# PRESS LAMINATION MANUFACTURING PROCESS OF PREPREG COMPOSITES

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**Abstract:**
Prepregs are products of combining a modified resin system with a preform of reinforcement textiles to obtain the desired properties. This thesis studies the main principle of making prepreg, the industrial processes that manufacturers use, and how to apply that process on a smaller scale for the Arcada lab room.

The author did research on the two most commonly used groups of processes: hot-melt and solvent coating processes. The result shows the importance of precise control of the resin content of the uncured prepreg because it ensures the right amount of resin to fill out all the internal areas of the textile. The initial amount of resin and the excess resin to be removed have to be calculated beforehand. The change in the amount of resin inside the system leads to a change in the total thickness of the prepreg. Research has shown that, by controlling that change in thickness of the prepreg, we can ensure that the exact amount of excess resin can flow out without causing fiber distortion and voids creation.

Next, the author had to test out different combinations of glass fiber, Jute, and carbon fiber and resin systems by hand laminating. The result showed mismatches between the textile structure and the resin viscosity, with the additional effects of surface tension, flow speed, or the use of additives. Higher density textiles behave better with pressure, while lower-density one's exhibit flaws like porosity and yawn displacements.

A small scale prepreg machine was then designed based on controlling the resin content to deal with the problems of voids and incomplete wetting. It can be made by assembling laser cut parts while a set of screws while controlling the height of the working surface. The machine is compact, easy to assemble, and can be maintained or upgraded by other students. This can provide better control of quality for the prepregs made in the Arcada lab. The main downside is that the machine and the prepregs made by hand impregnation cannot be tested for physical properties due to the Covid-19 pandemic.

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## Abbreviations and Units

| TERM | DEFINITION | UNIT |
|---|---|---|
| **m** | Mass | *kg* |
| ***M*** | Area mass | $kgm^{-2}$ |
| ***t*** | Thickness | *m* |
| ***w*** | Width | *m* |
| ***A*** | Area | $m^2$ |
| ***V*** | Volume | $m^3$ |
| ***f*** | Volume fiber fraction | - |
| ***F*** | Force | *N* |
| ***ρ*** | Density | $kgm^{-3}$ |
| ***N*** | Extensive property | - |
| ***η*** | Intensive property | - |
| $\boldsymbol{F_{displacement}}$ | Displacement forces | *N* |
| $\boldsymbol{F_{vertical}}$ | Force acts in vertical direction | *N* |
| $\boldsymbol{F_{horizontal}}$ | Force acts in horizontal direction | *N* |

# 1 INTRODUCTION

## 1.1 Motivation and purpose

Prepregs, or Pre-impregnated materials, are the semi-finished product of inserting a modified resin system into layers of reinforcement fibers or fabrics. Its potential of maximum strength properties compares to other traditional methods lead to global usage in various application, such as the aerospace industry, automotive, wind turbine, etc. Market research in 2013 showed that more than half of the global fiber production is for prepreg manufacturing, and this figure is increasing annually (Lengsfeld, et al., 2015). To obtain the best properties of the prepreg, a production line must be controlled and operated with precise machinery. This is why making prepreg is considered more complex and difficult compared to other traditional materials.

In Arcada, students practice making prepreg by vacuum or press laminating. Between the two methods, press laminating has the advantage of well-defined surfaces and thickness measurement, which make it more comparable to the process in the industry. Resin is applied by hand into layers of fiber, and then excess resin is removed by rolling motion. Finally, the whole preform is put into the hydraulic press machine and leave there to finish curing. Like the process in the industry, many elements need to be defined for the best result. The key elements of the process are the resin content, the pressure applied to the system, and the duration that pressure being active. Between them, resin content is considered the most important and the hardest to control precisely. This creates the motivation for this thesis, which is to better understand how to control the resin content of a prepreg, and how to do that without the help of precise machinery. It would be very helpful to have a system that provides a degree of quality control to every prepreg made in the lab room of Arcada.

## 1.2 Objectives

The aim of this thesis is to understand the theory of making a prepreg, how manufacturers are doing it, and how to apply the same process to a smaller scale. Therefore, the objectives of the thesis are listed as follow:

- Study the process line of making prepreg in the industry and the principles behind making a good prepreg.
- Combine different combinations of resin and textiles to find out which materials are suitable for press lamination.
- Design a laminating machine to control the resin content of the prepreg and improve the hand lamination process.

# 2 LITERATURE REVIEWS

## 2.1 The model problem

Making a good prepreg requires precise control and a good understanding of the resin flow and how it behaves under the influence of heat or pressure being added in the cured state. As the author is using the pressed laminating process, the laminate is put into a press machine to cure after the hand lamination is done. Figure 1.1 shows how the resin flows inside the laminate moves and how the whole system is reacting to the pressure. The top layer is usually a breather, which is a layer of fiber that allows the airflow and excess resin to exits the laminate, and in this case, vertically. The plies of the textile below the breather lose its excess resin to the breather and being pressed closer to each other. This creates a change in resin content and thickness of the laminate, which is essential in predicting and controlling the final thickness and properties of the prepreg.

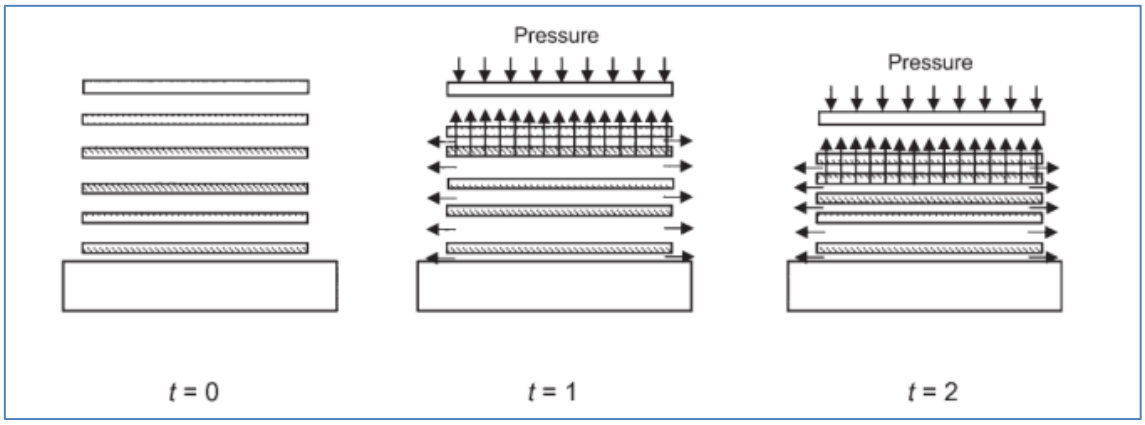


***Figure 1.1*** *Resin flow in horizontal and vertical directions under pressure over time. (Campbell, 2010, p.210)*

The initial amount of resin put into the system is an influent of the motion of flow inside a prepreg system. To better understand that motion and its effect on the whole preform, we can relate it to an easier system: a water barrel (as shown in figure 1.2). Suppose the water barrel has an amount of water at height $H_1$, an internal pressure $P_0$, and a hole with dimension $d$ at height $H_2 < H_1$. This hole allows the water between H1 and $H_2$ to flow out of the barrel, with the velocity depending on the size of the hole. The difference in pressure between the inside and outside of the barrel also contributes to helping the water flows out. However, the speed of the flow can increase if we apply another pressure $P_1 > P_0$ to the top of the barrel, squeezing out more water per second. Eventually, the water level will decrease down to $H_2$ after time t, and the water stop flowing out. By this time, no more pressure should be applied to the barrel, or it will start deforming the barrel.

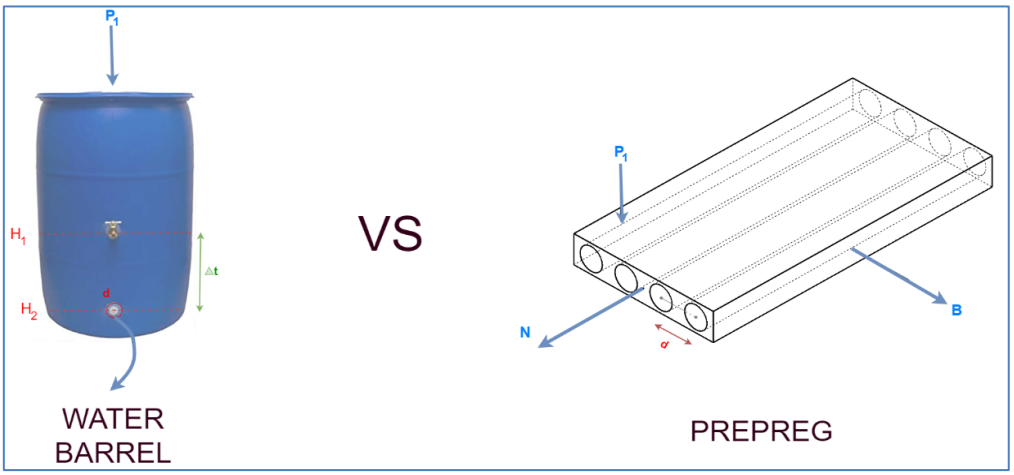


***Figure 1.2*** *Comparison between a water barrel and prepreg system.*

The same concept can be used for a prepreg system. After the resin is put into the textile by hand impregnation, excess resin needed to be removed from the $d$ area between the yawns. This also reduces the thickness from $t_0$ to $t_1$, which is the same as the two levels of water in the barrel. We also must define this thickness, but this will be discussed in chapter 2.3.1. Ideally, we want enough resin to fill the area between the yawn (Navier-Stokes flow) and inside the yawn (Brinkman flow). The preform is pressed down vertically, and resin flows out in the direction of the yawn and decreases the thickness of the whole system. However, there is more thing to be considered, compared to the water barrel. First is the amount of resin to put in at the start and later remove out of the system. This depends on the fluid properties, mainly the viscosity, because it will affect the way it flows within the textile. The pressure should be higher than the Navier-Stoke flow between the yawn and Brinkman flow inside the yawn to drive the resin out, but also not too high. For example, too much high viscosity resin with high pressure will lead to high displacement force and will probably ruin the product. One last element to note is that resin will cure in a relatively short time, so pressure must be a function of time.

## 2.2 Manufacturing processes

As mentioned earlier in this thesis, the material is named "prepregs" is because of the pre-impregnated resin matrix that is being put into the fibers. This matrix has the potential to reinforce the already lightweight fiber to make a good performance fiber composite. The matrix is often very viscous and can be made by both thermoplastics and thermosets. Meanwhile, fiber materials are delivered in various forms: uni-, bi- or multidirectional, woven, or non-woven, or fabric in mats or rovings. Figure 2.3 shows how the finished prepregs are delivered in unidirectional (UD) and fabric forms.

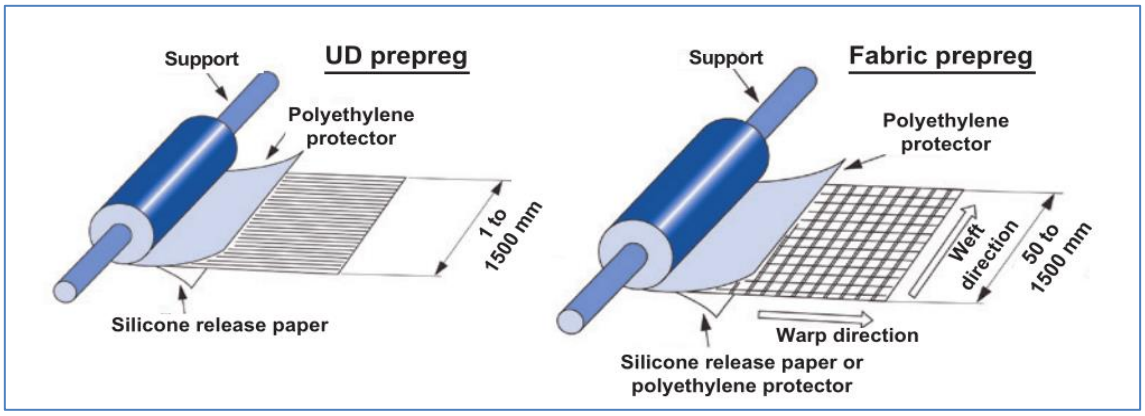


***Figure 2.3*** *Delivery form of UD prepreg (left) and fabric prepregs (right) (Hexcel, 2013, p.5)*

The current state of prepreg manufacturing promises a very high level of consistency in quality. However, the processes are complex and difficult: manufacturers must consider many parameters like temperature, winding, or drying, and then adapt to individual processes with each product. Furthermore, the base material requires cautious handling, while the finished product needs to be carefully stored and refrigerated. The selection of the manufacturing process is also important: manufacturers can base on the nature of the fiber reinforcement and matrix to plan what to expect how the final product will perform. In this chapter, the two most common impregnating methods in the industry, which are hot melt processes and dipping solvent processes, is being discussed. Both methods utilize the same design of production line, which is shown in figure 2.4: they consist of the following stations: creel set, impregnation/calender station, and cutting/winding station.

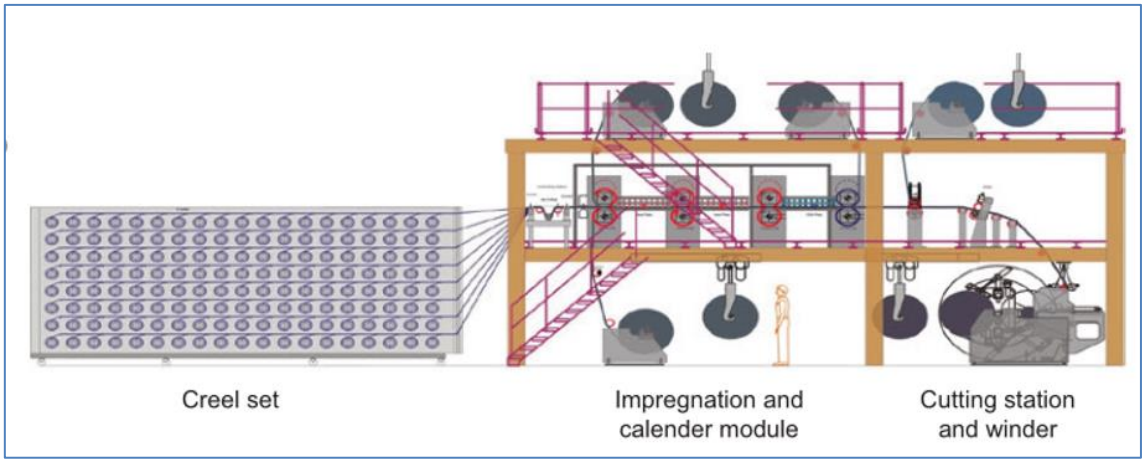


***Figure 2.4*** *Schematic design of a prepreg manufacturing line. (Lengsfeld et al., 2015, p. 31)*

### 2.2.1 Hot Melt Processes

Hot melt processes require the production of suitable resin coating, which is used in the impregnation zone later explained in this section. The coating's base material consists of epoxy resin, tougheners, curing agents, and other components if needed. The tougheners make the prepreg resin very viscous and will cure at elevated temperature, so it is homogenized when being extruded with the system. The mixture is then extruded and stuck into silicone-coated carrier paper by heated calender rolls. The papers are rolled into cores and refrigerated to be ready for the next processing step. Figure 2.5 summarizes the whole production line of resin coating. This line is continuous, offer large quantities of resin firm with very high consistency in product quality, which explains why it is being used widely, especially in the making of automotive, aircraft, and other industries.

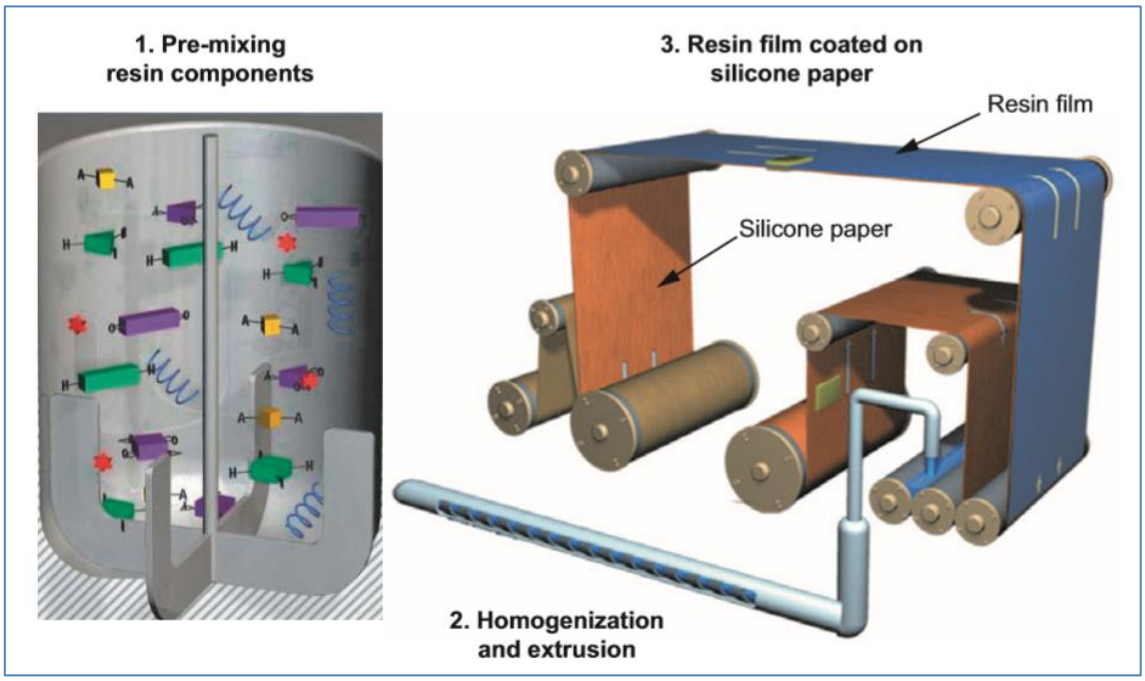


***Figure 2.5*** *Schematic of resin film production line. (Lengsfeld et al., 2015, p. 32)*

A hot melt system is often automated: it directly feeds the resin film into the prepreg line. Figure 2.6 presents a hot melt prepreg production line, divided into three zones: pre-impregnation, impregnation, and post-impregnation. The first zone has a creel set with bobbins of glass or carbon fiber rovings or tows. The finished prepreg's fiber areal weight (FAW) and nominal width decide the number of bobbins in the set. Fiber

rovings or tows are led to the machine by guide rolls and fiber eyelets. The creel set has a special mechanism to control and maintain the same level of fiber tension of every bobbin. This proves to be one of the crucial parameters for high-quality prepregs: fiber tension affects the tensile strength while also prevent buckling and wrinkles in the finished products.

The last section of the pre-impregnation zone is the comb and spreader. The comb separates a certain amount of roving per comb hole to prevent the fiber from crossover each other. The number of roving per comb hole is also adjustable to tune the nominal width of the fiber bed and help the spreader bars to achieve the target FAW uniformly across the web (C.A.Litzler Co., 2020). In some larger prepreg machine, they utilize a double comb system to further control the outcome quality. Next, the fiber goes through a spreader, where it passes several spreader and guide bars. The bars usually have small and fixed diameters, but they can be adjustable by change the spacing between them and the angle that the fiber passes over them. By doing that, spreaders help achieve a uniform distribution of FAW across the prepreg area while also partially affect the wettability of the finished products.

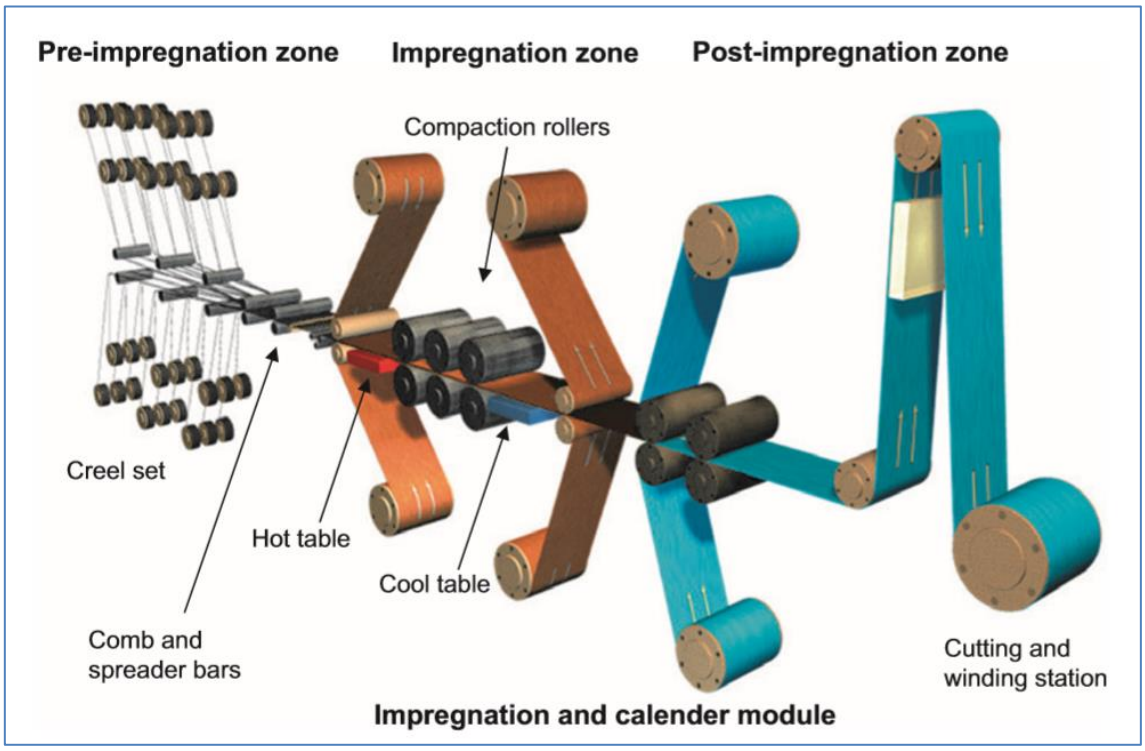


***Figure 2.6*** *Schematic of hot melt prepreg production line. (Lengsfeld et al., 2015, p. 33)*

At the center of the production line are the impregnation zone, consist of two tables (one hot and one cold) and several compaction rollers. These rollers are the heart of the whole production line because the parameters that it controls here mostly decide the outcome of the machine. But before going into the zone, the fiber is sandwiched between two resin films, which is mentioned at the start of section 4.2.2. However, these films do not have to be the same; in fact, they usually have different areal weight. This is because the manufacturer can tweak the areal weight of one or both of them to control the resin content of the uncured prepreg (in wt.%). According to Lengsfeld et al., 'typical resin contents range from 30 to 45 wt.% for carbon fiber prepregs, and from 40 to 60 wt.% for glass fiber prepregs'.

