I. ABSTRACT
Composite tubing is known for its high strength and lightweight characteristics, but also for its high cost. The goal of many SAE teams is to implement composite materials into vehicle design without vastly increasing cost. RIT does not have the capability to develop composite tubing on its own, but could benefit from the use of such materials. The goal of this project is to develop a low cost, first generation filament winding machine which produces simple composite tubing. With this platform as a stepping stone, future Senior Design teams can improve upon the design and increase the scale and scope of tubular composite manufacturing. Learning more about composite materials and design, this project has an end goal of having a machine that can produce plastic reinforced tubing at or near raw material cost.

II. NOMENCLATURE
Resin – adhesive/polymer matrix that holds fibers together
Impregnation – the process of wetting fibers with resin to a desirable level (volume fraction, $V_f$) which is related to product quality
Creel – spool-like object that holds fibers
Resin Bath – container filled with resin, used to impregate fibers
Mandrel – object over which the fiber is wrapped to form different products depending on surface of revolution (i.e. a cylindrical shape will produce tubing)
Feed Eye – guides fiber to be laid onto mandrel from resin bath and creel
Fiber Orientation Angle – angle at which fibers are laid onto the mandrel, correlates to physical characteristics of product (i.e. tensile strength, compression strength, etc.)
Fiber Volume Fraction – ratio of volume of fiber to volume or resin
Programming Table – table generated that maps out steps for stepper motors to travel in order to achieve certain fiber orientation angles at varying speeds

III. BACKGROUND
Filament Winding is a process through which fibers are wrapped around a spinning body, known as a mandrel. The fibers are held to each other by an adhesive resin or epoxy, known as the matrix material. The fibers are “impregnated” with this material in a resin bath, guided by a feed eye, before being laid onto the mandrel. The fibers and matrix material are cured over time or with heat and the finished part is removed from the mandrel. The quality and characteristics of the part are determined by many aspects of the process including type of fiber and resin, tension in the fiber, ratio of fiber to resin volume (fiber volume fraction), and the angle at which fiber is laid (fiber orientation angle).
Donated from Dr. Hany Ghoniem, the team worked with a Craftsman Mk. 1 6-inch lathe because its basic functions are the foundation for simple 2 axis filament winding. The rotating headstock controls the mandrel while the rack and geared tool carriage guide the fiber as it’s laid. The fiber orientation angle that determines the characteristics of the finish part can be determined by the following formula:

\[ \theta = \frac{2\pi N_m}{V_c} \]

where, \( \theta \) is the fiber orientation angle; \( N_m \) is the rotational speed of the mandrel (lathe headstock); and \( V_c \) is the translation speed of the feed eye (lathe carriage).

Throughout the design process, mini teams were created to separate aspects of the machine in order to better focus concept generation, design, build, and test. The creel/tension team developed methods to hold the spool of fiber and provide tension to the fiber being laid. The mandrel team designed both the mandrel itself (in relation to how it would mount onto the lathe) and possible ways to remove the finished part from the mandrel at the end of the process. The impregnation system team developed methods to best fill the fiber with resin. The motors/control team researched the best motors to drive the system and effective methods in controlling the position and speeds of both the mandrel and feed eye in order to accurately wind a part.

IV. PROCESS

Creel/Tension

Overview

In order to properly wind the fiber onto the mandrel an amount of tension varying from 1-10 lbs is called for. This amount of tension ensures that there is no slack in the system and that you have a consistent wind. To ensure this tension we looked at various approaches to the problem. Some of the variety of solutions that we looked at included a variable spring rate rotary tensioner, using a torturous path, using rubber bushings for resistance, as well as using a motor to take up the slack.

Concepts

Initially we looked at a variable spring rate tensioner from Fenner Drives. While this device was more than capable of applying tension through a pulley it provided too much tension, approximately 30 lbs. Along with too much tension there were also concerns with positioning within the system as it would have needed to be mounted in line.

