Design and Fabrication of an On-Line Consolidation Facility for Thermoplastic Composites

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ABSTRACT: An experimental apparatus that utilizes continuous fiber reinforced thermoplastics to wind rings and short tubes has been developed. Termed an on-line consolidation facility, preimpregnated tow is consolidated while the ring is being wound. The three most important parameters for the consolidation process are time, temperature, and pressure, and the facility is designed to establish their optimum combination. Therefore, each component of the apparatus provides maximum flexibility and variability in terms of these parameters. This article describes the basic concept of the process and then shows how the concept can be realized.

The technique for heating the impregnated tow utilizes infrared radiation. However, additional heat sources are used to provide optimum temperature control at the nip point.

Finally, several types of preimpregnated tow are used to produce samples that prove the feasibility of the process and establish acceptable ranges on the parameters.

1. INTRODUCTION

RECENTLY MANY HIGH-PERFORMANCE advanced thermoplastics have been developed. Their mechanical and thermal properties are comparable or even superior to those of many thermosets. In particular, they offer such advantages as recyclability, thermoformability, weldability, and continuous processing by avoiding the time consuming curing stages. These thermoplastics have also been used as matrix materials for continuous fiber-reinforced composites. Various preimpregnated tapes and tows are already available on the market and are expected to be produced in large quantities in the future.

Currently only a few processing techniques are developed sufficiently to be used in large scale industrial applications. In all these processes, the thermoplastic material is melted and then consolidated under pressure. Some frequently used methods include friction, ultrasonic, and resistance welding. These process-

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ing methods can be regarded as discontinuous, because the plies are stacked in one step and consolidated in the following step. Continuous processes use a hot shoe, hot gas, infrared radiation, or infrared laser radiation to heat the tape or tow and consolidate it while the material is in motion.

Some studies have investigated infrared [1] or laser [2] energy to melt the thermoplastic matrix in a continuous process. However, the processing rates are still low compared with those obtained during wet winding, e.g. dry fibers pulled through a thermoset resin bath. Because heat conduction normal to the fiber direction is low, one of the major problems is how to quickly melt the matrix of the incoming tow without degrading the matrix on the surface. This problem can be overcome by subjecting the material to a longer heating period so that the heating power absorbed by the surface can be reduced.

The objective of this study is to develop an apparatus for the on-line consolidation of continuous fiber-reinforced thermoplastic tows. The facility will be used for the following applications:

- Experimental verification of residual stress models for tape or filament wound rings [3].
- Evaluation of different heat sources for the on-line consolidation process.
- Optimization of the processing parameters with respect to the product's performance.

2. REQUIREMENTS

2.1 Properties of Fiber-Reinforced Thermoplastics

The materials processed with the on-line consolidation facility can be any kind of fiber that is preimpregnated with a thermoplastic matrix material. Table 1 shows the properties of some standard composites of this group. These materials are currently available on the U.S. market [4,5,6].

2.2 Capabilities of the Ring Winding Apparatus

The winder must be able to use narrow tow, as well as wide tape, to wind rings

Table 1.

Material Fiber/Matrix	Manufacturer	V_f %	ϱ kg/m³	θ_p °C	$E_\parallel$ MPa	$\sigma_{\parallel z}$ MPa	$\sigma_{\parallel d}$ MPa
AS4/J2	DuPont	60	1540	300	124,000	1720	1050
Kevlar/J2	DuPont	60	1320	300	76,000	1310	260
Glass/2GT	DuPont	50	1970	290	34,450	565	345
AS4/PEEK (APC-2)	ICI	61	1600	400	134,000	2130	1100
IM-7/PEEK (APC-2)	ICI	61	1630	400	169,000	2890	1140
Carbon/PPS	Phillips	60	1620	280	124,000	1590	900
Carbon/PAS-2	Phillips	60	1640	215	138,000	1520	900
Glass/PPS (AG40-70)	Phillips	55	2000	280	46,200	910	765

and short tubes. The rings are to comply with the ASTM standard test method for the apparent tensile strength of ring or tubular plastics and reinforced plastics [7]. This standard specifies the dimensions of the ring as follows:

Inner diameter: d_r = 5.75 in = 146.05 mm
Width: W_r = 0.25 in = 6.35 mm
Thickness: t_r = 0.06 in = 1.52 mm

However, it also has to be possible to wind rings with an adjustable width of up to W_r = 1 in = 25.4 mm and a thickness of up to t_r = 1 in = 25.4 mm. The design has to allow for an easy modification of some of its components to wind rings of up to two inches (= 50.8 mm) in width.

