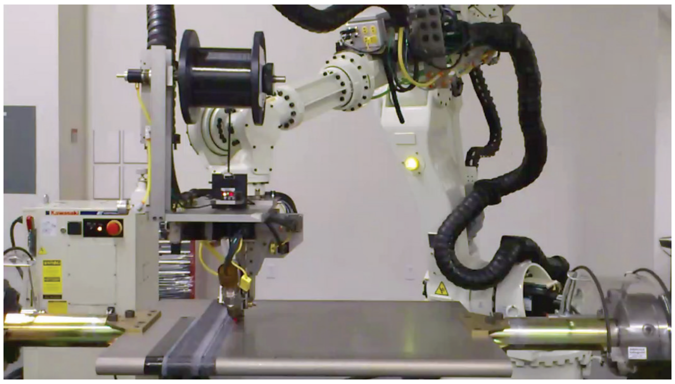


Fig. 1. Photo of an AFP machine.

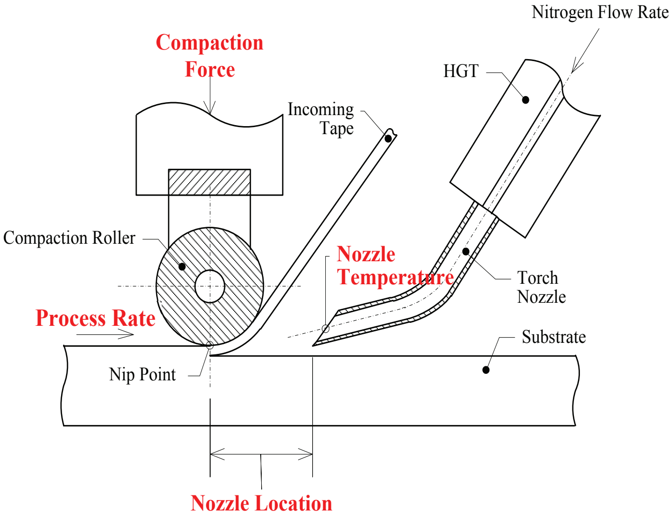


Fig. 2. Schematic of the tape deposition and devices.

Even though machines for automated manufacturing of composites are similar for both thermoset matrix and thermoplastic matrix composites, there are significant differences in the requirements for the intended purpose of the technology, the heating level, the need for subsequent processes, and the defects that may occur in the part, etc. For thermoset matrix composites, the intention of the automation is restricted only to the fast rate of material deposition. On the other hand, the intention of doing automation for thermoplastic composites is to eliminate all aspects of the manual work. For some structures, it may not be possible to use other techniques to make the thermoplastic composite part, and automation is the only way. In what follows, the automated manufacturing of thermoset matrix composites, followed by that of thermoplastic composites, will be presented.

Automated manufacturing of thermoset matrix composites

Description

The process of manufacturing of thermoset matrix composites using the conventional method consists of the following stages:

1. Prepreg control.
2. Tool preparation.
3. Prepreg deposition.
4. Vacuum bagging.
5. Curing.
6. Nondestructive evaluation and testing.
7. Trimming and machining.
8. Assembly.

The automation of the process can come in for steps 3, 6, 7, and 8. For ATL and AFP processes, only step 3 (prepreg deposition) is automated.

The fibre placement process is shown schematically in Fig. 3. The fibre tape (or tows) is fed to the NIP point under a compression roller. Preheating (to enhance the tackiness of the tape) may or may not be used. The pressure applied by the roller may help to reduce the debulking efforts for the stack of layers. The main objective in using automated lay up is to increase the speed of material deposition. After the stack of prepreg layers has been laid, the subsequent steps (vacuum bagging, curing, etc.) need to be carried out as in a conventional process.

Step 6 mentions 'Non destructive evaluation and testing'. This refers to the evaluation done on the final, solid piece of composites. In the case of automated material deposition, since many narrow strips are laid down, it is essential to check for the quality of the laid prepregs during the deposition period. Many defects such as tow misorientation, twisted tows, misalignment between neighbouring tows, laps, gaps, serrated edges due to cutting at the end of the courses, etc., need to be detected, and corrected if necessary at this stage. Leaving this detection to a later stage may make it impossible to detect the defects. As such, in addition to the Non destructive evaluation and testing in step 6, another step 3a (in situ defect detection) needs to be added for the automated process.

