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VARTM PROCESS WITH SOME MODIFICATIONS

By

Anupam Dhyani

A THESIS

Submitted to
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MASTER OF SCIENCE

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ABSTRACT

VARTM PROCESS WITH SOME MODIFICATIONS

By

Anupam Dhyani

Vacuum Assisted Resin Transfer Molding (VARTM) is a technique which has many parameters to be controlled and it is not always possible to have the same quality and similar properties with different batches produced by it. This makes it a manufacturing technique which is not suitable for mass production of composites. To be able to control all the parameters, when some of them affect, directly or indirectly, the others, is a challenge and is the main key to promoting VARTM. In this study, the properties of the specimens produced by VARTM will be discussed. The manner in which the properties could be controlled and how batch by batch repeatability of these samples can be maintained will also be addressed. A term "BUBBLE TRAP VARTM" is suggested for a modification made in the setup. Also how the modified technique could be used to manufacture two surface-finished and transparent (to a degree) specimens will be discussed. With the transparency, it would be possible to get a better insight of the voids suspended inside the sample and also will be able to study the inter-laminar damage which may occur when testing is done on the sample. Overall, this technique can be used to produce transparent and two surface-finished specimens and is cost effective.

To my father, Shri Pushp Raj Dhyani,mother Dr.(Mrs) Asha Dhyani, sister Apoorva Dhyani and the inspiration in my life, Jaya

ACKNOWLEDGEMENTS

I would like to thank Dr. Dahsin Liu, my research advisor, who has guided me in writing this thesis, and has taught me many valuable lessons in life. This work would not have been possible without his faith in me and his invaluable experience.

I would also like to thank my colleagues Dr. Elias Shakour, Goijing Li, Shawn Klann, Kirit Rosario, Jeffrey Fuller and Brandon Gulker. Without whose help, support, advice and invaluable camaraderie this work would not have materialized.

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CHAPTER 1

INTRODUCTION

1.1 Composites Background and History

Right from the primitive age, man has always been endeavoring to make things stronger, from reinforcing his house to strengthening monumental buildings. This continuous strive to build things stronger has led to the advancement of the materials he has been using. Prior to knowing the chemistry of metals and the use of advanced materials, man found his ways of strengthening all his belongings like his house, his means of transport, his weapons, his clothes and his utensils. He made his house of mud and reinforced it with straw so that it doesn't give in to inclement weather; it was his first idea of composites and was not named so then though.

With the advent of metals, man got a chance of building stronger components, things which were stiffer than his "primitive composites". This continued for many centuries until he refined the art of making stronger materials. With the increasing demand and diverse needs, e.g. to conserve energy, man had to come up with materials which were stronger yet lighter. This is how the modern composites took birth. In recent times, the art of composite manufacturing has refined itself to such an extent that right from paving our roadways with asphalt concrete or Portland cement, we are making the airplanes lighter as in the Boeing 787 "Dreamliner" which is 50% composite (by weight). Defense departments all around the world are shifting to composite materials for their combat vehicles as their use improves maneuverability, gives strength and high energy absorption. Even though conventional homogeneous metals like steel, brass and aluminum are still being used for the basic framework of structures; many advanced structures are being quickly replaced by composite materials. Not only do they give the advantages of low density (lightweight), high tensile strength, high stiffness and immense energy absorption, they can also be tailored for various customized engineering requirements and provide design flexibility. Composites also add to the overall aesthetics amalgamated with the engineering requirement. A composite is a combination of two or more materials (reinforcing elements, fillers and matrix binders) different in form and composition on a macro-scale. The constituents retain their identities, that is, they do not dissolve or merge completely into one material although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Composites continue to play an important role in industries like aerospace, automotive, marine, medical, military, recreational and many more. Due to the rapid spread of the use of composites in many important industries, it becomes vital to manufacture these composites for various requirements at reduced costs and high quality. During the last few decades, researchers and industries have invested lots of money in the development of cost-effective manufacturing techniques for composites [1]. For composite production, many different types of techniques are used currently in the industries. For example, RTM (Resin Transfer Molding), filament winding, autoclaving, SCRIMP™ (Seemann's Composite Resin Infusion Molding Process™), and spray gun techniques are some of the popular techniques available in the composite manufacturing market currently. While RTM has an advantage of producing composites with high fiber percentage, SCRIMP has the advantage of producing large composites in a very short time (e.g. the hull of a boat). Autoclaving possess has the advantage of making high-quality composites with low void content for maximum structural efficiency (e.g. the tails and wings of aircrafts). Filament winding (e.g. golf clubs) can provide engineering properties like high tensile strength. Although RTM, autoclaving and filament winding are very capable of producing high quality composites yet they are very expensive procedures as they are labor intensive and require very sophisticated tooling and high setup costs.

The constant need for a manufacturing technique which produces quality specimens and is low on cost led the composite manufacturing industry to give birth to Vacuum Assisted Resin Transfer Molding, commonly known as VARTM. With the capability of producing composites with a fiber volume fraction close to autoclaving, VARTM has, over the years, shown the potential of being an effective technique for manufacturing composites. Researchers all around the globe, over the past two decades, have shown special interest in this technique and because of the potential it possesses, have led to the refining of this process to a great extent. VARTM has developed into a technique, because of its simple setup and cost effectiveness, which has the potential of replacing classical techniques like RTM and autoclaving. Although RTM and autoclaving are widely used for high-quality composite parts, the research on VARTM has led to many possibilities in which it can be used in different capacities.

Research has been going on for some time and many aspects of VARTM have been looked into. Since there are many parameters involved in this technique, studies have been made to address these problems and conclusions have been drawn out to assist the development of this technique. Some of the parameters involved are flow of resin in the preform, dimensions of the composite manufactured, compaction and permeability of the preform. Researchers have addressed these issues in detail and have come up with some solutions to the problems encountered.

1.2 Literature survey

The literature on VARTM technique has been surveyed and categorized into the following areas as the studies are done for various parameters.

1.2.1 Flow of Resin

Studies have been done on the flow of resin through the fiber preform in the VARTM process. Because voids formed during the mold filling stage of VARTM become defects in the fabricated part, Johnson and Pitchumani [2,3] studied the flow and came up with an active flow control strategy to eliminate these defects by guiding the flow along a desired path. By implementing local induction heating they found out that the viscosity of the resin and the in homogeneity of the permeability of the preform layup. By their active flow control they were able to reduce fill time, improve flow front uniformity and eliminate dry spot formation.

Grimsley et al [4] studied the effects of compaction on the flow of resin. They also studied the change in the direction of the flow front as the thickness of the stacked layers of fabric increased. They concluded that as the thickness of the preform increased, the through thickness flow of resin became faster.

Heider et al [5] studied the flow in thick sections and found out that the flow times were increased and void formation was more likely to happen, so they came up with a design methodology where they placed several layers of distribution media of varying lengths through the thickness of the part. They improved the infusion times with their setup along with reducing voids; however the flow field was very complex. They did not address the concerns about property change due to the inter laminar distribution media.

SCRIMP (Seemann's Composites Resin Infusion Molding Process) [1], which is a patented technique, was widely used in the manufacturing of large structures such as boat hulls. The feasibility of this technique was reviewed by Beckwith et al.

Yoon et al [6] studied the gravitational effects during the flow of resin in VARTM for tall structures. They came up with an analytical solution for flow and pressure prediction by incorporating the gravitational effects; however the assumptions made were one dimensional, laminar and incompressible resin flow, and homogeneous and uniform thickness preform. The parametric studies indicated the important parameters influencing the flow time including mold angle (0^0-90^0), permeability, radius and length of injection tubes and preform cross-sectional area. They concluded that the flow time could be reduced for downward infusion (gravity assisted) case where the resin bucket was placed at the same height as the inlet tube. Also the length of the infusion tube and the area of the preform could affect the flow times.

Bender et al [7] investigated the flow rate control for VARTM which allowed vacuum pressure to be applied to the resin bucket to generate a computer controlled vacuum differential between the injection and vent gate. They also studied how to control the resin flow to reduce void content in the part. The system successfully controlled the flow for a wide range of permeability and viscosity values

Walsh et al [8] suggested a method alternative to conventional VARTM known as FASTRAC which reduced cost and wastage. They used a double vacuum bag with an optional distribution media option. The cost was reduced by eliminating the distribution media thus causing less wastage.

1.2.2 Compaction / Permeability

The effect of flow time, permeability and compaction were discussed in [9-17]. These studies detailed the permeability study and the factors affecting the permeability. Algorithmic models developed for flow front determination and permeability effect were also detailed in these studies. Fiber permeability had a strong influence on resin impregnation behavior. A procedure was developed for determining the anisotropic in-plane permeability of fiber performs from constant flow rate molding. Gauvin et al [10] designed and optimized a reliable mold filing model with accurate description of resin flow through the reinforcement. Dong [11] proposed a computational procedure for permeability based on flow front location and flow time data was derived. Hammani [13] discussed the factors affecting the permeability measurement in VARTM. He characterized the parameters affecting and observed the effect on infused length and fiber fraction.

1.2.3 Improvement of Quality

The quality of the specimens such as thickness, surface finish, void content and flow control were compared with other techniques such as RTM and autoclaving in [1,18-24]. Solange [12], Gama et al [13], Juska et al [18] discuss the various parameters which were involved and the challenges in controlling these properties. Some new methods were also proposed in these studies such as silicone bagging and FASTRAC. The thickness variation and surface quality were discussed in [25,26]. Heider et al [5] discussed the surface quality of the techniques like SCRIMP, VARTM and silicone bagging.

1.2.4 General / New techniques

New methods and techniques such as reusable vacuum bags, multiuse tooling system, water soluble tooling, double chamber VARTM and UV-VARTM were proposed in the studies [22,23,27-29]. Double chamber VARTM used two molds which were made of wood or plastic. This process was capable of making large parts and could be used to make thermoplastics as well. UV-VARTM did not need extensive training and licensing and reduced the cost of the final product. Reusable vacuum bag helped reducing the cost of vacuum bags giving the same finish as the ones which use the one-time used vacuum bag. Water soluble tooling assisted in making complex shapes as once made, could be dissolved in water and reshaped for further use.

1.3 Statement of Problem and Objectives

Vacuum Assisted Resin Transfer Molding is a process which involves many parameters to be controlled. These parameters affect directly or indirectly each other and thus make them difficult to control simultaneously. They produce large variations in the properties and quality of the samples produced with VARTM, due to effect of one or more parameters involved, thus hindering VARTM from being a commercial composite manufacturing technique. To understand the behavior of the parameters individually and simultaneously, and to be able to control most of the parameters involved, is the primary goal of this study. Another goal is to obtain batch-to-batch repeatability of the samples manufactured by this technique. Some modifications for achieving the objectives of the study would also be made to the existing procedure so that the desired result can be achieved.

1.4 Organization of the Thesis

This thesis is organized into six chapters overall. Chapter 1 gives a brief introduction to composites, summarizes the literature survey done on composite manufacturing; it also defines the problem posed and the objectives of the study.

Chapter 2 describes in detail the setup, the raw materials used and the precautions to be taken while setting up the procedure to manufacture composites with VARTM.

Chapter 3 details the various case studies done while making the specimens. It also explains the various modifications made to the current setup and proposes a suggested setup which helps control some of the parameters effectively. It also explains how the various setups can be used effectively.

In Chapter 4, the first portion explains the various testing methods involved. The second portion presents the results and discusses the outcome and gives reasons for the outcome.

Chapter 5 briefly describes the use of the proposed technique for manufacturing large and complex structures like sandwich composites and arches with VARTM.

Chapter 6 summarizes the conclusions drawn and recommendations for future work in this topic are proposed.

Some tables, pictures and data which are not presented in the chapters are listed in the appendices.

CHAPTER 2

VACUUM ASSISTED RESIN TRANSFER MOLDING

With so many composite manufacturing techniques available in the industry it becomes essential to select a process which is easy to use, is cost effective and produces composite materials which are of high uniformity and quality. This chapter briefly summarizes the Vacuum Assisted Resin Transfer Molding (VARTM). It also explains in detail the necessary raw materials and conditions required to manufacture composites with the VARTM technique.

As the name suggests this technique uses vacuum pressure to pull out resin from the inlet to the outlet which is connected to a vacuum pump, with vacuum pressure through an already laid reinforcing fabric material. The reinforcing material is placed on a single flat tool. On top of this is placed an infusion media which assists the flow of resin through the reinforcing fabric.

VARTM is an inexpensive technique to produce composites. Unlike Resin Transfer Molding (RTM), which uses two molds and an injection pressure to infuse the resin in the fabric, VARTM uses one mold and vacuum instead, this by itself reduces the cost tremendously. Although fiber volume fraction is slightly less than that produced by autoclaving, it does not require any sophisticated equipment such as an autoclave and can be done at room temperature. All these characteristics make VARTM a potential candidate for replacing some current techniques to a great extent and by reducing the cost of manufacturing, making composites readily available in the industry and other applications.

There are some elements which are necessary to be considered when this technique is employed for manufacturing composites. The elements necessary are reinforcing fabric (such as glass, carbon or Kevlar fiber), binding material (a mixture of resin and hardener). The tooling or the mold and vacuum bag are the other elements that are involved in the process. Another important element is the vacuum pressure which assists the resin to transfer from the inlet to the outlet wetting the reinforcing fabric.

2.1 RAW MATERIALS

The VARTM system constitutes of laying the preformed fabric onto a smooth surfaced tool (which acts as the first mold). Some release material like wax is applied to the mold so that after the cure of the part it is easy to demold the part from the fixed mold. Then the resin inlet and vacuum outlet piping is placed at both the ends of the laid fabric. A low permeability infusion media and a release fabric are placed on top of the fabric and finally the vacuum bag is placed on top; the vacuum bag is sealed with the help of a sealing tape and vacuum is drawn using a vacuum pump. After the setup of this process, the resin is infused (pulled by the vacuuming force of the pump) through the fabric. Thereafter the inlet and outlet manifolds are clamped so that the resin inlet can be stopped. The impregnated fabric is let to cure. The curing time is decided by the type of resin and hardener combination used for the resin impregnation.

The Figure 2.1 below shows the schematic of the VARTM process.

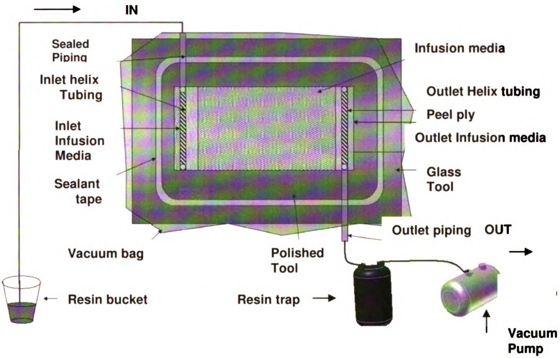


Figure 2.1 Schematic of the VARTM setup

2.1.1 MOLD

This is usually a stiff material which does not change its shape. For making flat panels it is usually chosen to be a smooth plate so that one side of the composite has a smooth finish. In this case, glass was used as it had fine finish and was stiff. It was also used because it was transparent and the resin flow could be monitored from both sides. Figure 2.2 shows the glass mold.

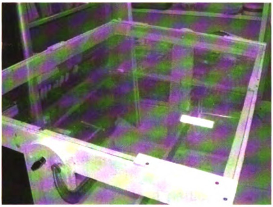


Figure 2.2 Glass mold

2.1.2 MOLD RELEASING WAX

This is usually applied to the tool surface before the placing of the fabric. After the application of the wax it was set to dry and then wiped off with a clean cloth or paper towels, giving a fine finish to the tool side and making it so smooth that the impregnated preform would not stick to it once it cures and could be taken off easily. A solid release wax with the trade name TR-102 manufactured by TR industries was used in this study as shown in Figure 2.3

Figure 2.3 Molding wax

2.1.3 REINFORCING FABRIC

The backbone of any composite material is the reinforcing fibers. They are usually stacked in layers when the composite part is produced. The materials generally are E (electrical Grade) glass, S (structural grade) glass, carbon or Kevlar fibers. There are many forms of these fibers; some are unidirectional which are stitched together. Some are woven in coarse manner while some in a fine weave. Each type of fabric caters to a particular need. Each layer of the fabric can be stacked at different orientations and of varying thicknesses depending on the engineering application. Figure 2.4 shows the various fabrics used in the study.