The three most important parameters during the winding process are temperature, pressure, and speed. All parameters must be variable, since the apparatus will be used to find their optimum combination.

The temperatures of the tape, mandrel, and compaction roller must each be independently controlled. The temperature of the tape must reach the highest processing temperature of the materials listed in Table 1. To evaluate different heat sources for the melting of the tape, it is desirable to make them easily interchangeable. It is necessary to control the temperature of the mandrel and the compaction roller between T_{min} = 0°C and T_{max} = 150°C. To verify the model on residual stresses in filament wound rings that has been developed by two of the authors [3], it might become necessary to install insulation rings on both sides of the ring. Therefore the apparatus has to provide enough space to mount insulation rings of up to one inch (= 25.4 mm) in width and thickness.

The pressure is influenced by two components:

- The tape's tension, which should be adjustable up to F_t = 15 lbs = 67 N.
- The compaction pressure, which should be controllable up to a pressure of P_c = 200 pounds per linear inch = 35.000 N m^{-1}.

The winding speed has to be adjustable up to at least v_t = 100 ft min^{-1} = 0.508 m s^{-1}.

3. DESIGN OF THE ON-LINE CONSOLIDATION FACILITY

3.1 The Basic Principle

The concept on which the apparatus' design is based can be viewed in Figure 1. The raw material, i.e., the preimpregnated tow, is stored on a spool held by the tensioner. From the tensioner the tape runs through a preheater, where it is heated to a temperature close to the processing temperature of its thermoplastic matrix material. After leaving the preheater, the tape is wound on the mandrel. At the same time, the nip-point heater applies additional heat to the tape and to the surface of the preceding layer. The temperature must be sufficient to melt the thermoplastic material so that the layers of tape stick together. The compaction roller applies pressure on the nip-point to improve the bonding between the

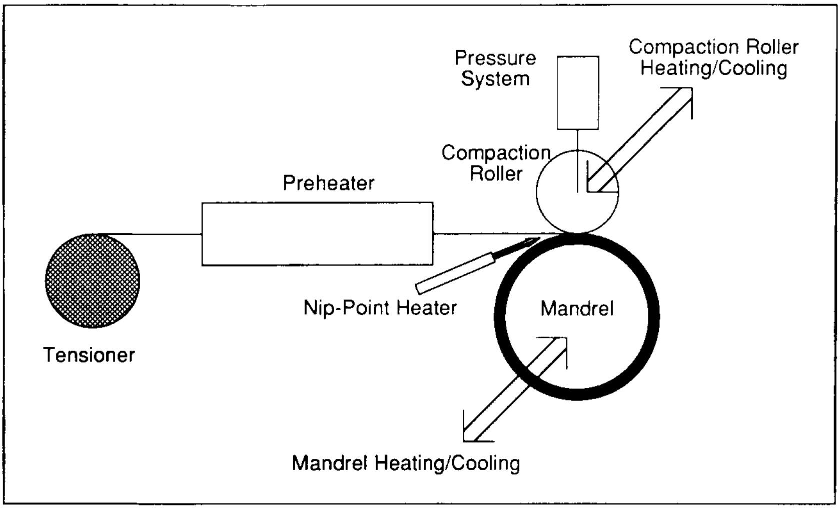

***Figure 1.** Schematic illustration of major components of the on-line consolidation facility.*

layers. The mandrel as well as the compaction roller can be heated and cooled in order to influence the temperature history during the winding process.

3.2 Fixed Mandrel vs. Fixed Nip-Point

There are basically two concepts concerning the kinematics of the winding process:

1. The first concept [2] uses a fixed compaction roller so that the position of the nip-point does not change. This means that the mandrel has to gradually increase its distance from the compaction roller as the ring gains thickness. At the same time, the mandrel moves parallel to its axis of rotation.
2. The other concept is to rotate the mandrel around a fixed axis and move the compaction roller away from it as the ring builds up. Simultaneously the pay-out eye moves parallel to the mandrel's axis of rotation.