After the first calendar, the fiber is heated in a heating table with infra-red light to decrease the viscosity to approximately 10 Pa.s (Lengsfeld, et al., 2015). The temperature is decided base on the behavior of the matrix under heat, the speed that the resin bed is being fed into the machine, and the wanted impregnation level. After being heated, the material is fed into several calender rolls, which press the matrix into the fiber bed from both sides. These rolls are called compaction rolls, and it can be the most important component of the process. They can also be fully or partially heated to control the resin viscosity. The distance between the upper and lower rolls is the number one factor to control the degree of impregnation of the prepreg. That distance is set by changing the roll clearance or the applied pressure being put on the fiber bed. Here is where all the complexity and difficulty of the hot-melt process show most dramatically: the finished product's quality is affected by different parameters like line speed, temperature, matrix viscosity, etc., and they mutually influence each other. The most critical of them must be process temperature because, in each processing step, the resin system only makes certain limited reactions, which is caused by the increasing temperature. Some of these reactions are often desired to alternate the viscosity and the resin flow of the prepreg during curing state and the next component manufacturing.

After the impregnation is done, the cooling table cools off the material to about room temperature before they enter the post-impregnation zone. Here the resin film's carrier paper is removed and replaced with new silicone-coated paper or polyethylene film. The

new film is chosen base on the customer's desire, mainly to avoid contamination, prevent the prepreg from adhering to itself and destroy the structure, or as a preparation for the next process, either by hand lay-up or automated production. The prepreg is then cut in the dimension of the customer's desire with rotary knives. Finally, it is wound up into cores, sealed in a film bag, and put into a deep-frozen state until it reaches the customer, as shown in figure 2.7.

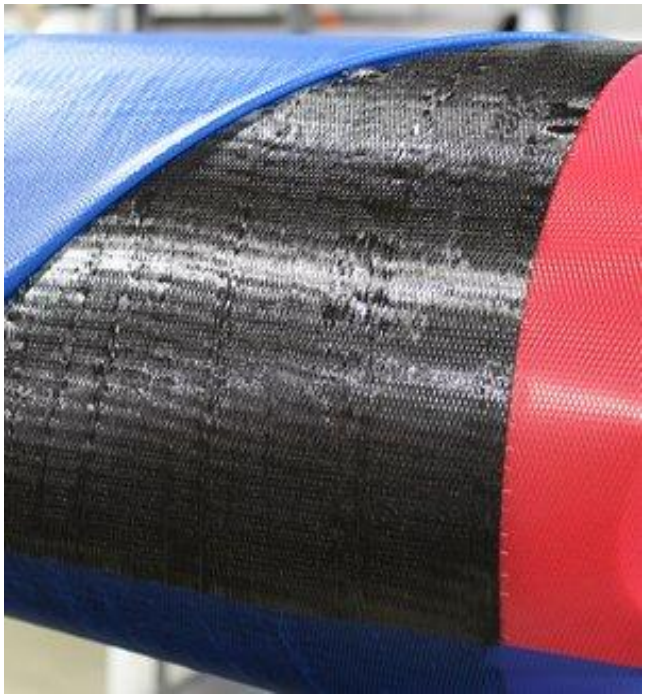

***Figure 2.7*** *A roll of UD carbon fiber prepreg with silicone-coated papers. (Fibre Glast Developments Corp., 2020)*

### 2.2.2 Solvent coating/dip methods

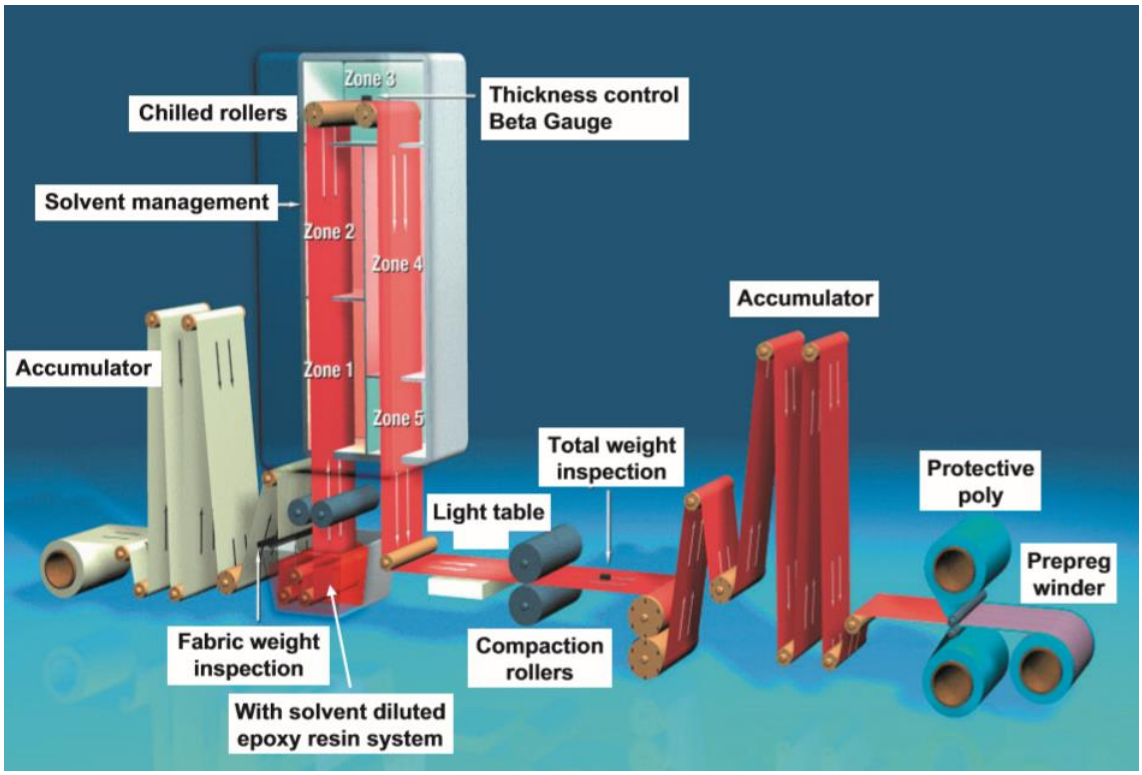


***Figure 2.8*** *Solvent coating/ dipping process (Lengsfeld et al., 2015, p. 36)*

A solvent coating/dipping production line is relatively different from the hot-melt line. Figure 2.8 shows an overview of the line, where the difference can be seen. This machine can be used for impregnating fabrics, but more often, it is for fiber tows, which is a long tow of fiber wound into carton core. The advantage of this form is that it has a much faster winding speed and higher consistency in resin content compared to fabrics. The finish products are called tow prepregs or towpregs (figure 2.9). The method allows the resin to fully penetrate the tow, which ensures the wettability of the prepreg. Rather than using the creel set in hot melt, solvent dipping uses a roll unwinder to unwind the tow from its core much faster. Here the tension of the fabric can be determined and controlled to prevent the formation of wrinkles and warpage on the fabric. Throughout the production line are sensors for weight inspection, one before the tower and one before the finishing step.

***Figure 2.9*** *A finished tow prepreg (Northern Composites, 2020)*

After the initial weight of the reinforcement is inspected, it runs through a solvent bath, which is diluted with the epoxy resin system. Inside the bath, the solution's capillary forces make sure the whole area inside the fabric is dipped with resin. The viscosity of this solution is determined by the resin content and the temperature of the bath. There is also a calender roll here to control the resin content and later prepreg thickness: it squeezes out the right amount of excess resin with the help of a doctor blade (figure 2.10). The tow is then fed into a vertical tower, which is separated into different zones. The tower has adjustable temperature control for each zone to achieve the desired properties of the prepreg. The heat and circulating air inside the tower also evaporate most of the volatile content of the material to meet the cost and environmental requirements. The material is then cooled down by the chilled rollers to immediately stop the resin flow and curing reaction of the prepreg. Also, in the same zone is the Beta Gauge for thickness control for testing the prepreg thickness. If modification is needed, the manufacturer can adjust the space between the compaction rollers that will be mention later in the production line.

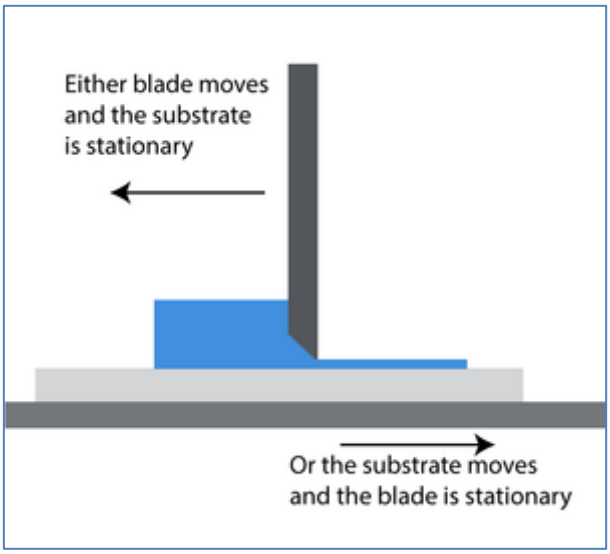


***Figure 2.10*** *Doctor blade mechanism for coating (Ossila Ltd, 2020)*

After leaving the tower, the material is optically tested with a light table for possible defects. It then has its areal weight determined by the compaction rollers. The total weight inspection sensor checks the weight one last time before the material is accumulated and laid upon films or silicone-coated carrier paper. The paper also helps to prevent contamination and self-sticking of the prepreg before they are wound on cores and sealed up in film bags, ready to be delivered. Unlike in hot melt processes, the prepregs do not have to be trimmed because its width is already decided by the width of the fabrics from the start of the line.

With its differences compared to hot melt processes (HM), solvent dipping processes have their advantages and disadvantages. The process is relatively easier to control compared to HM because the most important parameter is the solvent content, which can be adjusted with little to no problem depending on the desired properties of the prepregs. This also means it is easier to used high viscosity resin systems, even if there are insoluble particles inside them. Because the whole surface of the fabric is dipped into the solvent, the resin can penetrate the fiber and fill out all the area (both Navier-Stokes and Brinkmann, which is mentioned in chapter 2.1). Lastly, the finished prepregs usually have higher tack, which means it can adhere to other surfaces easier in subsequent production step, compared to the prepregs made by HM. However, this also depends on the combination of the resin system, fabric type, process temperature, and solvent con-

tent, which require manufacturers to be flexible in choosing which processes for each product and customer.

One big problem with the solvent coating process is that it cannot be used when there is unidirectional (UD) fiber involved. It is not common to use just UD fiber as reinforcement, but it can be used with other types of fiber, as the author has experienced in section 4.1. Without the weft interconnecting the warps, high viscosity resin can easily destroy the formation of the fiber, the same problem when doing the cold press in section 4.1. Lengsfeld et al. (2015) mentioned another solvent dipping process suitable for UD fiber, which is called the drum system, but it is only capable of small production runs and experimental cases. Another disadvantage that has to be mentioned is the solvent: its volatile content relates to many environmental concerns and regulations, while organic solvents have very high material and waste disposal costs. These problems reduced the use of solvent dipping processes and led manufacturers to experiment and use hot melt process in the last two decades (Lengsfeld, et al., 2015).

### 2.2.3 Manufacturing parameters

The finished prepreg properties are heavily influenced by the selection of parameters during the manufacturing process and also the process method itself. This section will explain some of the most common parameters that have an important effect on the materials: resin content, level of impregnation, and tack.

The resin content of the prepreg is the easiest parameter to control out of the three parameters. It is given in wt.%, which is the percentage of resin areal weight to prepreg areal weight. Resin content helps to define the final cured ply thickness and the total weight of the finished prepreg material.

***Table 2.1*** *Physical prepreg properties changes when resin content varies at 35 wt.% (Lengsfeld et al., 2015, p. 40)*

| | Unit | Physical prepreg properties | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prepreg areal weight | $g/m^2$ | 197 | 199 | 200 | 202 | 203 | 205 | 206 | 208 | 209 | 211 | 213 | 214 | 216 |
| Resin content | % | 32.0 | 32.5 | 33 | 33.5 | 34 | 34.5 | 35 | 35.5 | 36 | 36.5 | 37 | 37.5 | 38 |
| Resin areal weight | $g/m^2$ | 63 | 65 | 66 | 68 | 69 | 71 | 72 | 74 | 75 | 77 | 79 | 80 | 82 |
| Fiber areal weight | $g/m^2$ | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 | 134 |
| Resin volume content | % | 39.30 | 39.85 | 40.39 | 40.94 | 41.48 | 42.02 | 42.56 | 43.09 | 43.63 | 44.16 | 44.69 | 45.22 | 45.75 |
| Fiber volume content | % | 60.70 | 60.15 | 59.61 | 59.06 | 58.52 | 57.98 | 57.44 | 56.91 | 56.37 | 55.84 | 55.31 | 54.78 | 54.25 |
| Cured ply thickness (CPT) | mm | 0.123 | 0.124 | 0.126 | 0.127 | 0.128 | 0.129 | 0.13 | 0.132 | 0.133 | 0.134 | 0.135 | 0.137 | 0.138 |
| Compo-site density | $g/cm^3$ | 1.60 | 1.60 | 1.59 | 1.59 | 1.59 | 1.58 | 1.58 | 1.58 | 1.58 | 1.57 | 1.57 | 1.57 | 1.57 |

In their company product brochure, Hexcel Corporation (2013) did an experiment to show the change of various physical properties when the resin content is changed, while the fiber areal weight remains constant at 134 $g/m^2$. As shown in table 2.1, the most significant changes are observed in cured ply thickness (CPT) and fiber volume content (FVC). As the resin content rising, it increases fiber volume content while also decreases the cured ply thickness.

The level of impregnation is also another important parameter to consider during the manufacturing process. It shows how much the resin has penetrated and wetted the fiber material bet when being processed. A manufacturer can try different combinations of fiber and resin arial weight as well as different impregnation methods to adjust the level of impregnation.

However, the degree of adjustment also depends on the processes. For example, solvent coating processes often provide a fuller impregnated prepreg than the hot-melt process. This will prevent the formation of porosities and air pockets trapped inside the material because it is not possible to do so in subsequent process steps. Sometimes, some applications that required less than 100% impregnation will need the prepreg being made by hot melt processes because they can control the level of impregnation within certain limits. Some parameters can be varied during hot melt processes, such as impregnation temperature and duration or fiber arial weight, to further control the level impregnation. That level of control is important to manufacture UD prepregs: they have a thin interior area for resin flow and air removal. This means UD prepregs should not be fully impregnated, or the air trapped inside could not be removed, and porosities can be formed. The level of impregnation can also affect other properties like the drape and tack of the product. A low level of impregnation makes the material feel "softer", hence more flexible and drape easier to the surface. On the other hand, an uncured prepreg with a higher level of impregnation is harder to be handled or shaped into the mould when laying up. To make the exact product with the exact level of impregnation, manufacturers have to repeat the process many times while trying a new combination of parameters. These parameters are interdependent, but the most influencing is the manufacturing process, additives used, or the desired dimension of the final products.

The last property that the manufacturer should consider is the tack (or tackiness) of the prepreg. Tack determines the ability of the prepreg to stick onto the mould surface or adhere to itself. Having a good stick to the mould surface is essential to prepreg because most of the time, the prepreg is moulded into the product's shape. But when corrections are needed and the prepreg is peeled off, a good tack prevents the individual plies from slipping off from each other and keeps the formation. Even though tack is an important property, there is no standardized scale of tack being used in the industry. This is because of the variety of materials used in manufacturing while no universal testing methods have been invented. To deal with this problem, manufacturers usually make separate testing procedures for a specific group of products or some time for each application as well. One other acceptable reason for this is because tack is not easy to control while being affected by many other parameters, which is shown in figure 2.11.

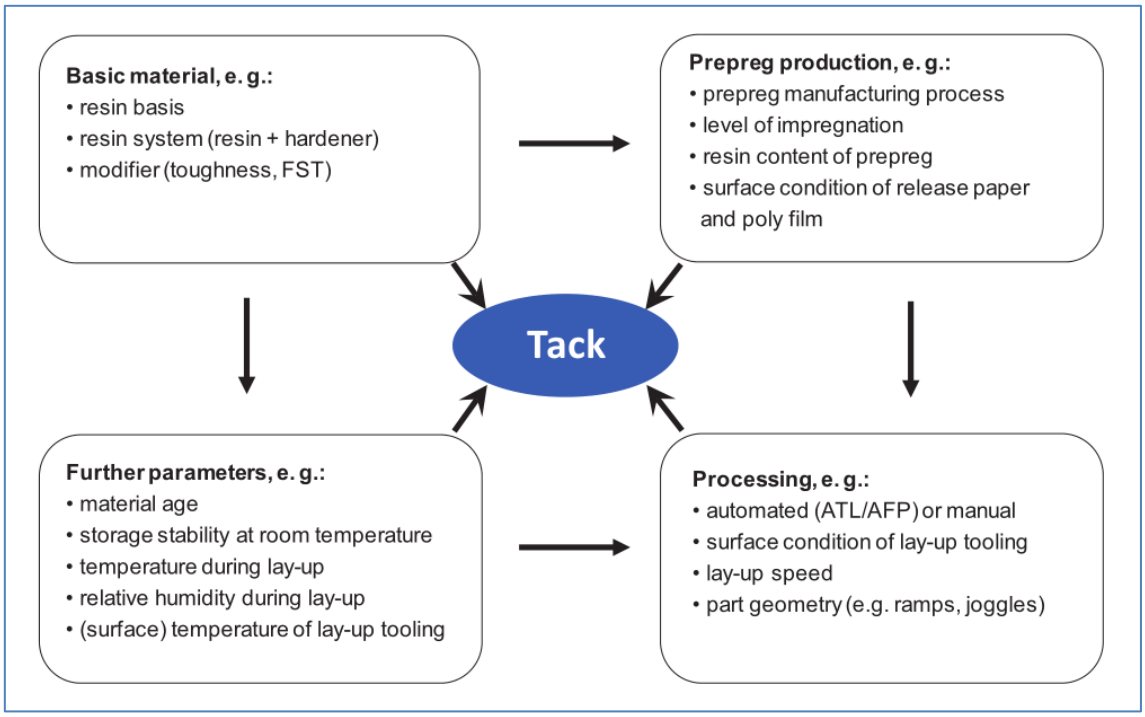


***Figure 2.11*** *Parameters affect tackiness (Lengsfeld, et al.,2015, page 44)*

These parameters also influence each other and also participate in deciding the final properties of the prepreg. Out of the four main groups, the raw material is having the most significant impact on the tackiness. Besides the easy part, which is controlling the resin content, the material selection has to be exclusively decided by the desired properties that the component gets in the cured state.

The tackiness of the prepreg is also influenced by the process that is used to make it. Manufacturers have to choose the most suitable process for each product because if there are errors, the only solution is to change the process method. Then there is a need for an expensive re-qualification of the materials used in the process and other related parameters like material aging and ambient conditions like humidity and temperature during the process. To sum up, there are a lot of parameters that can influence the outcome of a prepreg manufacturing process, and that is what makes the process more complex and difficult to manage.

## 2.3 Control the resin content

### 2.3.1 Thickness of a laminate

Controlling or predicting the final cured thickness of a laminated prepreg is a crucial part of the production process. This thickness is desired based on the need of the customers for their subsequent component manufacturing processes. Because a prepreg can be considered as a compound of mainly two components: the resin and the textile, so its properties, such as density, mass, or volume, can be calculated in the same way as a compound, with little modification.

If a compound that includes two components 1 and 2 is being considered, its engineering constants can be written as follow:

Total volume: $V_{total} = V_1 + V_2$ (1)

Total mass: $m_{total} = m_1 + m_2$ (2)

Volume fraction: $f_1 = \frac{V_1}{V_{total}}$ ; $f_2 = \frac{V_2}{V_{total}}$ ; $f_1 + f_2 = 1$ (3)

Density $\rho = \frac{m}{V}$ (4)

From equation (2) and (4), we got:

$$m_{total} = m_1 + m_2 <=> \rho_{total} V_{total} = \rho_1 V_1 + \rho_2 V_2 \ (5)$$

Apply the volume fraction from equation (3), then:

$$\rho_{total} V_{total} = \rho_1 f_1 V_{total} + \rho_2 f_2 V_{total}$$

$$=> \rho_{total} = \rho_1 f_1 + \rho_2 f_2 \ (6)$$

This means the total density $\rho_{total}$ of a two-component compound is the sum of the two-combining density $\rho_1 \ and \ \rho_2$, but with the scaling factor of the volume fraction $f_1 \ and \ f_2$.

Equation (6) can be simplified as:

$$\rho_{total} = \rho_1 f_1 + \rho_2 (1 - f_1) \ (7)$$

To apply the same calculation for a prepreg lamina with known area mass ($\frac{kg}{m^2}$), which means in practice, the student can control this by weighing the dry textile plies before

doing the lamination. The system now consists of resin and dry textile, to the total volume is:

$$V_{total} = V_{resin} + V_{textile}$$

$$m_{total} = m_{resin} + m_{textile}$$

With fiber volume fraction $f = \frac{V_{textile}}{V_{total}}$ $and$ $1 - f = \frac{V_{resin}}{V_{total}}$

Consider:

$$1 - f = \frac{V_{resin}}{V_{total}} = \frac{\frac{m_{resin}}{\rho_{resin}}}{A.t_{total}} \quad (8)$$

Here the total volume $V_{total}$ equals the area A multiply by the total thickness $t_{total}$. The mass of resin is also equal to the total mass minus the textile mass. Now equation (8) can be rewritten as:

$$1 - f = \frac{m_{total} - m_{textile}}{\rho_{resin}.A.t_{total}}$$

$$\boxed{t_{total} = \frac{m_{total} - m_{textile}}{\rho_{resin}.A.(1-f)}} \quad (9)$$

There is one more way to calculate the total thickness of a prepreg lamina, which include the usage of fiber volume fraction $f$ and the area mass of textile $M_{Fiber}$.