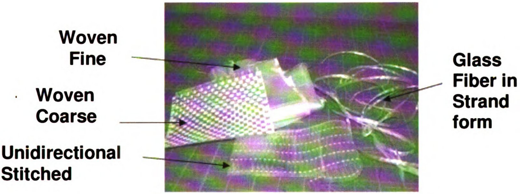


Figure 2.4 Reinforcing fabric

2.1.4 RESIN

With the advancing chemical knowledge, resins are being tailored such that they can be used in the most effective manner. The resin is used to impregnate the fabric preform. The characteristics of the resin which directly affect the VARTM process are viscosity, gel time and the type of resin. Less viscous resin might infuse very quickly resulting in deformed parts, the deformation is due to the uneven wetting of the fabric making some portions resin rich and the others full of voids, while faster curing resins (usually with high viscosity) gel too quickly and cannot sometimes impregnate the entire part.

Most commonly used resins are vinyl esters and epoxy resins. Styrene emission is one of the drawbacks of the vinyl esters, which causes shrinkage of the parts resulting in stresses between the layers. They are not expensive though. On the other hand, the epoxy resins are used very commonly as there is fairy less emission. They are provided with hardeners of varying viscosities so that one can control the type of flow (fast or slow which depends on the resin viscosity) by changing the hardener. In this study the resin and hardener used were manufactured by PROSET (resin 117LV and hardener 226).

Table 2.1 below shows the various resin/ hardener used in the study.

Table 2.1 Types of resin / hardener combinations

PRO-SET Epoxy Technical and Handling Data			
Property	**117LV/224**	**117LV/226**	**117LV/229**
Density g/ml	**1.114**	**1.09**	**1.114**
Viscosity cP	**800**	**350**	**310**
Mix Ratio Weight	**100:33**	**100:30**	**100:31**
Mix Ratio Volume	**100:34**	**100:35**	**100:37**
Pot Life 100 g sample in min			
65° F	**29**	**85**	**110**
72° F	**21**	**44**	**61**
80° F	**15**	**25**	**40**
Working Time @ 72° F	**20 min**	**1 hr**	**2 hrs**
Gel Time @72° F	**2.25 hrs**	**3 - 3.5 hrs**	**5 hrs**

Figure 2.5 shows the 117 LV and 226 hardener. A detailed properties chart is available in the Appendix C.

Figure 2.5 Infusion resin and hardener

2.1.5 MEASURING BALANCE

A sensitive measuring balance shown in Figure 2.6 was used to measure the amount of resin and hardener mixture to be used for infusing. This has to be very sensitive (measures up to .01 grams) as inaccurate weights can cause uneven curing and change the properties of the resin flow inside the preform, also cause gel times to change. This was observed when in one of the experiments the resin and hardener were not mixed accurately, the mixture started to over-heat and due to this exothermic reaction the mixture in the resin pot started giving out huge amounts of black fumes with intolerable smell and all the epoxy spilled out of the pot after melting the pot. Also the gelling color changed from the regular amber color to a dark brown shade. This inaccuracy can cause hazardous changes, so care should be taken that the measured amount is as accurate as the measuring balance can measure, slight changes may cause irrevocable damage.

Figure 2.6 Measuring balance

2.1.6 INFUSION MEDIA

This is used to distribute the resin from the inlet piping to the preform.The resin moves in the thickness direction thereafter. The infusion media is placed on top of the preform. The inlet manifold is placed on it as it extends on the inlet side beyond the preform, on the outlet it only extends a little so that it does not touch the outlet helix tubing. The gap between the outlet helix tubing and the infusion media is approximately 31.75 mm (1.25 in). There are many types available in the market and all are used in different capacities. The infusion media used in this study was INKA 7001 manufactured by Colbond-USA Inc. Figure 2.7 shows the various types of infusion media used. It should also be noted that the use of infusion media qualifies the process as Seeman Composites Resin Infusion Molding Process (SCRIMP) which is a patented technique. This study is only for academic discussion and use of the infusion media will only help study the process better. Also comparing the technique in this study to the already in use SCRIMP will help better understand the process.

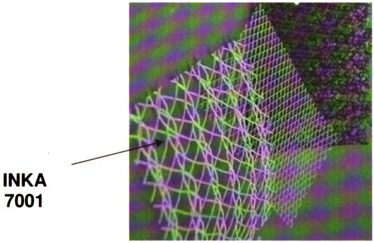


Figure 2.7 Infusion media

2.1.7 RELEASE FILM / PEEL PLY

This is a cloth like material which is porous and allows the resin to flow through it; however, it does not let the resin stick to it. It also allows the infusion media not to adhere to the preform. This release fabric is normally a finely-knit nylon or other material that repels resin and doesn't allow the resin to adhere to it. The release fabric used in this study was Ply by Composites One (Figure 2.8)

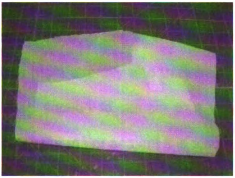


Figure 2.8 Peel ply / release fabric

2.1.8 VACUUM BAG

The vacuum bag is easily one of the vital components of VARTM. It forms the second mold (flexible) and covers all the components such as the fabric, peel ply, infusion media and inlet and outlet helix tubing. It also maintains the vacuum pressure gradient and helps contain the resin in the system. It is fixed to the solid mold (glass base) with the assistance of mastic sealing tape i.e. tacky tape. There are a few types of vacuum bag, some used are of non stretchy material and others are flexible. The advantages, drawbacks, functioning and the ways of set up would be discussed later in the chapter. Figure 2.9 shows the two bags.

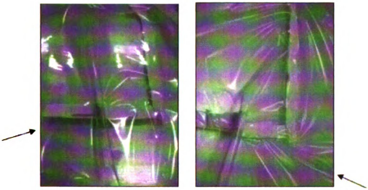


Figure 2.9 Vacuum bag

2.1.9 SEALANT TAPE

This tape is used for the vacuum bag to stick to the mold; it adheres to both the vacuum bag and glass mold strongly and thus helps to completely draw out air and seal the vacuumed section to remain that way. It makes the system airtight. Apart from its use as the major sealant it is also used in the sealing of the various joints in the manifold system (inlet and outlet). Also it can be used to cover any sharp portion inside the bag which could cause the bag to rupture and ruin the vacuum. The tape comes in various grades depending on the temperature. Yellow sealant tape was used in this study shown in Figure 2.10.

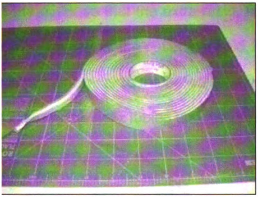


Figure 2.10 Sealant tape

2.1.10 INLET AND OUTLET PIPING

Inlet piping is used to draw resin into the vacuum chamber and outlet is attached from the vacuum chamber to the resin trap (discussed later). This pipe has to be sturdy enough not to collapse with 1atm of vacuum pressure. It should also be transparent as flow of the resin can be monitored and controlled. In this study, polyethylene pipes were used as they meet both the requirements.

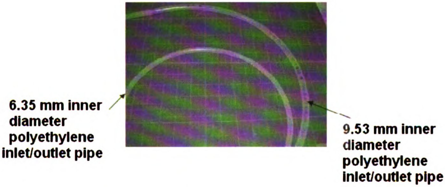


Figure 2.11 Inlet and outlet pipes

2.1.11 HELIX TUBING

Helix tubing is special spiral tubing which is used for the distribution of the resin inside the vacuum bag. It is used both on the inlet (to distribute the resin equally on the inlet) and on the outlet so that the extra resin, flowing away from the fabric towards the outlet with the help of the outlet manifold, is collected in the resin trap. The flow of resin is perpendicular to the helical tubing giving maximum resin distribution. Figure 2.12 shows the helix tubing and the perpendicular flow.

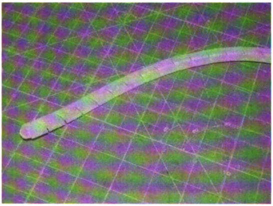


Figure 2.12a Helix tubing

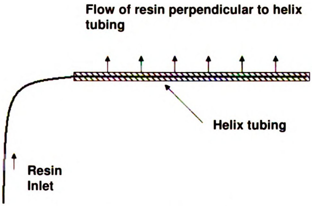


Figure 2.12b Perpendicular flow

2.1.12 CLAMPING VISE

These vices are used to clamp the piping before the infusion so that the inlet end is blocked and no air can enter the vacuum chamber, which is the vacuum cavity within the vacuum bag sealed with the sealant tape. It is also used to further clamp both the inlet and outlet pipes once the resin has completely infused. This collapses the piping and help in the control of the flow in the system. Figure 2.13 shows the vices.

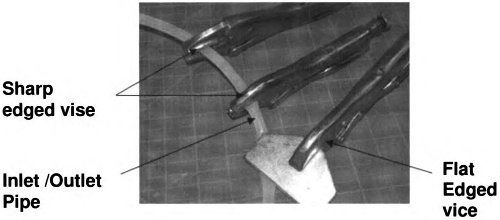


Figure 2.13 Clamping vise

2.1.13 CUTTING TOOLS

The cutting tools include the scissors; it is used to cut the fibers from large rolls of fabric. It is difficult to cut these fabrics as the scissors do not allow enough pressure to be applied as the fabrics are tough and cause the fabric to be cut unevenly. This happens because the fabrics are slippery due to the fiber being subjected to sizing when being manufactured. Thus it becomes necessary to use a roller cutter which provides better cutting power and assists in easy cutting of the fabric. The blade of the roller cutter is basically round. The fabric is placed on a cutting mat and the roller is used to cut the fabric. (Figure 2.14)

Figure 2.14 Cutting and scraping tools

2.2 EQUIPMENT

The equipment used in the entire process is detailed in this section

2.2.1 RESIN TRAP

This is a bucket which is used to prevent the resin from going to the vacuum pump and thus it collects any extra resin coming out of the resin manifold towards the vacuum pump. It is sealed so that no vacuum pressure is lost. It also is mounted with a gage which measures the vacuum pressure and indicates the loss of pressure should there be any leak in the vacuum bag. It also acts as a vacuum reservoir which means that even if the vacuum pump is turned off the trap would not let the maintained vacuum pressure to be lost. Figures 2.15a and 2.15b show the resin trap.

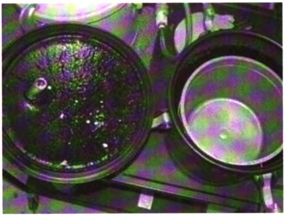
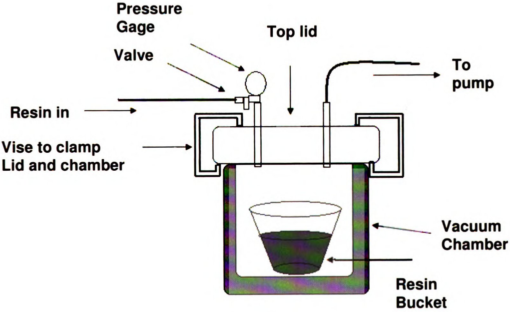


Figure 2.15a Open and closed view of the resin trap



2.15b Schematic of Resin Trap

2.2.2 VACUUM PUMP

The vacuum pump shown in Figure 2.16 is the main driving force which draws out the entire air from beneath the vacuum bag and maintains a pressure close 1 ATM or 101 kPa under the vacuum bag, i.e. the vacuum chamber which sometimes loses a little bit of pressure. The pump makes noise and it sometimes hinders the process of hearing the leaks which may be present in the vacuum bag or the interface between the sealant and the vacuum bag. To remove this defect we use an ultrasonic detector to detect the leaks in the bagging. This is done by placing the detector's head near the tacky tape seal and if there are any variations in the digital meter inbuilt in the detector we know that there is a leak and it is to be take care off.

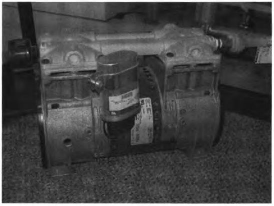


Figure 2.16 Vacuum pump

2.2.3 ULTRASONIC LEAK DETECTOR

The ultrasonic detector used in this experiment was made by Am probe Inc known by the trade name ULD 300. This is shown in the Figure 2.17 below. Typically, human can hear frequencies from 20 Hz to 20 kHz, with sound from 20 kHz to 100 kHz being termed ultrasonic. Turbulence created by air or gas, forced through a small orifice, generates ultrasonic sound. This ultrasonic leak detector is designed to locate the source of the ultrasonic sound emissions. These ultrasonic sound emissions are converted by the Leak detector to a range that can be heard by humans, the sound generated by this unit is 32 times lower in frequency than the sound that is received. Thus small leaks can be detected which may be potential cause for the part to be defective with air voids if the leak is not detected.

Figure 2.17 Ultrasonic leak detector

2.3 BASIC SETUP OF VARTM

Now that we have discussed the raw materials and equipment in detail, a detailed study of the set up should be made to understand the process and to minimize the losses while setting it up.

2.3.1 STEP 1- Tool preparation

This is the starting point of VARTM. The tool or the solid mold has to be carefully prepared. Mastic sealant tape is placed on the tool to outline the area which would form the vacuum cavity. The tool is then first cleaned with acetone which removes any waxy material from the previous tests. Wax is applied with a smooth cloth provided with the wax to the glass mold and let to dry for 15 minutes; this causes the wax to stiffen and assists the cleaning process. Thereafter it is cleaned with paper towels to give a smooth and shiny finish; one of the purposes of applying wax is to fill the micro-pores in the tool, resulting in a shiny finish. The wax is removed with the help of paper towels, care must be taken that no specs of the dried wax are left on the tool when the fabric is placed on the tool or else this might hamper the smoothness of the glass tool. The Figure 2.18 below shows the setup of this step.

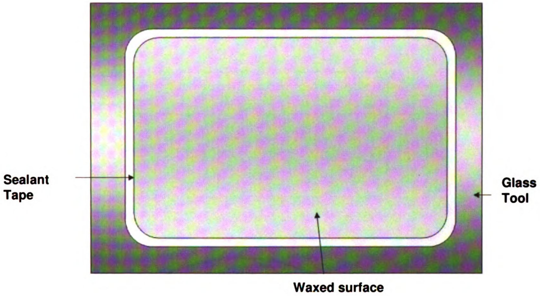


Figure 2.18a Step 1-Mold preparation

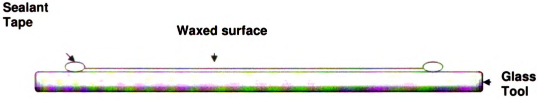


Figure 2.18b Step 1-Mold preparation

2.3.2 STEP 2- Fabric layup

The next step is to place the fabric on top of the tool. The Figure 2.19 shown below depicts the placing of the fabric on top of the tool.