The method of torturous path depended on the use of friction between the rolling surface of the rollers located within the bath and their shafts. The issues with this design were that we had little control over the final tension value as well as little to no adjustability once the machine was built.

Another method we considered was using rubber bushings to provide a resistance to the pull of fiber from the spool. The first iteration of this design was to simply use a cylindrical rubber bushing to take up the clearance between the shaft diameter and the inner diameter of the spool. While this method is certainly capable of providing the required resistance it leaves little room for adjustability. The subsequent second iteration of this design used tapered rubber stoppers. These rubber stoppers were bored to the shaft diameter and fit to the spool. Furthermore with the addition of a threaded rod as the shaft itself it provided an avenue for improved adjustability by using a wing nut. By tightening or loosening the wing nut the tension can be changed.

The other major design we studied was the use of an electrical motor or brake to effectively take up the slack and provide resistance to the pulling motion and therefore impart tension into the fiber. We began with looking at an electromagnetic brake or clutch, the prices associated with these devices and their required controls was too high to be considered a good solution. The next iteration was an electric motor on the spool shaft itself. At the time this solution was also outside the budget. The other issue with using an electrically controlled system as opposed to a purely mechanical system is of course the control structure. To have a properly operating system their needs to be feedback from some type of tension sensor. This will be discussed further in the future design considerations.

With these possible designs choices in mind we selected the tapered rubber bushings/stoppers. We felt that this method provided the least amount of questions from an adjustability and implementation perspective. Coupled with the relative low cost comparatively this method was chosen over the others.

To begin the design of the support structure that with the spool and tension comprises the creel we need to look at the requirements of the system. To ensure the fibers receive no damage in the process while the carriage moves it is suggested in the ASM Composites Handbook that the angle of the fiber from the spool to the resin bath not exceed 20 degrees [1]. With the relative location of the resin bath and mandrel known it was a relatively simple process of using basic trigonometry to determine the required location of the spool.

For the structure itself the design began with mounting pieces of 2”x1/8” aluminum with a support piece in place to assist in preventing bending towards the mandrel. While this system worked well in bending towards the mandrel, due to a miscalculation the design showed instability in side to side motion. To remedy this issue the pieces were remade from 1” L
stock of 1/16” thickness. Then installed this system was adequate.

![Figure 4.1 Table with flat stock creel structure](image1)

![Figure 4.2 L bracket creel structure](image2)

**Mandrel**

**Overview**
The mandrel is the object on which the fibers in the filament winding process are wrapped around. The finished product is a composite tube whose outer diameter and shape matches that of the mandrel. After the process is completed; general procedure has the mandrel removed, leaving the hollow, cured structure remaining. Although the mandrel can essentially be any shape, controlling the speeds in line with changing surface areas becomes very intricate and complex. The mandrel shape used accommodates customer needs while fitting the scope of the developed control system in order to precisely and accurately lay fibers. The surface finish of the mandrel is critical in the filament winding process. All imperfections in the surface will be reflected in the finished part, and in order to maintain high quality, the mandrel must maintain a certain diameter with limited tolerance. In relation to finished part removal, a mandrel with a smooth finish will provide less resistance and less potential damage.

**Concepts**

There are multiple options for part removal from the mandrel that fall into 2 categories: (1) mandrel deformation or (2) mandrel lubrication (used in conjunction with deformation).

1. **Mandrel Deformation** relates to the material properties of the mandrel. Foams and other dissolvable materials (such as Aquacore) have the positive attribute of being removable but also carrying negative attributes of being both brittle and carrying poor surface finishes. The combination of the tension of the fiber and rotation of the mandrel can produce unwanted nicks and recesses in the mandrel that will be reflected in the finished part. Wax and other heat released materials are more promising and further testing can be done to see their responses and reactions in the process. Wax mandrels bring the positive effect of melting away during the oven curing process. One concern would be the application of heated resin to the wax mandrel, which may produce unnecessary deformation and compliance. Metals, such as Aluminum and Steel, provide smooth surface finishes and can be machined for tighter tolerance limits. Another aspect of metal mandrels is metal expansion under heat. Further testing must be completed to see if the change in area is significant enough for finished part removal.