The area mass is $M_{Fiber} = \frac{m_{textile}}{A} \left(\frac{kg}{m^2}\right)$

While fiber volume fraction is:

$$f = \frac{V_{textile}}{V_{total}} = \frac{m_{textile}}{\rho_{textile}.A.t_{total}}$$

$$=> f = \frac{M_{Fiber}}{\rho_{textile}.t_{total}}$$

The total thickness is then:

$$\boxed{t_{total} = \frac{M_{Fiber}}{\rho_{textile}.f}} \quad (10)$$

To sum up, the whole idea of the above calculation is that at a base level, one can calculate the final thickness of a laminate with all the basic parameters related to the added fiber and textile. This calculation is the core idea of the small scall laminating machine that is presented in section 4.3. Now the pressure has to be taken into consideration because this also affects the properties of the cured prepreg.

### 2.3.2 Volume of excess resin

In the last section, the author has given the theoretical calculation of the thickness. However, under the application of pressure, the resin flows inside the material changes and, thus, alternate the thickness of the whole system unpredictably. To combat this problem, manufacturers will make a prediction of the volume of excess resin based on the change in thickness in the final product. This allows them to calculate the amount of initial resin to put in to obtain the desired thickness without wasting too much excess resin. This can be formulated as followed.

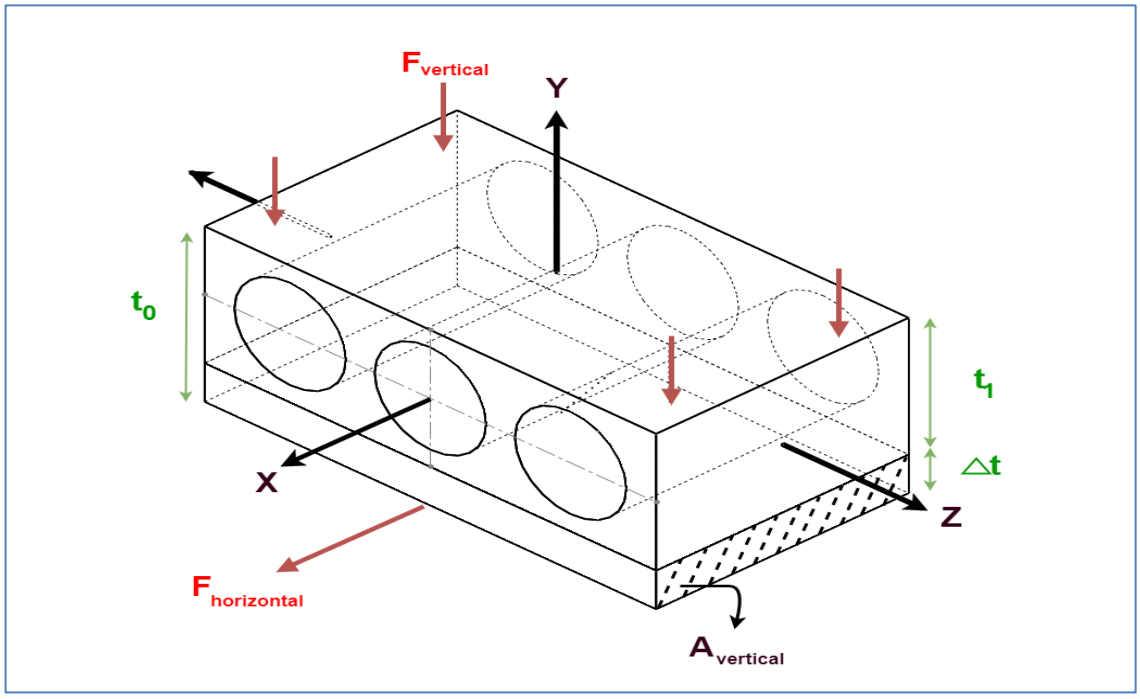


***Figure 2.12*** *Schematic of a unidirectional prepreg under hydrostatic pressure.*

Suppose the prepreg (figure 2.12) has the initial thickness $t_0$ consist of layers of unidirectional textile with known area mass $M$ with unit $\frac{kg}{m^2}$. The thickness $t_0$ is:

$$t_0 = \frac{M}{\rho f_0} \quad (11)$$

With $\rho$ is the density of the textile and $f_0$ as the intrinsic volume fiber fraction of the resin.

After being pressed with $P_{vertical}$, excess resin is removed and the total thickness of the prepreg decrease to $t_1$, while the volume fiber fraction also change to $f_1$.

$$t_1 = \frac{M}{\rho f_1} \quad (12)$$

The change in thickness $\Delta t$ can be calculated as:

$$\Delta t = t_0 - t_1 = \frac{M}{\rho}\left(\frac{1}{f_0} - \frac{1}{f_1}\right) \quad (13)$$

Alternatively, this can be rewritten for faster calculation:

$$t_0 f_0 = t_1 f_1 \rightarrow t_{end} = t_{start}\frac{f_{start}}{f_{end}}$$

$$\Delta t = t_{end} - t_{start} = t_{start}\frac{f_{start}}{f_{end}} - t_{start}$$

$$\Delta t = t_{start}\left(\frac{f_{start}}{f_{end}} - 1\right) \quad (14)$$

Because $P_{vertical}$ is a hydrostatic pressure acting in the prepreg, it is also equal at any point with the same height. It is also the pressure acting on the resin flow:

$$P_{resin} = \frac{F_{vertical}}{A_{horizontal}} \quad (15)$$

This pressure also creates a resin movement inside the prepreg, either in the X directions (Navier-Stokes flow) or in the Z direction, which can displace the yawns if the pressure gets big enough to overcome the movement inside the yawn (Brinkman flow). The yarn displacement pressure can be calculated as:

$$P_{displacement} = \frac{F_{displacement}}{A_{vertical}} \quad (16)$$

$$F_{displacement} = P_{resin} A_{vertical} = P_{resin}(\Delta t\, L)$$

Using equation (15) from above, we get:

$$F_{displacement} = \frac{F_{vertical}}{A_{horizontal}}(\Delta t\ L) = \frac{F_{vertical}}{wL}(\Delta t\ L)\ (17)$$

However, in practice, the further the resin travel in the Z direction from the center of the prepreg, the bigger the displacement force it causes to the outer yawns. We can call this distance $s_{flow}$, hence the force is now:

$$F_{displacement} = F_{vertical}\frac{\Delta t}{s_{flow}}\ (18)$$

As shown in figure 1.2, the force $F_{displacement}$ is perpendicular to yarn in the flow direction, which also makes it bigger at the edge of the textile. Figure 4.30 in chapter 4 Results shows this yawn displacement very clearly.

An amount of excess resin should be removed to get the desired thickness $t_1$. This volume of resin can be calculated as followed:

$$\boxed{\Delta V_{excess\ resin} = \Delta t \cdot A_{horizontal}}\ (19)$$

Overall, this equation can be used to calculate the amount of excess resin, with an initial thickness $t_0$ and fiber volume fraction $f_0$ as your choice. Taking into consideration the hydrostatic pressure and the displacement forces, we can calculate the exact amount of resin we want inside the prepreg. However, in reality, we have to put more than that amount to make the resin fill all the space inside, which will confirm maximum strength properties. This amount of resin also depends on the resin's properties. For example, with high viscosity resin: too much resin movement will cause the yawn to displace. The last thing to consider is how fast we applied the pressure to the prepreg to squeeze out the excess resin without damaging the yawn and keep enough resin inside. This sums up the whole process in the industry; however, as we are making a practice prepreg, we can focus mostly on controlling the resin content of the prepreg.

## 2.4 Navier-Stokes equation

### 2.4.1 Introduction

In physics, a fluid is known to have no shear modulus, which means it cannot support any shear stress in static equilibrium. It can only resist a relative rate of deformation in a dissipative, frictional manner. The rate of deformation is called its viscosity. Unlike solids, which can respond to both shear stresses and normal stresses, fluids can only do the same to normal stresses with restoring forces called pressure. Fluids have free surfaces that need some free energy to form. The amount of free energy needed to form the free surfaces is called surface tension, which is also a core element of how a fluid can flow. In the equilibrium state, fluids will try to minimize their surface energy by forming rounded droplets. The shear stress in fluids is a function of strain rate or the change in strain/deformation of the material with respect to time. If the stress in a fluid is directly proportional to the rate of strain, that fluid is called Newtonian fluid. On the contrary, a fluid is called non-Newtonian when its stress is not proportional to the rate of strain ('Fluid', 2020).

Studying the fluid's behavior, or fluid mechanics has a history that dates back to at least the ancient Greek time as when Greek mathematician Archimedes first investigated fluid static and buoyancy. He is known for the famous word "Eureka" and the Archimedes' principle, which many considered to be the basis of hydrostatic. Advancements in fluid mechanics have been made by many mathematicians in the following centuries when more experiments and investigations are made. One of the biggest results is the foundation of Navier-Stokes equations, which is named after French physicist Claude-Louis Navier and Anglo-Irish mathematician George Gabriel Stokes. These equations are exceptionally useful for explaining many phenomena of scientific and engineering interest related to fluids. They are applied for almost any type of fluid, from the blood flow in the human body, the flow of water in the sea to the flow of winds circulating in the air. This helps experts model the weather, predict the sea currents, study the blood flow, or design the aircraft wings based on how the airflow around it. The Navier-Stokes equations are still a mathematical interest for many till today because they are not fully

solved yet. It is called one of the seven most important open problems in mathematics, offering an award of 1 million USD offered by The Clay Mathematics Institute for the person who can solve it. These equations are also important in analyzing the flow of resin inside the prepreg and will be discussed later in this chapter, together with other important laws and flow analysis techniques ('*Navier–Stokes equations*', 2020).

In this thesis, the author will try to explain the Navier-Stokes equations (69) from the most basic knowledge of fluid mechanics. This includes the idea of a fixed mass system and the usage of control volume analysis and differential analysis to analyze the momentum in a control volume. The result and the full Navier-Stokes equations can be seen in chapter 2.4.8.

### 2.4.2 Methods of studying fluid mechanics

When studying fluid mechanics, there are different ways one can analyze a certain flow. The commonly used methods are control volume, infinitesimal systems and experimental. Control volume analysis (or integral analysis) is a quick tool but crude because it usually involves many assumptions and approximations. The results of this method are generic forces or mass flow rate, which mean this is good for preliminary study. Overall, it yields reliable quantitative information. Infinitesimal systems, or differential analysis, is the process of deriving governing equations for a certain mass resulting in partial differential equations. Unlike the control volume analysis, this method does provide velocity profiles of the flow, or so-called the boundary layer. The solutions to these equations depend on if the flow being inviscid or not. The Euler equation (which is not mentioned in this thesis) is used for inviscid flow, while the Navier-Stokes equation is for viscid flow. These equations are time-consuming and laborious to solve by hand. However, the rapid development of the computer in the last century enabled them to be solved numerically with computing power. This method of analyzing forms the basis of Computational Fluid Dynamics, or CFD for short (SimScale, 2020).

The last method is experimental study, in which experimentalists do a dimensional analysis before experimenting. This method is needed when a situation or scenario is so

complex that numerical methods are not adequate to understand. Those situations are mostly sub-scale of full-scale systems, where one tries to study something in their reduced scale first and then see how it scales up to the real world. To understand the flow inside a system of prepreg, we will focus more on the Infinitesimal systems method in this chapter (Ron Hugo, 2015)

### 2.4.3 Basic terminology

The velocity field $\vec{V}$ describes the distribution of velocity in any given region and is the most important property of a fluid as all other properties follow from it. The velocity of the flow is a vector function of space and time (Ron Hugo, 2015):

$$\vec{V}_{(x,y,z,t)} = \hat{\imath}.u(x,y,z,t) + \hat{\jmath}.v(x,y,z,t) + \hat{k}.w(x,y,z,t)$$

Or $$\vec{V} = \hat{\imath}.u + \hat{\jmath}.v + \hat{k}.w \quad (20)$$

Where $\hat{\imath}, \hat{\jmath}, \hat{k}$ are the unit vector and $u, v, w$ are the velocity component in X, Y, Z directions. Here kinematic properties of the flow can be mathematically derived from the velocity field.

Acceleration is also something very important when analyzing a flow because of its relation to Newton's second law, and can be written as follow:

$$\vec{a} = \frac{d\vec{V}(x,y,z,t)}{dt} = \frac{\partial \vec{v}}{\partial t} + \frac{\partial \vec{v}}{\partial x}\frac{dx}{dt} + \frac{\partial \vec{v}}{\partial y}\frac{dy}{dt} + \frac{\partial \vec{v}}{\partial z}\frac{dz}{dt} \quad (21)$$

As $u, v, w$ are the velocity component in X, Y, Z directions, they can be written as:

$$u = \frac{dx}{dt} \qquad v = \frac{dy}{dt} \qquad w = \frac{dz}{dt}$$

Acceleration is then:

$$\vec{a} = \frac{\partial \vec{v}}{\partial t} + \left(u\frac{\partial \vec{v}}{\partial x} + v\frac{\partial \vec{v}}{\partial y} + z\frac{\partial \vec{v}}{\partial z}\right) \quad (22)$$

With $\frac{\partial \vec{v}}{\partial t}$ is the local acceleration, which is the rate of change of velocity with respect to time at a given point in the flow field. Meanwhile, the term $u\frac{\partial \vec{v}}{\partial x} + v\frac{\partial \vec{v}}{\partial y} + z\frac{\partial \vec{v}}{\partial z}$ is the

convective acceleration or the rate of change of velocity due to the change of position of fluid particles in a fluid flow.

Many physical properties of a fluid can be expressed mathematically in terms of the flow velocity. For example, when the flow is steady, the $\vec{V}$ does not vary with time. A fluid is considered incompressible when the divergence of the $\vec{V}$ is zero. A flow is irrotational if the curl of $\vec{V}$ is zero. Divergence and curl are two important vector relations that we will mention later in this chapter. To sum up all the above:

$$Steady\ flow: \frac{\partial \vec{v}}{\partial t} = 0 \ (23)$$

$$Incompressible\ flow: \nabla \cdot \vec{V} = 0 \ (24)$$

$$Irrotational\ flow: \nabla \times \vec{V} = 0 \ (25)$$

### 2.4.4 Fixed mass system

When an object is being modeled as a continuum in continuum mechanics, it comes with assumptions that the substance of the object fills the space it occupies. This means that the object is put into a fixed mass system, allow fundamental physical laws like conservation of mass, conservation of momentum, and conservation of energy to be derived from it. These equations can be expressed as follow:

- Conservation of mass: the mass of the system does not change with respect to time

  $$\frac{dM}{dt} = 0 \ (26)$$

  where that mass can be defined:

  $$M_{system} = \int_{mass(system)} dm = \int_{V(system)} \rho \, dV \ (27)$$

- Conservation of linear momentum: the forces are equal to the time rate of change of momentum within the system

  $$\vec{F} = \frac{d\vec{p}}{dt} \ (28)$$

  With linear momentum $\vec{p}$ to be defined as:

$$\vec{p} = \int_{mass(system)} \vec{v}\ dm = \int_{V(system)} \vec{v}\ \rho\ dV \quad (29)$$

- Conservation of angular momentum with the specific angular moment $\vec{H}$

$$\vec{H} = \int_{mass(system)} \vec{r} \times \vec{v}\ dm = \int_{V(system)} \vec{r} \times \vec{v}\ \rho\ dV \quad (30)$$

- Conservation of energy, or the First Law of Thermodynamics:

$$\dot{Q} + \dot{W} = \frac{dE}{dt} \quad (31)$$

Where: $\dot{Q}$ is heat transfer across the boundary

$\dot{W}$ is work across the boundary

$E$ is the energy within the system, which can be defined as:

$$E_{system} = \int_{mass(system)} e\ dm = \int_{V(system)} e\ \rho\ dV \quad (32)$$

With $e = u\ + \frac{v^2}{2} + gz$ (energy per unit mass)

### 2.4.5 Control volume analysis – Conservation of mass formulation

Reynolds transport theorem is a very useful tool to transfer the above equations of basic laws to use in a control volume system where there is mass crossing the boundary and create a flow of motion. The theorem is the necessary framework to move the derivative within the integral or the rule of differentiation under the integral sign. This would provide a system derivative of the control volume formulation of the above conservation laws and other basic equations of continuum mechanics.

As a start, the extensive property and intensive property are defined as N and η, respectively. The extensive property can be the total mass, linear momentum, angular momentum, or energy, while the intensive property is the value of extensive property per unit mass. With the two properties, we can formulate an equation that applied to all the conservation laws, which can be expressed as:

$$N_{system} = \int_{mass(system)} \eta \, dm = \int_{V(system)} \eta \, \rho \, dV \quad (33)$$

This means that we can integrate the extensive property either across the mass or across the system. The properties for the four governing equations of basic laws can be rewritten as:

- Conservation of Mass: $N = M;\ \eta = 1$
- Conservation of Linear Momentum: $N = \vec{p};\ \eta = \vec{v}$
- Conservation of Angular Momentum: $N = \vec{H};\ \eta = \vec{v} \times \vec{v}$
- Conservation of Energy: $N = E;\ \eta = e$

The Reynolds transport theorem can be written as followed, which links the system approach to the control volume, with respect to both the volume and the surface area.

$$\boxed{\frac{dN}{dt}\Big| system = \frac{\partial}{\partial t} \int_{CV} \eta \, \rho \, dV + \int_{CS} \eta \, \rho \, \vec{v} \, d\vec{A}} \quad (34)$$

We can now rewrite the conservation of mass in a control volume formulation. This will be useful to understand the Navier-Stokes equation when we apply conservation laws to an infinitesimal control volume for the differential analysis method.

With $N = M;\ \eta = 1$, conservation of mass is now:

$$\boxed{\frac{\partial}{\partial t} \int_{CV} \rho \, dV + \int_{CS} \rho \left(\vec{v} \, d\vec{A}\right) = 0} \quad (35)$$

There are some special cases for this equation:

- Incompressible flow or flow with constant density $\rho$, then:

$$\int_{CS} \rho \left(\vec{v} \, d\vec{A}\right) = 0 \quad (36)$$

- Steady flow, where all the time rate of change will go to zero ($\frac{\partial}{\partial t} \equiv 0$), then:

$$\int_{CS} \rho \left(\vec{v} \, d\vec{A}\right) = 0 \quad (37)$$

- Uniform flow over the area, where the velocity vector does not change:

$$\int_{CS} \rho \left(\vec{v} \, . \, d\vec{A}\right) = \pm |\rho \, v \, A| = \pm \dot{m} \quad (38)$$

Here $\dot{m}$ is the mass flow rate, or the mass flux with the unit of kg/s or lb/s.

With $N = \vec{p};\ \eta = \vec{v}$, the conservation of momentum is now:

$$\boxed{\vec{p} = \frac{\partial}{\partial t}\int_{CV} \vec{v}\rho\, dV + \int_{CS} \vec{v}\rho\vec{v}\, d\vec{A} = \overrightarrow{F_S} + \overrightarrow{F_B}} \quad (39)$$

Where $\overrightarrow{F_S}$ and $\overrightarrow{F_B}$ are surface forces and body forces, respectively.

After applying the basic laws of conservation to the finite control volume, the result is an integration of the given velocity profiles. Therefore, control volume analysis is sometimes called integral analysis, and it is often considered a large-scale analysis because of the integration over the control volume and the control surface.

### 2.4.6 Differential Analysis - Equation of Mass Conservation

The differential analysis applies the basic laws of conservation into an infinitesimal control volume, rather than a finite volume in the last method. This volume is very small, so the analysis is concerning fluid mechanics on a point to point basis. Therefore, differential analysis is considered a small-scale analysis of one particle of fluid, and then scale up the whole system to see how it works in real-life problems. This also requires a large amount of computing power, so it is the basis of a field called computational fluid dynamics, where numerical analysis and data structures are used to solve fluid-flow-related problems. The equation of mass conservation is applied to an infinitesimal control volume, which is illustrated in figure 2.13 below, to understand the method.

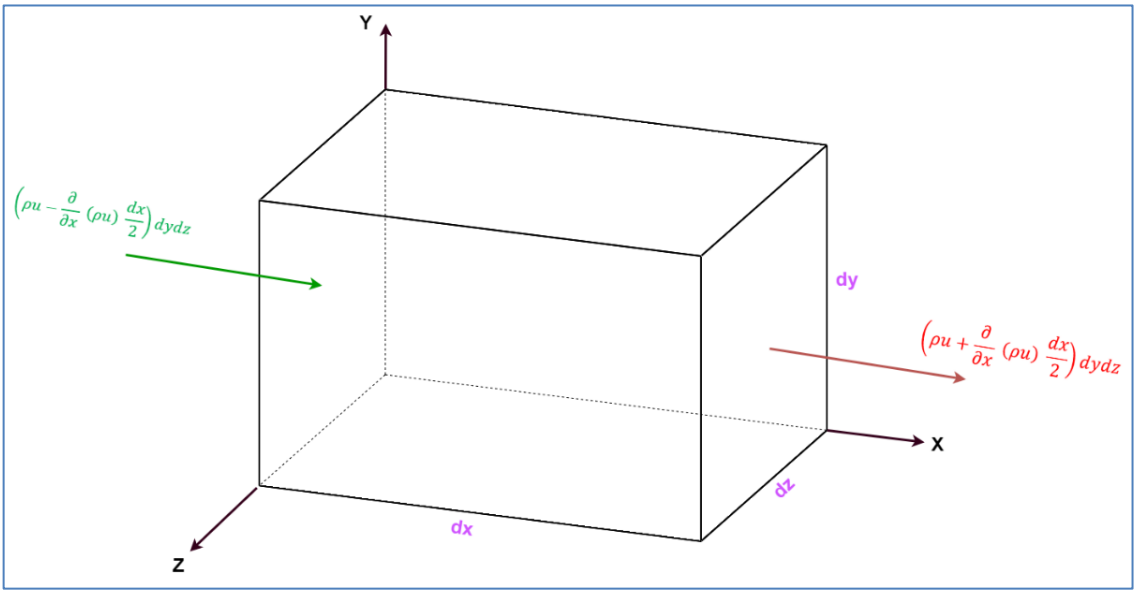


***Figure 2.13*** *Mass flux coming in and out of an infinitesimal control volume.*

Consider the mass flux coming in and out of the volume in the X direction, and the same can be applied to other directions. As we found out earlier for mass flux:

$$\dot{m} = \rho\, v\, A \quad (40)$$

However, because this is a Taylor series expansion, so we have to add the expand part, assuming the expansion starts from the center of the cube.

$$\dot{m}_{out} = \rho u.\, dydz + \frac{\partial}{\partial x}(\rho u)\frac{dx}{2}dydz = \left(\rho u + \frac{\partial}{\partial x}(\rho u)\frac{dx}{2}\right)dydz \quad (41)$$

$$\dot{m}_{in} = \rho u.\, dydz - \frac{\partial}{\partial x}(\rho u)\frac{dx}{2}dydz = \left(\rho u - \frac{\partial}{\partial x}(\rho u)\frac{dx}{2}\right)dydz \quad (42)$$

Mass flux coming into the system has a minus sign because we are expanding in the negative direction from the center of the cube. As we figure out when applying the conservation of mass, or so-called the continuity equation in fluid, in control volume analysis:

$$\frac{\partial}{\partial t}\int_{CV}\rho\, dV + \int_{CS}\rho\,(\vec{v}\, d\vec{A}) = 0 \quad (43)$$

The first term can be re-expressed as the time rate of change of the volume of the differential element:

$$\frac{\partial}{\partial t}\int_{CV}\rho\, dV = \frac{\partial}{\partial t}(\rho\, dxdydz) \quad (44)$$

To work with the second term, we have to look at mass flux coming in and out of each of the surfaces of the cube. It is important to notice the sign or the direction of the flux. The flow coming in is considered a negative sign and vice versa.

$$\int_{CS} \rho\left(\vec{v}\, d\vec{A}\right) = \left\{-\left|\left(\rho u - \frac{\partial}{\partial x}\,(\rho u)\,\frac{dx}{2}\right) dydz\right|\right\} + \left\{+\left|\left(\rho u + \frac{\partial}{\partial x}\,(\rho u)\,\frac{dx}{2}\right) dydz\right|\right\}$$

$$+ y - faces + z - faces \quad (45)$$

Put the above term back to the continuity equation, and we got:

$$(43) => \frac{\partial}{\partial t}\rho\, dxdydz + \left(\frac{\partial\, \rho\, u}{\partial x} + \frac{\partial\, \rho\, v}{\partial y} + \frac{\partial\, \rho\, w}{\partial z}\right) dxdydz = 0$$

$$=> \frac{\partial\, \rho}{\partial t} + \frac{\partial\, \rho\, u}{\partial x} + \frac{\partial\, \rho\, v}{\partial y} + \frac{\partial\, \rho\, w}{\partial z} = 0 \quad (46)$$

The sum of the last three terms is the divergence operator of $\rho\vec{v}$, with $\vec{v} = (u; v; w)$ :

$$\nabla \cdot (\rho\vec{v}) = \frac{\partial \rho\, u}{\partial x} + \frac{\partial \rho\, v}{\partial y} + \frac{\partial \rho\, w}{\partial z} \quad (47)$$

The differential form of the continuity equation is now completed:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\vec{v}) = 0 \quad (48)$$

This equation is used as a numerical method to solve the governing equations of motion in fluid mechanics analysis.