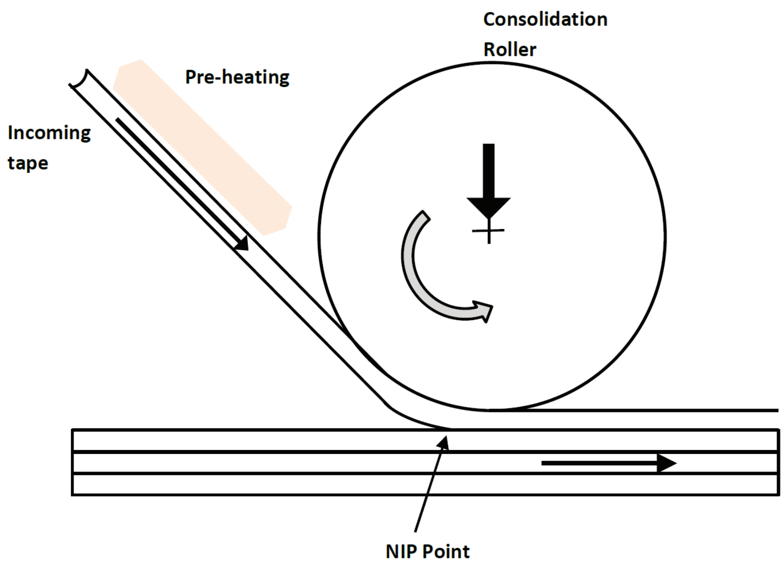


Fig. 3. Fibre placement process.

The process of automated manufacturing of composites

The automated machine usually consists of the following five main components:

A spindle axis to mount the mandrel: this spindle provides the rotation of the mandrel.

A mechanism to deliver the composite tows to the NIP point: composite tows can be single tow of multiple of tows. Simple machines can feed one tow at a time, or a course of up to 32 tows is possible. The tow width can vary from 1/8 inch (3.18 mm) up to 1/2 inch (12.7 mm). Composite tows are usually prepregs of thermoset composites, such as glass/epoxy or carbon/epoxy. The tows normally come from creels, either mounted directly on the depositing head or from a chamber located in the vicinity of the machine. In the case of thermoset composites, to avoid some curing of the thermoset resin during storage before the AFP process, the tow chamber is usually refrigerated.

A mechanism to heat the tows: for thermoset composites, preheating of the prepreg may be done. Heating is used to slightly decrease the viscosity of the resin. This in turn serves to increase the tack of the tow(s) to facilitate bonding to the substrate.

A mechanism to apply pressure on the deposited tow for consolidation: it is necessary to apply pressure at the NIP point (Fig. 3) to consolidate the material.

For thermoset matrix composites, this pressure does not have to be very high. Normally, a load of about 40 lbs is sufficient. This consolidation load helps to eliminate the need for pressing used in HLU and possibly the need to do frequent debulking, which can save time. The AFP only does the deposition and consolidation of the stack of prepregs, but it does not perform the curing procedure. The stack of prepregs needs to be bagged and cured after the AFP process. This procedure has the disadvantage that two processes are involved (deposition by AFP and bagging as well as curing afterwards) which is time consuming and costly. However, the advantage it has is that the defects that may be induced during the AFP process may be eliminated during the subsequent curing process.

A mechanism to move the NIP point forward: AFP is a continuous process. Once a strip of material is deposited, the machine advances the NIP point to the next material strip for continuous processing. It is desirable to have as fast a speed as possible from the production point of view. Since there is a secondary process of curing in either autoclave or oven, defects such as voids that occur during the deposition stage may be corrected during the secondary stage. As such, the speed of deposition can be high.

Advantages of AFP: there are many advantages in using the automated material deposition:

- Faster rate of material deposition - Reduced debulking time: with an increasing use of composite materials in many engineering structures, there is urgent need to increase the rate of production. The normal rate of material deposition by HLU is about 1 kg/hr. The rate of material deposition by AFP depends on the type of machine. A machine that deposits multiple tows has a higher rate of material deposition than a machine that deposits one tow at a time. The normal rate of material deposition of an AFP machine is about 10 kg/hr [1]. Besides the high rate of material deposition, the compaction applied during the AFP process helps reduce the time required for debulking as usually occurring during the HLU process.

- Less material wastage: since the process is one form of additive manufacturing, tows and layers of materials are deposited on design. As such, the material wastage is much less than in the case of HLU. Fig. 4 shows the situation where a sheet of prepregs is cut at 45^o to make 45^o layers in a laminate ABCD, for HLU. The cut-off materials at the corners are a waste. There is a terminology in the aircraft industry called the Buy/Fly ratio, referring to how much material ends up flying from the amount that was bought. It can be seen from Fig. 4 that this ratio can be about 2. For parts with more complicated geometry, this ratio can go up to 3. This does not happen when narrow tows are placed at a certain desired orientation in the AFP process. Fig. 5 shows the configuration to make the laminate ABCD using AFP lay up tow-by-tow. It can be seen that there is a lot less waste of material. Composite materials are expensive. The use of AFP can reduce the material waste, which in turn results in cost saving and more environmentally friendly manufacturing.