2. **Mandrel lubrication** pertains more specifically to metal mandrel materials. Heated activated release agents and lubrication can be applied to the mandrel prior to the winding process. Theoretically, after curing, the finished part should be easier to remove. Further testing has to be done to confirm removability of finished part.

**Manufacturing**

Mandrel specifications fall into the same specifications of the finished part in terms of length; where the outer diameter of the mandrel equals the inner diameter of the composite tube. The mandrel’s outer diameter ranges from 15/16” to 1 15/16”, while the length ranges up to 12”. The material chosen was Aluminum 6061 for ease of machining and good corrosive resistance. The material’s potential for smooth surfaces and low cost made it a strong selection. One side of the mandrel requires a .5” diameter step for connection to the chuck, while the other requires a center drill to be set with the live center of the tailstock.

**Impregnation System**

**Overview**

In order to produce a plastic reinforced tube by wet the filament winding process, a resin impregnation system is required. This component serves as the point where the dry fiber tow is saturated by liquid resin, therein replacing the air with a resin matrix material. The control of this process is critical to the quality of the overall product as it determines the volume fraction of fiber compared to the overall volume of the produced
part. Too little resin will not effectively hold the fiber together whereas too much resin will compromise the structural integrity of the part. The desired strength characteristics of composite parts generally come from the properties of the fiber, or reinforcement material. The resin serves to maintain the position of the fiber and create a network that can transfer the load from fiber to fiber.

**Concepts**

Three types of concepts were explored to accomplish the resin impregnation of the fiber; fiber dip style bath, drum bath, and tube style. When compared, the fiber dip style was chosen. This allowed easier manufacture and better fiber impregnation than the drum type, while providing an acceptable amount of tension in the tow when compared to the tube style system. The fiber enters through a ceramic feed eye and travels through a series of rollers. The position of the rollers provides bending of the fiber tow to ensure proper resin impregnation. Before exiting the bath, the tow passes between squeeze rollers to remove excess resin and exits through a feed eye to the mandrel.

![Figure 4.3 CAD representation of resin impregnation system design](image)

**Manufacturing**

The RIT machine shop’s sheet metal break was used to cut the aluminum plates for the sides of the unsealed box. The shop instructor completed welding of the side plates. Roller supports were cut in the band saw then finished in a lathe. Due to a labor-intensive roller design, CNC machining was considered but could not be completed on time, therefore manual machining on a lathe was used. Three brass rollers provide bending to the fiber tow. AS tapered design was implemented so the resin converges to the center of the roller. The reduction of diameter in the center of the rollers ensures the fiber tow stays in position. To minimize leaking though the support holes, the squeeze rollers were stepped down so resin drips back into the bath. To insert the ceramic feed eyes, holes were drilled in the front and back faces. Slots provide flexibility of the aluminum face to snap the ceramic ring in place.

**Motor Selection**

**Overview**

The first step in the design phase of the Motor/Controls of the Filament Winding Machine was motor selection. In typical Filament winding applications, servo motors are used due to their high accuracy and efficiency. Two motors were required; one for the mandrel that would rotate in one direction at a constant velocity while the other would move transversely carrying a load back and forth. The main concern for these motors was the load requirement or the torque that it would have to basically overcome. For the mandrel, over 200 oz-in of torque was required, while the feed eye required 50 oz-in.