### 2.4.7 Differential analysis – conservation of linear momentum

The same process of deriving the differential equation can be done to the conservation of linear momentum. Using the control volume formulation of the laws that we mentioned earlier:

$$\overrightarrow{F_S} + \overrightarrow{F_B} = \frac{\partial}{\partial t}\int_{CV} \rho\vec{v}\, dV + \int_{CS} \vec{v}\rho\vec{v}\, d\vec{A} \quad (49)$$

Applying this to an infinitesimal element of volume $dV = dxdydz$ (figure 2.14) will yield the equation:

$$d\overrightarrow{F_S} + d\overrightarrow{F_B} = \frac{\partial}{\partial t}(\rho\vec{v})dxdydz + \int_{CS} \vec{v}\rho\vec{v}\, d\vec{A} \quad (50)$$

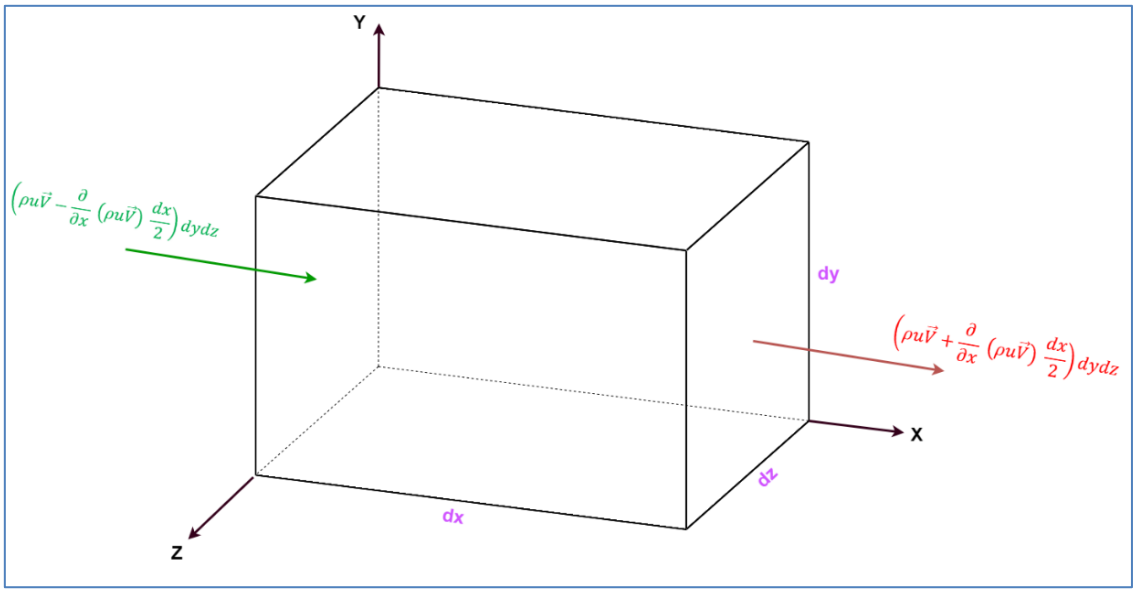


***Figure 2.14*** *Momentum flux coming in and out of an infinitesimal control volume.*

Consider the momentum flux coming in and out of the volume in the X direction, and the same can be applied to other directions. As momentum flux is equal to the mass flux times the velocity vector of the flux, we can write the two momentum fluxes as:

$$p_{out} = \rho u\vec{V}.dydz + \frac{\partial}{\partial x}\left(\rho u\vec{V}\right)\frac{dx}{2}dydz = \left(\rho u\vec{V} + \frac{\partial}{\partial x}\left(\rho u\vec{V}\right)\frac{dx}{2}\right)dydz \quad (51)$$

$$p_{in} = \rho u\vec{V}.dydz - \frac{\partial}{\partial x}\left(\rho u\vec{V}\right)\frac{dx}{2}dydz = \left(\rho u\vec{V} - \frac{\partial}{\partial x}\left(\rho u\vec{V}\right)\frac{dx}{2}\right)dydz \quad (52)$$

Now we can expand the latter term of equation (50), and the same process of using Taylor Series Expansion is applied:

$$\int_{CS} \vec{v}\rho\vec{v}\, d\vec{A} = \left\{-\left|\left(\rho u\vec{v} - \frac{\partial}{\partial x}\left(\rho u\vec{v}\right)\frac{dx}{2}\right)dydz\right|\right\} + \left\{+\left|\left(\rho u\vec{v} + \frac{\partial}{\partial x}\left(\rho u\vec{v}\right)\frac{dx}{2}\right)dydz\right|\right\}$$

$$+ y - direction + z - direction$$

...

...

$$\int_{CS} \vec{v}\rho\vec{v}\, d\vec{A} = \left\{\frac{\partial}{\partial x}(\rho u\vec{v}) + \frac{\partial}{\partial y}(\rho v\vec{v}) + \frac{\partial}{\partial z}(\rho w\vec{v})\right\}dxdydz \quad (53)$$

Put this back to equation (50):

$$d\overrightarrow{F_S} + d\overrightarrow{F_B} = \left\{\frac{\partial}{\partial t}(\rho\vec{v}) + \frac{\partial}{\partial x}(\rho u\vec{v}) + \frac{\partial}{\partial y}(\rho v\vec{v}) + \frac{\partial}{\partial z}(\rho w\vec{v})\right\}dxdydz \quad (54)$$

Using the del operator ∇ and re-ordering will result in:

$$d\overrightarrow{F_S} + d\overrightarrow{F_B} = \vec{v}\left[\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v})\right] + \rho\left(\frac{\partial \vec{v}}{\partial t} + u\frac{\partial \vec{v}}{\partial x} + v\frac{\partial \vec{v}}{\partial y} + w\frac{\partial \vec{v}}{\partial z}\right) \quad (55)$$

However, the term $\left[\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v})\right]$ is the continuity equation, which is derived earlier, so in this case, it is equal to zero, leaving the equation:

$$d\overrightarrow{F_S} + d\overrightarrow{F_B} = \rho\left(\frac{\partial \vec{v}}{\partial t} + u\frac{\partial \vec{v}}{\partial x} + v\frac{\partial \vec{v}}{\partial y} + w\frac{\partial \vec{v}}{\partial z}\right) \quad (56)$$

The right side of the equation is the total acceleration of a particle that occupies the control volume, as mentioned above in the material or substantial derivative. For the two forces on the left side, the body forces are easier to explain: it contains only gravitational forces.

$$d\overrightarrow{F_B} = d\overrightarrow{F_{grav}} = \rho \vec{g}\, dxdydz \quad (57)$$

The surface forces include the pressure and the viscous shear stress of the fluid. The viscous stresses can be written as stress tensor $\sigma_{ij}$, or as a matrix:

$$\sigma_{ij} = \begin{bmatrix} -p + \tau_{xx} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & -p + \tau_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & -p + \tau_{zz} \end{bmatrix} \quad (58)$$

Figure 2.15 is the schematic of how the stresses apply to that element. However, we can focus on the stresses acting on the X direction with Taylor Series Expansion.

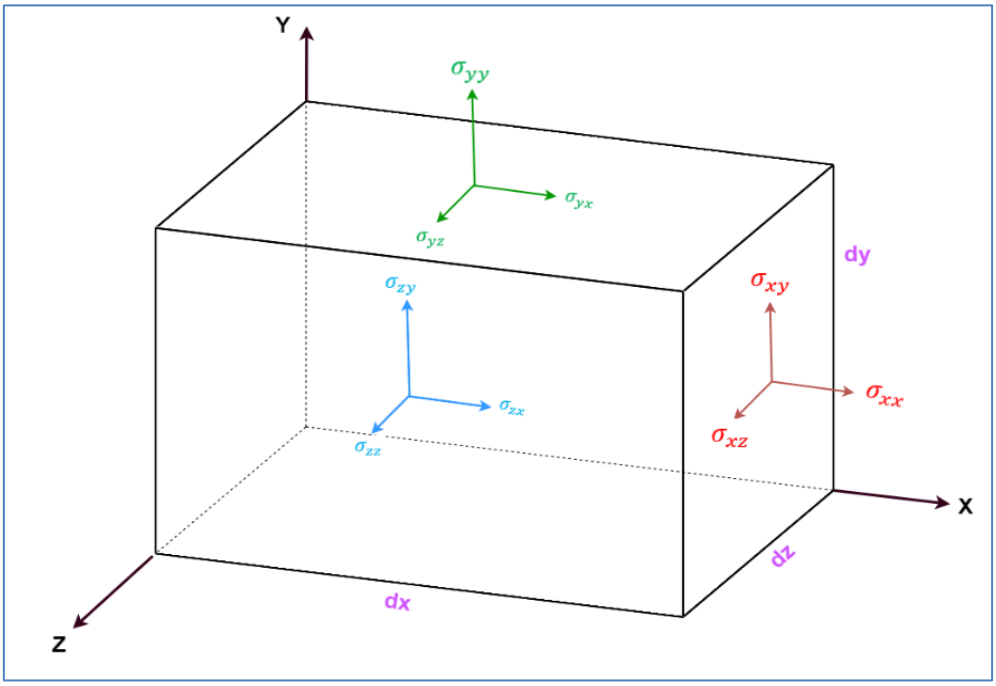


***Figure 2.15*** *Stress tensor acting on an infinitesimal control volume.*

The sum of the forces acting on the X direction is:

$$dF_{s_x} = \left[\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}\right] dxdydz \quad (59)$$

Introducing the stress tensor $\sigma_{ij}$ will yield:

$$\frac{dF_{s_x}}{dxdydz} = \frac{dF_{s_x}}{dV} = \frac{-\partial p}{\partial x} + \frac{\partial}{\partial x}(\tau_{xx}) + \frac{\partial}{\partial y}(\tau_{yx}) + \frac{\partial}{\partial z}(\tau_{zx}) \quad (60)$$

The same process can be done for the Y and Z direction:

$$\frac{dF_{s_y}}{dV} = \frac{-\partial p}{\partial y} + \frac{\partial}{\partial x}(\tau_{xy}) + \frac{\partial}{\partial y}(\tau_{yy}) + \frac{\partial}{\partial z}(\tau_{zy}) \quad (61)$$

$$\frac{dF_{s_z}}{dV} = \frac{-\partial p}{\partial z} + \frac{\partial}{\partial x}(\tau_{xz}) + \frac{\partial}{\partial y}(\tau_{yz}) + \frac{\partial}{\partial z}(\tau_{zz}) \quad (62)$$

Now equation (56) is completed. Because it is now a vector equation of 3 directions, so the equation is now written as a system of equation:

$$\begin{aligned}
\rho g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}(\tau_{xx}) + \frac{\partial}{\partial y}(\tau_{yx}) + \frac{\partial}{\partial z}(\tau_{zx}) &= \rho\left(\frac{\partial \rho}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) \\
\rho g_y - \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}(\tau_{xy}) + \frac{\partial}{\partial y}(\tau_{yy}) + \frac{\partial}{\partial z}(\tau_{zy}) &= \rho\left(\frac{\partial \rho}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) \quad (63) \\
\rho g_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial x}(\tau_{xz}) + \frac{\partial}{\partial y}(\tau_{yz}) + \frac{\partial}{\partial z}(\tau_{zz}) &= \rho\left(\frac{\partial \rho}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right)
\end{aligned}$$

However, this system of equation is not usable, because the shear stress $\tau$ is not defined. The problem is to find a relation to make $\tau$ a function of velocity. The Navier-Stokes equation is the solution to this relation.

### 2.4.8 Navier-Stokes flow

The Navier-Stokes flow is based on the equations of Claude-Louis Navier and George Gabriel, which describe the motion of viscous fluid substances. For analyzing the flow inside a prepreg, this equation is for the open space between the yawns. Brinkman flow is for the flow inside each yawn, where porosity is taken into consideration. Some assumptions come with Navier-Stokes equations: the examined fluid must be a continuum, and all the fields of interest like pressure, density, temperature, and flow velocity have to the differentiable. The equation is also a special continuity equation, which means it can be derived for the conservation laws of mass, momentum, and energy.

Continue with equation (63) of chapter 2.4.8, a relationship between the shear stress $\tau_{ij}$ and the velocity field is needed. Assuming the fluid is Newtonian, we can apply the stress tensor to the infinitesimal control volume above. We can narrow down all the relation as below:

$$\tau_{xx} = 2\mu\frac{\partial u}{\partial x} \qquad \tau_{yy} = 2\mu\frac{\partial v}{\partial y} \qquad \tau_{zz} = 2\mu\frac{\partial w}{\partial z}$$

$$\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x}\right) \quad (64)$$

$$\tau_{xz} = \tau_{zx} = \mu\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right) \quad (65)$$

$$\tau_{yz} = \tau_{zy} = \mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \quad (66)$$

The right side of the system of equation (67) can be rewritten with the material derivative:

$$\frac{D\vec{v}}{Dt} = \frac{\partial \vec{v}}{\partial t} + u\frac{\partial \vec{v}}{\partial x} + v\frac{\partial \vec{v}}{\partial y} + w\frac{\partial \vec{v}}{\partial z} \quad (68)$$

Now the derivation of the Navier-Stokes equations can be written as:

$$\boxed{\begin{aligned} \rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) &= \rho\frac{Du}{Dt} \\ \rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) &= \rho\frac{Dv}{Dt} \\ \rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) &= \rho\frac{Dw}{Dt} \end{aligned}} \quad (69)$$

Another form of the Navier-Stokes equation can be derived as a particular form of the Cauchy momentum equation. This is called the convective form of the Navier-Stokes equation:

$$\boxed{\rho\frac{D\vec{u}}{Dt} = -\nabla p + \mu\nabla^2\vec{u} + \rho F} \quad (70)$$

Because the equation is the way to apply Newton's second law $F = ma$ to fluid motion, we can see the resemblance between the two. The left side includes density $\rho$ of the fluid, which can be considered as mass, and $\frac{D\vec{u}}{Dt}$ is the change of velocity vector with re-

spect to time, which is the acceleration. The right side is the total forces of the system, both internal and external. The external force $\rho F$ is usually a gravitational force, but it can change depending on the situation. The other two internal forces include pressure-gradient force $\nabla p$ (the force created by the change of pressure in the flow) and fluid friction $\mu\nabla^2\vec{u}$ (the forces created by fluid viscosity). Fluid friction can be conceptualized as the force created as different layers of fluid move and slide against each other. If the fluid has a high viscosity, which means it has a denser amount of fluid layers and thus has higher fluid friction.

Noted that the above form is only for irrotational flow. If the flow has vorticity and turbulent (which is not considered in the situation of prepreg flow), the concept of Lamb vector by British physicist Horace Lamb is widely used. The Navier-Stoke is now written as:

$$\rho\frac{D\vec{u}}{Dt} = -\nabla p + \mu\nabla^2\vec{u} + \frac{1}{3}\mu\nabla(\nabla\cdot u) + \rho F \quad (71)$$

With the convective acceleration term written as:

$$u\cdot\nabla u = (\nabla\times u)\times u + \frac{1}{2}\nabla u^2 \quad (72)$$

Where $(\nabla\times u)\times u$ is called the Lamb vector.

## 2.5 Materials

A composite material, or in short composite, is a combination of materials with different properties. Each of the components has its strengths and weaknesses, but when successfully combined will provide the composite their best properties. These components also do not blend in the mix, which means that they can still be recognized and distinguished from each other. In nowadays industries, a composite is typically made from fusing long fibers into a polymer matrix. The long strings of fiber provide strength and stiffness; however, they are brittles and can break under compression or torsion. Meanwhile, the resin matrix will provide the shape of the composite and also protect the fibers by maintaining their form and evenly distributing the load throughout the length of the strings. These composite are more commonly known as Fiber-reinforced Polymer composites (FRP), although sometimes the letter P can also stand

for plastic. Plastics are not composites, but many types of plastic can be reinforced to be stronger and better, hence the name. This combination has the potential to produce some of the strongest and most versatile materials that have ever been developed in the industry (Composites Lab, 2016).

However, the idea of a composite is not a new finding, as Fagan (1996) pointed out that it was used back in 3300 BC as the form of the mudbricks. Using dried mud as the matrix with strings of straw as the reinforcement, and the final product is a composite having both good tensile strength and compressive strength. The mudbrick is used throughout the history of mankind, building homes and structures that last until today. Another popular successor of the mudbrick today is concrete, a composite material made of fine and coarse aggregate bonded by cement. In their blog, Cement Trust (2011) proved that concrete is one of the strongest composite materials used construction materials in the world as its usage almost double steel, wood, plastics, and aluminum combined.

Aside from construction, composites are constantly improved to fit more function than just simply adding more strength or mechanical properties. With the addition of fillers, additives, core materials, or an extra surface finish step, engineers can improve the manufacturing process while enhancing the performance and appearance of composites. These elements overall widen the use of composite, for example, one can make the composite to be a good conductor or insulator. This proves to be very useful in electrical applications such as making transistors, solar cells, sensors, detectors, and so on (Australian Academy of Science, 2015).

The manufacturing processes of FRP hugely depend on the matrix. There are commonly used two groups of plastic: thermoset and thermoplastic, with meltability is their main difference. Thermosets consist of crosslinked polymers that form irreversible chemical bonds between them. This results in thermosets having very good chemical and heat resistance while also provide structural integrity for the products. However, the material created can not be recycled nor re-moulded or reshaped. Uncured thermosets are used as the resin system of the composite because of their lower viscosity than molten thermoplastics. Thus, thermosets have higher flowability and better wettability for more complicated geometry like thin walls or long flow paths.

On the other hand, thermoplastics are more versatile, fitting more applications while being eco-friendly and providing the ability to deeply modify the material. They are used as the matrices of the system, where they are heated, melted, and then injected or pressed into a mould. This is also where the final geometry of the component is shaped. The matrix is cured here and the process is completed.

***Table 2.2*** *Comparison between different manufacturing methods (Lengsfeld, et al., 2015, p. 7)*

| Method | Personnel cost | Capital investment cost | Level of automation | Production rate | Component quality/ Mechanical properties | Miscellaneous | Application example |
|---|---|---|---|---|---|---|---|
| Hand lay-up | 3 | 0 | 0 | 0 | 0 | Open process (health hazards) | ▪ Prototypes and exclusive items<br>▪ Swimming pools |
| Vacuum infusion | 3 | 0 | 0 | 0 | 1 | Suitable for large parts | ▪ Rotor blades for wind turbines<br>▪ Boats |
| Pultrusion | 0 | 3 | 3 | 3 | 3 | Only suitable for profiles | ▪ Pipes, tubes and profiles |
| Filament winding | 0 | 3 | 3 | 1 | 3 | Not suitable for complex geometries | ▪ Pressure tanks |
| RTM | 1 | 2 | 2–3 | 2 | 2 | Suitable for mass production | ▪ Automotive parts<br>▪ Small aircraft parts |
| Prepreg/ Autoclave | 2 | 2 | 1–2 | 1 | 3 | Limited prepreg shelf-life | ▪ Racing car parts<br>▪ Aerospace components<br>▪ Repair patches |

0: Low 1: middle 2: high 3: very high

Different manufacturing methods offer a variety of applications with a different combination of material and scale of production. Table 2.2 illustrates these differences between the most common methods. Fiber-reinforced materials are used in applications that require a material with good mechanical properties while maintaining a relatively low weight to the whole products. Carbon-fiber reinforced plastic (CFRP) is well-known for its ability to reduce the weight of the component. The amount of weight reduction can be up to 70% compared to steel and as much as 30% compared to aluminum in some circumstances. Industries that utilizing the advantages of CFRP are automotive, aerospace, military, or in making wind turbines.