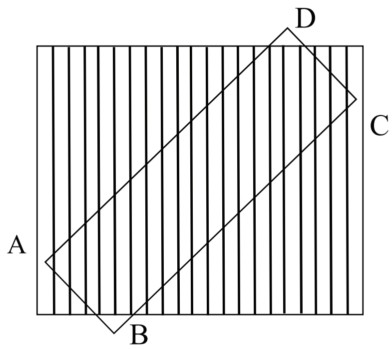


Fig. 4. Corner pieces in a sheet of prepregs are cut off, resulting in material waste.

- More repeatability-Less variability: since AFP is done by machine, there is more repeatability and less variability in the quality of the part as compared to conventional process such as HLU, which depends on the skill of the workers at different periods of the work week. When numerous technicians are expected to interpret engineering drawings, while placing material in the same exact location and direction, the process falls short many times. 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 analyses pre-established machine paths before ever reaching the shop floor; and thus, eliminates potential waste of material and machine time [2].

- Less manual labour intensive: conventional composite manufacturing techniques, such as HLU, are labour intensive, whereas AFP is less labour intensive. The use of AFP evens out the difference in labour rates from one region to another.

- AFP is essential for large structures: to deposit composite materials on large structures, it is not practical to use HLU where people have to climb up on large frames. The use of automation allows the construction of large structures more easily.

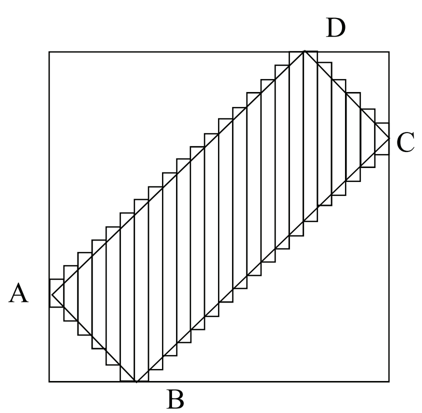


Fig. 5. Less waste of material when the tows are laid down using AFP.

- Ability to steer fibres: one unique characteristic of AFP, as compared to other techniques for the manufacturing of composites, is the ability to steer the fibres. As such, the fibre orientations can vary not only from one layer to another, but also from location to location within the same layer. It is then possible to orient the fibres in the direction where the load is high. This can result in more effective use of materials [3].

- Smoother transition between design as well as manufacturing and vice versa: since the path for AFP is designed and controlled by computers, the transition between design and manufacturing and vice versa is smoother as compared to conventional methods. Thanks to computer aided design, and analysis methods, such as finite element method, the design of composite structures has been well computerized. If a labour intensive technique such as HLU is used, the bottleneck for the process of product development lies with manufacturing. If automation for manufacturing can be done, then the transition between design and manufacturing can become seamless. This certainly can speed up the product development process.

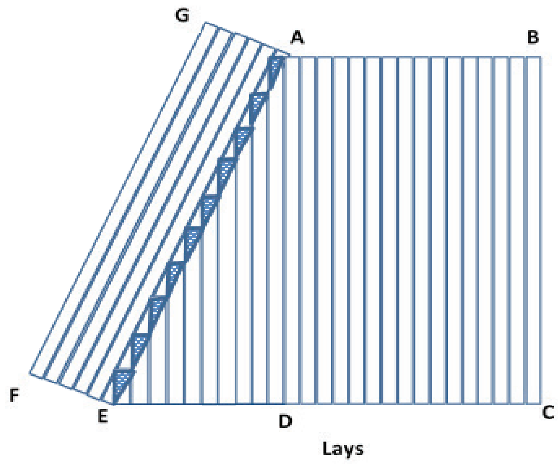
Disadvantages of AFP

The disadvantages for automated composites manufacturing using either ATL or AFP are as follows:

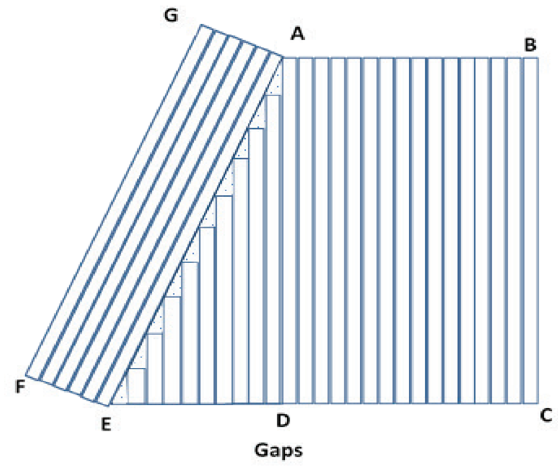
New technology and cost of machine: AFP is a very new technique for manufacturing of composites. It has been used by major companies such as Boeing, Airbus, Bombardier and Bell Helicopter to make many aircraft components. From the university level, there has been limited amount of work done. As such, significant experience from industrial applications has been acquired; but the fundamental knowledge and understanding of the process is limited. Besides, the cost of the machine is very high, and not many universities or small companies can afford the machines.