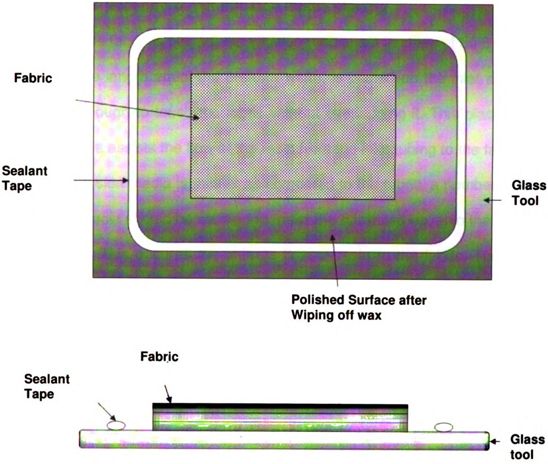


Figure 2.19 Step- 2 Fabric layup (top and side view)

2.3.3 STEP 3- Inlet and outlet Infusion media placing

When the fabric is placed, the infusion media, cut in strips of 50.8 mm (2 in) width and the length equal the preform width, is placed on the inlet side of the fabric just enough to touch the fabric without overlapping it. This placing of the infusion media assists the flow of the resin from the inlet tubing to the fabric. Also since the infusion media is thinner as compared to the fabric, a number of layers of infusion media should be stacked to make the thickness equal to the thickness of the fabric. This ensures the uniform flow of resin to the fabric. The infusion media, cut into 25.4 mm (1 in) broad strips equal to the size of the preform, are placed on the outlet side of the fabric just touching the fabric in similar manner as the inlet side infusion media placing. The thickness of the infusion media on the outlet does not matter to a great extent as it only assists the resin to flow out of the system; however it also assists the back flow of the air. (Figures 2.20a and b)

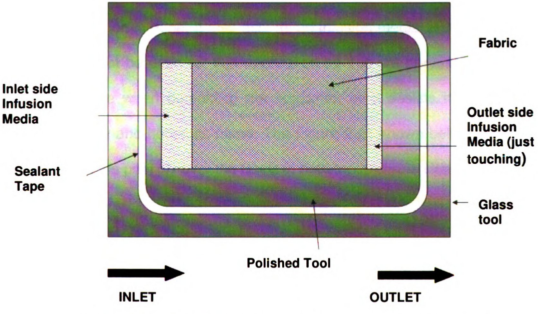


Figure 2.20a Infusion media on inlet and outlet (top view)

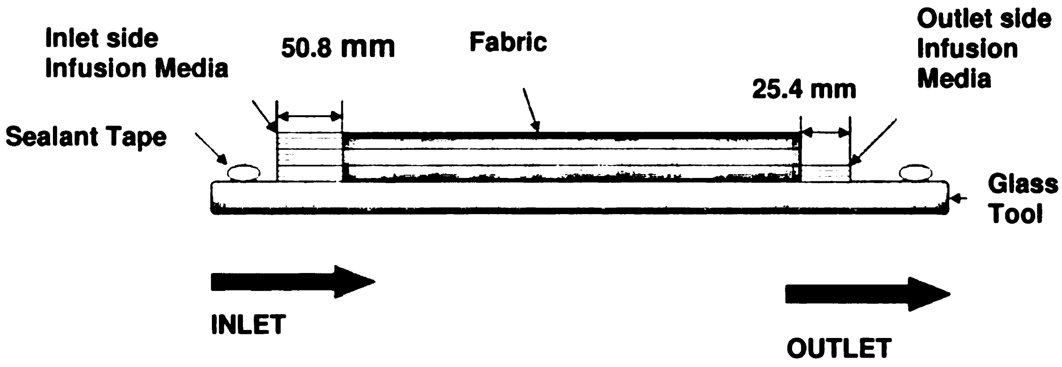


Figure 2.20b Step 3-Infusion media on inlet and outlet (side view)

bubbles as it does not trap the bubbles due to its high permeability. Figure 2.20 shown depicts the inlet and outlet placing of the infusion media.

2.3.4 Step 4-Peel Ply placing

Peel ply is cut and placed on top of the fabric so that it overlaps the inlet and the outlet distribution media; it is adjusted such that it exceeds the infusion media on the outlet side by 25.4 mm (1 in). The peel ply would not allow the infusion media which is placed on top of it (discussed in next step) to stick to the fibers once infusion is done. It also acts as an infusion media as it is perforated, although it cannot be used for that application as it is not porous enough. This plays a vital role when demolding the specimen as it assists the process by peeling off easily and hence its name. The Figure 2.21 shown below depicts the step of placing the peel ply over the fabric in both top and side view.

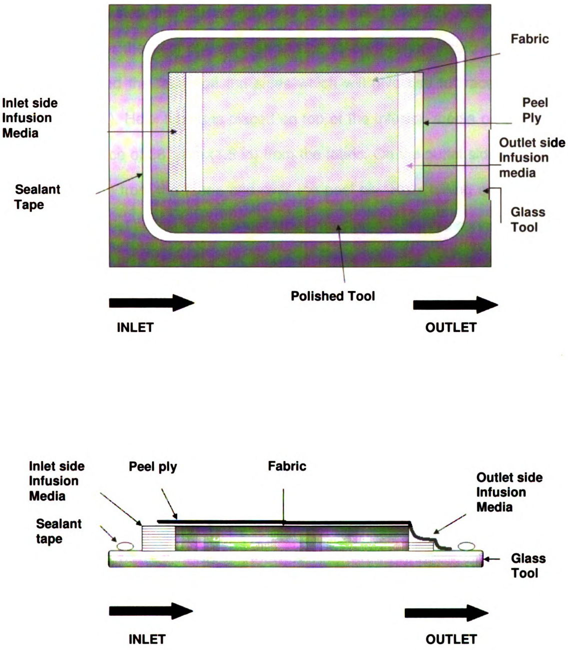


Figure 2.21 Step 4–Peel ply placing

2.3.5 STEP 5-Infusion Media and Helix tubing

. In the next step, the infusion media is cut to the same size as of the fabric and placed over the peel ply, care should be taken that the distribution media does not exceed the fabric on the sides which will give rise to" race-tracking" (explained later). Helix tubing is placed on top of the infusion media on the inlet side at a distance of 38.1mm (1.5 in) from the fabric. On the outlet side it is also 38.1mm (1.5 in) from the fabric and over the peel ply. Helix tubing on both the inlet and the outlet side is to be connected to the piping. They are connected with either a T joint or a straight joint. Figure 2.22a shows the two types of joints which were used in the setup. The advantage of the straight joint is that it is easier to setup and seal and also the flow of resin from the bucket is more uniform in the straight joint. In the T- joint, first of all it becomes difficult for it to seal with the sealant in the periphery and second of all the distribution of resin is non-uniform.

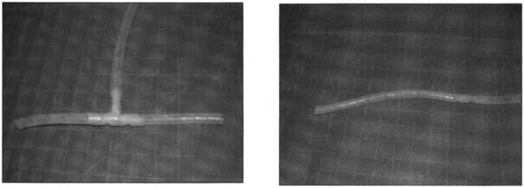


Figure 2.22a T-joint and straight joint

The figure of the classical (straight) inlet and outlet is shown in Figure 2.22b below. Once these are connected the vacuum bag is placed on the entire setup.

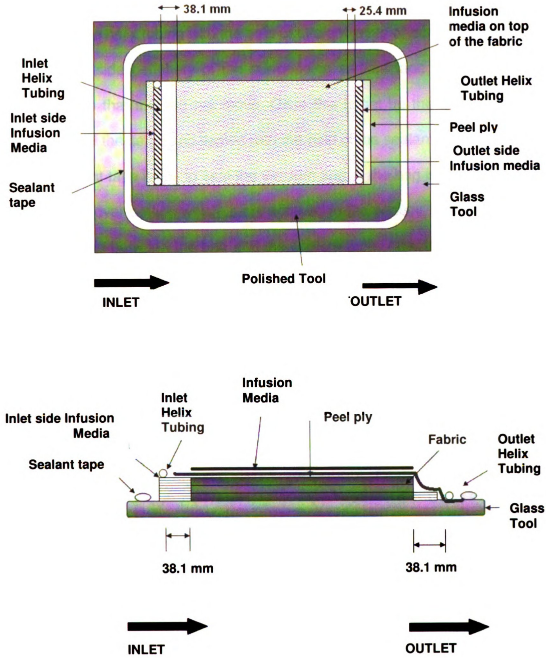


Figure 2.22b Step 5-Distribution media on top and helix tubing

2.3.6 STEP 6-Placing inlet and outlet tubing and vacuum bag

This step involves the placing of the inlet and outlet tubing. These are connected to the helix tubing with the help of straight joints or connectors and are fixed to the outside periphery of the surrounding sealant tape with the help of sealant tape so that they do not move. Once this is set up the vacuum bag is placed on top of the setup and sealed with the help of the sealant tape.

The sealant tape helps to seal the vacuum bag. If the bag is large and does have some left over portion which is not adhered to the sealant, pleats are made to avoid any gap between the bag and the sealant tape. After this step the inlet piping going to the resin reservoir is clamped and the vacuum pump is initiated. Figure 2.23 below shows the set up of tubing and vacuum bag.

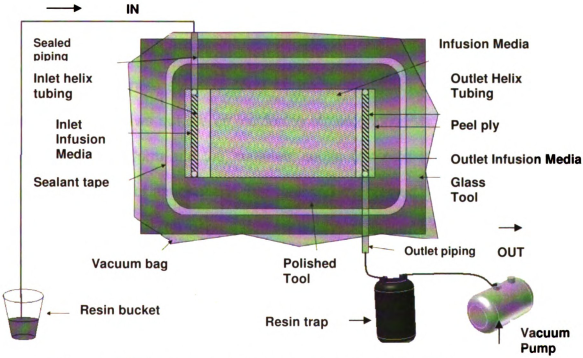
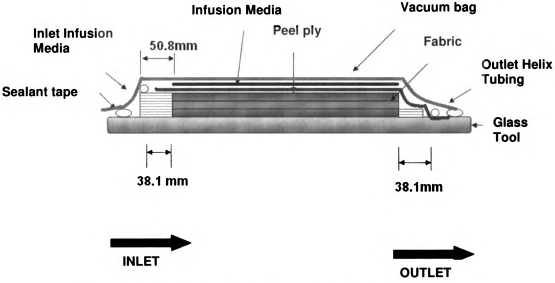


Figure 2.23 Inlet and outlet tubing and vacuum bagging

Figure 2.23 Inlet and outlet tubing and vacuum bagging continued



Inlet and outlet tubing and vacuum bagging (side view)

2.4 PROCESSING

2.4.1 Vacuuming process

Once the entire setup is done as explained earlier the vacuum pump is started which draws out the air inside the chamber. The vacuum bag takes the shape of the preform and the materials above and next to it. The pressure is drawn to 1 ATM of atmospheric pressure and maintained through out the resin infusion processes. The gage mounted on the resin trap reads the amount of vacuum pressure in the vacuum chamber. It reads 27psi for maximum vacuum pressure. If the reading in the gage drops then it is possible that there is a leak. By monitoring the gage the leaks are detected. Thereafter the leaks are detected by placing ear close to the sealant tape and a whistling sound is noticed. Sometimes due to excessive noise of the vacuum pump, it becomes difficult to isolate the leaking noise and thus the vacuum pump is placed far away from the setup with large tubing connecting the trap. After sealing the tape the noise is decreased. Once the audible noises are fade out, but still minute leaks may be present which can be detected using an ultrasonic detector. Once all the leaks are taken care off, the pump is shut down to check that there are no leaks. If there are still some leaks, the gage will indicate a drop in pressure and thus leaks can be further sealed.

The vacuuming process is a tedious process as, due to human error it is bound to have some leaks in the vacuum bag-sealant interface. And in this process the vacuum pressure is the main driving force. Thus careful monitoring in the vacuuming process is necessary. Figure 2.24 shown below shows the complete setup ready to be infused with resin.

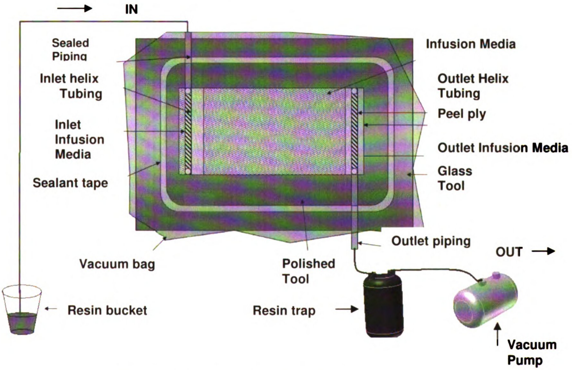


Figure 2.24 Complete VARTM setup

2.4.2 Infusion process

After the complete setup of the vacuuming process, the final step is to infuse the resin through the preform. The resin and the hardener are measured using the sensitive balance and mixed with the specified mixture ratio provided by the manufacturer. The cup is placed under a fume hood, so that the emitting fumes are drawn out and user is safe. Once the resin is placed under the hood, the inlet tubing is placed in the cup so that it fully dips in the resin mixture, the inlet clamping vise is opened and the resin flows through the tubing to the inlet helical tubing. Once the resin reaches the outlet the inlet tubing is clamped again so that no air is introduced into the preform. The outlet is clamped so that the resin coming out of the outlet tubing does not reach the resin trap because once the resin hardens it is difficult to remove it from the inlet valve of the resin trap. The pump is left running and the specimen is left to cure overnight. (Figure 2.25)

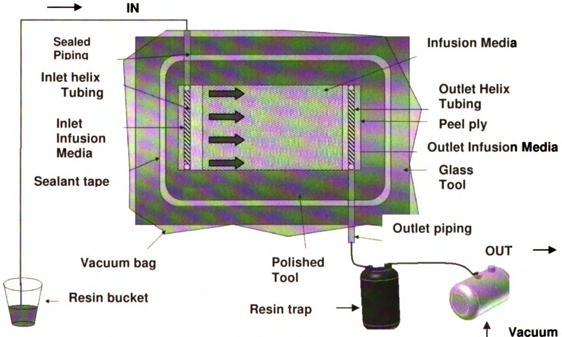


Figure 2.25 Complete VARTM setup with flow

2.4.3 De-molding process

After the specimen is cured, the pump is shut off and the vacuum bag is removed. The peel-ply which is on top of the preform is then removed; it is easily removed due to its nature of not sticking to the resin at all. The specimen is removed easily from the glass mold as the surface is finished coated with wax.

This details the procedure of VARTM. The problems encountered and the ways to overcome them, also the changes made to the VARTM process are to be studied in the next chapter with the help of case studies and hands-on experience with the VARTM technique.

CHAPTER 3

CASE STUDIES

Vacuum Assisted Resin Transfer Molding (VARTM) is a process which has many parameters to be controlled simultaneously and it becomes quite challenging to maintain the specimen's repeatability. To analyze this, some of the parameters involved in the manufacturing of specimens with VARTM were studied. One parameter at a time was altered, keeping the rest constant, and its effect was observed and then controlled with respect to the others. Several changes to the setup were applied too and a final setup was arrived upon. This chapter discusses in detail the various changes made and their effects in the manufacturing of glass/epoxy composites with VARTM.

3.1 RESIN FLOW

The flow of resin in the preform plays a vital role in the final part configuration and properties. In this section we would study the effects of various fiber type, orientation and thickness of the preform on the flow of the resin. Some amendments to the setup are also made to study their effect on the flow of resin. The resin flow in the fabric can be approximately modeled by 1-D Darcy's Law

$$Q = \frac{K * A * \Delta p}{\eta} . \frac{1}{x} = g * \frac{1}{x} \qquad (1)$$

Where,

Q	=	resin flow rate in (cm^3/sec)
K	=	permeability of the fabric in (cm^2)
Δp	=	pressure gradient between the inlet and the outlet in (Pa)
η	=	viscosity of the resin in (Centipoises)
A	=	area of the fabric (cm^2)
x	=	position of the flow front in (cm)

Equation (1) shows that the flow rate Q in the fabric is directly proportional to the permeability K of the fabric, area A and the pressure Δp gradient between the inlet and the outlet; the equation also shows that the flow rate is inversely proportional to the length x of the fabric explaining that as the distance from the inlet increases the flow will be slower towards the outlet. (Appendix D)

To improve the flow rate a low permeability infusion media (INKA 7001) is placed on top of the topmost layer of the fabric.(this is a patented process known as SCRIMP) This improves the flow of resin in the fabric. However due to the presence of the infusion media the flow becomes as shown in the Figure 3.1 below. The micro-gaps shown in the figure are exaggerated to show it clearly.

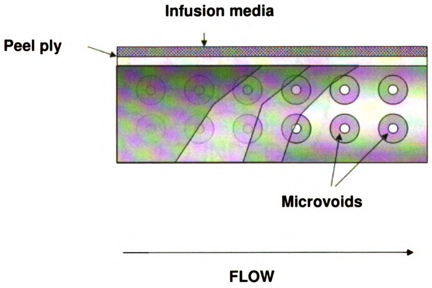


Figure 3.1 Flow of resin in the fabric

The Figure 3.1 above shows how the resin flows through the fibers. Since the flow is accelerated on the topmost layer and the resin reaches the outlet very quickly, the fabric is not evenly wetted, giving non-uniformity to the part prepared. To study the flow, tests were conducted. These tests were conducted with various types of fiber, various orientation and thickness of fibers and will be detailed in the following sections. Actual picture of flow mentioned in Appendix B

3.2 ORIENTATION OF FIBERS

This test was conducted to observe the flow in the various orientations of the fibers in the preform. Preform of unidirectional fabric with a density of 0.00041 g/mm^2 (12 oz/yard^2) were cut in 127 mm X 127 mm pieces and stacked in 6 layers at orientations of $[0]_6$, $[15]_6$, $[30]_6$, $[45]_6$, $[90]_6$ (fiber oriented in the direction of the flow is 0^0). This setup is shown in the Figure 3.2 below.