The advantage of the first solution is that the pay-out head and the nip-point heater do not have to be moved.

The disadvantages are the complex design that is necessary to give the mandrel three degrees of freedom, and the necessity to use strong bearings and motors to accelerate the rather heavy mandrel.

The strong points of the second winding concept are:

- The design is more economical, due to the separation of degrees of freedom, i.e., the mandrel rotates and the compaction roller and the pay-out eye move linearly on separate axes.
- The total weight that has to be accelerated and decelerated during the winding process is relatively small.

- If additional heating and cooling devices have to be mounted around the mandrel at a later date, their design will be much simpler.

On the other hand, in this case it is necessary to install a more sophisticated tow guiding system, to make sure that the tape runs through the preheater properly. In addition, it is rather difficult to design a fixture that makes the nip-point heater follow the movements of the nip-point.

Comparing the pros and cons of the two solutions, it was decided that the second concept would be much easier to incorporate and did not have any major weakness.

3.3 Horizontal vs. Vertical Axis of Rotation

Having decided to rotate the mandrel around a fixed axis, the choice remained whether to rotate it around a vertical or horizontal axis. Unlike Beyeler et al. [2], it was decided to choose a horizontal axis for the following reasons:

- It is much easier to remove the mandrel from the shaft to strip off the ring.
- There is no axial force in the mandrel drive shaft.
- The pay-out head which moves parallel to the mandrel axis does not have to be accelerated against gravity.

3.4 Selection of the Tensioner

The tensioner has the task of keeping the tension in the tape at a constant level while the tape is unwound from the spool. All tensioners have three components in common: a shaft to hold the spool; a locking system to hold the spool on the shaft; and a brake or clutch to control the torque in the shaft. Depending on their torque controls, the tensioning systems that are available on the market can be divided into three categories:

1. The simplest form of a tensioner has a control for the brake or clutch, that keeps the torque at a constant level.
2. Mechanical tensioners have a brake that is controlled through a feedback device and a sensing unit. These are located next to the spool. The sensing unit can be a rotary dancer or festoon, preloaded with a spring or a pneumatic cylinder.
3. Closed-loop electronic tensioners have a tension sensor between tensioner and nip-point. In addition they feature a microcomputer to adjust the torque of a bi-directional servo motor according to the reading of the sensor. The servo motor works as a brake, but it can also rewind the tape if it has too much slack.

Systems of the first category are rather inexpensive, but they have the disadvantage of not accounting for the decreasing diameter of the spool. As a result, the tension in the tape increases with time.

The second kind of system offers a simple but easily adjustable closed-loop tension control. The cost is moderate and depends on the tension range and the accuracy of the sensing unit.

Systems of the third category are probably the most accurate tensioners, because the sensing unit can be located right before the tape reaches the nip-point and thus compensate for the friction in the tape guiding system. The disadvantages of this system configuration are cost and that the sensor would represent a heat sink for the preheated tape.

For the on-line consolidation facility designed here, a tensioner of the second category was selected, because it offered a good compromise between performance and price. It features a rotary festoon and provides two different tension ranges (1.5 lbs = 6.7 N to 5 lbs = 22.2 N and 5 lbs = 22.2 N to 15 lbs = 66.7 N) depending on the threading path of the tape through its rollers. The tension is variable through the use of a Nitrogen pressurized cylinder. The pressure regulator and gauge can be mounted up to 10 feet = 3 m away from the tensioner in a control rack to allow easy control over the tension during the process.

3.5 Selection of the Preheater

Basic computations using the laws of thermodynamics show that the tape has to absorb a power of up to 3.74 KW per inch of tape width at the maximum winding speed. The following heating techniques were considered for the preheater.

Resistance heating requires an electric current to be sent through the carbon fibers. This is theoretically possible, but it is very sophisticated and does not work for glass or aramid fibers.

Hot rollers or sliding shoes could be induction or resistance heated. Since they increase the tension in the tape, they can only represent a good solution if the tension sensor is located after the preheater.

Ultrasonics can be applied by pressing a vibrating metal rod against the tape, but the friction between the rod and the tape would change the tension in the tape.