Occurrence of laps and gaps: since narrow tows [between 1/8 inch (3.18 mm) to 1/2 inch (12.7 mm)] are used in the process, there may exist laps and gaps between the tows and courses. Situations where laps and gaps occur are summarised below:

Boundaries of areas where the border direction is at an angle with the fibre direction: when lay up is done to cover the surface of an area bounded by a border that is at an angle with the fibre direction (Fig. 6), either gaps or laps will exist. The figure shows the situation where strips of fibres need to be deposited to cover the area ABCDEFG. Vertical strips are to cover the area ABCD while inclined strips are to cover the area EFGA. In Fig. 6A, vertical strips in region ADE extend beyond the boundary AE and cause overlaps in the inclined strip on the side of AE. This is because the cutter in the AFP machine can only cut in a direction perpendicular to the strip direction. In Fig. 6B, the vertical strips in the region ADE are cut short of the boundary AE, giving rise to gaps.



(A) Laps.



(B) Gaps.

Fig. 6. Laying up over a non-rectangular area can produce laps or gaps.

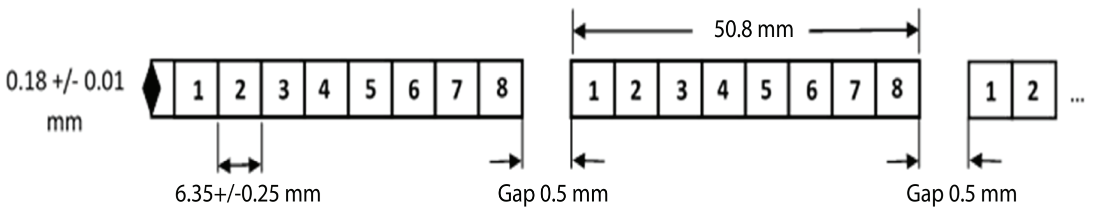


Fig. 7. Manufacturer recommended gap between courses [1].

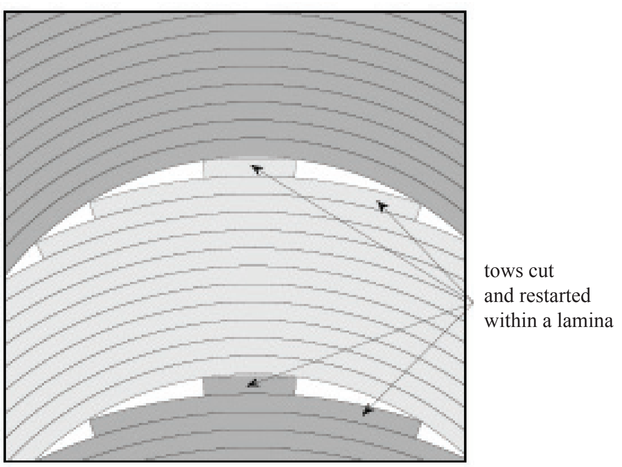


Fig. 8. Gaps created by fibre steering [4].

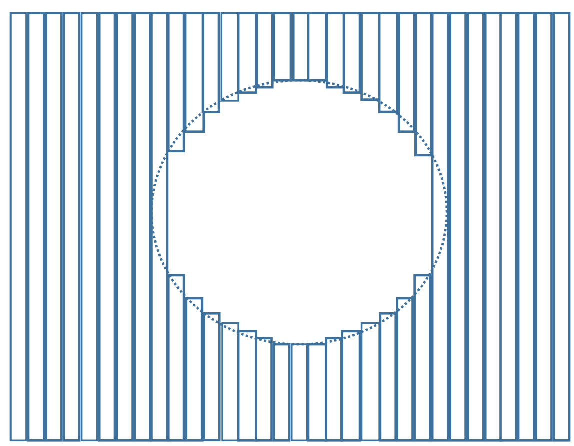


Fig. 9. Serrations at boundaries.

In a situation as in Fig. 6, where one cannot avoid either laps or gaps, gaps are preferred over laps. This is because laps give rise to stress concentrations. Gaps also give rise to stress concentration, but some resin flow during the process may fill up the gaps and reduce the stress concentration.

Aircraft manufacturers impose a gap of 0.5 mm between each series of n ribbons, with n depending on the placement head used. Fig. 7 illustrates this rule for tape laying head of n = 8 ribbons. This gap prevents the creation of an overlap, which is generally forbidden by the aircraft manufacturers. The value of this gap is defined according to the machine tolerances. The placement of a caul plate on top of laminates containing gaps may also reduce the effect of the gaps [1].

Fibre steering: fibre steering creates curvatures. When regions of different curvatures meet, gaps can be created (Fig. 8).

Serrated edges at boundaries: during AFP laying up, individual tows can be cut to fit the boundary of a curve. However, since the cut is always normal to the length direction of the tape, there are serrations at the curved boundaries (Fig. 9). As such, finishing work needs to be done.