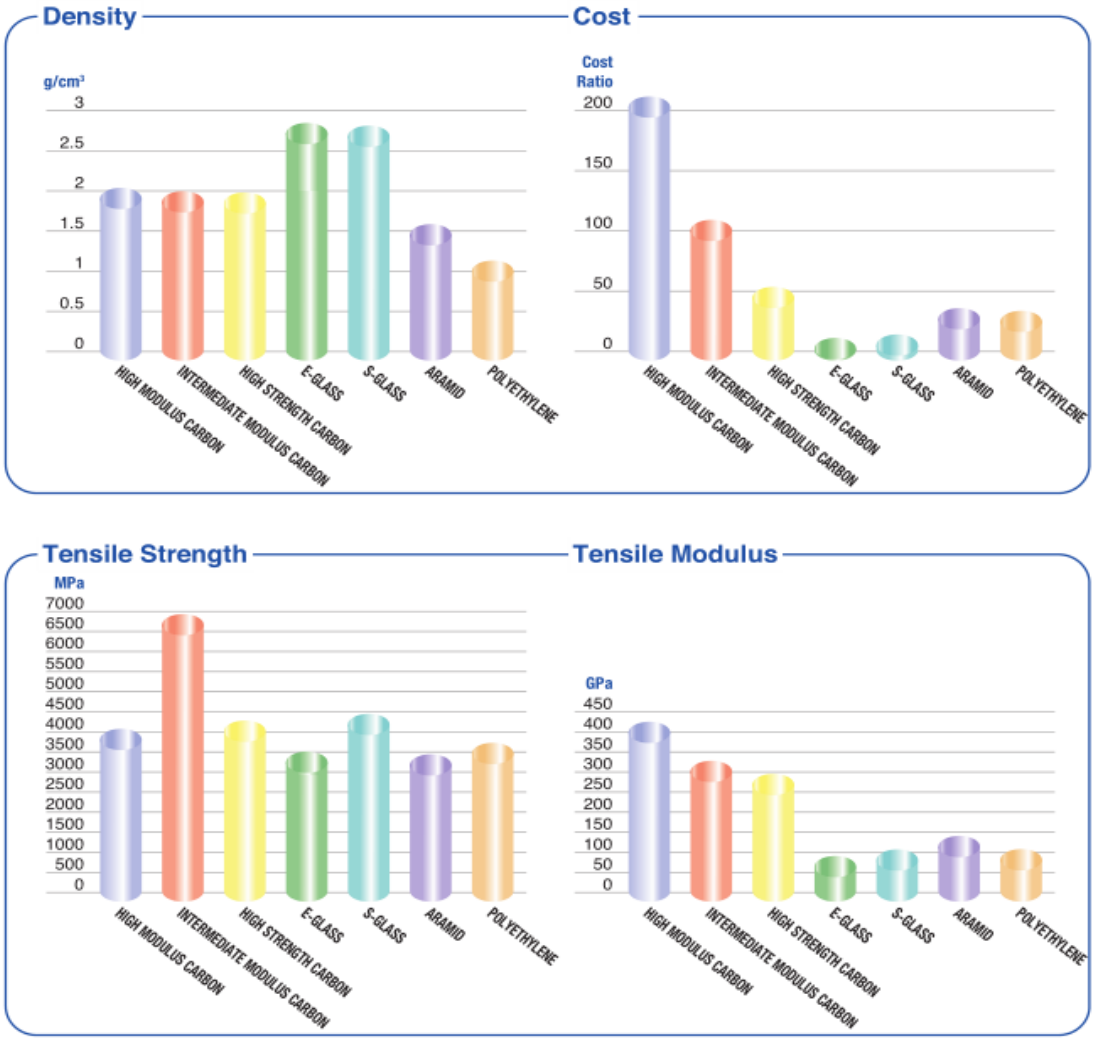


***Figure 2.16*** *Comparison between the most commonly used fibers (Lengsfeld, et al., 2015, p. 18).*

The usage of the material is increasing annually worldwide, partially because of the growing concern of global warming and other environmental issues. Companies are using more CFRP components in building airplanes, cars, or trucks to not only reduce the weight of them but also lessen fuel consumption and $CO_2$ emission. Most of these components are made using prepreg technology. In fact, more than 54% of the carbon fiber global production is used for manufacturing prepregs, making this material appear in more applications than ever. In this chapter, the two main components of a prepreg system are being discussed, which is the resin matrix and the textile. The complexity of how these two components combine offers an interesting question for manufacturers to answer and expand the range of products.

### 2.5.1 Resin matrices

The main task of a resin matrix is to bind the fibers together in a certain order and become the protection layer to these fibers after cured. Some of the properties of the composite that is decided by the matrix are toughness, usage temperatures, or moisture and fluid resistance, et cetera (Campbell, 2010). Resin matrices used to make prepregs can be categorized into two groups: thermosets and thermoplastics. The main difference between them is the ability of thermosets to create a three-dimensional crosslinked structure, while thermoplastics do not. Crosslinking is the product of heat-driven chemical reactions, where the heat is generated by the chemical reactions themselves or provided externally. This results in a different production line with distinctive methods, parameters, product properties, and so on. The two following subsections will discuss further the differences between them.

#### *2.5.1.1 Thermosets*

Thermosets usually have low molecular weight and low viscosity. During the curing process, thermoset polymers connect to form permanent crosslinks over a long period. After curing, the products by thermosets are infusible and insoluble. Figure 2.17 shows the most commonly used thermoset resin matrices, together with their characteristics and usages. Campbell (2010) divided these thermosets into addition-curing and condensation-curing systems.

| | |
|---|---|
| Polyesters | Used extensively in commercial applications. Relatively inexpensive, with processing flexibility. Used for continuous and discontinuous composites. |
| Vinyl Esters | Similar to polyesters, but are tougher and have better moisture resistance. |
| Epoxies | High-performance matrix systems for primary continuous-fiber composites. Can be used at temperatures up to 250–275 °F. Give better high-temperature performance than polyesters and vinyl esters. |
| Bismaleimides | High-temperature resin matrices for use in the temperature range of 275–350 °F with epoxy-like processing. Requires elevated-temperature postcure. |
| Cyanate Esters | High-temperature resin matrices for use in the temperature range of 275–350 °F with epoxy-like processing. Requires elevated-temperature postcure. |
| Polymides | Very-high-temperature resin systems for use at 550–600 °F. Very difficult to process. |
| Phenolics | High-temperature resin systems with good smoke and fire resistance. Used extensively for aircraft interiors. Can be difficult to process. |

***Figure 2.17*** *Relative characteristics of thermoset resin matrices (Campbell, 2010, p.64)*

Polyesters, epoxies, bismaleimides, and cyanate esters are addition-curing polymers. The chemical reactions of this group do not result in a by-product, unlike the condensation-curing polymers. The chemicals have different operation temperatures: epoxies can be used up to 135 ℃, while bismaleimides work in the range of 135 ℃ to 175 ℃. This relatively low operation temperatures make them the dominant in commercial applications, but not usually in high-performance composites because of their lower mechanical properties and environmental resistance. An exception for this is cyanate esters, a new class of resin that is developed to compete with both epoxies and bismaleimides. Their main selling points are the low level of moisture absorption and good electrical properties, although being somewhat hindered by a higher price tag.

The condensation-curing systems consist of polyimides and phenolics. The chemical reactions of these polymers during curing usually give off water or alcohol, hence the name condensation-curing. Both of the polymers can be operated at a very high temperature, like polyimides can be up to 315 ℃. Even though the higher working temperature is an advantage, condensation-curing polymers are harder to process in practice, due to the by-products. They have to be removed in some way before the resin harden, or else it will create voids and porosity inside the finish products and lower their performance and quality.

#### *2.5.1.2 Thermoplastics*

Thermoplastics were developed to replace thermosets in the late 1980s and early 1990s, costing hundreds of millions of dollars from the government and companies in the military and aerospace industry (Campbell, 2010). The attempts failed, and now thermoplastics are only used in a handful of applications for commercial and military aircraft. This is because, despite the potential advantages of thermoplastics in theory, they prove to be more complicated in practice. These problems are explained in this section.

Thermoplastics are high molecular weight resin systems that reacted fully before processing. Their main structural difference is that they melt and flow during the process but do not create the crosslink reaction like thermosets. This means that thermoplastics can be reprocessed by simply heating them: they are often thermoformed into different structural shapes. Theoretically, they have an advantage in forming and joining processes, but this turned out differently in practice. The number of shapes that they can be formed into is limited to the very basics, while the number of times that the material can be reprocessed is also limited: multiple reprocesses can result in material degradation and fiber distortion.

As thermoplastics do not go through any chemical reactions, they are tougher and have better damage tolerance compared to the thermosets at the time. However, a different approach in reinforcing the thermosets has brought the toughness of the two to a comparable level. Manufacturers found out that by adding thermoplastics into the thermoset resin, the system is much tougher, to the point that this not an advantage for thermoplastics anymore.

The processing methods of thermoplastics also need to be considered. One good thing is that the process is very safe for the workers, as the materials are fully reacted. Compared to thermosets, thermoplastics have much shorter processing time: in minutes or even seconds in some cases. The equipment like autoclaves and other related materials have to be able to operate at high temperatures, as high-performance thermoplastics are processed at the temperature up to 425 ℃ [Campbell, 2010]. Maintaining the products is relatively easier than thermosets: they do not need to be refrigerated like thermosets and thus have essentially infinite shelf life. However, manufacturers may need to put them through drying to remove surface moisture before undergoing further processing.

### 2.5.2 Technical textile

Long continuous fiber strings are woven or stitched together to make sheets of fabric, which is then impregnated with the resin matrix to form a structure for the composite material. There are at least two threads of fiber for each fabric called warp and weft. The way that these two threads interlaced is called weave style, and weave style varied depending on the fabric crimp and drapeability.

Crimp can be demonstrated as the waviness of a fabric. This crimp is usually caused by a high density of fiber interlocking, mainly due to the weave style. When a load is applied to a fabric, the yarn crossover points exhibit relative motions of slip and rotational motion. The slip then contributes to the load in the horizontal direction, overall reducing the stability of the whole fabric's structure. Thus, low crimp fabrics provide better mechanical performance because of their fiber being straighter and carrying higher loads.

Drapeability is related to the fluidity and rigidity of the fabrics. Good drape fabric is usually slightly more flexible and easier to lay up over complex forms. Common examples of good drape fabrics are silk or satin. On the other hand, a low drape fabric is stiffer. This kind of fabric is often heavier than good drape, but not always. Low drape fabrics tend to hold their shape in the lay-up process, which make the process more complicated if there are complex shape in the mould like curves or edges. However, neither

forms of fabric are better than the other because it serves different purposes and applications. Good drapeability allows the fabric to cover and adhere to the mould easier while also reduces the weight of the product. But when the application does not require a complex form but more rigidity, low drape fabrics are more useful.

### 2.5.2.1 Woven textiles

Woven textiles are made of warp (0°) and weft(90°) strings of fiber in a regular pattern (or weave style). This interlocking mechanism also supports the integrity of the textiles. Depend on the arrangement of the warps and wefts, one can decide the surface smoothness and stability of fabric to serve certain applications. Figure 2.18 demonstrated the most common weave styles in the industries.

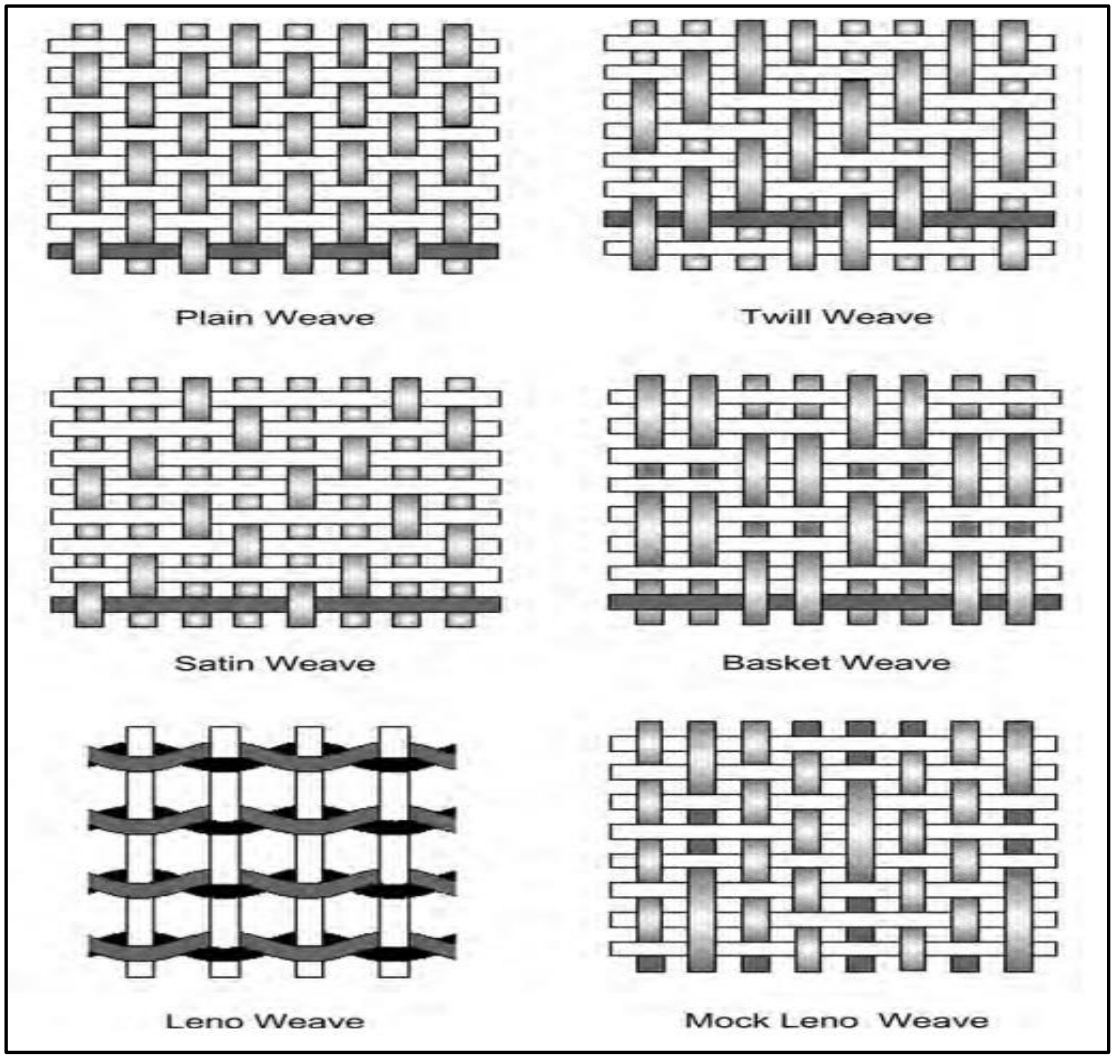


***Figure 2.18*** *Common weave styles for woven textiles (Campbell, 2010, p.53)*

Plain weave and basket weave are the two basic forms of weave style. Plain weave consists of one warp going alternately over and under one weft (1x1). This symmetrical and balance structure gives plain weave textile good stability and reasonable porosity. Additionally, plain weave structures are generally strong, slippage resistant, and excellent abrasion resistance. However, the close arrangement of fibers makes plain weave a high crimp material, which also lessens the performance in certain mechanical properties. Plain weave structures are also the hardest to drape around profiles, so the selection of yarn quality is very important to overcome the weakness of this weave style.

Basket weave is a slight modification of plain weave, where two or more warps alternately interlaced with two or more wefts. Although systems like 2x2 and 4x4 exist, basket weave does not need to be symmetrical, for example, 8x2, 5x4, etc. This means that the fiber is less closely arranged and comes with certain improvements compared to plain weave. The textiles are more soft, elastic, and wrinkle resistant. Textile's surface is flatter, which means less crimp and technically more mechanical performances. However, the basket weave system is less stable and has lower abrasion resistance compared to plain weave.

With twill weave, one warp yarn passed under and over two or more weft yarns in a diagonal pattern. There are many variations of twill weave, but they can be recognized by the twill line or the diagonal line running across the fabrics. Because of the arrangement, yarn intersections in twill weave are less frequent, and longer yarns move more freely in the system than plain weave. Overall this results in a slight reduction of stability, but the advantages are far more superior wettability and drapeability of the textile. Twill weave systems are also more flexible, lower crimp, smoother surface, and slightly better mechanical properties.

#### *2.5.2.2 Non-woven textiles*

Another common type of textile is non-woven textile, also known as non-crimp textile/fabric (NCF). As the name suggests, the textile has no crimp on the surface because the layer of fiber is not woven but instead stitched or knitted. NCF is generally engineered fabrics, consists of a structure of multiple layers of unidirectional textiles.

This means every layer of textiles can have their fiber orientation, with the most popular is 0º, ±45º, or 90º. The fiber tows are connected by a thin yarn that stitched them together. In warp-knitted textiles, the yarn goes in a zigzag pattern along the length of the fabric. For comparison, the yarn in weft-knitted textile runs along the width of the fabric. Compared to other technologies, the manufacturing machine of NCF is more productive. A combination of multiple layers of fiber in just one fabric is proved to be a faster and cheaper process. With the yarn is the only limiting factor, the fiber tows in NCF can move easier. Even though this might mean more slippage, but here the advantages outweigh this: NCF is more flexible and can be wrapped around almost any complex shapes or moulds. Additionally, there are no interlocking between the yarns, thus also no crimp and generally better mechanical properties compared to woven textile. NCF is also expected to have higher delamination resistance and impact strength.

The most common structures for NCF are biaxial, triaxial, and quadriaxial, depend on what application they are used for. Sometimes, multiple layers of the same orientation (namely 0º and 90º) can be used to make a single sheet of fabric. This is known as a unidirectional fabric (UD). Because all the fiber tows are running in one direction, without any surface crimp, unidirectional fabrics can obtain the best mechanical properties in the longitudinal direction, for example, strength, stiffness, or flexural strength. This proved to be useful in such applications that economically require relatively good performance. The part produced with UD fabric can be designed to use less resin in the process and reduce the part thickness, weight, and also cost. Nowadays, it is common to observe the increasing usage of UD fabric in the aircraft industry, particularly for demanding applications with a high aspect ratio like wind blades, poles, or stringers. They can also be used for reinforcing discrete areas where additional strength or stiffness is needed.

# 3 METHODS

## 3.1 Hand laminating

In practice, pressing a lamina require good knowledge of the compatibility between different textiles and resin. In Arcada, students can experiment with many kinds of textiles. In this thesis, the author will make laminations with the following textile and resin, listed in table 3.3.

***Table 3.3*** *List of materials for hand impregnation*

| **Textile** | **Resin mixture** |
|---|---|
| Biaxial Fiberglass | Bistitron VE370 resin |
| Jute | Thixotropic Additive |
| Unidirectional Fiberglass | Peroxide |
| Carbon Fibers | Atlas resin |

After the curing is done, these factors are examined and evaluated: wettability, yarn displacement, uniform thickness, and the number of holes and spores on the surface. To produce the best outcome, the student must precisely control the resin content to not only have enough resin to prevent voids but also not too much resin to potentially dislocate the yawns. This means that the resin content has to be calculated in advance and modify depending on the result of each combination of material. The press force of the machine is set to 27.5 tons, but it can also be set at a lower level and then increase to 27.5 tons later.

In hand impregnation, it is very important to understand that the resin cures quickly after being taken out of the container, so the preparation should be quick and in a logical order. Preparation includes the machine, the mould, and the materials, which is the textile and the resin mixture. It is important to wear a lab coat and gloves while handling chemicals during this process. The press machine usually takes about half an hour to heat up and ready to press, so it should the first step to turn on the machine. The mould consists of two metal plates, where the lamina is kept inside. One can use a piece of mi-

cro glass to scrape out the microparticle of dirt from the surface of the plate. When the surface is clean, apply a good amount of release agent for easier removal of the lamina after the pressing is done. Then the edges of the plate should be taped carefully from one side so that the excess resin cannot exit from the mould when pressing and dirty the machine.

Preparing the textiles is the most tedious part of the process: it requires precise cutting and patient, as the textile is very fragile, and the lamina needs to be uniform. It is easier to use a sharp scissor and cut the textile without pushing the scissor ahead while placing the textile on a flat surface or holding it as straight as possible. Prepreg often has the formation of 4x4 or 2x2, so we can prepare the number of layers accordingly. For this process in Arcada Lab, each layer of textiles should be 50 x 50 centimeters, as precise as possible. This is a good time to take out the resin, pouring it into a bucket. Add a small amount of peroxide, which is usually stored inside a fridge, and mixing them slowly until dissolved. Preparation is completed, and the hand impregnation can begin.

Start laying up the first layer of textiles and add a good amount of resin. Then the student can use a roller or similar tool to rub the resin into the textile, from the center outwards. This should mix the resin evenly to the textile while the rolling motion squeezes out excess resin. It is also important not to apply downward pressure, as it might dislocate the fibers and ruin the whole lamina. One can notice the change in color of the textile and see which area is not fully covered with resin yet to add more. However, this should not be overdone because, as we repeat the same steps with other layers, the resin might eventually fill out all the area inside the preform.

Now the mould can be closed with the other metal plate. The tapes prepared earlier can be used to seal the mould, but an air hole must be left for the excess resin to flow out when pressing. The mould can be put into the press machine. The pressure is set, and the level is pulled down to start the machine. As the clamp closes down on the mould, the student must check if there is any leakage of resin. If there is (as figure 3.19 shown), the machine should be stopped and cleaned because it would be harder when the resin is cured. The mould might also need more tapes for a better seal and then start the ma-

chine again. Depend on the resin, the curing time and the clamp pressure can be adjusted accordingly. Now the student can come back and clean the table with acetone, so the working surface is clean and ready for the next process.

***Figure 3.19*** *Resin leakage through the air holes.*

## 3.2 Small scale prepreg machine

### 3.2.1 Design requirement

This section presents the approach that the author took on building a small scale prepreg machine that can be used in the lab room. The machine is not required to make an industry-standard prepreg because, as it is found out throughout this chapter, it is very hard to be obtained without machinery and precise control of parameters. The principle of the machine is to control the thickness of the unpressed textile, as we mentioned in chapter 2.3.1, and therefore control the resin content of the prepreg. Overall, this should improve the quality of the current products compared to the current process of hand impregnation. The design of the machine is modeled after the machine used in hot melt processes that are mentioned in chapter 2.2.1, or particularly the impregnation zone of that machine.

As a smaller scale of the industrial machine, this prepreg machine has unique requirements to be considered. First is that the machine should be made without the involvement of electrical components. This means that it only focuses on the mechanism of the

compaction rolls, where the area between the rolls decide the degree of impregnation of the finished products. Assembling the machine should also be easy: it can be put together quickly to be used in classes or practices, then cleaned up and disassembled after. The components should be easily replaceable, and other students can design their improvements and upgrades with the tools available in Arcada.