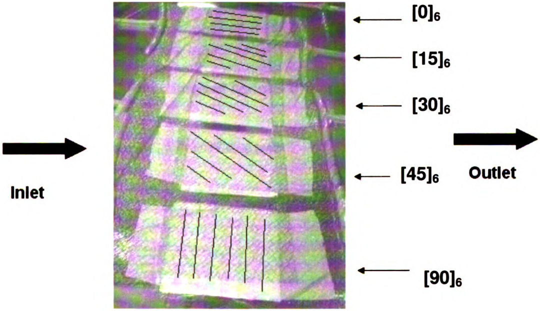


Figure 3.2 Fiber orientation

It was observed that even with the infusion media on top there was variation in the flow of resins in different orientations. It was observed that the fibers oriented in $[0]_6$ took the maximum time and the one at $[90]_6$ infused the fastest. The Figure 3.3 shows the flow of resin in the various fabric orientations.

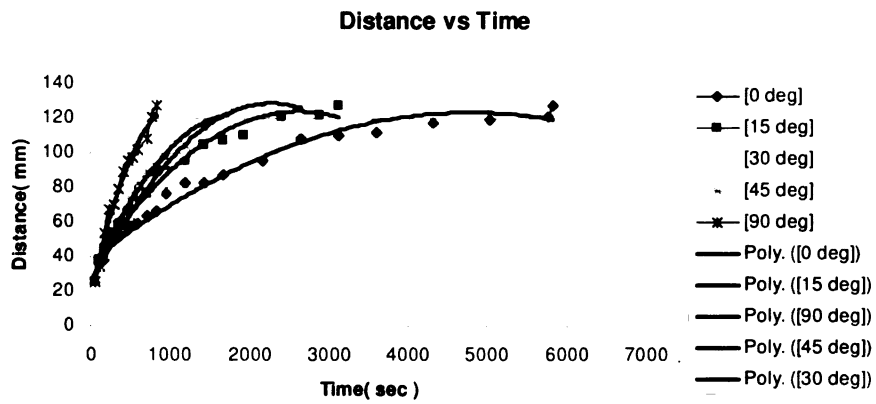


Figure 3.3 Flow times of various orientations of fibers

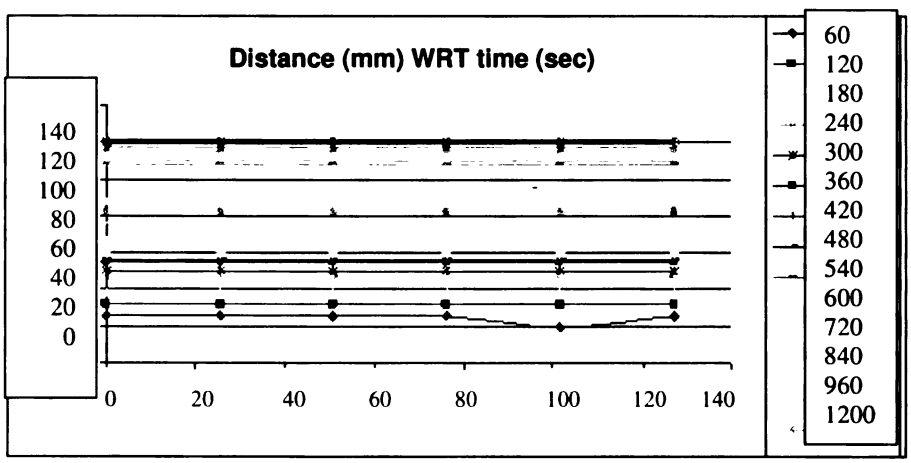


Figure 3.4 Flow lines at different time intervals for $[0]_6$

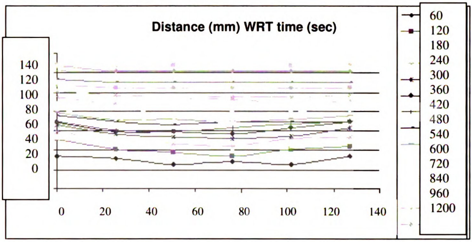


Figure 3.5 Flow lines at different time intervals for $[15]_6$

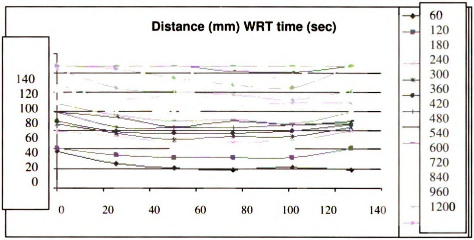


Figure 3.6 Flow lines at different time intervals for $[30]_6$

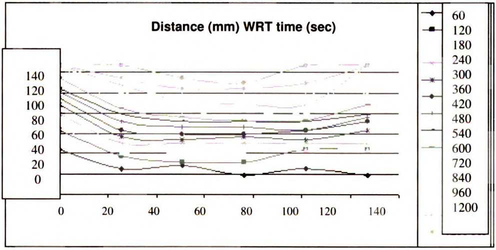


Figure 3.7 Flow lines at different time intervals for $[45]_6$

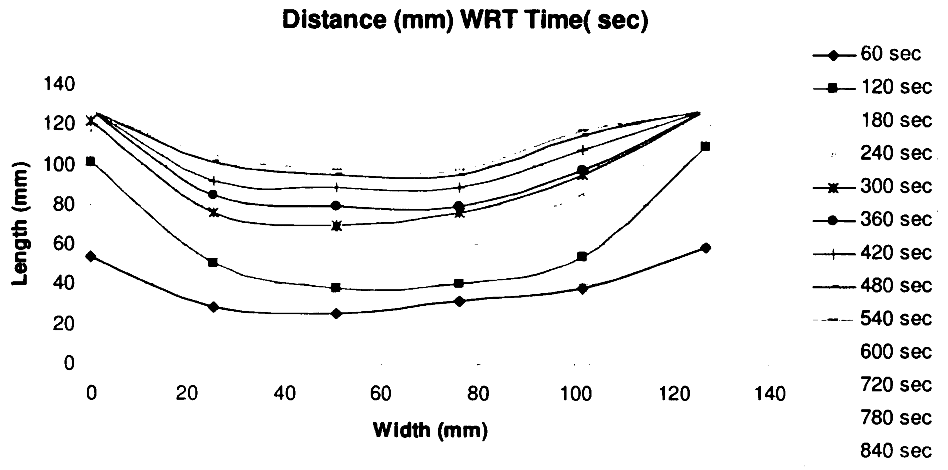


Figure 3.8 Flow lines at different time intervals for $[90]_6$

Along with the difference in the flow times there were also variations of the thickness in the parts manufactured. The flow lines were marked at various intervals and were plotted for different angle orientations as shown in Figures 3.4 to 3.8. The thickness variation in the part was attributed to the uneven flow in the preform. It could be concluded that the permeability of the fibers changed with the angle even though the exact nature of the flow with various fiber angles was not known. However this showed that the variation in the flow changed the part thickness at different positions in the part.

It was also observed that the flow front was much more uniform in the lower angled preform lay-up and became less uniform as the angle of orientation increased. It was also observed that as the angle of orientation increased the flow in the sides increased as compared to the center portion. Due to this, it was also observed that as the angles increased, the thickness in the sides also increased as compared to the center portion, this was attributed to the accumulation of resin in the sides because the resin reaches the outlet faster through the sides which left the sides resin rich. The Figures 3.9 to 3.13 below show bag side surface and the variation in thickness with the angled fabric.

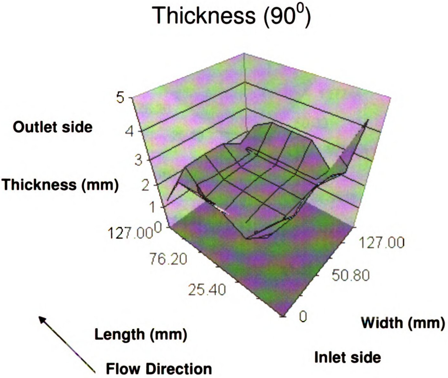


Figure 3.9 Thickness variation at $[90]_6$

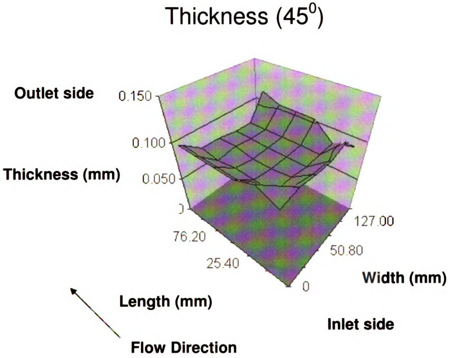


Figure 3.10 Thickness variation at $[45]_6$

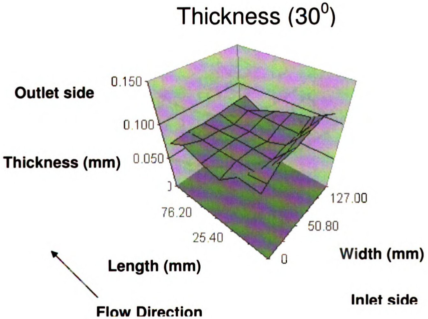


Figure 3.11 Thickness variation at $[30]_6$

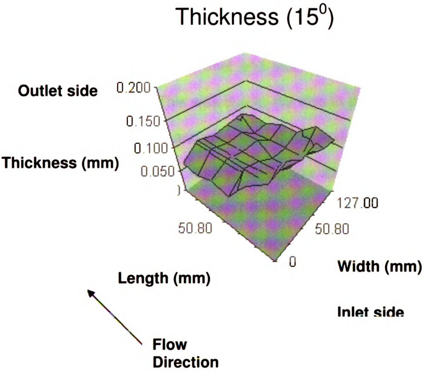


Figure 3.12 Thickness variation at $[15]_6$

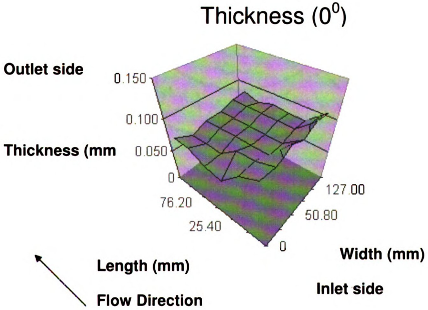


Figure 3.13 Thickness variation at $[0]_6$

The figures show that the variation in thickness is more in the higher orientation angle. One other observation made was that all the specimens had resin accumulated near the inlet and thus the thickness was more at the inlet side of the specimen. This was due to the loss in the pressure gradient between the inlet and the outlet and due to that the resin coming from the inlet tubing accumulated and made a reservoir near the inlet. This caused the inlet side of the specimen to be thicker as compared to the other sides.

In order to observe the actual flow of resin through the preform it was necessary to remove the infusion media so that the flow front was not strongly guided by the infusion media. The same setup was used but this time without infusion media as shown in Figure 3.14.

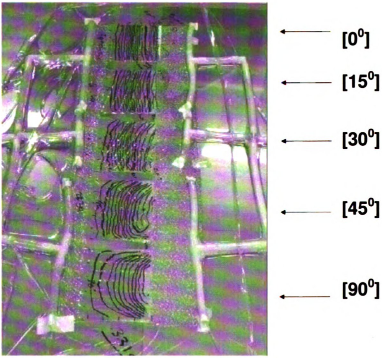


Figure 3.14 Setup of fabric at various angles

Similar trends were observed as far as the flow was concerned; however, the thickness variations were lesser. This may be attributed to the fact that the flow was not accelerated and the variations were minimized, however the trends of the flow were similar to those with the infusion media, yet the thickness variation was less. It was also observed that the unidirectional fiber was difficult to infuse, the reason for which would be discussed later in the chapter. To understand the effect of infusion media another test was conducted, and discussed in the next section.

3.3 INFUSION MEDIA

As it was observed that the removal of the infusion media form the top of the topmost layer of the fabric slowed down the process and gave less variation with the thickness of the part produced. To address the effect of infusion media in the flow of resin through the preform, varying lengths of infusion media were placed and the flow was observed with unidirectional 90^0 fabrics (as that was the fastest among the lot in the previous test). The setup changed is shown in the following figures. The infusion media placed to cover the entire preform in Figure 3.15b, was removed from the preform and placed half way through the preform on the outlet side as shown in Figure 3.15c. This test was done under the same conditions as the previous test. From this test a very important observation was made and is discussed later in this section.

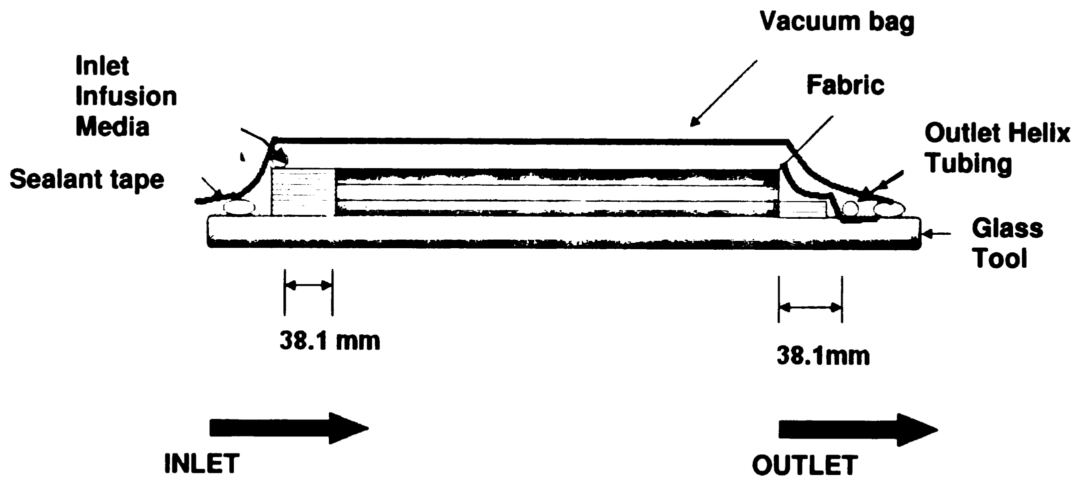


Figure 3.15a Setup with No Infusion media

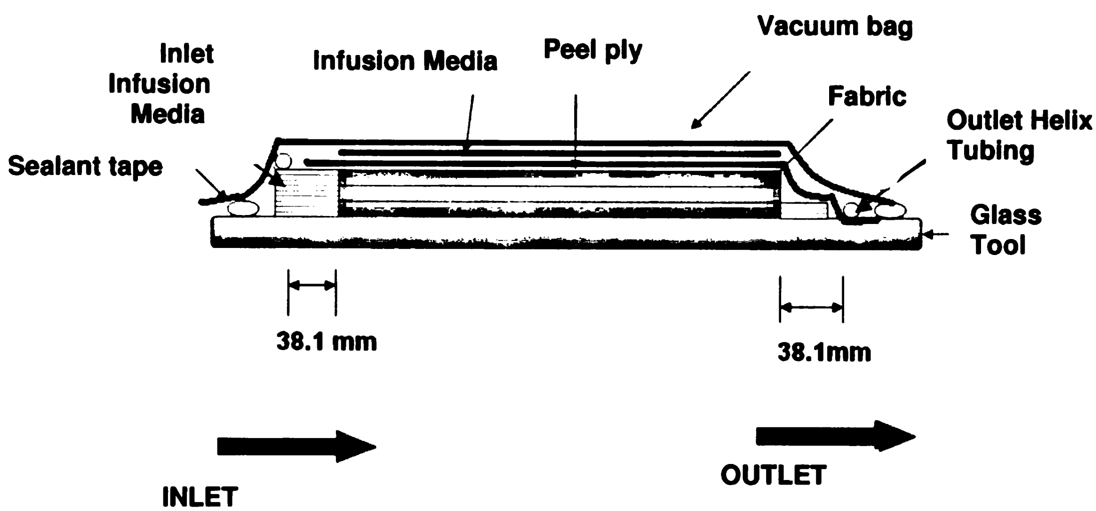


Figure 3.15b Setup with Infusion media

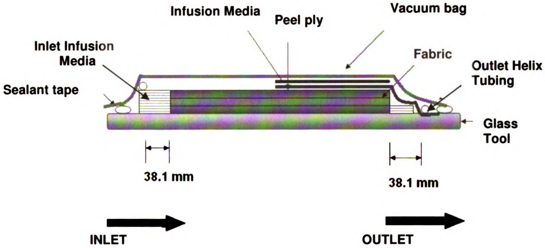


Figure 3.15c Setup with Half way Infusion media

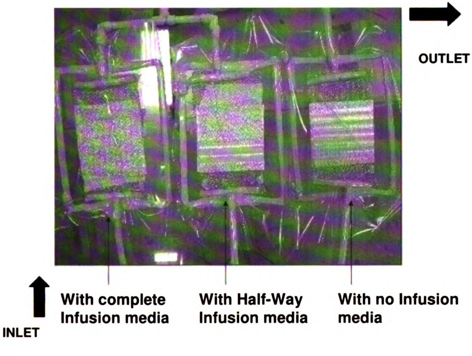


Figure 3.15d Combined picture of all the three setups

The Figures 3.15a to 3.15d above show the three setups with varying lengths of infusion media placed on top of the fabric. It was observed that the resin in the setup with the infusion media was the fastest (319 sec), followed by the one with half- way infusion media (489 sec) and the one without the infusion media was the slowest (546 sec). All the specimens were the same dimensions, 127 mm X 127 mm (5 in X 5 in). The main purpose of the infusion media was to accelerate the process of infusion through the fibers.