Limitations and defects due to fibre steering: as mentioned above, AFP can provide fibre steering, which is advantageous. However, there are areas of limitations and issues:

- Limitation of radius for steering: The radius for steering depends on the limitation of the machine (how small a circle can the machine move around its perimeter). The other limitation is the width of the tow. During steering, the tow is sheared where the fibres on the outside of the steered circle have to move more than the fibres on the inside of the circle. When the fibres are constrained by the viscous matrix, there is strong resistance against shearing. If sufficient shear load is applied, buckling may occur. By using dry fibres (no matrix) [5], the resistance against shearing is less. The dry fibres can be laid up to make the preforms, and resin can be infused later as in the Liquid composite moulding process. There is also the idea of continuous shearing of fibres with simultaneous injection of resin to wet the fibres [6].

- Fold overs: if the steering radius is too small for the width of the tows, fold overs may occur (Fig. 10).

Fig. 10. Fold overs due to fibre steering (in the band with smaller radius).

Issues to be resolved

Considering both the advantages and disadvantages of using AFP for thermoset matrix composites, many major companies in the aerospace industry have used these processes to make important aerospace structures for the past several years. The remaining issues of concern are as follows:

High speed inspection of defects: even though the speed for material deposition is high, the speed for defect inspection is relatively slow. It is necessary to be able to detect the defects in situ such that correctional action can be taken before subsequent layers are placed. One recent technique is by taking thermal photographs of the material that is just deposited [7].

Design allowables for laminates containing defects: the existence of laps and gaps in placing tapes or tows using AFP cannot be avoided. As such, new design allowables for laminates containing these features need to be developed for design purposes. Some work has been done on static performance [8] and fatigue performance [9] of laminates containing gaps.

AFP for thermoplastic matrix composites

Traditional method of manufacturing - potential benefits

Traditional methods of manufacturing of thermoplastic composites (long fibre) have been some form of moulding, such as compression moulding, thermoforming (with membrane), or thermostamping (with match metal dies). These methods can provide good parts, but their limitations include the small size of the sample (limitation on the size of the mold); and these methods cannot be used to make structures of revolution, such as cylinders. The advent of the AFP machine enables the manufacturing of larger parts and parts with different shapes, such as curved panels, and parts with a surface of revolution, such as cylinders. Thermoplastic composites offer advantages over thermoset composites in the following aspects: No shelf life; the process can be done in one step, without the need for a secondary process such as curing in an autoclave or oven; thermoplastic composites have higher fracture resistance, as compared to thermoset matrix composites; and it is easier to recycle thermoplastic composites as compared to thermoset composites.

Particular characteristics of AFP for thermoplastic composites

The automated manufacturing of thermoplastic composites has many similarities with that for thermoset composites, in terms of kinematics of motion of the machine. However, there are many differences. Fig. 11 shows the schematic of AFP for thermoplastic composites.

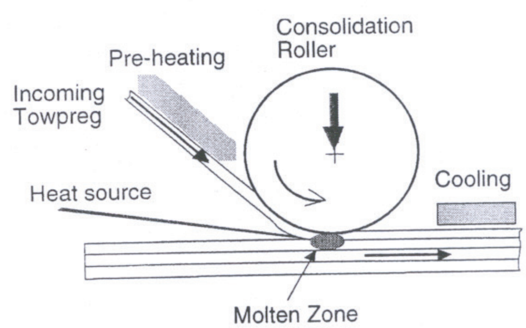


Fig. 11. AFP for thermoplastic composites.

Heating: for thermoplastic composites, intense heating needs to be done at the NIP area. Heating is usually done using a hot gas (nitrogen) torch, or a laser [10, 11]. For machines using the hot gas torch, the temperature at the nozzle of the torch can go up to 950°C. This temperature can drop significantly at the NIP point. The hot gas is usually aimed at the roller (for the application of compression pressure), rather than directly on the thermoplastic tape. This means that the heating of the tape is done mostly by heat conduction from the roller, rather than by convection from the hot gas. This is to avoid excessive temperature of the tape and possible erosion of the material due to the flow of the hot gas. For machines using a laser, different types of lasers (near infrared diode laser, ytterbium fibre laser) with powers ranging from 2 to 20 kW are available. The advantage of laser heating over torch heating is that the laser heat is focussed on the composite rather than on the roller. This is because heating is done by the absorption of phonons by the fibres. The heated fibres then heat up the matrix material. As such, a soft roller such as a silicone rubber may be used (as compared to steel rollers used in a torch heating machine). However, the speed of movement of the machine has to be fast to avoid excessive heating. The fast speed of material deposition is desirable from the production point of view. On the other hand, too much speed also gives rise to void formation.

Deformation and transformation of the material during processing: the thermoplastic composite material undergoes significant transformation and deformation during processing. Fig. 12 shows the different stages that the material has to go through. Each of these different stages need to be well understood. For this, consider a volume of material to be followed in the whole process.