To minimize the amount of material needed, the author decides to use a laser cutting machine to make the components. The main material is MDF because it is a cheap material but works very well with laser cutting. The thinness of the material also makes the machine lighter, while if being design in the right way, it does not sacrifice the rigid structure of the machine. Laser cutting also promises millimeter-scale precision, so each component can interlock with each other according to the design, without the need for adhesive or glue in assembling them. A 2D design file is needed to guide the laser cutting machine, which can be made in vector graphics software like Inkscape.

### 3.2.2 The components

There are three groups of components for this machine: the frame, the working area, and the rail. The frame of the machine is made from 3 components called the A part, B part, and connecting feet. Two A parts and four B parts connect, as shown in figure 3.20, while being secured by four circular connecting foot at the corners. In the body or A parts are holes to connect the support legs, while B parts have long cut-outs for the rail to move along their length while also provide a place to slide in the lower table. This rectangular frame holds the working surface in place when applying the resin to the fiber reinforcement with the hand roller.

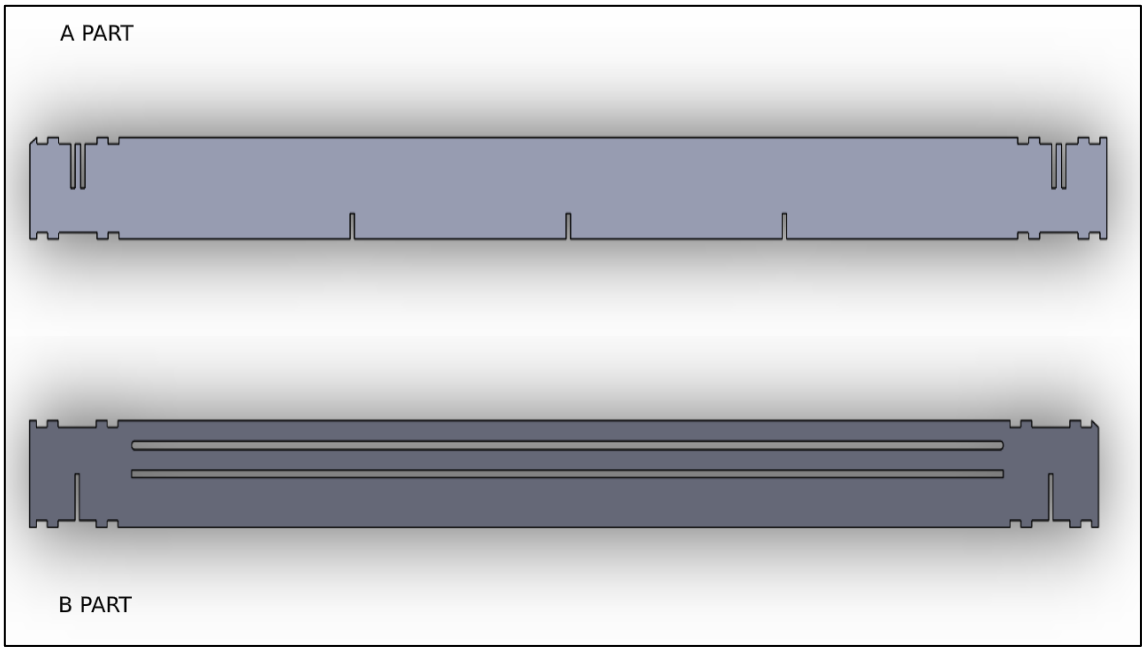


***Figure 3.20*** *A part and B part.*

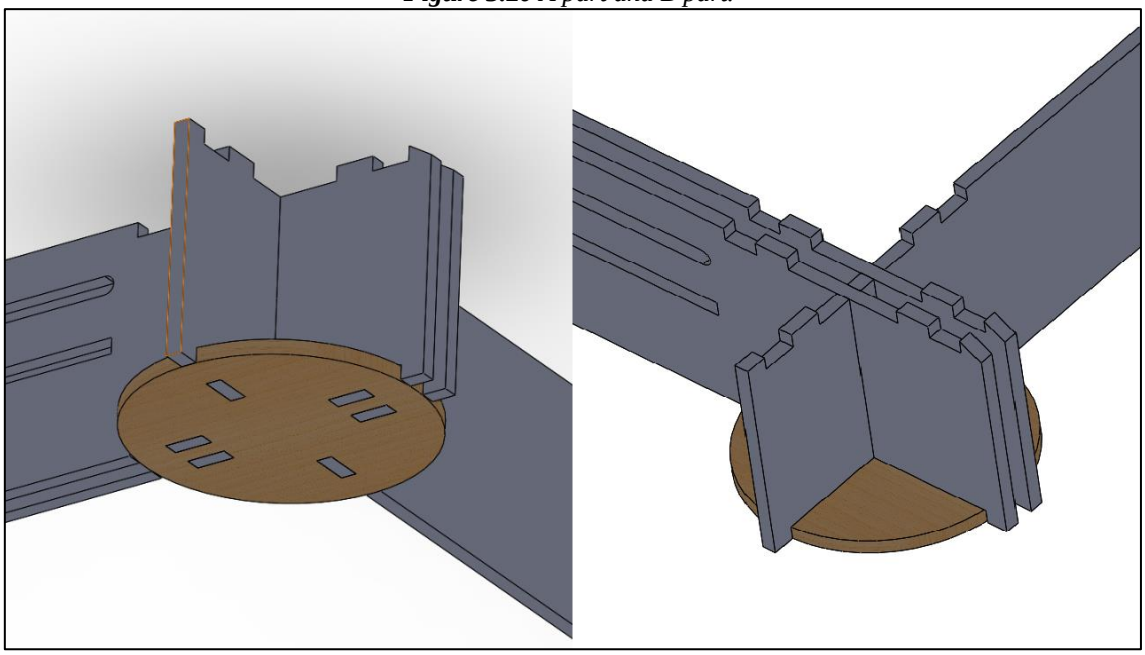

***Figure 3.21*** *A part and two B parts connected by a foot at the corners.*

The working surface consists of two tables: one lower table and one bigger upper table, connecting by four screws at four angles. These four screws are identical and in charge of adjusting the height of the upper table, which also decides the area between the table and the roller. The upper table is where the fiber bed is placed for impregnation. It also has a 7x10 net of holes with identical dimensions, which are used for the excess resin to exit the preform. The resin is then collected by placing a small bucket or something sim-

ilar in the lower table. This table is secured by three support legs, which also interlock with the frame to stabilize the working area.

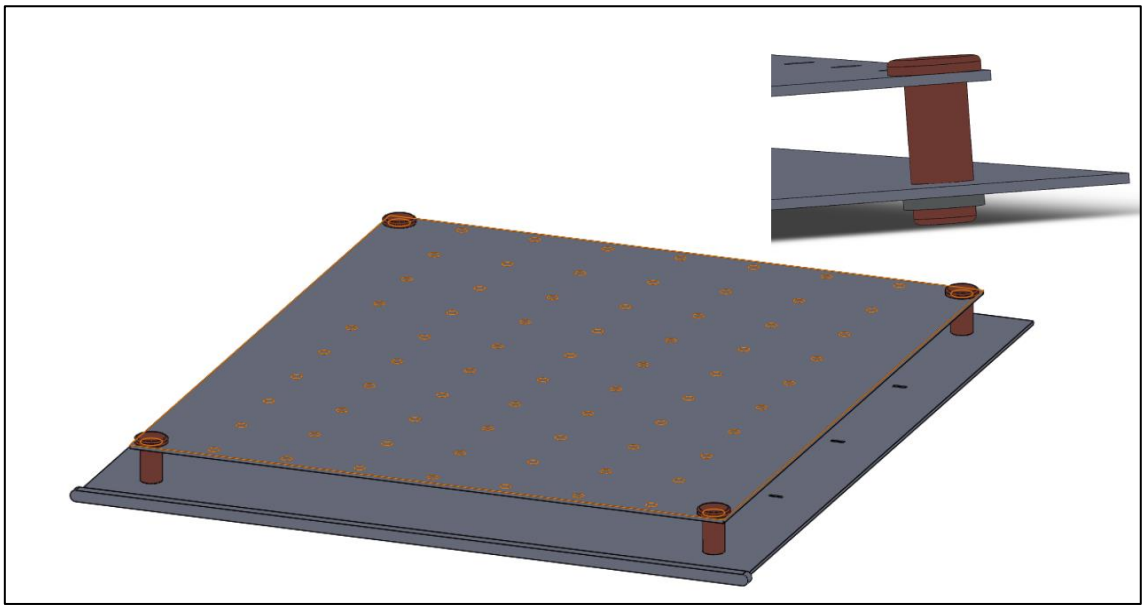

***Figure 3.22*** *Two tables assemble and the height adjustment by the screw*

Lastly, the rail travels in the area between two B parts on each side, carrying the core of the roller and press the resin into the fiber bed. This rail is moved by holding the handle, which also helps to lock the rail into the two B parts. The core of the roller is sandwiched between the two rails, then travel exactly parallel to the surface of the table. All the engineer drawings can be found in Appendix section.

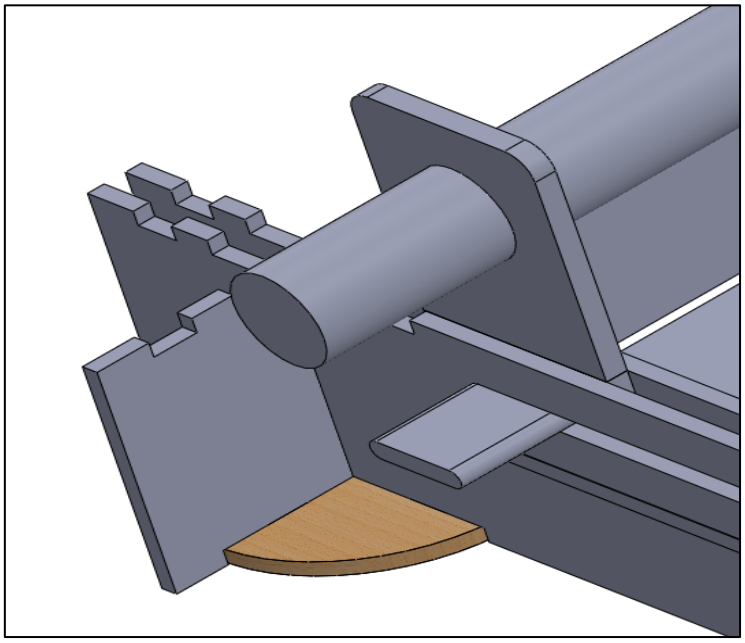

***Figure 3.23*** *Rail moves between two B parts by moving the handle.*

# 4 RESULTS

## 4.1 Hand laminating experiments

***Table 4.4*** *The result of hand lamination experiments.*

| Number | Textile | Resin | Surface | Uniform thickness | Wettability | Yawn displacement |
|---|---|---|---|---|---|---|
| 1 | Biaxial x4 | Atlas | lot, on both sides, small but everywhere | ok | ok | no |
| 2 | Jute x4 | Atlas | lot, only in center of top side | slightly off | ok | no |
| 3 | UD x4 | Atlas | few, on both sides, more on edges | ok | ok | no |
| 4 | UD + Jute x4 | Atlas | lot, on both sides, in the center | slightly off in edges | bad | no |
| 5 | Biaxial + Jute x4 | Atlas | lot, on top side | bad | bad, esp in center | lot, on edges |
| 6 | Biaxial + Jute x4 | Atlas | few, more on center | ok | bad, esp in center | slightly, on edges |
| 7 | CarbonFiber (2) + Jute (4) x6 | Atlas | lot, on top side | ok | ok | lot, on edges |
| 8 | CarbonFiber woven x8 | Bistitron + thixotropic additive | few to none | ok | ok | extreme, on edges |
| 9 | CarbonFiber woven x8 | Bistitron w/o additive | few to none | ok | ok | extreme, on edges |

After the curing is done, the lamina can be taken out of the machine for evaluation. Nine samples have been produced in a few separate phases. Using the results and evaluation that the author has from the previous phase, he can choose what combination of material and resin to make the next batch of lamina. This chapter will demonstrate how and why these combinations are used and what did the author learn from the finished products.

**PHASE 1: Sample number 1,2,3**

In the first phase, the author will the testing to withstand the cold press lamination process of each textile. Each textile is set up in a 2x2 formation and being added with the same resin textile. The resin content is change after each test to make sure that the resin can fill up the textile as much as possible. As shown in table 4.4, UD fiberglass performs better than the other in terms of voids density, and the voids appear mostly on the edges, which might be the result of have not enough resin to fill up the textile. UD fiberglass also has a much higher density than the other, which is partially contributed to the better result.

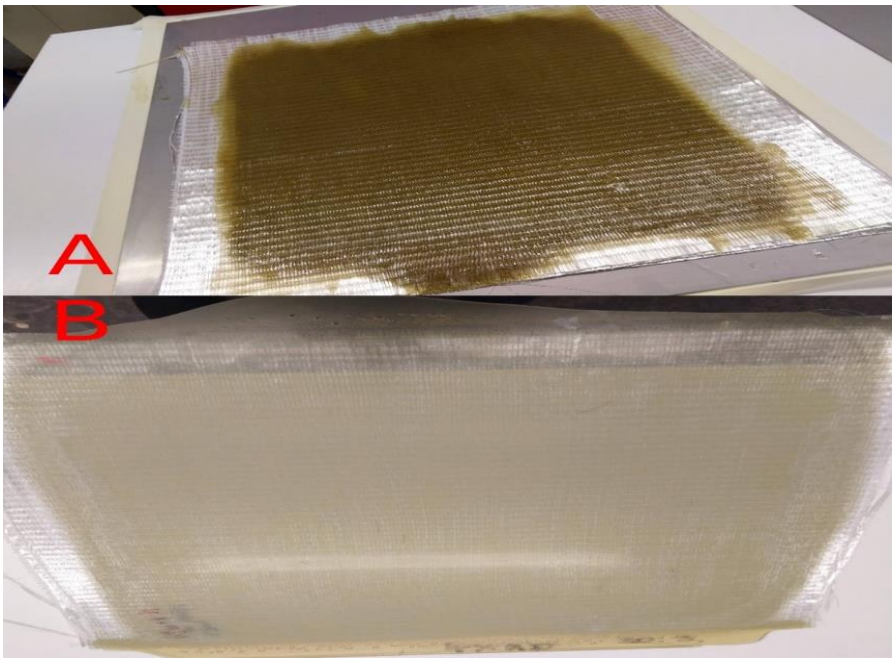


***Figure 4.24*** *Sample 3 UD x4 (A. Hand lay-up process, B. Finished sample)*

Biaxial fiberglass and Jute samples exhibit more voids in their surface, both top and bottom (as shown in Figure 4.25). Biaxial fiberglass is very lightweight, but the fact that it has low density makes it a bad choice for the cold press laminating process. The sample has too many voids and holes on both top and bottom surfaces. The reason might also be the lack of resin content; however, it might be better to used UD fiberglass because of the better structure and its better behavior with the resin.

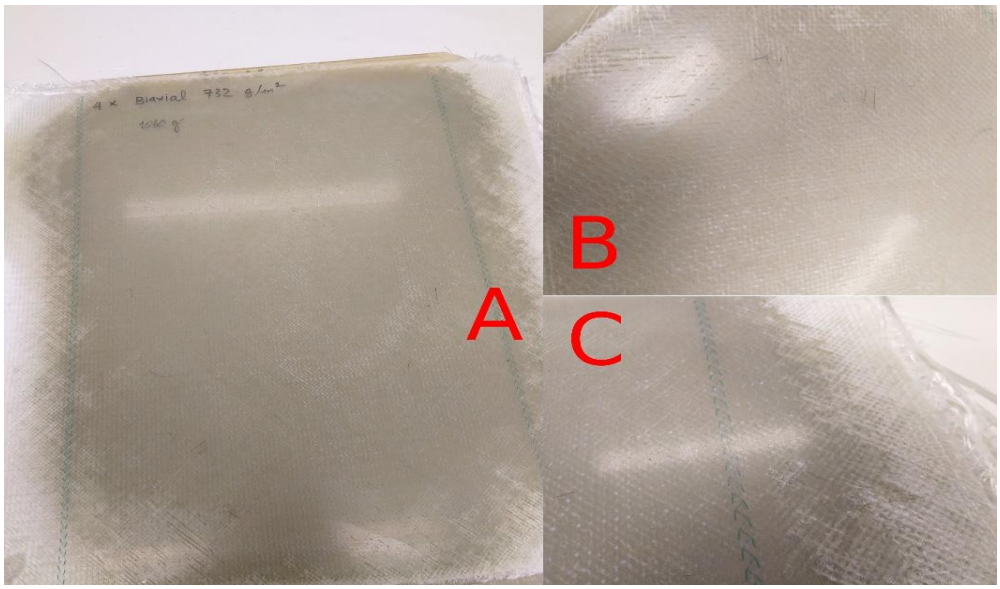


***Figure 4.25*** *Sample 1 Biaxial x4 (A. Overview; B. Voids in the top surface; C. Edges)*

Jute is a good damper material, which means that it is very useful as a material for applications that are related to vibration. However, its low density creates a mismatch between it and the resin viscosity. Most of the resin is pushed down to the bottom by gravity, which filled up all the bottom layers. However, not enough resin remains in the top layers because they are squeezed to the sides, either by surface tension or by the fast flow speed of low viscosity resin. In the end, even though the amount of resin is enough, it got squeezed to the edges, and the prepreg still has voids in the surface. After all the samples are examined, it is recommended that the author try to combine the textile, and see which combination works better and try to control the resin content accordingly.

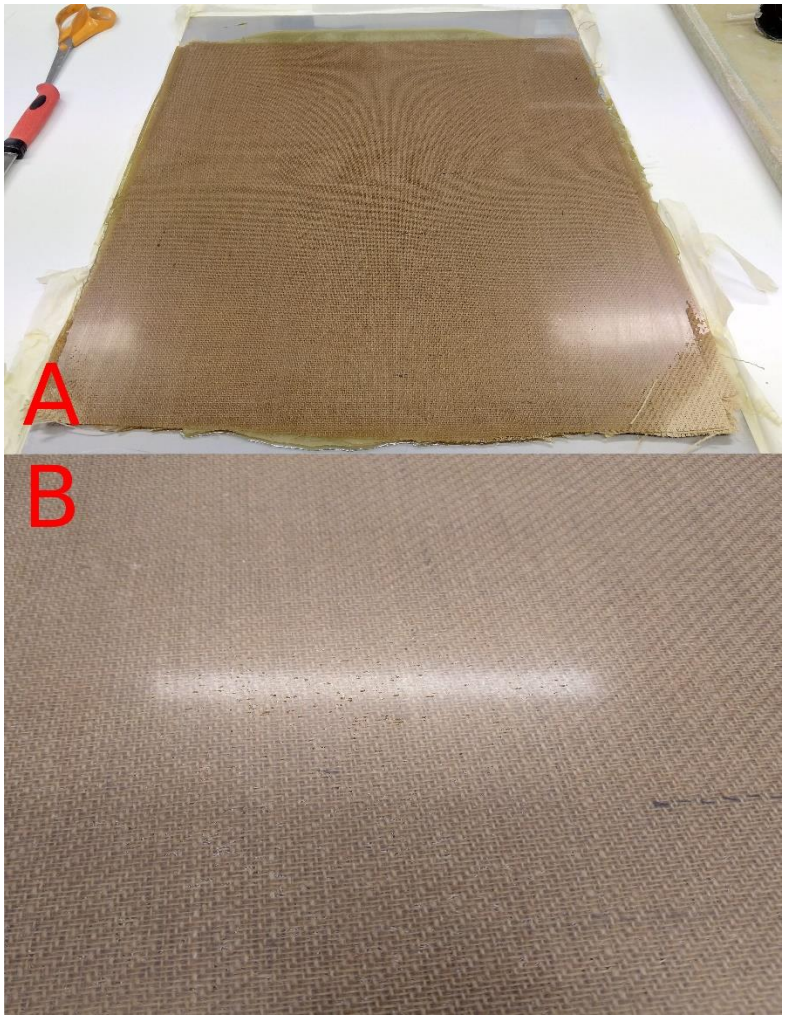


***Figure 4.26*** *Sample 2 Jute x4 sample (A. Overview; B. Voids in the top surface)*

**PHASE 2: Sample number 4,5,6,7**

In this phase, the author decides to combine different kinds of textiles with various viscosity levels, as this is common in the industry. The result of this phase is best illustrated in sample number 4: a combination of Unidirectional fiberglass and Jute. The problem can be seen at the start of the process: although the student applies the rolling force in either the horizontal and vertical direction of the yawns, the resin seems to be stuck in certain areas and might dislocate the yawn if more pressure is applied. This resulted in a wetting problem clearly shown in the cured prepreg, which is illustrated by figure 4.27B.

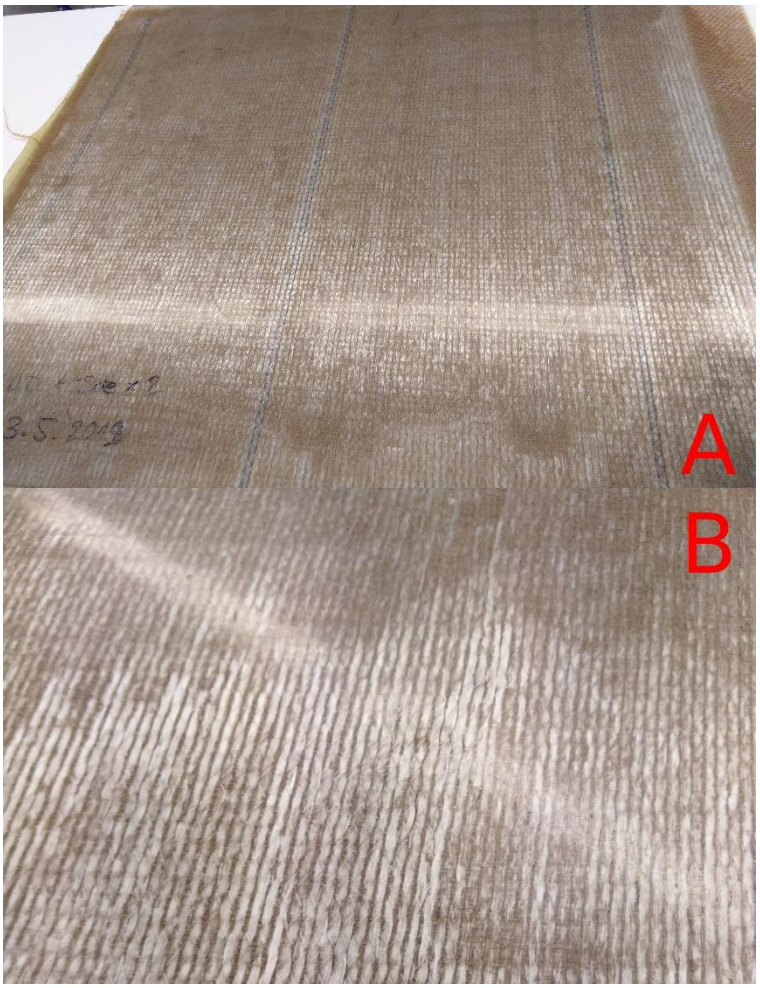


***Figure 4.27*** *Sample 4 with UD fiberglass and Jute. (A. Overview; B. Wettability problem)*

A good explanation of the problem is the mismatch between the textile structure and the resin viscosity. Unidirectional fiber (UD) is a high-density textile, while Jute is low-density, which makes them a common combination in the industry. However, the Atlas

resin in Arcada has a low viscosity, so it cannot easily flow through the yawns and just travels through the area between them. This is why the wettability of the sample is not good, where the yawns are very visible to the eyes. As more resin travel to the edges, it also makes the sample less uniform in thickness and creates more holes in the center of the part.