High frequency waves can heat the material by causing the molecules in the thermoplastic to oscillate. However, this method only works with thermoplastics containing polar molecules. In addition, these waves are difficult to generate and can be hazardous to electronic equipment and human beings.

Laser light has already been used to heat thermoplastic tape [2], but the maximum speeds obtained are only about 0.05 m s^{-1}, because only a small area of the tape is exposed to the radiation.

Infrared radiation is easy to generate and to control. However, since it can be harmful to the eyes, a cover is necessary around the heating elements.

Hot gas has a poor efficiency, since not only the tape but also the gas have to be heated. Furthermore, the heat conduction coefficient between the gas and the material is low. Open flames provide a high density of energy, but they are usually so hot that they may degrade the polymer.

For the reasons stated above, infrared radiation was selected for the preheating. The on-line consolidation facility's preheater consists of two infrared heaters that have a total wattage of 10 kW at 600 V. They are mounted so they face each other simultaneously heating both sides of the tape. To supply the heaters with the required voltage, each heater needs two buck boosters to increase the house voltage from 197 V to 240 V and one transformer to reach 600 V.

The heating power of an infrared lamp can be controlled by reducing the voltage of the power supply. This can be done in three different ways:

- The use of a serial resistor is the least expensive solution, but it has the disadvantages of low efficiency and high heat output.
- The installation of a variable transformer has the advantage of high efficiency at moderate cost.
- The use of a silicon controlled rectifier offers high efficiency and the option of a closed loop temperature controller. Its disadvantage lies in the strong electronic noise that can be harmful to any adjacent computer. The cost is slightly higher than that of a variable transformer. Here the decision was made for the silicon control rectifiers because of control advantages. Each infrared heater has its own independent power controller, so that the top and the bottom surface of the tape can be heated with different power levels. The control units are mounted on the primary side of the transformers since their cost is lower for low voltages. They may also be mounted far enough away from computers to avoid damage.

3.6 Tape Guiding System

The tape guiding system ensures that the tape's path through the preheater does not change while the spool diameter decreases and the ring on the mandrel builds up. It also controls the tape's movement parallel to the mandrel's axis of rotation. It consists of two ceramic rings mounted on either side of the preheater. The size of the rings depends on the width of the tape. The rings are held by stainless steel pay-out eyes that can accommodate rings of various sizes. When being compared with metallic rings, ceramic rings have the following advantages:

- The coefficient of friction between the tape and the ring is reduced such that the deviation of tension is minimized.
- The resistance to wear is greater.
- The thermal conductivity is reduced, which means that the ring does not represent a significant heat sink.

To reduce friction, it would have been better to use small rollers, but rollers would help to dissipate the tape's thermal energy. In addition, they require more space, causing the distance from the preheater to the nip-point to become longer. This would result in an unwanted cooling of the tape.

3.7 Nip-Point Heater

The techniques that were considered for the nip-point heating are basically the same as those for the preheater. However, the efficiency of the heating system does not have to be a major concern, since the amount of energy that has to be applied by the nip-point heater is much smaller than that of the preheater. Since one application of the on-line consolidation facility is the evaluation of different heat sources for the nip-point heater, it was not necessary to purchase an expensive and sophisticated piece of equipment. For the reasons stated above, a hot-gas gun was chosen for the initial test runs.

3.8 Mandrel

The outside diameter of the mandrel is determined by the size of the ASTM standard test ring [7]. The mandrel has to be long enough to wind rings that are at least two inches (= 50.8 mm) wide. In addition, it has to extend one additional inch (= 25.4 mm) on both sides of the ring in order to hold insulation rings that can reduce boundary effects.

A major concern is the implementation of a heating and cooling system. A closed system with a heated and cooled medium such as oil would create serious sealing problems, since the mandrel has to be removed from the apparatus after each run to strip off the ring. Therefore it is advantageous to use an open system with heating and cooling media that do not contaminate the work area. The most viable solution for this concept was the use of hot air for heating and liquid nitrogen for cooling. Both media are blown into the hollow mandrel. To monitor the temperature, a sliding surface thermocouple senses the temperature on the outside of the mandrel. Because the mandrel can get very hot, it is made of stainless steel.