Due to the low permeability of the preform, the resin flowed very quickly (213 sec) on the top side of the fibers with the infusion media as shown in the Figure 3.1. Also because the infusion media was significantly thicker than the peel ply, the vacuum bag did not conform completely to the media leaving gaps which assisted in the flow of resin. However, in the case where there was no infusion media on top the bag very perfectly contoured the laid down fabric and the permeability of the top layer was reduced as compared to the case with the infusion media. Due to this the permeability of the fiber was the resisting force in the setup. No acceleration was provided the flow time on both tool and top side was (546 sec). In the third case it was also observed that the resin moved in a similar trend as the setup with no infusion media but accelerated when it reached the distribution media placed half way through the fabric. The Figure 3.16 shows the progress of the flow in all the three cases.

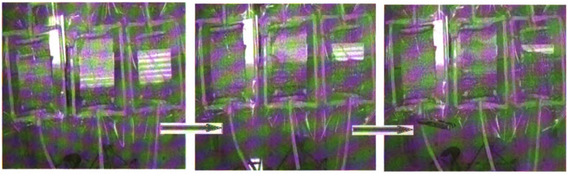


Figure 3.16 Flow of resin through the three setups

Another very important observation was made in this study. Due to the smoothness of the vacuum bag in the case where no infusion media was used, the top layer was smoother as compared to the one with infusion media and peel ply on top (the roughness in this case was due to the peel ply as it was perforated in nature and gave corrugations to the top surface profile).

With smooth finish, the composite specimens were visibly clearer than the ones with the corrugated finish. In the case where only half-way infusion media was used one half was clear and the other half (with infusion on top) was unclear. This also confirmed that the presence of peel ply was the main cause of the clarity of the specimens. Even though the transparency and clarity highly depended on the degree of matching of the refractive index of both the resin and the fiber, surface finish played a vital role in the clarity of the specimen. Because the optical study of the composite was outside the scope of this thesis it would not be discussed further in great detail.

Another very important observation was made that after the fiber had been infused completely, the air bubbles could not retract back into the fabric. Also, the extent of retraction was greatest in the setup with infusion media followed by the setup with half-way infusion media and then the setup with no infusion media.

This extent of bubbles was negated to a great extent with more resistance as in the case of the setup with half way infusion media.

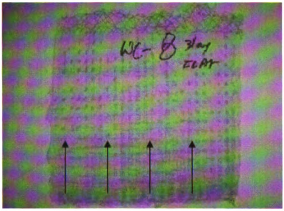


Figure 3.17 The air bubbles retracting back in the setup with no infusion media

At first this was also attributed to the type of fabric as different fabrics had different permeability and resistance to this back flow of residing bubbles. The void percentage was as high as 8% in the setup with infusion media. Another study was conducted due to this behavior which will be discussed in the next section.

3.4 TYPE OF FABRIC

This test was conducted to see the effect of types of glass fabric on the air bubble retracing back. The glass fibers used were unidirectional (density 0.00041 g/mm^2 (12 oz/yard^2)), fine woven 2D fabric (density 0.000406 g/mm^2 (12 oz/yard^2), coarse woven 2D (density 0.000813 g/mm^2 (24 oz/yard^2)) and quasi 3D interwoven fabric. No distribution media was placed on top (only on the inlet and outlet) (Figure 3.15a).

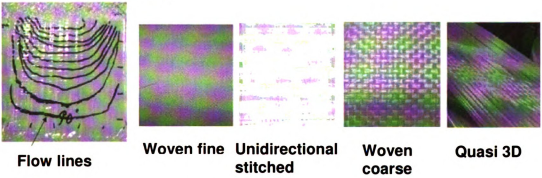


Figure 3.18 Types of fabric

It was observed that no matter what the type of fabric was, the bubbles always retraced back into the fiber after infusion, due to the overlapping distribution media at the outlet. In other words, it was due to the decrease in gradient compaction pressure with the increasing distance from the inlet of resin. The extent of retracted bubbles was most in the setup with the infusion media as the infusion media assisted the flow of bubbles due to its high permeability. This was attributed to the fact that since the infusion media placed at the outlet had a considerable amount of thickness the vacuum bag did not exactly conform to its shape thus creating channels for it to flow back. To be able to stop these air bubbles to retract and still maintain the flow through the fiber was a challenge.

The infusion media was removed from the top and the outlet side .The most suitable material within the scope of VARTM was the peel ply which acted as a fine distribution media, let the vacuum bag take its shape, and did not let the air bubbles, already trapped in it, to retrace back. It acted as a natural throttle, trapping the displaced air bubbles and preventing them form retracting backwards into the fibers. The setup is shown in the Figure 3.19 a), b) and c). A new name was suggested for this setup “BUBBLE TRAP VARTM”.

This setup was used for all the experiments discussed further in this thesis. The fact that the peel ply acted as a natural throttle decreased the visible air bubbles in the specimens made. Testing for the void volume fraction will be discussed in later chapters.

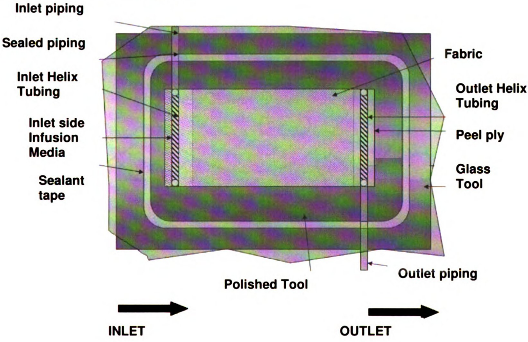


Figure 3.19a Bubble trap setup (top view)

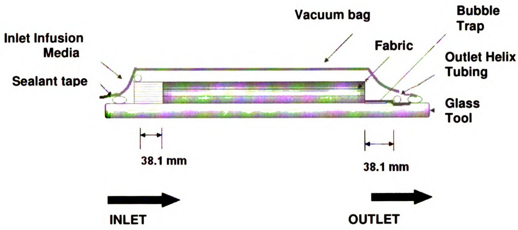


Figure 3.19b Bubble trap setup (side view)

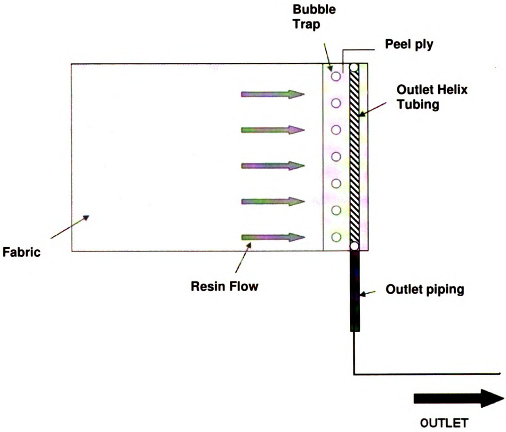


Figure 3.19c Bubble trap setup

Since only the vacuum bag was on top of the fiber in this technique, it gave a fine finish to the upper surface at a microscopic level but it took the shape of the fabric at a macroscopic level, thus the overall surface finish was not as good as was expected. Due to direct contact of the vacuum bag with the resin, the bag stuck to the fabric, while demolding. To remove this defect, the bag was coated with liquid wax (Locktite) with a cloth. It was found that the bag came off easily after the specimen gelled completely. The need to have a smoother surface on the bag side was a challenge. Silicone rubber was thought of as a better alternative as it was flexible and had a smooth surface finish and a tendency of not sticking to the resin. The tests done with silicone bagging will be discussed in the following section.

3.5 SILICONE RUBBER SHEET

Silicone rubber was made in the laboratory to get a smooth finish on one side of the bag so that it could be used as the second finished side in the VARTM process. The process of making the silicone rubber was very simple and is discussed briefly. A glass plate was laid on the table and was waxed using ICE WAX manufactured by the Gentex Company. After the wax dried, it was cleaned with the help of paper towels to give the glass a smooth finish so that the rubber placed on it could be easily removed after it dried. The silicone rubber came in gel form in containers with nozzles and was dispensed using a dispenser gun. The silicone was dispensed using the gun and was carefully spread with the help of a brush. When the first layer had dried the next layer was placed on top of that

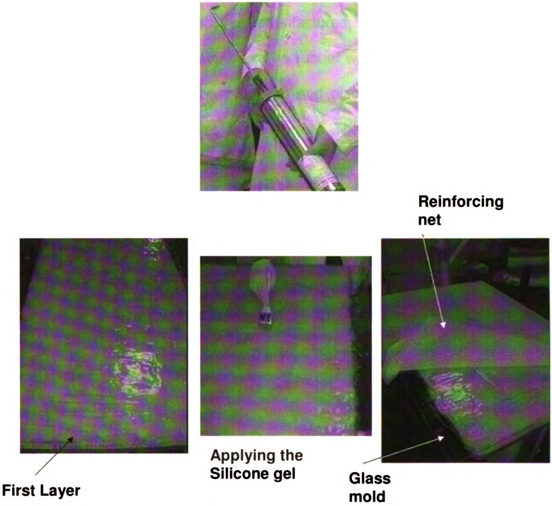


Figure 3.20 Making the silicone bag

layer in the same manner. A net like reinforcing material was placed when the third layer was still wet. This reinforcing net gave the strength to the rubber. After the layer of reinforcing material three more layers of the silicone gel were applied and the setup was left to dry. After all layers had dried, the silicone sheet was carefully taken off the glass mold and it had a glass like finish on the glass side. Figure 3.20 shows the entire process of silicone making the silicone sheet.

Once the silicone sheet was manufactured, it was used as the second flexible mold under the vacuum bag. The rubber was cut into pieces exactly the length of the specimen to be produced and placed on top of the fabric, the vacuum bag was placed thereafter and sealed. The setup is shown in the Figure 3.21 below.

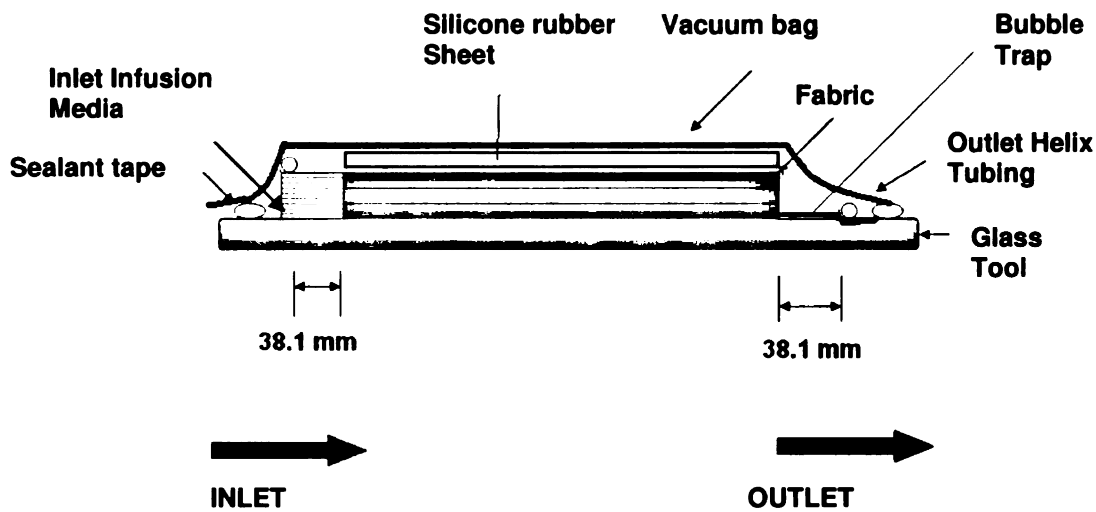


Figure 3.21 Silicone rubber setup

A few interesting observations were made using the setup with the silicone rubber sheet. It was observed that the surface towards the silicone sheet side had glass like finish; however, there was a dry spot which was created. The dry spot was a region in the composite material where the resin had failed to impregnate the fabric. The reason for the formation of this dry spot was due to the race tracking effect.

Race tracking developed because the silicone rubber sheet was thick (6 mm (0.236 in)). And the vacuum bag on top did not conform enough to it, creating a low-resistant channel for the resin and thereby a dry spot in the specimen. Figure

3.22 below shows the flow pattern of the resin in this setup. Figure 3.23 shows how the contouring of the vacuum bag fails with the silicone sheet on top.

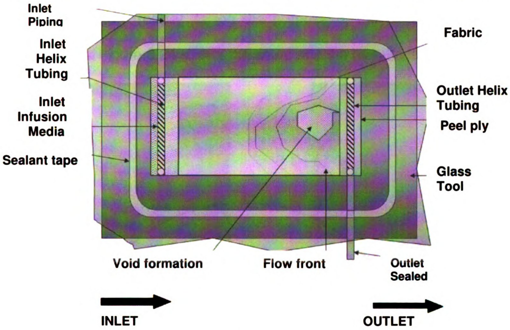


Figure 3.22 Formation of dry spots with the silicone sheet setup

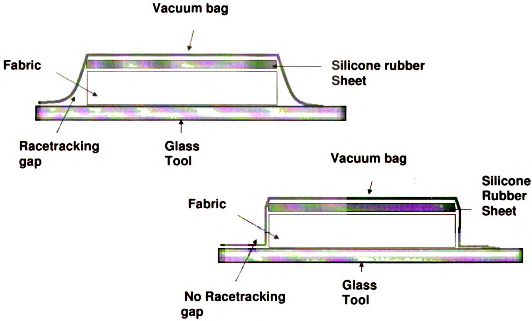


Figure 3.23 Cross-sectional view of the setup with / without gap

A thinner sheet of rubber was thought to be an immediate answer to this problem; however a thinner sheet would have less stiffness and would conform to the fabric more readily, failing the purpose of the silicone sheet to obtain surface finish. Figure 3.24 shows the setup and the manufactured part.

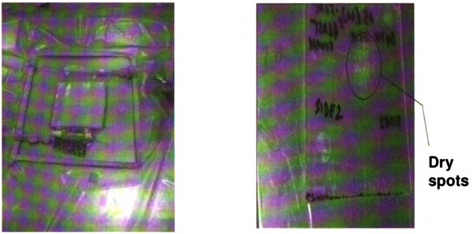


Figure 3.24 Setup with the silicone rubber sheet

Another very important observation was made during this experiment which was that the part produced was thicker (4.7mm) than the regular set-up specimen (4.32 mm). The reason of this will be explained in the next section. The silicone rubber sheet was however the best answer to the two sided finished specimens and it could, because of its flexible nature could be utilized for 3D shapes like domes and arches. . Test with and without the silicone rubber on top of the fabric were done and seen that the thickness of the part with silicon rubber increased by 17.5% as compared to the one without the silicone rubber. The surface finish was obviously better in the specimen with the silicone rubber on top. Since the thickness was difficult to maintain and there was formation of dry spots with the use of silicone rubber this technique was discarded. This technique, however, was feasible where the geometry of the specimen was complex. The silicone rubber being flexible could conform to any desired shape. The only challenge was to reduce its overall thickness to a degree where it would give fine finish, producing no race tracking channels and yet not take the exact shape of the fabric.