Stage A: stage A presents the position of a volume of material in a piece of tape that is being processed. Some preheating may be done on this material volume. The heat transfer equation can be written as follows:

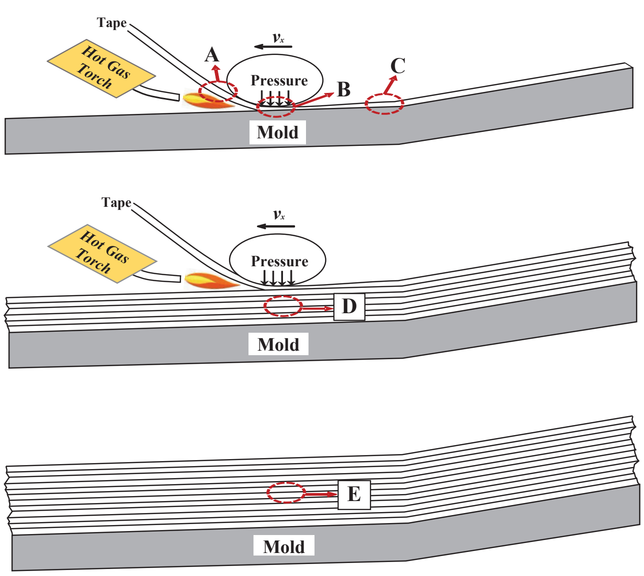


Fig. 12. Stages during the AFP process for thermoplastic composites.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(K_{xx}\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(K_{zz}\frac{\partial T}{\partial z}) \quad (1)$$

Where ρ is the material density, c_p is the specific heat, K_{ij} are the coefficients of thermal conductivity, and T is the temperature of the material volume.

Stage B: three events occur at this stage.

First, intense heat is applied at this stage to melt the resin. For thermoplastic resin, such as PEEK (Polyetheretherketone), the melting point is about 390°C. The heat source used can be either a hot gas torch, a laser, or a heat lamp.

Secondly, sufficient amount of pressure needs to be applied to consolidate the new layer onto the substrate layer. Consolidation requires the flattening out of any waviness that existed inside the tow beforehand. Additionally, the surface of the incoming tow needs to get into intimate contact with the surface of the substrate. A degree of intimate contact D_{ic} is defined as the ratio of the surfaces not in contact over the overall surface of the tow. The degree of intimate contact varies from 0 (no intimate contact) to 1 (full intimate contact). To have full intimate contact, not only does the pressure need to be sufficient, but there should also be sufficient time for it to occur [10].

Thirdly, during the time of intimate contact, there should be sufficient time to allow for reputation of the molecules across the interface so that bonding takes place. The reputation motion of the molecules depends on the viscosity of the resin. Smaller viscosity would facilitate motion. To have good quality laminate, there should be good bonding.

Stage C: the intense heat source has gone past the volume of material. If a single roller is used, pressure is also released from this volume of material. The events that happen at this stage are as follows:

- Heat transfer: the volume of material is exposed to heat convection to the surrounding area. Equation (1) can be used again with a different boundary and initial conditions. The temperature of the material volume depends on the distance it is from the current NIP point.

- Crystallization: crystallization depends on the rate of cooling. The rate of cooling may depend on the distance of the material volume from the current NIP point. If there is significant variation in the rate of cooling along the distance, then the crystallization rate will also vary.

- Deconsolidation and formation of voids: if the temperature of the material volume is above the glass transition temperature, due to the release of pressure, the material may deconsolidate, and voids may form. This certainly depends on the speed of translation of the roller along the direction of the process. Slower speed will allow more time for the material volume to cool down, and hopefully the temperature may be below Tg before the release of the pressure. However, this may run in an opposite direction to the desire of having a higher rate of production. One possible way to compensate for this is to add a second roller, as shown in Fig. 13.

- Solidification: if the material volume is far enough from the current NIP point, the material may cool past the Tg and solidification of the resin may take place.

- Relaxation: the time lapse from stage C to stage D depends on the speed of the process, or whether there is some interruption (pause). The material volume may undergo stress relaxation during this time.

Stage D: at this stage, the intense heat source returns to the same position as the material volume, except for the deposition of another material volume on top of the material volume under consideration. Events that happen at this stage are as follows:

- Heat transfer: equation (1) can be used again but with different boundary and initial conditions.

- Consolidation: due to the pressure applied on the upper material volume, the material volume under consideration may be under consolidation again. This influences the properties of the material volume.

The material volume may undergo stage D many times, depending on how many times the roller and heat source go over its position. For analysis, it is necessary to examine the state of the material volume as many times as necessary until its state becomes stabilised.