It is also necessary to provide a means to attach the beginning of the tape to the

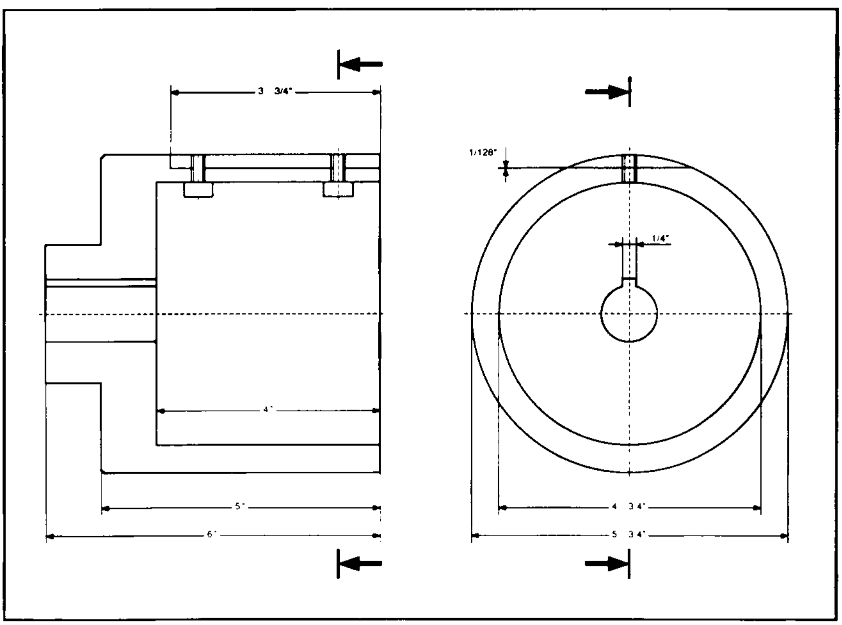

Figure 2. Mandrel.

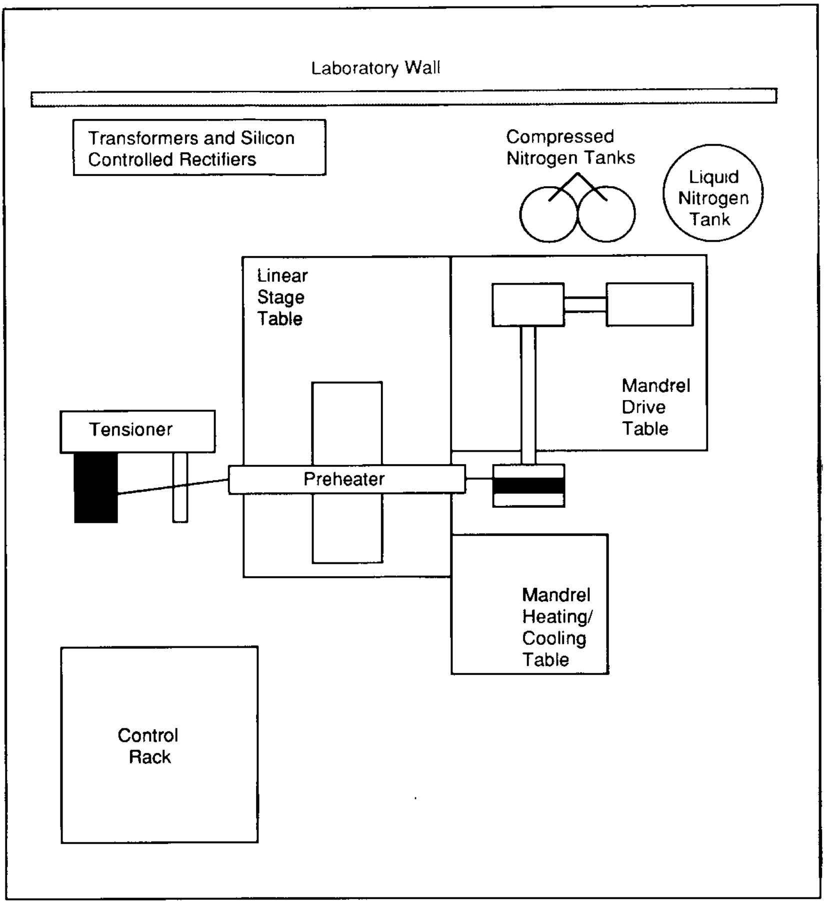

Figure 3. *Structure of the setup.*

mandrel. This is made possible by a removable section bolted to the mandrel body. To attach the tape, two bolts are loosened, the tape inserted in the slot, and the bolts tightened again. A drawing of the mandrel can be viewed in Figure 2.