3.6 COMPACTION

Compaction plays an important role in the manufacturing of composites with VARTM. Not only does it affect the resin flow in the specimen, but directly affects the fiber volume fraction and void volume fraction in the part.

Grimsley, Cano and Loos studied the effects of compaction [4]. They concluded that as the stack thickness of the fabric increased the compaction pressure increased and the overall fiber volume fraction increased; this could be attributed to the increase in the amount of nesting which also meant the fabric was much more compact and had less air gaps already. This also increased the flow rate of the resin through the fabric in the through thickness (discussed in detail in the next section). Also, drawing the vacuum pressure for long hours (5 hours) increased the compaction and thereby increased the fiber volume fraction in the specimen

Another test was conducted in which the vacuum pressure drawn was left for varying time duration ranging from 10 minutes to 5 hours. It was observed that the fiber volume fraction increased by 11.3% from the first (10 min.) to the last case (5 hours). The effect of leaving the vacuum pump on for longer time also had an effect on the resin flow time and flow front. The Table 3.1 below shows the various infusion times at different compaction time.

Table 3.1 Flow times at different compaction times

Batch	Dimensions	No. of Layers	Compaction time	Infusion time
1	6" x 6"	5	0 min	6 min 18 sec
2	6" x 6"	5	15 min	6 min 0 sec
3	6" x 6"	5	1 hr	5 min 52 sec
4	6" x 6"	5	2 hr	5 min 37 sec
5	6" x 6"	5	3.5 hr	5 min 21 sec
6	6" x 6"	5	5 hr	5 min 20 sec

3.7 SPECIMEN DIMENSIONS

It was also imperative that this technique was feasible for all sizes of parts manufactured. VARTM is a technique which almost entirely depends on the vacuum pressure, the permeability and compaction of the fibers, it was important to determine the amount of area the resin will cover with all these restraints. Tests with different dimensions of length, width and thickness were done. Fabric was laid up with dimensions ranging from 127 mm^2 (5 in^2) specimens to 508 mm x 203.2 mm (20 in x 8 in) specimens. The positioning of the inlet and outlet tubing was also changed. The stack lay-up of [0/90] 2D interwoven fabric (density of 0.000813 g/mm^2 (24 $oz/yard^2$)) was increased from 3 to 22 layers.

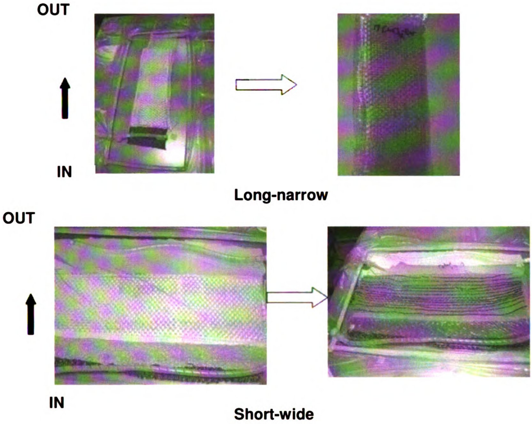


Figure 3.25 Setup with different dimensions

Various observations were made. The parts with smaller dimension infused totally, the parts with longer distance between the inlets an outlet did not infuse completely and due to loss in the pressure gradient towards the outlet the bubbles trapped in the portion of the fabric not infused, retracted back due to pressure gradient loss and damaged the parts. The parts that had the fabric laid up in horizontal direction (shorter length between inlet and outlet, yet larger widths) infused completely. Figure 3.25 shows the long narrow and short wide setup.

It was also observed that as the stack lay-up of the fiber increased (3 layers to 8 layers), the flow was accelerated in the layers where there was no infusion media. Also the through-thickness flow accelerated as the thickness increased. The flow front also reversed its direction from moving faster in the top (bag side) to moving faster in the bottom (tool side) as shown in Figure 3.26.

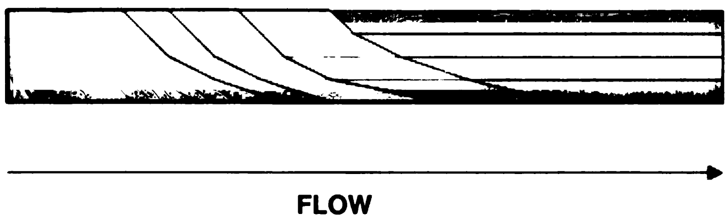


Figure 3.26 Schematic of flow front

It was also concluded that even though the resin moved large distances with this technique it was limited because of the loss of pressure gradient and retarding of the resin flow towards the outlet, shown in Appendix B.

Figure 3.27 shows the various fabrics stacking sequence for 2D woven glass fabric. It shows how with the increase in the fabric thickness on the flow changed (becomes faster in thick specimens). It was observed that the fiber volume fraction increased with the increase in the fabric stacks as the void volume decreased significantly. It was observed that with the increase in the thickness of the fabric layup, the thickness variation at different points in the manufactured parts decreased from 8 % to 4.5 %.

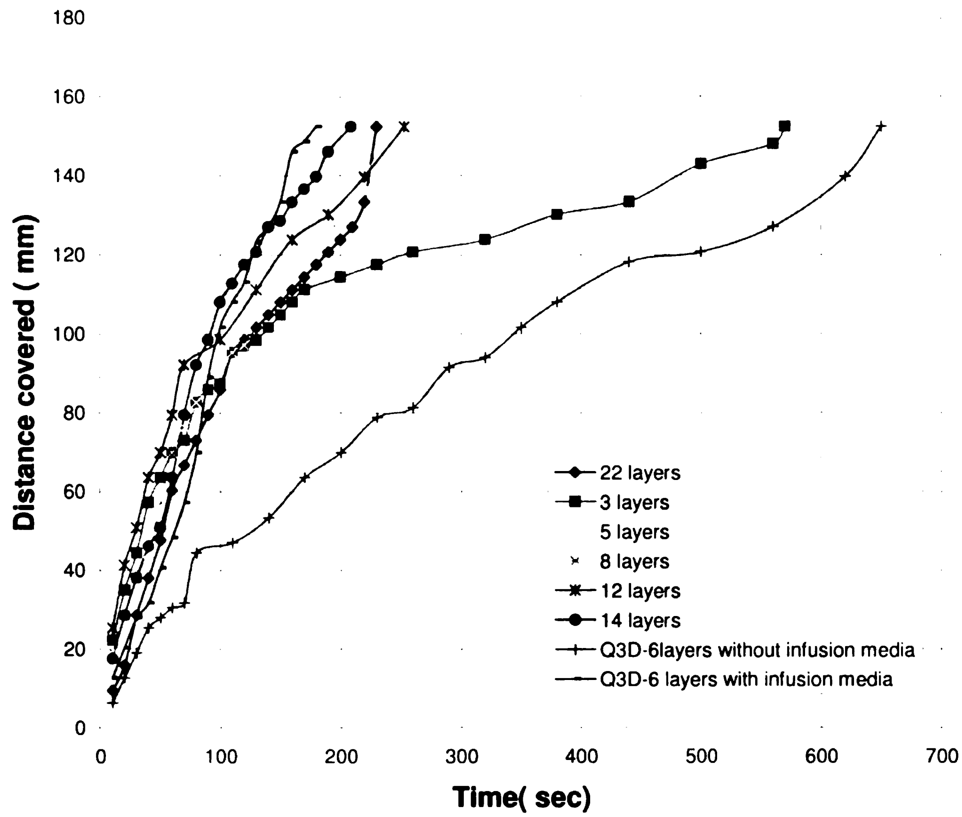
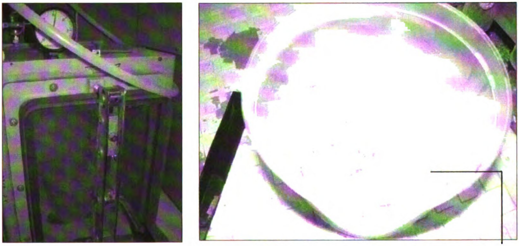


Figure 3.27 Flow times with varying stacking sequence

It was concluded that the flow of resin was accelerated in thick stacks of fabric. The resin would travel a greater distance and would cover a large area of the fabric and thus larger parts could be manufactured with the same technique if the stacks were thick enough. Complex shapes could also be manufactured with this technique; however that area has still to be studied. Since the vacuum bag took the shape of the fabric, smooth finish on both sides of the specimen was a challenge and was to be achieved within the scope of VARTM. Maintaining constant thickness was also another aspect which would make the sample consistent in volume fraction.

One of the reasons the voids were formed in the fabric was the preexisting air bubbles in the resin due to mixing. This caused the air bubbles to travel through the fabric and increase void volume fraction. This formation of air bubbles was natural and could be only eliminated before the infusion took place. A vacuum chamber was used and the pre-mixed resin pot was placed in the chamber. Vacuum was drawn in the chamber. It was observed that the bubbles rose up to the top of the pot and collected there, reducing the number of air bubbles in the pot and thus reducing the void formation (6.34 % to 4.79 %) in the fabric (Figure 3.28). Care was taken that the resin was not “degassed” for large duration as this would affect the pot life of the resin, which would affect the infusion time through the fabric. This might also cause premature gelling of the resin and the manufactured parts may be defective and not give desired results.



Bubbles drawn to the top of the pot

Figure 3.28 Degassing of the resin with the vacuum chamber

3.8 FINAL SETUP

To achieve the desired results of constant thickness, low void volume fraction (high fiber volume fraction), smooth finish and transparency, the setup was suggested as given in Figures 3.29a and 3.29b.

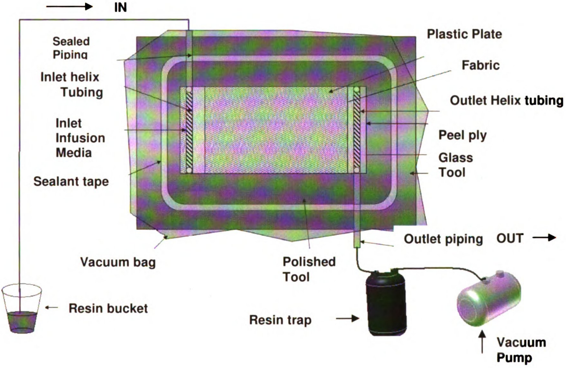


Figure 3.29a The final setup (top view)

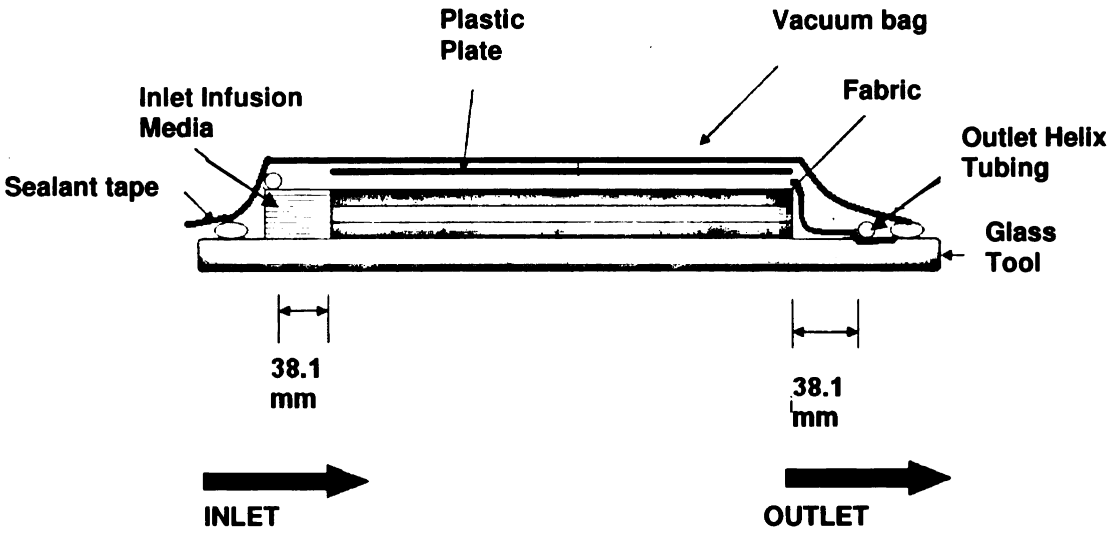


Figure 3.29b Final setup (side view)

The use of a thin, glass finished, stiff yet flexible plastic sheet assisted in achieving the desired result. The reason to use a thin sheet was to take into account the race tracking phenomenon which was the cause of dry spots.

Race tracking is a phenomenon where the infusion resin follows the easiest path (path of low resistance) either through the side of the setup or the fabric where there is a gap to pass.

The vacuum bag took the shape of the thin sheet in the sides and prevented the resin from moving through the sides. The flat plate helped in giving the specimen a fine smooth finish which in turn helped in improving the transparency of the specimen. The transparency also depended on the effective matching of the refractive indices of the resin and the reinforcing fabric. The peel ply at the outlet helped trapping the bubbles. The thickness was controlled by using a dam

(Figure 3.30) of desired thickness and placing dead weight on top of the plate sitting on the dam.

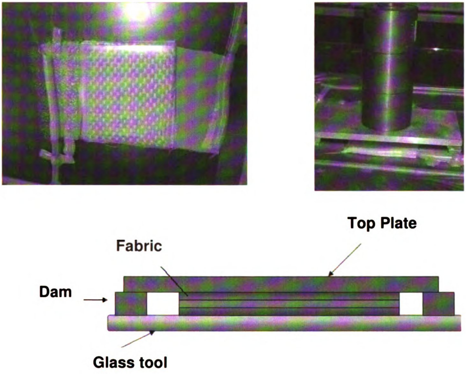


Figure 3.30 Final setup

3.9 CHANGES TO THE FINAL SETUP

It was desired to have a uniform faster flow of resin, constant thickness, transparency and two sided glass finished surface in the composite. In the final setup all except the uniform faster flow was achieved. To address this issue some amendments were made in the setup. A thin perforated plastic film (to give the fine finish) known by trade name E2760 release film, manufactured by Richmond Aircraft, and peel ply (to accelerate the resin flow) were introduced between the fabric and the plastic plate. This setup is shown in Figure 3.31.

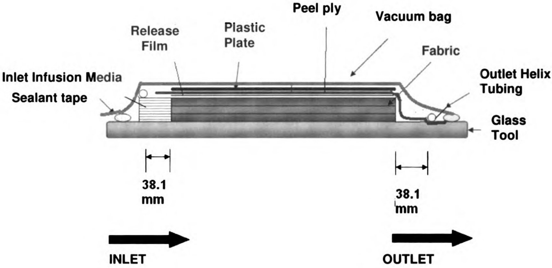


Figure 3.31 Final setup (side view)

The thin perforated plastic sheet had a property of not sticking to the resin once the resin dried; also since it was perforated it assisted the flow. Due to the fine finish of this thin sheet it also gave a fine finish to the sample unlike the case where peel ply was placed right on top of the fabric. Table 3.2 below compares the flow times with the various setups.

Table 3.2 Chart showing the flow time using the various setups

Number	Setup	Dimensions	No of layers	Infusion Time(sec)
1	With infusion media	6 x 6 inch	8 layers	310
2	With perforated sheet, Top plastic sheet and peel ply	6 x 6 inch	8 layers	361
3	With only plastic sheet	6 x 6 inch	8 layers	382
4	With no infusion media and no plastic plate	6 x 6 inch	8 layers	400
5	With silicone bag	6 x 6 inch	8 layers	391

The peel ply assisted the flow of resin through the fabric. The uniform thickness was taken care of by the plastic plate. This setup gave the desired faster resin flow, finished surfaces, transparent specimens and uniform thickness to the specimens.

The fiber volume fraction achieved by this technique was very high (59 %) and almost as close to that produced by prepreg (63%). Another observation made was that the gap between the top fiber layer and the thin plate acted as a distribution media and the flow front accelerated the same way as it did on the tooling side (Appendix B). This effect was taken to advantage and large panels were made which infused completely in less time. This eliminated the use of distribution media and thereby cutting the cost. The simple setup could be used for complex geometry also. This technique had the advantages of manufacturing two sided glass finished parts; it also reduced the cost because the raw material used was reduced. Another major advantage was the reduction of voids in the part and thereby achieving a high fiber volume fraction which was close to those achieved by prepreg. High fiber volume fraction could also be achieved by making the dam slightly less high as the desired thickness which, after the application of dead weight, would smother out the extra resin in the sample thereby giving high fiber volume fraction in the manufactured parts. The technique was user friendly and could be done at room temperature. The desired thickness could be achieved by forming dams on the outside of the vacuum bag and putting dead weight on. Finally it was a clean process and could be taken to advantage make large parts.