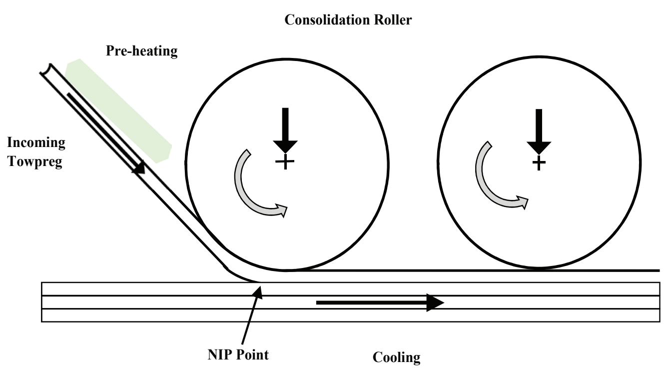


Fig. 13. Addition of a second roller to prevent deconsolidation.

Stage E: stage E represents the stabilised material state. The stresses that exist at stage E may be taken as the residual stresses in the piece of material produced by AFP.

Advantages and disadvantages

Post treatment: one of the main advantages in doing AFP for thermoplastic composites is the elimination of the post treatment of the composite structures after AFP. The secondary process in putting the composite structures in an autoclave, or oven (in case of vacuum bag only prepregs) is time consuming and costly. However, for this to be effective, the quality of the laminates made by AFP alone should be of sufficient quality. To achieve this, the speed of processing for thermoplastic composites needs to be very slow to allow enough time for autohesion. The time taken due to the slow speed is still much shorter than the time involved in going through a secondary process. In addition, the defects that may be created due to AFP material deposition for thermoplastic composites (such as laps, gaps) cannot be corrected in the secondary process, when it is intended that there is no secondary process.

Distortion of the part: there are significant temperature gradients in a composite part made of thermoplastic composites. The temperature gradient can be along three directions.

- There is a temperature gradient along the x direction (direction of movement of the NIP point), because the heat source moves along this direction. When the heat source is focussed at a certain location x_1, the temperature at that location is high. At the next instant, the heat moves away to a location $x_2 = x_1 + \Delta x$, the temperature at x_1 decreases and becomes smaller than the temperature at x_2, and so on.

- A similar situation occurs along the y direction. When a strip of material is laid along the x direction at a position y_1, the temperature along the strip is higher than the temperature at other y locations.

- When many layers are placed one on top of the other, there is a temperature gradient along the z direction.

Due to these complex temperature gradients, a thermoplastic composite part tends to distort during processing, even for a unidirectional flat plate. Fig. 14 shows a distorted flat composite plate. In fact, the distortion occurs for structures with free edges. For structures without free edges, such as a cylindrical tube, the distortion does not occur. This is due to the constraint provided by the geometry.

Fig. 14. Distorted flat plate, made from unidirectional layers [12].

In-plane waviness: When the roller is made of hard material and particularly when the width of the roller is smaller than the width of the tow (which should be avoided), in-plane waviness of the fibres may occur (Fig. 15).

Fig. 15. In-plane waviness of fibres [13].

Ability to make unique structures: there are unique structures that can only be made using AFP, and that other techniques cannot. One example is thick curved thermoplastic composite tubes that can exhibit similar performance as thick aluminum tubes in terms of stiffness, strength, and elongation [14]. Fig. 16 shows such a tube. It is not possible to make thick thermoplastic composite tubes using other techniques of manufacturing.

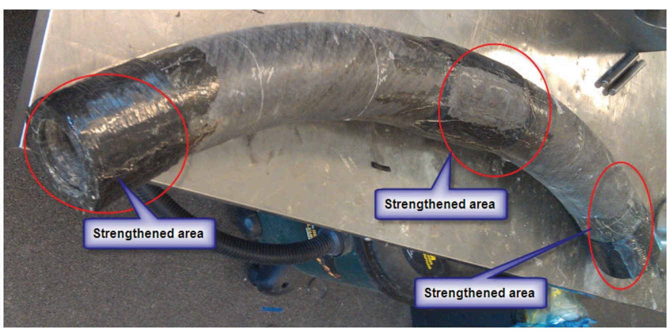


Fig. 16. A curved, thick thermoplastic composite tube made by AFP [15].

Issues of concern

There are more issues of concern for AFP processing of thermoplastic composites as compared to thermoset composites.

To produce laminates with quality similar to those made using compression moulding or autoclave: the conventional way to make structures out of thermoplastic composites is either compression moulding or autoclave. These techniques have their own advantages and disadvantages. For advantages, the quality of laminates made from these processes are usually good. For disadvantages, first the size of the sample is limited by the size of the press or the autoclave. Secondly, for compression moulding, it is sometimes difficult to assure spatial uniformity of temperature and pressure. For autoclave processing, due to the high temperature required, sealing of the vacuum bag is difficult and expensive. For AFP, the main drawback is the duration of time that sub-laminates are under contact for autohesion is very short (in the order of a fraction of a second) as compared to minutes in compression or in autoclave. Another factor that contributes to the lack of bonding is the deconsolidation right after the NIP point. When the roller moves away from the material volume under consideration, the pressure on that material volume is released. If this happens before its temperature goes below the glass transition temperature Tg, deconsolidation will occur. The interlaminar strengths of samples made using AFP are usually less than those made using autoclave [16].