**Concepts**

Due to our relatively low budget and restricted amount of time, several cut backs and crucial decisions were made in regards to the motors and controls aspect of the project. The first major decision was whether to go with the AC motor that was provided by Dr. Ghoneim and adjust the speed using a frequency modulator. The motor was rated at 1725 rpm and 1/4 horsepower. Therefore, the motor would need to be stepped by at least a 15:1 ratio. Mechanically reducing this speed using gears would be an extremely inefficient system and using a frequency modulator would drive our cost up. It was quite obvious to us that this motor was not the correct choice for our application. After this was understood, we went on to explore different options such as stepper and servo motors. For the mandrel, a stepper motor was more ideal because of the capabilities and opportunities for advancement. Even though for our particular project, it was required that the mandrel rotate in one direction at a constant RPM and a simple DC motor could have been used along with a controller that would reduce the speed, the problem was that purchasing a controller with the capabilities of reducing the mandrel from thousands of RPM’s to speeds varying from 10 to 60 RPM maximum would be expensive. The best option would be to go with a stepper motor. If future design teams feel that it is necessary to incorporate more control in which they would need to vary the mandrel speed throughout the process, then they would already have the motor capable of doing so. For the feed eye, a stepper motor in general was more attractive for this application because of the lower cost and reduced complexity. Typically servo motors are used in filament winding machines because of the complexity of feeding the fiber from multiple spools, high tech impregnation system, necessity to maintain temperature, tension in the system, etc. Since funds and programming capabilities were limited, the stepper motor was chosen to drive the feed eye.

**Motor Mounts**

**Carriage**
Because the carriage/resin impregnation system is required to transversely travel along the length of the mandrel, the stepper motor was mounted directly to the lathe cutting tool carriage. To provide a mounting face for the motor, aluminum square profile tubing was used as a box providing room for the motor and carriage shaft coupling. Aluminum was chosen to dissipate heat created by the motor during operation.

**Spindle**
The design attempts to combine style with functionality while integrating the motor as part of the machine. Aluminum square tubing was used to raise the support from the table level. Aluminum angle supports were used at the base of the tube and cut to match the width and curve of the existing machine. Again aluminum was chosen to effectively dissipate heat created during motor operation.

**Controls Selection**
As for the controls aspect of the project, drivers were required for the motors. For the feed eye, the MBC25081 Bipolar Microstep driver was used to control the motor which was capable of running four, six, and eight lead step motors. Other features of the driver are that it has an output current range of 0.5 to 2.5 amps/phase and operate off 12VDC minimum to 24VDC maximum. Lastly, it features resolutions from 200 to 1600 steps per revolution. For the mandrel, the MBC05641 Microstep motor driver was used which has an output current capability 0.5A to 5.0A maximum and operates from 24VDC to 48VDC. The amount of steps per revolution ranged from 200 to 12,800 steps. Each driver was connected to a microcontroller, specifically the Atmega 128 microcontroller. The purpose of this was to act as a clock signal for the drivers which would in turn control the amount of steps per revolution and therefore the speed, direction, acceleration, etc. Basically, pre-defined tables that were constructed in Microsoft excel were loaded into the microcontroller that stored position and velocity settings that map out the direction and number of steps to output to the drivers. The program that loads the tables was constructed using the AVR Studio 4 software program, while the Tekbots Universal Programmer software was used to load the code onto the microcontroller. Basically, the program loads all necessary constants and then indexes through the table for the mandrel. Once the mandrel reaches a certain amount of steps per revolution or at the correct RPM, the feed eye is initialized and begins indexing through its pre-defined table. Once a certain amount of passes, which again is pre-defined, is reached, the feed eye carriage is stopped, the fiber is cut, and the mandrel reduces its speed for the curing process.

**V. RESULTS AND DISCUSSION**

**Creel/Tension**

**Testing**
To test the system design the creel was setup, the fiber run through a mockup of the resin bath and pulled through. The fiber was then tied to a digital hanging weight scale. The fiber was then pulled as if being would on the mandrel noting the reading from the scale. With this test we were able to confirm that our creel system was capable of providing up to the maximum 10 lbs of tension required. Any addition of an impregnation system would increase viscous losses within the system and provide further resistance for even more tension.