3.9 Pictures of the Facility

This section shows a sketch and some pictures of the apparatus. The sketch in Figure 3 visualizes how the components of the facility are arranged relative to each other in the laboratory. Figure 4 gives an overall view of the entire apparatus. A close-up of the nip-point (Figure 5) shows some details of the facility around the mandrel.

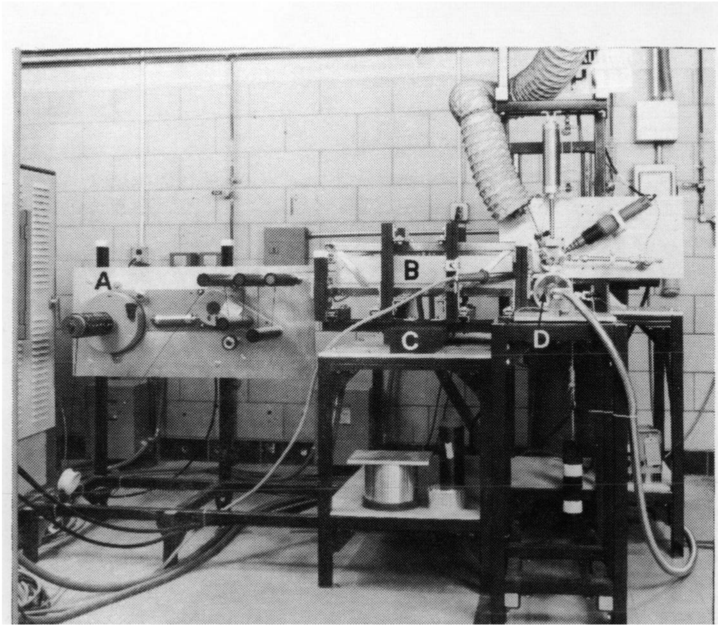

Figure 4. *Overall view (A: tensioner, B: preheater, C: linear stage, D: mandrel).*

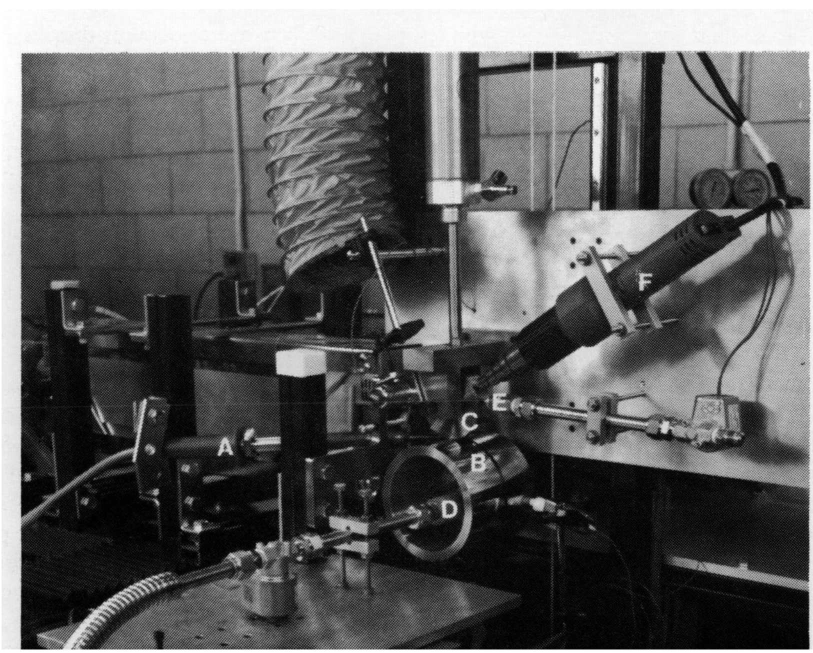

Figure 5. *Close-up of the nip-point (A: nip-point heater, B: mandrel, C: compaction roller, D: mandrel cooling-nozzle, E: compaction-roller cooling-nozzle, F: compaction roller hot-air gun).*

4. PRELIMINARY TEST RESULTS

Table 2 shows the protocol sheet of preliminary tests performed on the new on-line consolidation facility. The properties of the materials used were presented in Table 1. Since a fast and qualitative rating was desired, the consolidation was evaluated by the sound the ring made when dropped on a hard surface.