To produce laminate with a minimum amount of voids: voids occur due to the lack of consolidation (or de-consolidation). Also, if there are gaps that occur due to the misalignment of tows, for thermoset composites, these gaps may be filled with resin during the curing process in the secondary stage. However, for thermoplastic composites, since there is no secondary stage, these gaps will appear as voids. The application of a repass (running the process again with a similar temperature and pressure, but with no addition material deposited) may help reduce the void content [17].

To produce laminates with good surface finish: the use of hot gas at a high flow rate may produce rough surfaces. The roughness also occurs because these surfaces do not benefit from the close contact with a smooth mould. The use of a repass may improve the surface finish [17].

ACKNOWLEDGEMENTS

The financial support provided by the Natural Sciences and Engineering Research Council of Canada is appreciated. Contributions in terms of efforts of many generations of students, research associates, and research assistants are appreciated.

REFERENCES

[1] J. Sloan (2008), *ATL & ATP: Sign of evolution in machine process control*, High performance composite magazine.

[2] C.B. Anderton and A. Colvin (2017), *A roadmap to automated composites*, Proceedings of the society of materials and process enginering.

[3] Mohammad Rouhi, Hossein Ghayoor, Suong Van Hoa, Mehdi Hojjati (2014), "Effects of structural parameters on design of variable stiffness composite cylinders made by fiber steering", *Composite structures*, **118**, pp.472-481.

[4] A.W. Blom (2010), *Structural performance of fiber placed, variable stiffness composite conical and cylindrical shells*, Ph.D thesis, Technical University of Delft.

[5] R. Klomp de Boer (2008), *Automated preform fabrication by dry tow placement*, Report NLR-TP-2008-789, National Aerospace Lab, NLR, The Netherlands.

[6] Kim Byung Chul, Paul Weaver, Kevin Potter (2014), "Manufacturing characteristics of the continuous tow shearing method for manufacturing of

variable angle tow composites", *Composites Part A: Applied Science and Manufacturing*, **61**, pp.141-151.

[7] Berend Denkena, Carsten Schmidt, Klaas Voltzer, and Tristan Hocke (2016), "Thermographic online monitoring system for AFP process", *Composites Part B*, **97**, pp.239-243.

[8] K. Croft, L. Lessard, D. Pasini (2011), "Experimental study on the effect of AFP induced defects on performance of composite laminates", *Composites, Part A*, **42**, pp.484-491.

[9] Yasser Mamoud Elsherbini, and Suong Van Hoa (2017), "Experimental and numerical investigation of the effect of gaps on fatigue behavior of unidirectional carbon/epoxy AFP composites", *Journal of Composite Materials*, **51(6)**, pp.759-772.

[10] R. Pitchumani, S. Ranganathan, R.C. Don, J.W. Gillespie, M.A. Lamontia (1996), "Analysis of transport phenomena governing interfacial bonding and void dynamics during thermoplastic tow-placement", *Int. J. Heat Mass Transfer*, **39(9)**, pp.1883-1897.

[11] C.M. Stokes-Griffin, P. Compston, T.I. Matuszyk, M.J. Cardew-Hall (2015), "Thermal modelling of the laser-assisted thermoplastic tape placement process", *J. Thermoplastic Composite Materials*, **28(10)**, pp.1445-1462.

[12] Xiao Cai (2012), *Determination of process parameters for the manufacturing of thermoplastic composite cones using AFP*, Master of Applied Science thesis, Concordia University.

[13] Suong Van Hoa, Minh Duc Hoang, and Jeff Simpson (2017), "Manufacturing procedure to make flat thermoplastic composite plates by AFP and their mechanical properties", *Journal of Thermoplastic Composite Materials*, **30(12)**, pp.1693-1712.

[14] Bijan Derisi, Suong Hoa, Duosheng Xu, Mehdi Hojjati, Robert Fews (2004), "Composite tube exhibiting large deformation under bending", *Journal of Composite Materials*, **44(16)**, pp.2005-2020.

[15] S.C. Hui (2017), *Manufacturing procedure for curved thermoplastic composite tubes for helicopter landing gear applications*, Master thesis, Concordia University.

[16] M.A. Lamontia, M.B. Gruber (2007), *Remaining developments required for commercializing in situ thermoplastic ATP*, Proc. of the 2007 SAMPE conference and exhibition, Baltimore, MD.

[17] S.V. Hoa, F. Shadmehri, J.F. Simpson, M.I. El Geuchy (2017), *Effect of manufacturing parameters on the quality of thermoplastic composite made by AFP*, Proc. International Conference on Composite Materials, ICCM 21, Xian, China.