Combinations of biaxial fiberglass and jute (sample 5,6) also yield the same result: wettability problem and voids on the surface. Even though the textile appears to be very hard to wet (figure 4.28B) before pressing, but the wetting problem is less and appears mainly in the center of the lamina.

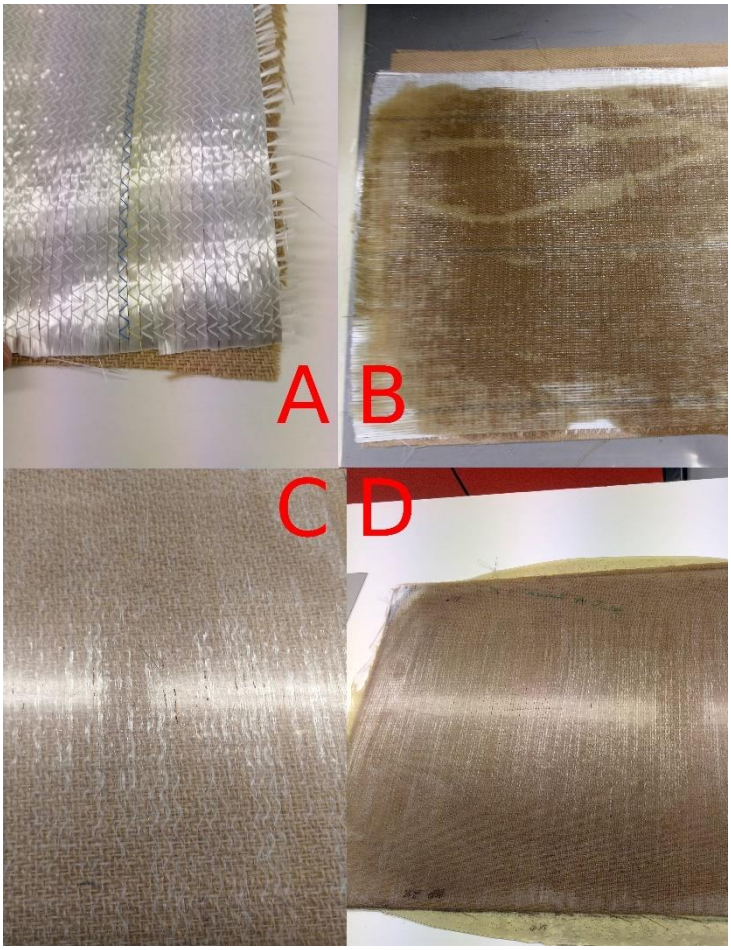


***Figure 4.28*** *Sample 5,6 with biaxial fiberglass and Jute. (A. Textile lay-up; B. Wettability problem; C. Voids in the center; D. Overview)*

The last combination of this phase is carbon fiber and Jute. The result shows the nature of the easy wetting of carbon fiber, but the number of voids in the surface is very extreme, with a little yawn displacement in the edges. This might be because of the low

viscosity resin that is being used so far. Additionally, working with carbon fiber is harder compared to the others: it is more sensitive to pressure, so a brush is recommended for this work, rather than a roller. The amount of resin content should be less than the other cases due to the lighter property of carbon fiber, which is shown in figure 4.29 where there is more excess resin.

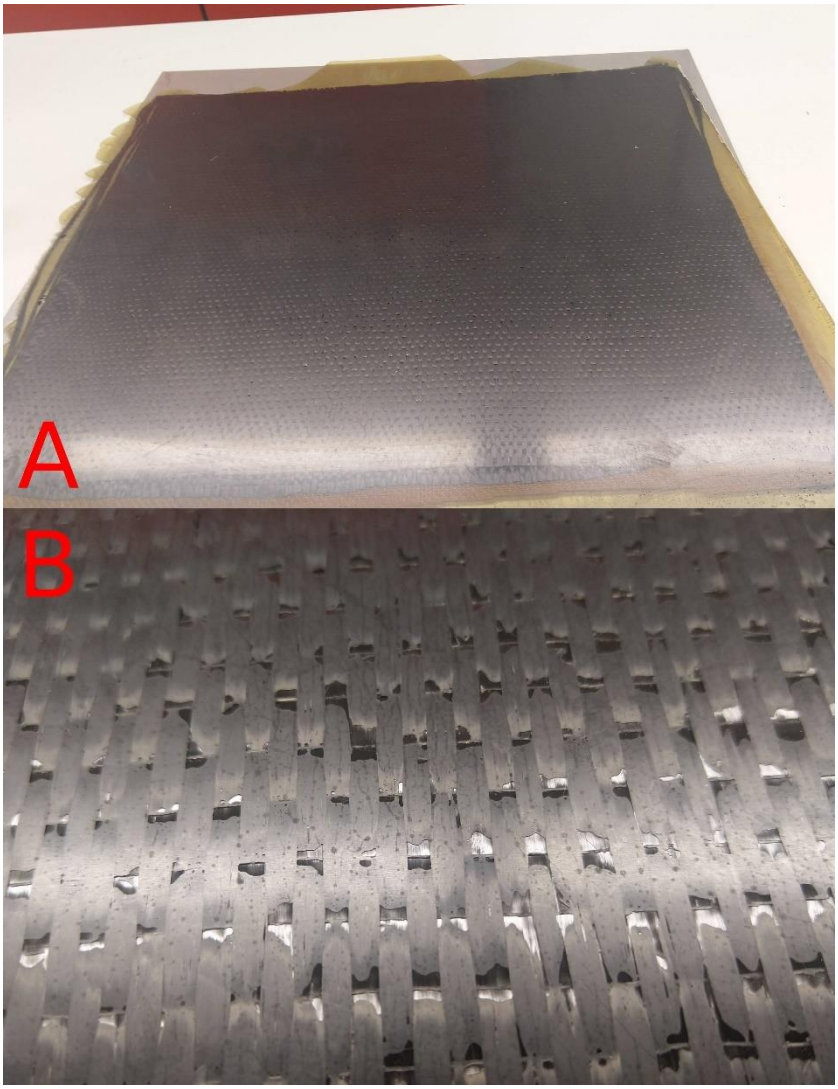


***Figure 4.29**. Sample 7 Carbon Fiber + Jute x6 (A. Overview; B. Voids in the surface)*

What we learn from these samples is using a low viscosity resin with a complex combination of high and low-density textiles is not a clever idea. For phase 3, the author will use a higher viscosity resin with carbon fiber. Additionally, the use of additive will also be evaluated in this phase, so we can see if it has any impact on the laminating process.

**PHASE 3: Sample number 8,9**

After having tested the compatibility of different textiles, the author decides to test the effect of using additives in the process of making prepregs in this last phase. The additive which is used here is thixotropic additives. Thixotropy is the property of fluids or gels to reduce its viscosity (or become less viscous) when being applied with force or pressure. After the force is removed, the fluid can revert to its initial state after a certain amount of time. This property is very common in many things that people use every day, such as toothpaste, ketchup, or lotions. It stays normal when being stored and becomes less viscous and flows faster when people apply force (by squeezing) to it.

In the prepreg industry, manufacturers can mix thixotropic additives into resin for many purposes. For example, if a resin with low viscosity is used with a high-density textile, what might happen is that the resin does not have enough time to fill up the area inside the yawn (or the Brinkmann flow is not enough); and by the time the prepreg is pressed, the faster flow will travel rapidly to the edge, and the prepreg ends up with holes and un-wet yawns. To combat this, people can use higher viscosity resin to have the better flow inside the yawn, plus adding thixotropic additives to speed up the fluid flow after pressed to fill out the area between the yawn, with almost the same degree of yawn displacement.

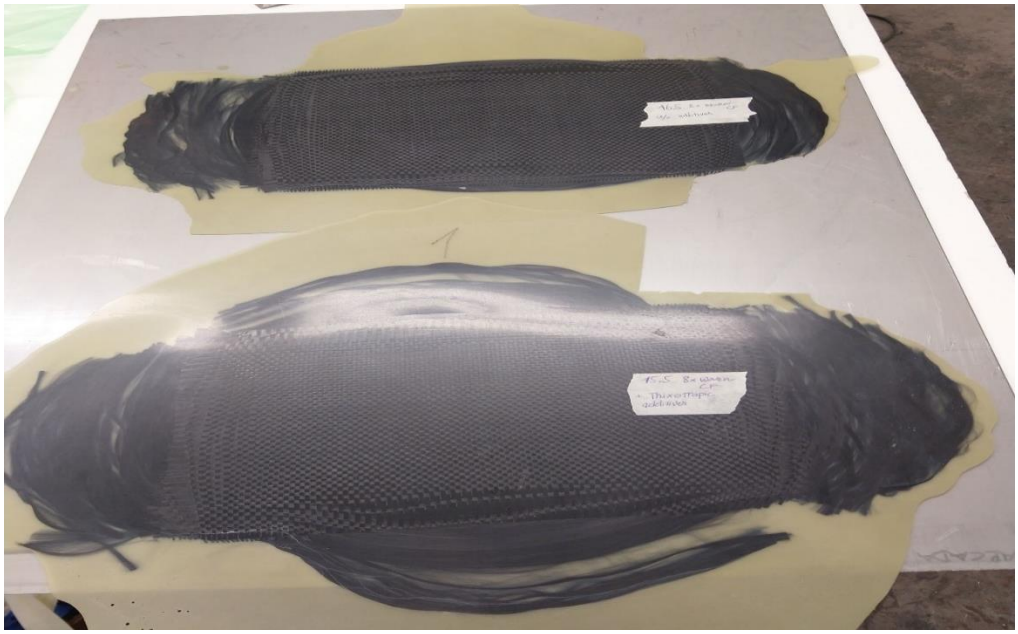

***Figure 4.30*** *Carbon Fiber prepreg samples. (Sample 8 with no additives in the top, and sample 9 with thixotropic additives in the bottom).*

For better visualization of this effect, sample 8 and 9 is done with the same method and same variables of force being applied (and little to none differences in resin content). As shown in figures 4.30, sample 9 exhibits more yawn displacement in the vertical direction. This is because of a faster flow of resin when being pressed by the machine. This degree of yawn displacement is not acceptable in the industry, but this experiment is to show what the additive can change the behavior of the resin and modify the outcome if being controlled precisely.

## 4.2 Prepreg machine

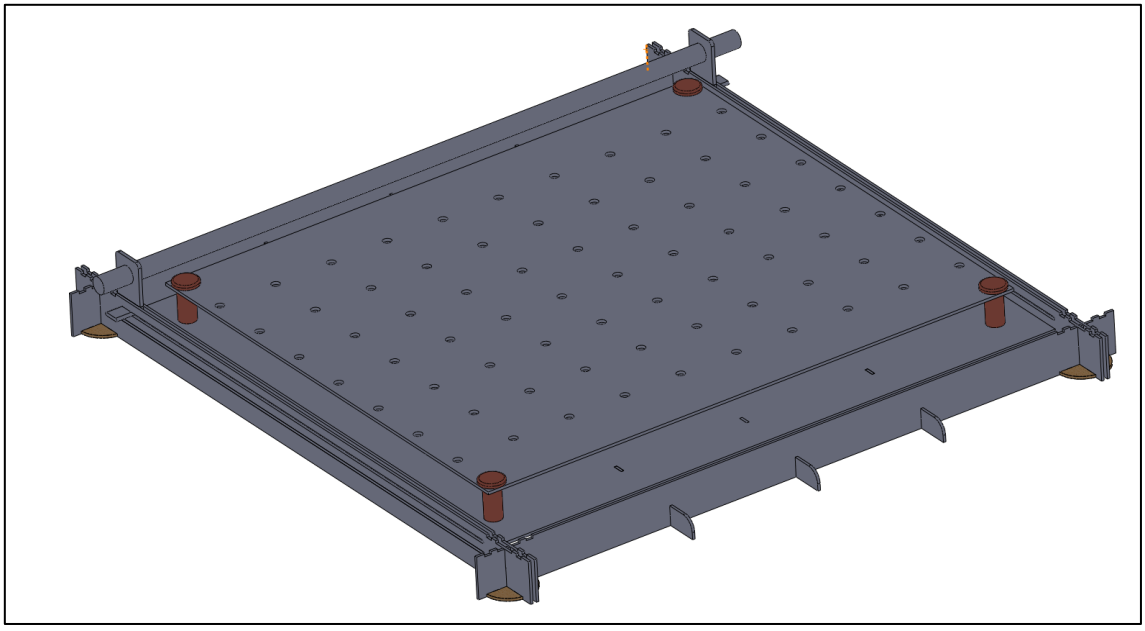

***Figure 4.31*** *The assembly of the small scale prepreg machine*

The fully assembled machine is shown in figure 4.31. The whole process of the machine starts with the most important part: controlling the height of the upper table by twisting the four screws at the same angle. This is to make sure the table is always parallel to the ground and provide a flat surface for the fiber to be placed on. The radius of the roller is also important: combining it with the height of the rail, one can calculate the desired thickness of the finished prepreg.

Then the right amount of resin is put on the fiber, being rolled over by the roller a few times before this process is repeated for the next layer of fiber. The rail moves the roller

in a horizontal direction and provides a consistent rolling motion to flatten the surface of the preform while slightly press the resin into the fiber and fill up the area inside. Excess resin can exit the system through the holes on the table and being collected by the bucket on the lower table. Depend on the properties of the resin, the density of holes can be adjusted to obtain the smoothest bottom surface.

After the impregnation is finished, the student should quickly twist the four screws and lift up the upper table. The whole preform is then transferred into the mould, which should be prepared beforehand. The mould is closed, and it is ready to be pressed. Lastly, the press machine can be started while the student checks for any leak resin (figure 3.19) and clean it if necessary.

Maintaining and cleaning have to be done right after every cycle because the cured excess resin is harder to clean and might affect the product's quality of the subsequent working cycle. The working surface should be clean and dust-free, and the upper table should be cleaned more carefully with cleaning chemicals and a piece of micro glass. The lower table, where most of the excess resin can be found, should also be cleaned in the same way. Even though the machine is relatively small and does not take up many spaces in the lab, the author still recommends it to be disassembled and kept away from direct sunlight and moisture. This should prevent the material from degradation and lengthen its lifespan.

# 5 DISCUSSION

## 5.1 Hand lamination result review

The hand lamination results are positive and understandable. The experiment covers most of the commonly used textiles and resins in Arcada together with combinations of them. The way each combination is chosen shows flexibility in material choice to adapt to the previous process and its result. The results answer the objective of the thesis: it shows the compatibility of the textiles to both the cold press lamination and to the different resins. This type of compatibility testing experiment is essential because it provides good preferences for everybody that will later repeat the process.

However, the aesthetic of the prepreg samples is not acceptable in the industry. The number of voids in the surface and yawn displacement at the edges are not totally caused by the properties of the materials. It might relate to the hardest factor to control when doing the lamination: the student techniques and experience. There are various small details during the process that can produce bad results, for example, how precise the cut of each piece of textile, how evenly the pressure is applied when the resin is rolled into the textile, etc. This problem does not often arise in the industry, as manufacturers mainly depend on machinery and make their process as least labor-intensive as possible.

The COVID-19 pandemic also affects the result of the experiment in many ways. There are many adjustments that could be made, if not due to the closure of the Arcada lab. One example is the change in the pressing force of the machine to see if it creates any differences. More combination of carbon fiber with other textiles would have yielded interesting results, but it could not be done in the time of this thesis. Together with the lack of material testing to the prepreg made by the small-scale machine, the pandemic creates a missed opportunity to make a lot of improvement to this thesis topic.

## 5.2 Prepreg machine design evaluation

The design of the prepreg machine is overall a successful attempt. The cost of the material is very little while still be able to give the machine stiffness during operation. After being cut and assembled, the machine's frame is very stiff and does not bend or flex. The assembly process is quick and easy because the parts fit together securely, without the need for nuts and bolts. Cleaning is simple, and the parts can be put into a container to maintain or transport. The individual part can also be re-made if it is broken, or re-design to the user's desire. The machine has a simple but functional design, and it provides a quality control method to make better prepreg from the lab room.

However, the author still sees room for improvement in the design. During the production of the parts by laser cutting, he faced the most problem cutting the two table parts. The laser cutting machine is commonly used in many public libraries in the countries, but it is too small to cut a full-sized table part. The temporary solution was to print two halves of the table and place them next to each other; but then it will give up the table's stiffness and if the two parts do not fit tightly, a lot of resin would escape the preform and ruin the lower surface of the prepreg. The author recommends that these two parts should be cut manually by a hand saw or band saw, even if these methods do not guarantee precision.

The upper table is the part that faces various problems, especially the size and the material. Although we mentioned above that the size of the table is too big for the laser cutting machine, this size is still smaller compared to a normal working surface. This means that the size of the finished prepreg is much smaller than the current method. The other problem is the table's material being thin sheet MDF, which is prone to scratches and dents because it is a relatively soft material. A scratched or dirty table is not a good working surface for any type of lamination process. Lastly, the way to transfer the preform to the mould needs improvements: the need to remove the upper table every time is problematic. It affects the efficiency and repeatability of the machine, as the height of the table has to be recalculated for every working cycle. One suggestion is to create a

mechanism to remove just the central part of the table and then put back after the material is transferred.

The lower table needs small adjustment: it does not have a way to contain the excess resin coming down from the upper table. This can be fixed easily by adding a small bucket or container. The excess resin can be measured to compare with the theoretical number in chapter 2.3.2 for better understanding. The last problem is due to the COVID-19 pandemic and the closure of schools and other studying facilities. The machine could not be put into operation and the author could not test the properties of the prepreg made by his machine. This is a missed opportunity, but the design is open for anyone who is interested in studying it further.

# 6 CONCLUSION

Plastic composites have the potential to make the strongest and most versatile material in the industry. Their properties can be adjusted or enhanced by the use of fillers, additives, or certain parameters setting. However, it requires a wide understanding of each component and how they work together to get it right. The approach of the thesis has provided a wide view of the complexity and difficulty of making a prepreg and how to implement them at a simpler and smaller level for students in Arcada.

In terms of theory, the thesis provided a guideline on understanding the Navier-Stokes equation, which is used to analyze the flow inside the prepreg. The equation is based on two methods of studying fluid mechanics: control volume analysis and differential analysis, which is then resulted in the relationship between shear stress $\tau_{ij}$ and the velocity field in which the fluid is being considered. After applying the common equations for a two-component composite, the author found out the relation between the change in thickness when the excess resin is removed. This is used to form the basis of controlling the resin content, which is by choosing the initial thickness of the lamina and predict the amount of excess resin during lamination.

Understanding the three key components: the resin matrix, the textile, the manufacturing process, and how they affect each other is essential to make the desired prepreg. Resin matrices consist of thermosets and thermoplastics, with the main difference is the ability to create a three-dimensional cross-linked structure of thermosets. Thermosets has lower molecular weight and viscosity, and a wider range of polymers to be more versatile in term of pricing and application. Thermoplastics are higher molecular weight and viscosity polymers, which are fully reacted before processing. They have a somewhat higher toughness level but are not usable in some applications. Technical textiles are made from the interlaced thread of fibers. The various way of how the threads connect is called weave styles, which have different levels of crimp and drapeability. Low crimp fabrics provide better mechanical performance because of their fiber being straighter. Good drape fabrics are more flexible and wrap around complex shapes easier, while low drape fabrics provide better rigidity when the shape is not difficult to work with.

With the textiles and resins available in Arcada, the author has made prepregs with different combination to test out which will work with cold press lamination. The process is a good practice for engineering students because it requires precise handling and patience to do a good hand laminating. Good results are shown when combining high and low-density textiles and then impregnating them with high viscosity resin. Although the aesthetic of the prepreg is not qualified, the result is a useful reference for other students to consider when working with these materials.

The theory is then used to design a small scale prepreg machine to help better control the resin content when making prepreg in Arcada Lab. The machine is based on the compaction rollers in a hot melt production line. By controlling the height between the roller and the table, one can precisely control how thick the lamina is and make the resin evenly distributed into the textile. The advantage of the machine is that it costs very little to make, being relatively compact, can be easily assembled, maintained, and upgraded. The machine is then manufactured by laser cutting and assembled, giving a good presentation of the design. Its design is simple but very functional, with a lot of rooms for improvement.