**Motors/Controls**

**Testing and Implementation**
When the parts were received, individual tests were performed on each component to ensure that they would meet design specifications. For the feed eye, a 24VDC source was applied to the driver along with a 5V peak to peak with 2.5V offset and 2 kHz frequency pulse was applied to the clock. This was accomplished using the signal generators in the Electrical Engineering laboratories. It was proven that the feed eye motor had the capabilities of driving the carriage along with the resin bath. By reversing the polarity of the direction bit on the driver, the motor reversed and moved transversely in the opposite direction. It was found that there was an extremely smooth transition when the direction was changed. A similar test was applied for the mandrel in which a signal generator was used as a clock signal with 24VDC applied to the input. For the load, a digital spring scale was used in which a force of 15lbs was applied to the mandrel. It was found that the motor did indeed have enough power to overcome this torque requirement. The 15lbs was rated as the maximum that the motor would have to overcome. Therefore, it was proven that the mandrel motor met the design specifications. Also, since the mandrel was running at such low speeds, 24V was an ideal input voltage. Because of this, a simple 24V and 6.5A power supply would be efficient to run both the mandrel and feed eye and still have enough power for future iterations. The feed eye drew roughly 0.5A, while the mandrel drew 2.5A.

For testing of the program, the clock signals of the mandrel and feed eye from the microcontroller were hooked up to an oscilloscope and analyzed. Figure 1.1 shown below displays the output waveforms of the mandrel and feed eye. The feed eye is shown on the top, while the mandrel is on the bottom. One should notice that the feed eye does indeed ramp up to speed, remain constant, and then decelerate. In figure 1.2, it shows the integrated system with delay incorporated. Again, the feed eye is shown on the top, while the mandrel is on the bottom.
The most practical way of testing the controls system is to dry wind a part. The input angle and actual angle of fiber can be compared while the fiber laying profile can be monitored and adjusted accordingly. Finding the maximum and minimum angles of wrap depend on the motor capabilities and the surface properties of the fiber and the mandrel. A control set of speeds for the mandrel were set from 10 to 60 RPM, avoiding running the carriage too quickly. Higher speeds require higher torques in order to move the carriage; therefore an angle wrapped at 60 RPM can be theoretically wrapped at any lower speed. Using an upper limit of 85° and stepping down a certain amount, angles lower than 65° could not be run at speeds higher than 10 RPMs. At 55°, the fibers began slipping off the mandrel, and therefore were not viable for a good part.

Profile Testing
Another issue that arose was the actual profile of the wind onto the mandrel. After 5 passes, the fibers began rewrapping on top of each other as the feed eye passed back and forth.

In order to correct the winding, the fiber thickness has to be measured and re-input into the program. Another aspect was the actual width of the part “dogbone”. The “dogbone” is the section of the part that has different quality and dimension characteristics that the desired part because of extra winding required at each end. In order to accomplish a complete layer at 75° and at 40 RPM, a “dogbone” width of 13 fibers is required.

Further testing has to be done to determine the relationship between “dogbone” width and fiber orientation angle, part length, and part diameter.

Impregnation System

Testing
The impregnation system was tested by first adjusting the rubber bushings giving tension to provide between 4-6 lbs of force. The fibers were run dry though the bath to see the effectiveness of the rollers. Minimal fiber abrasion and breaks were observed and were attributed mostly to poor carbon fiber quality coming off of the spool. The bath was then filled to the desired height (center point of bottom roller). Running the fiber through the bath, the bending of the fiber around the brass rollers allowed quality impregnation, while the nylon rollers provided significant removal of excess resin.
The impregnated fibers were cured over a period of a few days and weighed against fibers of the same length to quantify an aspect of impregnation.

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<th>Mass (g)</th>
<th>λ (g/cm)</th>
<th>Mass (g)</th>
<th>λ (g/cm)</th>
<th>V_f (%)</th>
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</table>

**Table 5.1 Impregnated vs. Dry Fibers**

The above fiber volume fractions ($V_f$) are too low for what the majority of customers are interested in. Human error in pulling of the fiber, the lack of use of the squeegee rollers and the lack of control of viscosity of the resin contributed to the excess resin causing a lower $V_f$.