For the first five rings, tow of carbon fibers preimpregnated with an amorphous polyamide matrix (J2-polymer, DuPont, USA) was used. While the first ring was being wound, heavy smoke was rising from the preheater. The ring showed a poor consolidation. It seemed that the heating power was too high so that the matrix material was vaporized.

For safety reasons, the motor chosen to drive the mandrel has substantially higher performance curve than necessary to fulfill the requirements listed in section 2. Therefore, it is possible to wind at speeds that are higher than initially required (up to v_t = 200 ft min^{-1} = 1.016 m s^{-1}). When winding the second and third ring, the winding speed was drastically increased and the heating power reduced. In addition, the rings have more layers than their predecessors.

When winding the fifth ring, the motion controller put down the layers with a 50% overlap. In addition, the winding speed was increased. The result was a ring that has better surface quality and much better consolidation than the first four rings.

Next, glass fibers preimpregnated with 2GT were used. The tow is thicker than the J2 used previously. Rings six and seven were also wound with a 50% overlap of the layers. While the rings wound, very little smoke was rising from the preheater. By grinding the ring edges, consolidation was noticed to be improved because of lack of voids. Comparing the two rings, one can assume that a higher tension and a higher compaction force have a positive influence on the consolidation. Figure 6 shows a picture of these two rings.

For rings eight through eleven, Kevlar preimpregnated with J2 was used. Although the heating power was increased and the winding speed reduced, the resin did not become hot enough to melt and consolidate. The reason for this could have been the absorption coefficient of the tape. Unlike the glass/2GT tape, the Kevlar based tow does not have carbon particles in the resin.

The twelfth and the thirteenth rings were used to optimize the setting of the preheater. Using the preheater as the only heat source did not lead to satisfactory results. The tow was either burned or not hot enough to consolidate. A hot-nitrogen gun was then added to heat the nip-point. This made a considerable difference improving consolidation significantly. At the same time the compaction roller was not used. As a result, the rings were thicker but not as wide as the previous ones. During tests fifteen to eighteen the nip-point heater remained in its position while the winding speed as well as the preheater power were reduced. The eighteenth ring was the best one made to date.

Up to this point, the temperatures of the mandrel and the compaction roller were not controlled during the process. Therefore, the temperatures increased while rings were being wound. Depending on the various processing parameters, the temperature of the mandrel increased about 5°C and that of the compaction

Table 2. On-line consolidation facility (test protocol sheet).