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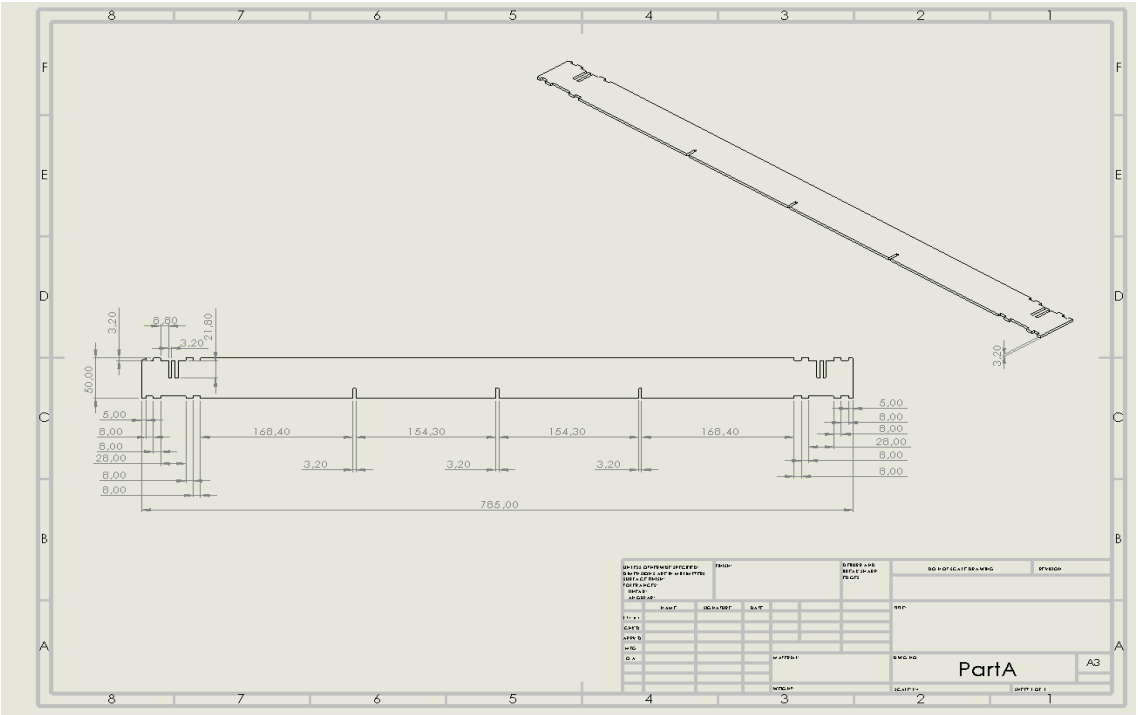
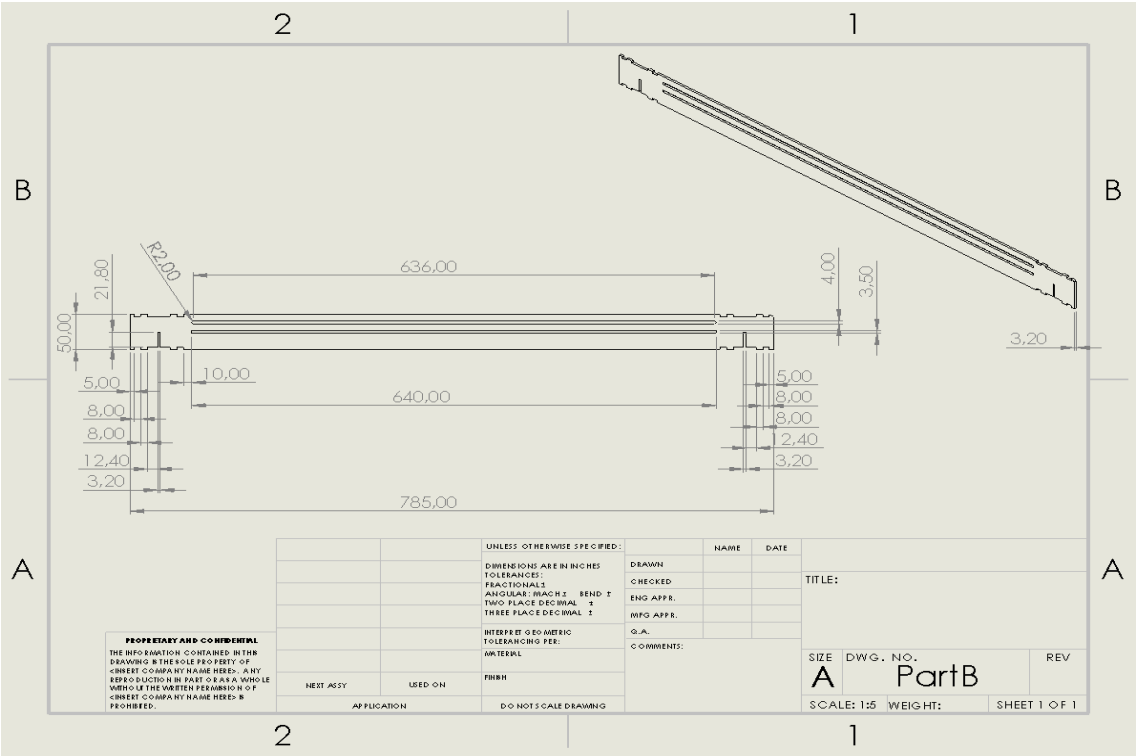
# 8 APPENDIX

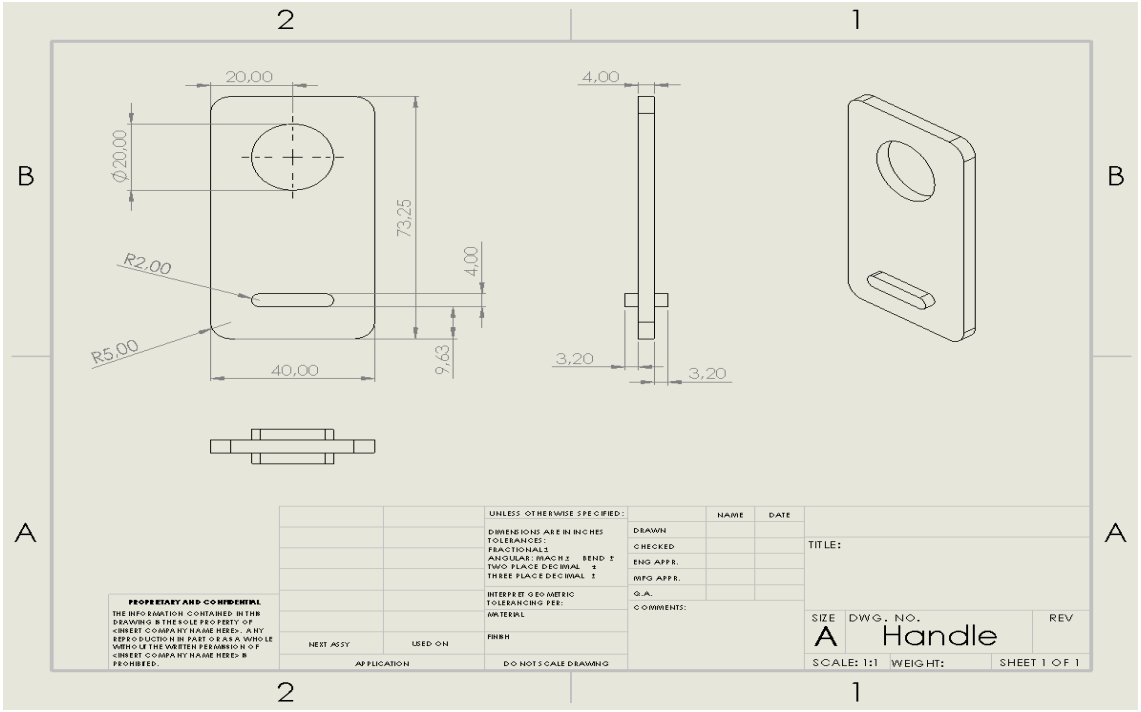
Part A



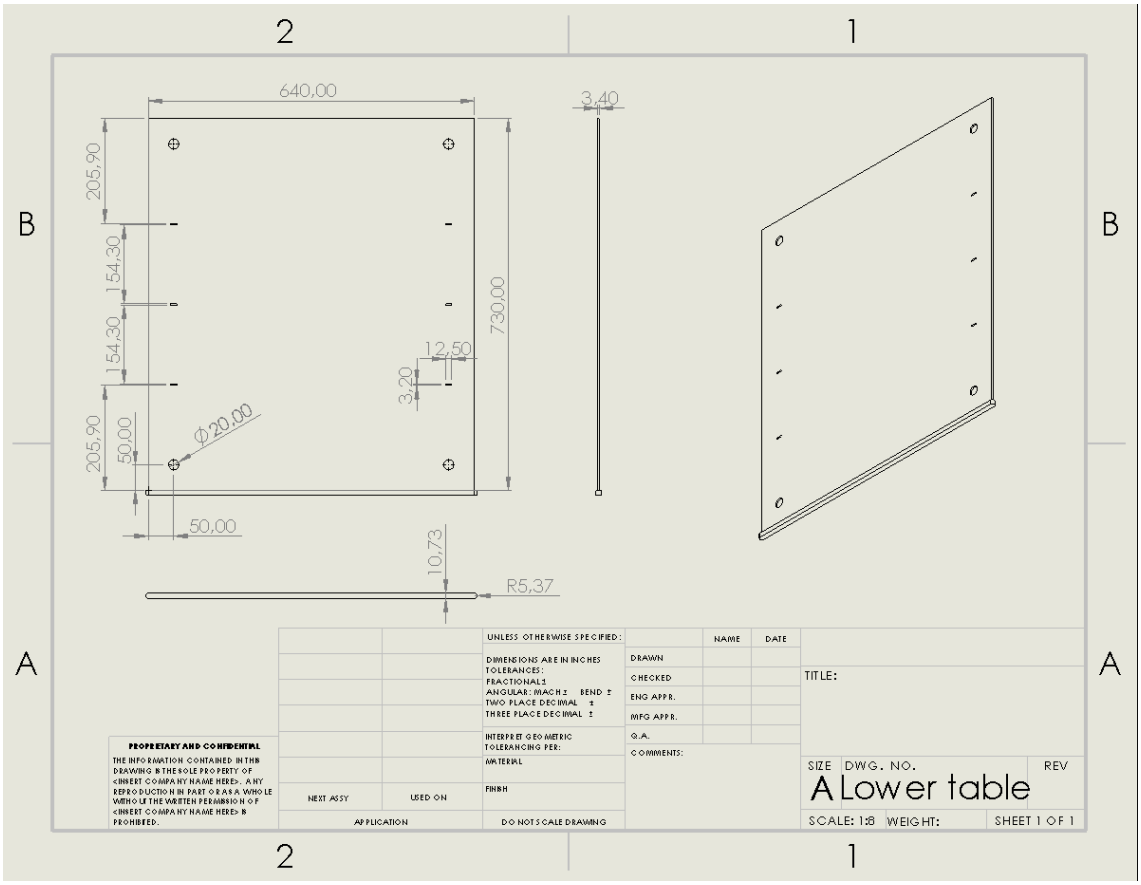

Part B



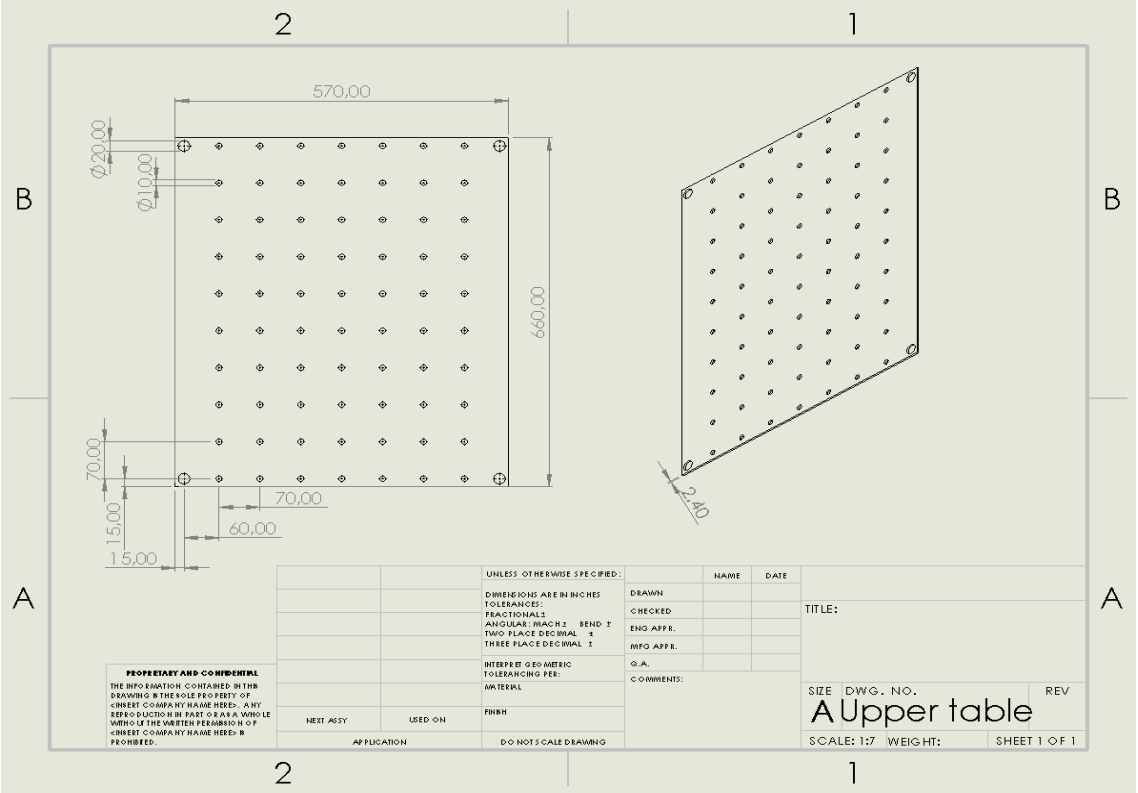
Handle



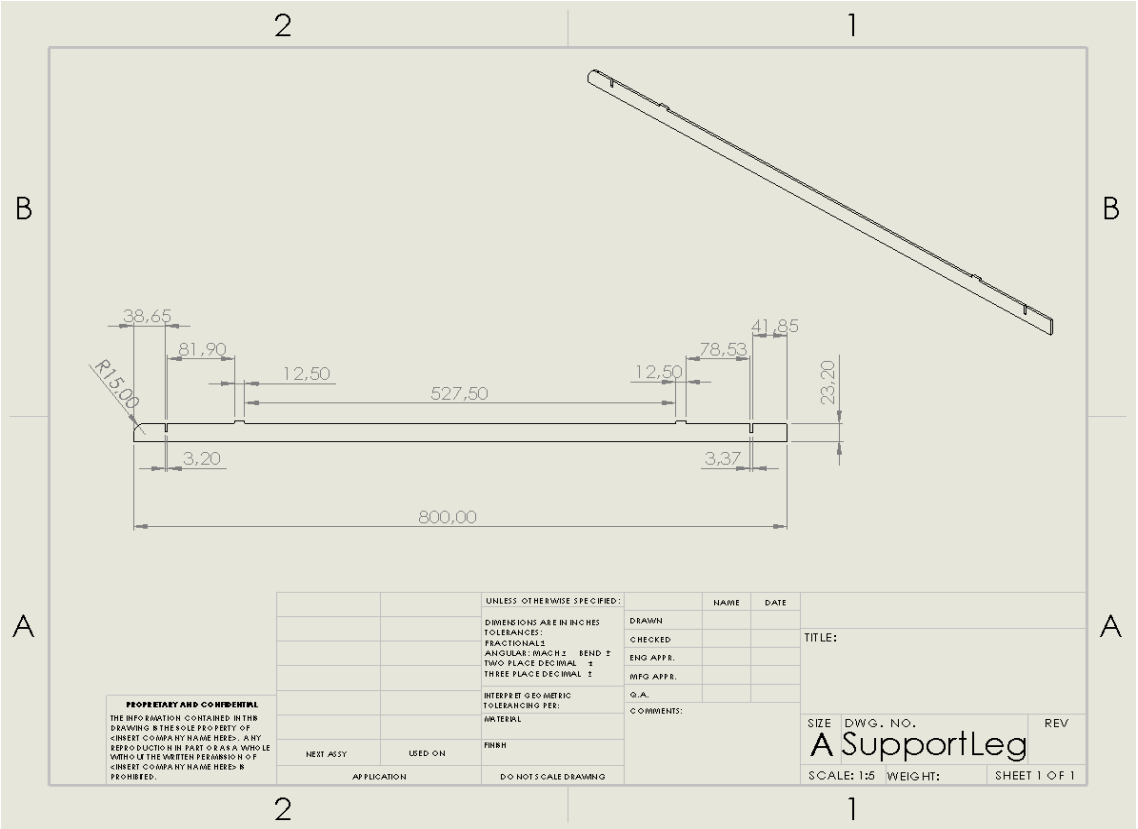

Lower table



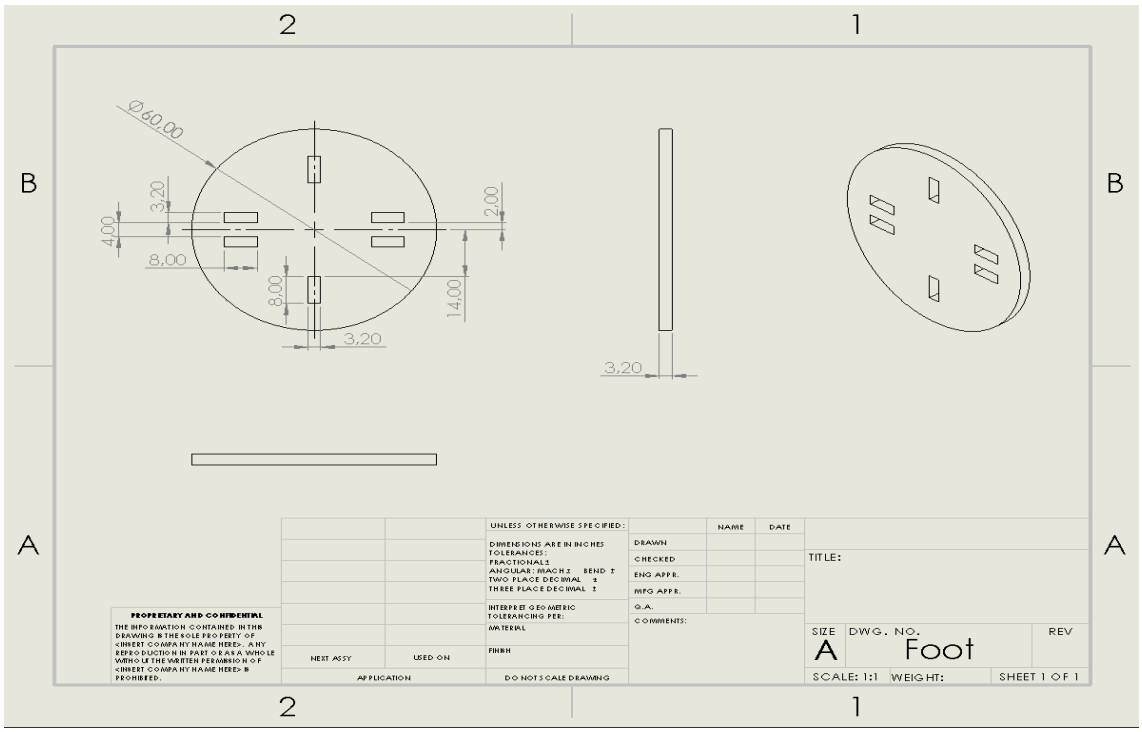
Upper table



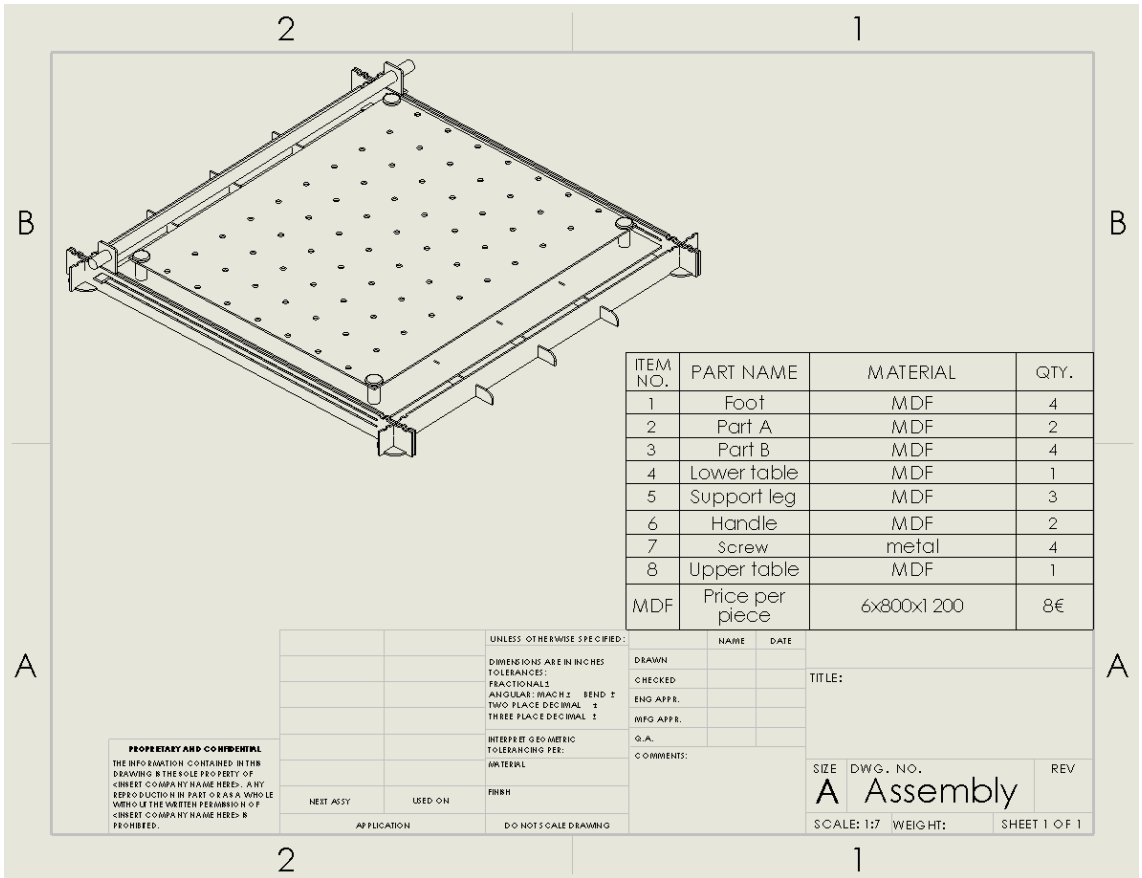

Support Leg



Foot




Final assembly and Bill of material



| ITEM NO. | PART NAME | MATERIAL | QTY. |
|---|---|---|---|
| 1 | Foot | MDF | 4 |
| 2 | Part A | MDF | 2 |
| 3 | Part B | MDF | 4 |
| 4 | Lower table | MDF | 1 |
| 5 | Support leg | MDF | 3 |
| 6 | Handle | MDF | 2 |
| 7 | Screw | metal | 4 |
| 8 | Upper table | MDF | 1 |
| MDF | Price per piece | 6x800x1 200 | 8€ |