3.10 SUMMARY OF CASE STUDIES

The various tests studied in this chapter are summarized in this section. The tests conducted were in this order; first the different fiber orientation was studied to study the effect of the varying angles in the flow of resin through the fabric. Flow lines were marked and flow rates were calculated. It was observed that the fabric oriented at 90^0 infused the fastest and the one at 0^0 moved the slowest

Next the effect of infusion media on the flow was studied by varying the area of the infusion media. The fiber type was also studied by setting different types of fiber and monitoring the flow of resin in these fibers.

Effect of fabric compaction was studied by varying the compaction time. The study for the effects of various fabric dimensions was another part of the observation.

Various setup changes were made such as use of silicone rubber and plastic plate to study the various flow patterns. With the help of all the studies conducted and parameters controlled, a final setup was reached at, which assisted in the arrival at the final goal, developing batch to batch repeatability with the VARTM technique

CHAPTER 4

TESTING METHODS AND RESULTS

This section details the testing methods used in this study. It also recommends the various precautions and standards to be maintained during the testing of the specimens

4.1 FLOW FRONT MONITORING

Primarily, the flow rate of resin was observed by using a highly sensitive stopwatch which could measure up to 1 millisecond. The stopwatch was activated as the resin flow front hit the fabric after passing through the inlet side infusion medium. Since the tool on which the samples were fabricated was made of glass and was transparent, it was possible to observe the flow front of the resin from both top and bottom sides with the use of cameras. On both the sides cameras were fixed and the footage was analyzed at various time intervals. Two cameras were used only for a few tests. In this manner, the variation of the flow front on the top and bottom could be calculated. The Figure 4.1 below depicts the setup of the cameras.

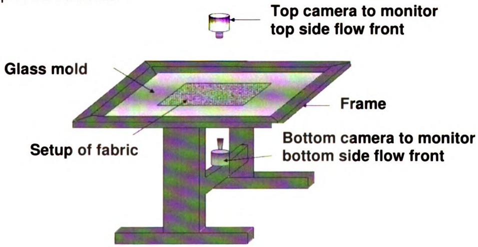
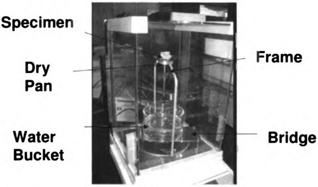


Figure 4.1 Top and bottom cameras for flow front monitoring

4.2 BURN OFF TEST

This test was used to calculate the void percentage and the amount of fiber volume fraction in the specimens manufactured by the VARTM process. In this test, first a small portion of each sample was cut and labeled. The samples were then placed in the oven to dry off any moisture which might be present. After this, a specially made balance was used to weigh the samples both in air and water. In the present study, the balance used was Sartorious BP 221S. The measuring scale measured accurately up to 0.1 mg changes. This setup used a base measurement frame. This frame had a basket on top which was used to measure the dry and wet mass of the sample. A bridge was used to hold the water cup such that the bridge and the water cup do not directly contact the measuring scale. All of this setup was enclosed in a glass cubicle. The scale was first zeroed and the glass cubicle was closed as the scale was sensitive to the movement of air. Once the scale stabilized and there was no fluctuation in the reading, the sample was placed on top of the basket and the glass cubicle was closed again. This was the dry mass of the sample and was noted down. After this, the cup was filled with distilled water to a height of 3-4 cm (usually filled enough to immerse the sample completely). The basket on top was also connected to another basket with a thin wire (with negligible weight). This basket immersed in the water and the sample was carefully placed in it so that there was no water splash which might cause an error in the measurement. The sample was again weighed and this was the wet mass of the specimen.

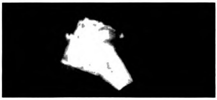
Once the dry and wet mass of the composite specimen was measured the specimen was taken under a fume hood and a propane torch was used to "burn off" the matrix from the composite. The composite specimen burned with a continuous flame till the time there was no matrix in the specimen. Once the entire matrix was burnt out, the continuous flame stopped forming thus we knew that the entire matrix was burned out. Once the matrix was completely burnt out the specimen was left to cool down. After it cooled the fiber-only specimens were again weighed in the same manner as mentioned above. After noting down the dry and wet mass of the burnt specimens, calculations of volumes, density and void content could be determined. The calculations are mentioned later in the section. Figure 4.2 below shows the setup of the test.



(a) Dry mass of un-burnt sample

(b) Wet mass of un-burnt sample

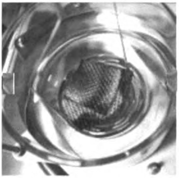
(c) Burning of matrix



(d) No end flame (burnt out matrix)

Figure 4.2 Burn off testing

Figure 4.2 Burn off testing continued



(e) Wet mass of burnout sample

The following notations are used in this section.

V_c = Volume of Composite (cm^3)

ρ_c = Composite Density (g/cm^2)

V_f = Volume of Fibers (cm^3)

ρ_f = Fiber Density (g/cm^2)

V_m = Volume of Matrix (cm^3)

ρ_m = Matrix Density (g/cm^2)

V_v = Volume of Voids (cm^3)

ρ_{water} = Water Density (g/cm^2)

m_c = Mass of Composite (g)

m_f = Mass of Fibers (g)

m_m = Mass of Matrix (g)

$m_{c(dry)}$ = Dry mass of Composite (g)

$m_{c(wet)}$ = Wet mass of Composite (g)

$m_{f(dry)}$ = Dry mass of Fibers (g)

$m_{f(wet)}$ = Wet mass of Fibers (g)

4.2.1 Composite Density and Volume calculation

The Archimedes' principle of buoyancy was used to calculate the volume and density of the composite. We needed the density of water and the dry and wet mass of the composite. The equations below show this relation and thus the values were determined.

$$V_c = \frac{m_{c(dry)} - m_{c(wet)}}{\rho_{water}} \tag{4.2.2.1}$$

$$\rho_c = \frac{m_{c(dry)}}{V_c} \qquad (4.2.2.2)$$

4.2.2 Fiber Density and Volume Calculation

As detailed above, after the complete burning of the matrix, only the fibers remained. This burning off of the matrix left some ashes and residue which were removed by rinsing and drying, otherwise the residue would hinder the accurate calculation of the fiber mass. The fiber volume and density were also calculated in the similar manner with the Archimedes' principle of buoyancy as the composite volume and density were calculated. The equations below were used for the calculation.

$$Vf = \frac{m_{f(dry)} - m_{f(wet)}}{\rho_{water}} \qquad (4.2.2.3)$$

$$\rho f = \frac{m_{f(dry)}}{Vf} \qquad (4.2.2.4)$$

4.2.3 Matrix Volume Calculation

By knowing the mass of the fibers and the, composite the mass of the matrix could be calculated using the formula given in Equation 4.2.2.5 below

$$m_m = m_c - m_f \qquad (4.2.2.5)$$

Once the mass of the matrix was determined, the volume of the matrix could be determined either by noting the value given by the manufacturer or by curing a small piece of the matrix and using Equations (4.2.2.1) and (4.2.2.2).

$$V_m = \frac{m_m}{\rho_m} \qquad (4.2.2.6)$$

4.2.4 Void volume and percentage calculation

After determining the volume of the composite, matrix and fibers, the volume of the voids could be easily determined by the relation given in equation (4.2.2.7) below.

$$V_v = V_c - V_m - V_f \tag{4.2.2.7}$$

Thereafter the void percentage in the composite could be calculated using Equation (4.2.2.8) shown below.

$$Void\% = \frac{V_v}{V_c} x100 \tag{4.2.2.8}$$

4.3 EDGE REPLICATION ON MICROFILM

This test was used to observe the thickness quality, the void distribution and the side profile of the composite specimen. A specimen was cut with a fine cutting tool so that the edge was straight and could be polished. Once the edge was cut clean, it was washed to wipe of any residue remaining after the cutting process. The edge to be replicated was then polished with polishing powders on a polishing cloth. The polishing powders used in this research were aluminum oxide powders manufactured by the Buehler shown in the Figure 4.3 below. Primarily the edge was polished by putting a 5μ powder on the cloth and some amount of water was poured to make it like a slurry paste and then polished. After polishing, the edge was observed to feel the roughness. It was cleaned with water and then again polished until the edge was smooth. The next step was to polish it with a 3μ polishing powder to give a better finish.

Thereafter a small amount of acetone was taken in a clinical syringe and spread in small quantity on the polished edge. Then quickly the edge was placed on the microfilm and pressure was applied and image of the edge was replicated on the microfilm. The film was then observed under the microfilm projector. It was digitally downloaded into the computer.

Figure 4.3 3μ and 5μ Polishing powders

4.4 IMPACT TESTING

The sole purpose of doing the impact test was to check the consistency in the properties determined from the test, such as impact energy and stiffness. To test the impact energy and stiffness of the composites, a DYNATUP 8250 drop weight testing machine was used. The schematic of the drop-weight impact testing facility is shown in the Figure 4.4. The setup consisted of a drop weight with the tup fixed at the end and was guided by two guiding rails. Various thicknesses of samples were to be measured and thus they were to be clamped very tightly in a specially made specimen holder. There were many characteristics in the resultant graph but the tests were conducted to measure only a few properties, which would be mentioned in this section.

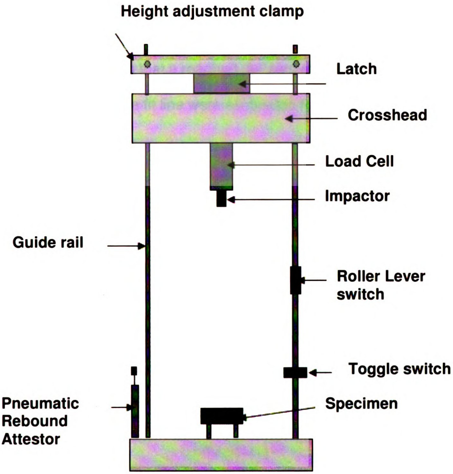


Figure 4.4 Impact loading machine setup

4.5 LOAD-DEFLECTION CURVE

Figure 4.5 below shows the desired load-deflection curve which gave us information about the two properties which were taken into consideration in this context, namely the absorbed energy and stiffness. The area under the load deflection curve was measured to be the energy absorbed by the specimen.

However, it could be observed that the last portion of the graph gave a noisy data. This was not considered while taking the energy absorbed as this was nothing but the data obtained when the impact tup had perforated the specimen and it retracted back, the friction due to the tup and the specimen caused the last part in the graph. This portion was truncated by using a trend line to fit the end part of the curve so that it reached the zero of the curve shown in Figure 4.5. The data points after the fit line were eliminated form the analysis.

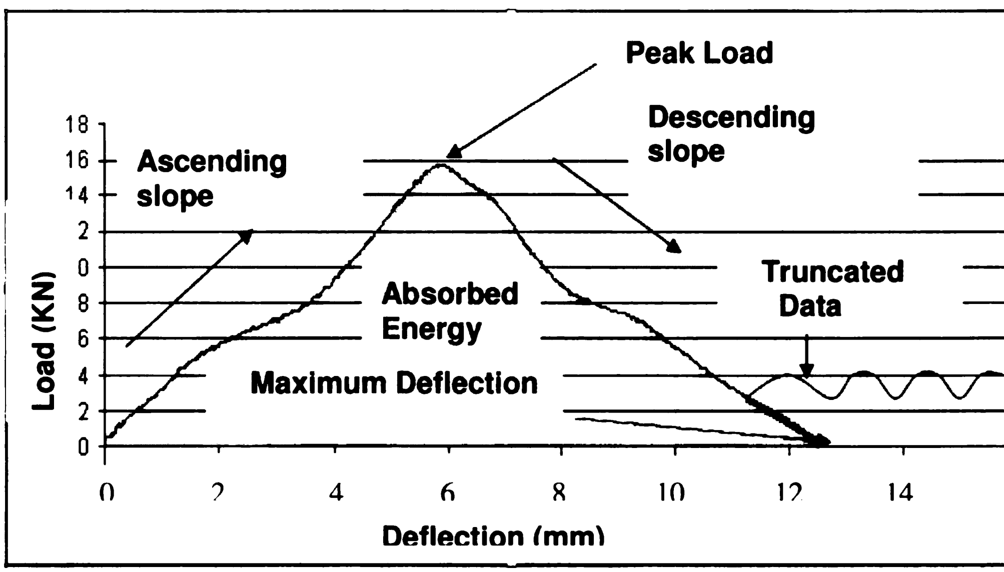


Figure 4.5 Load –deflection curve

There were two sections in ascending portion of the plot. The first slope was indicative of the "stiffness" of the specimen. The area under the curve which was the absorbed impact energy was determined by the integration of the force values form the zero to the maximum deflection shown in Figure 4.5. The highest point in the load-deflection curve was the peak load which was the maximum load felt by the impactor. The final point where the new trend line touched the deflection scale was called the “maximum deflection”.

As the samples manufactured in this study were transparent to a degree, the area of damage could be observed easily with the naked eye or by the backlighting method. The damage area in each layer could be observed but distinction could not be made as to which layer had a particular damage area. The study of damaged area was out of the scope of this study so that has not been addressed here. Figure 4.6 shown below depicts the impacted specimens with the damage areas.

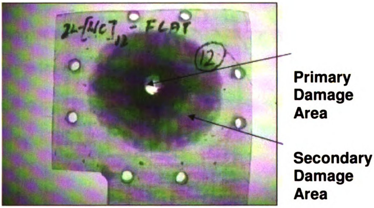


Figure 4.6 Backlit impacted specimen showing primary and secondary damage area

4.6 SUMMARY OF TESTING

Various tests were conducted during the manufacturing of the composites with the VARTM techniques. The flow of resin was tested with the various setups by varying the numerous parameters involved, their effect was seen and optimum conditions were generated. These tests involved using fibers oriented at various angles, fabric stacked in various thicknesses, the use of infusion media, and the use of silicone sheet, plastic sheet and perforated plastic film. The tests were also done by using various types of fabric to monitor the flow in each of the samples.

The void volume fraction and the fiber volume fractions were calculated with the help of the "Burn Off" test which is discussed later in the chapter. Another method incorporated was the "edge replication on a microfilm" of the samples to see the thickness, surface finish and to monitor the presence of voids; also the surface finish was recorded to measure the smoothness of the samples manufactured by VARTM.

Dynamic impact loading was also done to see the consistency in the properties of the samples produced by the technique. The transparency was used to determine the damaged areas after the impacted specimens were placed on a light table and the impact area was observed.

The various testing methods were detailed in this section. The various observations made by these tests were also presented.

4.7 RESULTS AND DISCUSSIONS

As the objective in this study was to obtain consistent properties of specimens made by VARTM batch after batch, this section details the results observed of the various tests done and the cause and effects are discussed. Some important deductions are also made.

4.7.1 RESIN FLOW

The flow of resin through the fabric is one of the governing factors which affect the properties of the specimen made by VARTM. As mentioned in previous sections various setups were used and their flow times were measured. The objective in this study was to obtain consistent flow of resin and other properties batch after batch.

4.7.1.1 FABRIC AT VARIOUS ANGLES

The fabric used in this test was unidirectional stitched glass fiber, stacked up in 5 layers with angles varying from 0^0 to 90^0, 0^0 being the fibers in the direction of the resin flow. The graphs (shown in the Figure 3.3) indicate that the flow of resin in the fibers oriented in the largest angles (90^0) is the fastest. This was attributed to the nesting (fibers cramped closely) [4] of the fibers as the angular variation within the weave changed. The channels through which the resin moved were highly diminished as the angle decreased. As a result, the flow of resin was uneven and void pockets were formed. Also, as the angle of the weave increased, the flow of resin became more uniform but started to accumulate in the sides due to less resistance in the flow or resin in the specimen creating resin rich areas in the sides. Due to the uneven, resin flow the properties such as void fraction and thickness showed large variation. Since the study of the small angle is out of the scope of this study only results would be presented.

The Tables 4.1 and 4.2 below show the thickness, density and the void percentage in the sample. The thickness mentioned is the average thickness of the sample.