Test No.	Date	Material	Tape Width [mm]	Ring Width [mm]	No. of Layers	Wind. Speed [m/s]	Preheat Power bottom [W]	Preheat Power top [W]	Nip-Point Heater Type	Mandrel Temp. [°C]	Comp. R. Temp. [°C]	Tension [lbs]	Comp. Pressure [psi]
1	03-10-89	AS4/J2	4.0	20	10	0.459	4800	4800	Hot-Nitrogen Gun	*25	*25	2.3	5
2	03-13-89	AS4/J2	4.0	20	20	0.716	4800	0	N/A	*25	*25	2.7	20
3	03-13-89	AS4/J2	4.0	20	20	0.716	4800	0	N/A	*25	*25	4.4	20
4	03-14-89	AS4/J2	4.0	20	40	0.716	4800	0	N/A	*25	*25	5.2	20
5	03-14-89	AS4/J2	4.0	20	40	0.819	4800	0	N/A	*25	*25	5.2	20
6	04-05-89	Glass/2GT	5.6	20	40	0.819	4800	0	N/A	*25	*25	5.2	30
7	04-05-89	Glass/2GT	5.6	20	20	0.819	4800	0	N/A	*25	*25	6.9	40
8	04-20-89	Kevlar/J2	4.0	4.0	40	0.717	2500	2500	N/A	*25	*25	8.0	30
9	04-20-89	Kevlar/J2	4.0	4.0	40	0.717	4800	4800	N/A	*25	*25	8.0	30
10	04-20-89	Kevlar/J2	4.0	4.0	40	0.348	4800	4800	N/A	*25	*25	8.0	30
11	04-20-89	Kevlar/J2	4.0	4.0	40	0.229	4800	4800	N/A	*25	*25	8.0	30
12	04-20-89	Glass/2GT	5.6	5.6	25	0.819	2500	2500	N/A	*25	*25	11.2	42
13	04-20-89	Glass/2GT	5.6	5.6	40	0.819	2000	2000	N/A	*25	*25	11.2	42
14	04-21-89	Glass/2GT	5.6	5.6	40	0.819	1000	1000	N/A	*25	*25	11.2	42
15	04-21-89	Glass/2GT	5.6	5.6	40	0.819	1000	1000	Hot-Nitrogen Gun	*25	*25	11.2	0
16	04-21-89	Glass/2GT	5.6	5.6	40	0.604	1000	1000	Hot-Nitrogen Gun	*25	*25	11.2	0
17	04-21-89	Glass/2GT	5.6	5.6	40	0.410	1000	1000	Hot-Nitrogen Gun	*25	*25	11.2	0
18	04-21-89	Glass/2GT	5.6	5.6	40	0.410	700	700	Hot-Nitrogen Gun	*25	*25	11.2	0
19	04-21-89	AS4/J2	4.0	4.0	40	0.604	1000	1000	Hot-Nitrogen Gun	*25	*25	8.0	0
20	04-21-89	AS4/J2	4.0	4.0	40	0.604	700	700	Hot-Nitrogen Gun	*25	*25	8.0	0

* = temperature at the beginning of the experiment.

***Figure 6.** Two rings made of glass/2GT.*

roller about 10°C. On the test protocol sheet, this is indicated by an asterisk preceding the value for the temperature.

5. SUGGESTIONS FOR FUTURE WORK

In its present state, the apparatus is capable of winding rings that comply with the requirements listed in section 2. Future use of the facility will show which additions will be necessary in order to adapt it to new applications. This section gives a few examples for possible modifications. Whether they will be incorporated or not depends on the result of future test runs and the needs of the individual user.

In order to compensate for the varying thickness of the incoming tape, it is desirable to have closed-loop temperature control for the preheater as well as for the nip-point heater. For the preheater, this can be achieved by measuring the tape's temperature with a thermocouple sliding on the tape's surface. A temperature controller can use the reading of the thermocouple to control the silicon controlled rectifiers of the preheater power supply. The silicon controlled rectifiers have a standard input module that can be addressed directly by most temperature controllers.

For the nip-point heater, it is not easy to install a temperature control because of the difficulty of measuring the temperature at the nip-point itself. Investigations have been made regarding the use of a pyrometer for this purpose, but a pyrometer measures the temperature not only of the object it is aimed at, but also of the atmosphere between the sensor and the object. However, it might be possible to use a pyrometer that measures the radiation only within a limited section of the infrared spectrum.

Another important parameter for the consolidation is the temperature on the surface of the already wound tape. The surface of both the incoming tape and the last layer have to be molten in order to obtain a good consolidation. Therefore it might be necessary to heat the preceding layer. This can be done by the heated mandrel, the nip-point heater, or an additional heat source.

The consolidation also depends on the cool-down rate of the tape after it has passed the nip-point. The cooling can be influenced by the cooled mandrel, the cooled compaction roller, or an additional heat sink.

In order to use the apparatus for the verification of a residual stress model [3], it is necessary that the boundary conditions of the model be simulated as well as possible. It might be advantageous to mount insulation rings on either side of the ring to reduce the heat flux from the ring into the atmosphere. Glass is one material that is very well suited for this application because it combines low conductivity, high heat resistance, and moderate cost.

In its present state, the Kevlar/J2 tape cannot be processed with the apparatus. However, this could be facilitated by using a resin that contains carbon particles, because carbon influences the spectral absorption coefficient of the material. The glass/2GT tape is an example of this kind of resin composition.

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