**Operation Instructions**

Operation Instructions for the control system and the filament winding machine can be found online at [https://edge.rit.edu/content/P09226/public/Home](https://edge.rit.edu/content/P09226/public/Home)

**VI. CONCLUSIONS AND RECOMMENDATIONS**

**Creel/Tension**

The tensioning system could certainly be improved in the future through the addition of electronic measurement and controls. These would be imperative in future designs utilizing multiple spools of fiber as differences in tension during winding could challenge the integrity of the part. With the assistance of Dr. David Orlicki (EET) we began a design for a future tensioning system featuring a DC gear motor and light sensor. In this system the fiber would be fed to a three pulley system. The first pulley is attached to a DC gear motor. The fiber is wound 2-3 times around the pulley to ensure no slipping as this is the pulley that will be responsible for taking up any slack. The fiber would then be fed down to a pulley attached to a tensioner. In this case this tensioner is of a set value with an attached adjustable spring scale. On this spring scale a light sensor would be attached. As the pulley moves up and down a flag attached to the scale would pass in front of the light sensor. This relationship would then be related to the tension in the fiber. Once relayed back the motor the system would be able to control slack in the line effectively imparting more or less tension.

**Mandrel**

Next steps for future iterations of the project include various mandrel shapes, including the creating of joints and more complex parts. Both joints and complex parts require more than two axes of movement. Varying cross sectional areas along a spinning mandrel, though, requires accurate control of speeds. As the feed eye travels along a non-uniform mandrel, the motor must increase and decrease speed along increasing and decreasing cross sectional areas, respectively, to maintain constant fiber orientation angles. Parts and mandrels as such require collapse or removable mandrels. Possible options are foam, Aquacore, or wax mandrels that can be dissolved with force, water, or heat. Obstacles to these options include poor surface finishes and brittleness, along with deformation resulting from warm or hot impregnated fibers.

**Impregnation System**

The resin bath system, although able to accomplish our needs and goals, can be improved. First, the materials used for rollers (brass and nylon) can be changed with extensive testing to determine change in quality of impregnation. Materials with very smooth surfaces are recommended to minimize fiber abrasion while bending, and non-stick materials are
recommended for squeegee rollers that remove excess resin.
Further improvements include easier assembly and disassembly of parts in bath in order to faster, more effective cleaning (with acetone) and similarly, quicker reassembly for more part winding.
The resin used (Adiprene K X028 [2]) is a viscous fluid and is heated to 50°C in order to reduce viscosity. Over time, the resin, dropping in temperature and beginning to cure, becomes thicker and more difficult to impregnate into the fiber properly. Future iterations of the project should consider a heating plate under the bath that will maintain a comfortable temperature to maintain desired quality in the part over lengthened winding times.

Motor Selection

Considering the limitations of our machine in terms of fiber orientation angle and running speeds, further analysis and time can be devoted to upgrading current motors in terms of torque capabilities. Higher torques will allow shallower angles than the minimum 70° and at higher speeds for a shorter process time. It is also in the scope of the project to begin winding multiple fibers at once, which also requires the mandrel motor to increase its capability.
Significant amounts of heat are generated from both motors over the winding process, especially the high torque mandrel motor. Currently, the aluminum motor mounts serve as a conducting surface to dissipate heat, but further research should be done for more effective heat transfer off of the motors.

Controls Selection

Currently, the control system is set up for simple interactions and pre-programmed tables for winding. Any emergency action must be taken in part by the operator by cutting power to the system. An active feedback system is recommended to detect fiber breaks or other emergency stop situations and react immediately by shutting down or halting the system.
The new tensioning system design can be fitted with switches that can detect total tension loss (fiber break) and concurrently shut down the system. It would also be wise to implement operator switches for Emergency Stop, Pause, and Reset, varying with possible troubleshooting and failure modes.

REFERENCES


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