Table 4.1 Specimens without infusion media

Specimen no	Orientation	Infusion media	Infusion time (sec)	Thickness(mm)	Density (g/cm^3)	Void (%)
1(a)	$[0]_6$	No	5760	1.33	1.83	4.71
1(b)	$[15]_6$	No	3120	1.41	1.82	4.91
1(c)	$[30]_6$	No	2640	1.66	1.80	4.98
1(d)	$[45]_6$	No	1740	1.56	1.79	5.23
1(e)	$[90]_6$	No	840	1.87	1.78	5.43

Table 4.2 Specimens with infusion media

Specimen no	Orientation	Infusion media	Infusion time (sec)	Thickness(mm)	Density (g/ cm^3)	Void (%)
2(a)	$[0]_6$	Yes	1380	1.98	1.81	4.78
2(b)	$[15]_6$	Yes	1083	2.01	1.80	4.93
2(c)	$[30]_6$	Yes	975	2.01	1.79	5.09
2(d)	$[45]_6$	Yes	827	2.12	1.79	5.33
2(e)	$[90]_6$	Yes	540	2.34	1.76	5.57

By looking at the tables, it was observed that the infusion time was largest in the weave specimen with the minimum angled orientation both in the case with and without infusion media. It was also observed that the thickness increased, density decreased and void fraction increased with the increasing angled weave in both the cases.

It was deduced that the average thickness increased with increasing angle because the flow rate was faster in the large angle weave. Due to the fast flow of resin through the sample, the accumulation of resin in the sides increased the average thickness in the sample.

The density decreased with the increase in the angle orientation as the same amount of resin impregnated the fabric better when the flow of resin was slow. The void percentage also increased with the increase in the angle because of poor resin impregnation due to fast flow of resin.

These observations were also confirmed when the infusion media was placed. The average thickness of all the samples with infusion media was more than those without the infusion media, the void percentage was also higher and the density lower. All these could be attributed to the infusion time in both the cases.

4.7.1.2 VARIOUS TYPES OF FABRIC

Various types of fabric were tested namely, hand laid $[0/90]_6$, unidirectional stitched $[0/90]_6$, fine woven 2D $[0/90]_6$, coarse woven 2D $[0/90]_6$ and Q3D $[0/90]_6$. The flow was measured in the same manner and the data was collected. All specimens in this test were oriented in 0/90 manner and were interwoven and no infusion media was used. All samples were $(127\ mm)^2$ $((5\ in)^2)$, 6 layers. The Table 4.3 below shows the flow of resin through the various fabrics and details the properties of the specimens.

Table 4.3 Flow time for various fiber types

Specimen type	Stacking Sequence	Infusion time (sec)	Thickness(mm)	Density (g/ cm^3)	Void (%)
Hand laid	$[0/90]_6$	800	1.87	1.81	4.30
Unidirectional stitched	$[0/90]_6$	847	2.07	1.85	4.22
2D(Coarse woven)	$[0/90]_6$	362	2.36	1.81	5.32
2D (Fine Woven)	$[0/90]_6$	497	2.19	1.84	4.90
Q3D	$[0/90]_6$	1800	1.92	1.92	3.47

It was observed that the 2D coarse woven had the fastest infusion time and the Q3D was the slowest to be impregnated. The thickness of the 2D coarse woven was the maximum among the lot and the density was largest in the Q3D fabric. The void fraction was observed to be largest in the 2D fabric.

The flow was relatively faster in the 2D coarse woven because there were fiber interstices, creating resin channels which allowed the resin to flow better. In the Q3D the fabric was denser as compared to the rest so the flow was hindered and slower resin flow was observed. The hand laid and unidirectional stitched did not vary to a great extent, while fine woven was faster than these.

The thickness variation was the largest in the 2D coarse woven and the least in the Q3D. This was again attributed to the quick flow and thus accumulation of resin towards the inlet side. All these samples were fabricated without placing the infusion media on top of the fabric. The void percentage was seen to be largest in the 2D coarse weave as the flow of resin was uneven and proper impregnation did not take place.

4.7.1.3 VARIOUS SETUPS

The samples fabricated for this test were made from the same2D coarse woven and the same stack sequence ($[0/90]_6$). The setups used were with infusion media on top, without infusion media on top, using silicone sheet on top, using plastic sheet on top, using thin perforated sheet, peel ply and plastic sheet on top (setups detailed in sections 3.3, 3.5, 3.8, 3.9). The Table 4.4 below shows the flow time of resin in all these setups. The table also shows the thickness variation, void fraction and density of all these specimens.

Table 4.4 Properties at various setups

Setup Type	Infusion time (sec)	Thickness (mm)	Density (g/ cm^3)	Void (%)
With infusion media	310	4.45	1.82	4.84
Without Infusion media	400	4.32	1.87	4.17
With top plastic Plate and dam only	382	4.00	1.92	1.71
With Silicone top sheet	391	4.70	1.73	5.23
With Peel ply, Perforated sheet, Plastic plate and dam	361	4.00	1.92	1.91

It was seen that the flow time of the sample with the infusion media on top was the fastest (this process is the patented SCRIMP process). The infusion media accelerated the flow of resin. The infusion time for the setup without the infusion media was slowest. This was because there was no other factor apart from the permeability of the fabric to accelerate the flow. The thickness variation was less than the setup with the infusion media but as compared to the other setups it was more. The density was higher than the one with the previous setup and void fraction was lesser than that with the infusion media on top.

The silicone sheet, also acting as a second mold assisted the resin to move quicker than the setup without the infusion media. This was because the silicone sheet was thick (6 mm) as compared to the specimen, and the vacuum pressure could not compact the fabric layers between the top and the bottom fabric layer so the micro-channels between each layer, assisted the resin flow. However, since the silicone sheet was flexible and conformed to the shape of the top fabric, the flow of resin was slower on the top layer as compared to those beneath it. As detailed in section 3.5 in Chapter 3, the race-tracking channels in the sides allowed the resin to flow faster through the sides and thus there were dry spots generated towards the outlet side. This phenomenon also led to the accumulation of resin on the sides which made the sample thicker through the sides. The overall thickness was also larger because the vacuum bag could not compact the specimen enough because of the silicone sheet.

The setup with the plastic plate on top was faster than that without the infusion media because the fine gap between the top layer of the fabric and the plastic plate acted as a path way for the resin to move quickly without any hindrance. The thickness was very uniform with a standard deviation of 0.13%. This was because of the fixed dam mentioned in section 3.8 in Chapter 3. The density also increased and the void volume fraction decreased.

The final setup with the perforated media, peep ply and the top plastic plate gave the best results as the flow was slower than that with the infusion media on top. The thickness was maintained with the dam. The density was also comparable with the previous setup (with just the plastic plate) the void fraction was also similar to the previous setup.

4.7.1.4 STACKING THICKNESS

Various stacking layers of fabric were used and the flow time was also monitored. The number of layers ranged from 3 to 22 layers of 2D coarse woven fabric, the flow time, volume fraction and the thickness variation were monitored. All these setups were without the infusion media or the plastic sheet. The Figure 4.7 shows the flow pattern. The Table 4.5 details the thickness, density and void percentage of the samples.

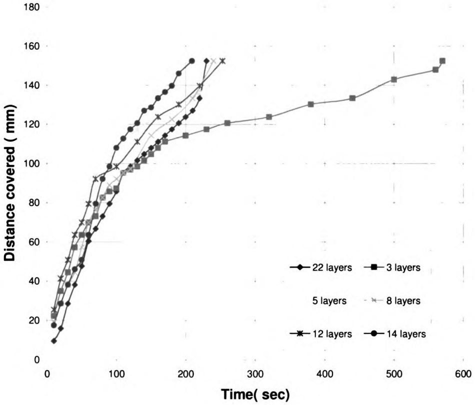


Figure 4.7 Flow time at different stacking thicknesses

Table 4.5 Properties at various stacking thicknesses

Type	No of layers	Compaction Time (sec)	Stacking Sequence	Infusion time (sec)	Thickness (mm)	Density (g/ cm^3)	Void (%)
2D coarse woven	3	600	$[0/90]_3$	570	1.79	1.78	4.78
2D coarse woven	5	600	$[0/90]_5$	318	3.16	1.82	4.22
2D coarse woven	8	600	$[0/90]_8$	253	5.68	1.82	3.98
2D coarse woven	12	600	$[0/90]_{12}$	240	7.82	1.91	3.94
2D coarse woven	14	600	$[0/90]_{14}$	230	8.29	1.90	3.65
2D coarse woven	22	600	$[0/90]_{22}$	209	10.17	1.97	3.1

It was observed that the thicker the sample the faster was the flow. This could be attributed to the increase in the through thickness permeability of the fabric [4]. The resin moved faster in the through thickness direction.

A contradiction with the earlier hypothesis was that if the flow of resin was faster the impregnation would be non-uniform and the void percentage would increase. It was seen that in this test this was completely opposite. The thicker samples showed lesser voids and greater density. This could be attributed to the fact that since the compaction time was the same for all the samples the amount of compaction for the thick stacks was not enough to compact it as thus resin channels were created, thus faster flow. In the previous case where the infusion media was placed on top the impregnation was non uniform and had more voids.

4.7.1.5 DIMENSIONS

As mentioned in Chapter 3, various dimensions were used to observe the flow pattern. Specimens ranging from 127 mm X 127 mm (5 in X 5 in) to 508 mm X 203 mm (20 in X 8 in) were used and the flow pattern was measured. It was observed that the specimens with larger distance to cover, covered the same amount of distance with the same flow rate but in the samples which were larger in length and placed length wise (inlet- outlet distance longer as shown in Figure 3.25 in Chapter 3) the flow rate diminished as the distance from the inlet increased. As explained in the Chapter 3, it was because of the loss of compaction pressure due to Darcy's Law that the flow retarded.

4.7.1.6 COMPACTION TIME

Another test done was to see the effect of compaction (the amount of time the vacuum is drawn on the setup). The setup was compacted under vacuum from 10 min to 5 hours. All the samples were of the same dimension, 6 layers of 152.4 x 152.4 mm, the same reinforcing material (coarse woven 2D, $[0/90]_6$), the same amount of infusion resin(371.5 g) and no infusion media.The Table 4.6 below shows the effect of compaction time on the flow, thickness, density and void percentage.

Table 4.6 Flow time and property variation with varying compaction time

Specimen No.	Compaction time (sec)	Flow time (sec)	Thickness (mm)	Density (g/ cm^3)	Void (%)
1	0	378	3.22	1.87	5.23
2	900	360	3.20	1.83	4.77
3	3600	352	3.18	1.82	4.76
4	7200	337	3.16	1.81	4.56
5	12600	321	3.12	1.81	4.29
6	18000	320	3.11	1.81	4.29

It was observed that the flow time improved due to compaction. The overall void percentage also decreased, the part thickness variation and density was similar in all cases. The reduction in void percentage was contradictory to the earlier hypothesis as the faster flow would diminish the part quality due to the poor impregnation of the fabric. It was justified that the reduction in the flow time was about 15 % however the reduction in void percentage was 20%. Also due to the compaction the flow in the through thickness direction increased which compensated for the poor impregnation with fast flow time.

4.7.2 LOAD-DEFLECTION CURVE

As discussed earlier in Chapter 3, the impact tests were done on some specimens. The goal of these tests was to investigate the consistency of the properties of the specimens manufactured by VARTM. This section discusses the properties obtained by the load-deflection curve. The Table 4.7 below details the properties obtained including stiffness, energy absorbed and maximum deflection of the samples tested. The Figures 4.8, 4.9, 4.10, 4.11 and 4.12 show the characteristics of the samples from different batches manufactured by the VARTM technique developed.

It was seen that the energy absorbed by the specimens increased with the increase in stacking thickness (overall thickness). This was deduced as more amount of impact energy would be required to completely penetrate a relatively thick sample.

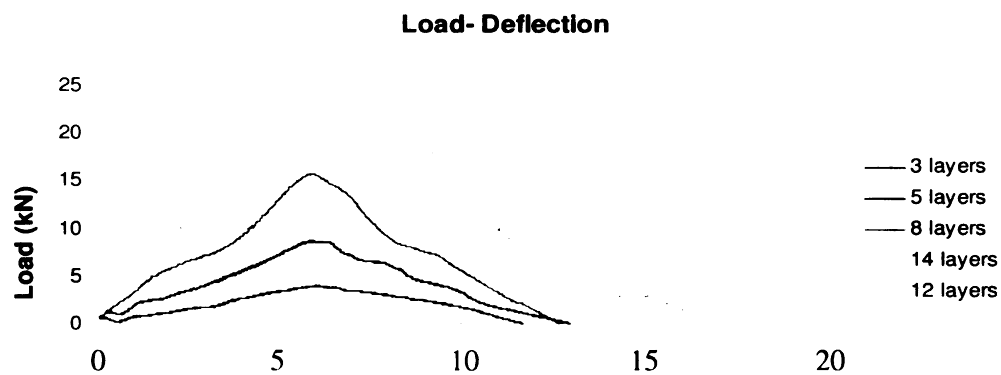


Figure 4.8 Load-deflection curves for various layers

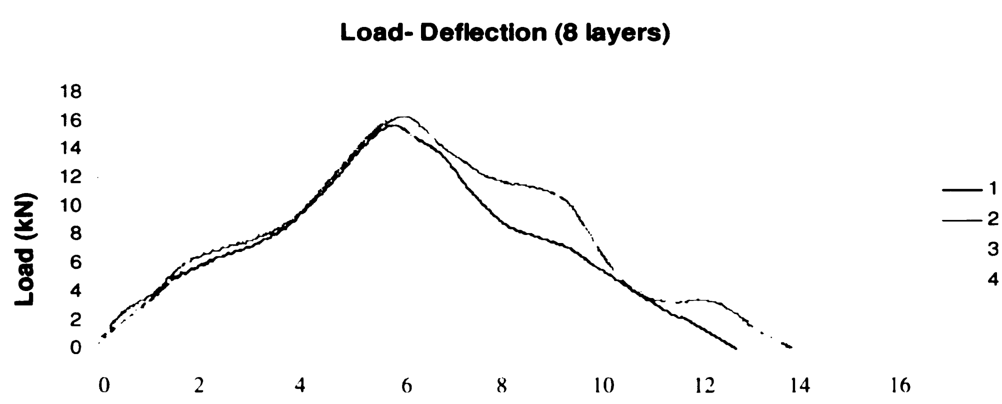


Figure 4.9 8-layer specimens with different batches

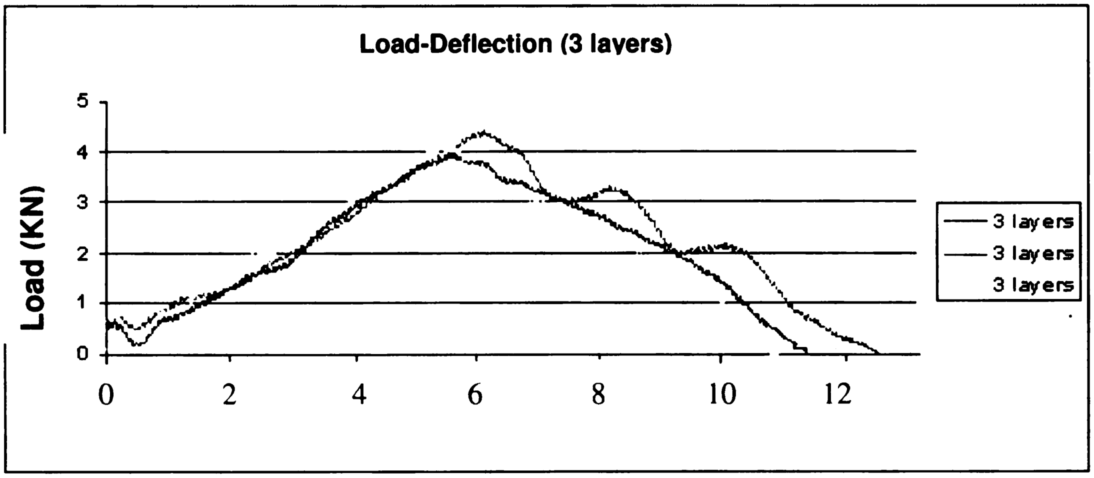


Figure: 4.10 3-layer specimens with different batches

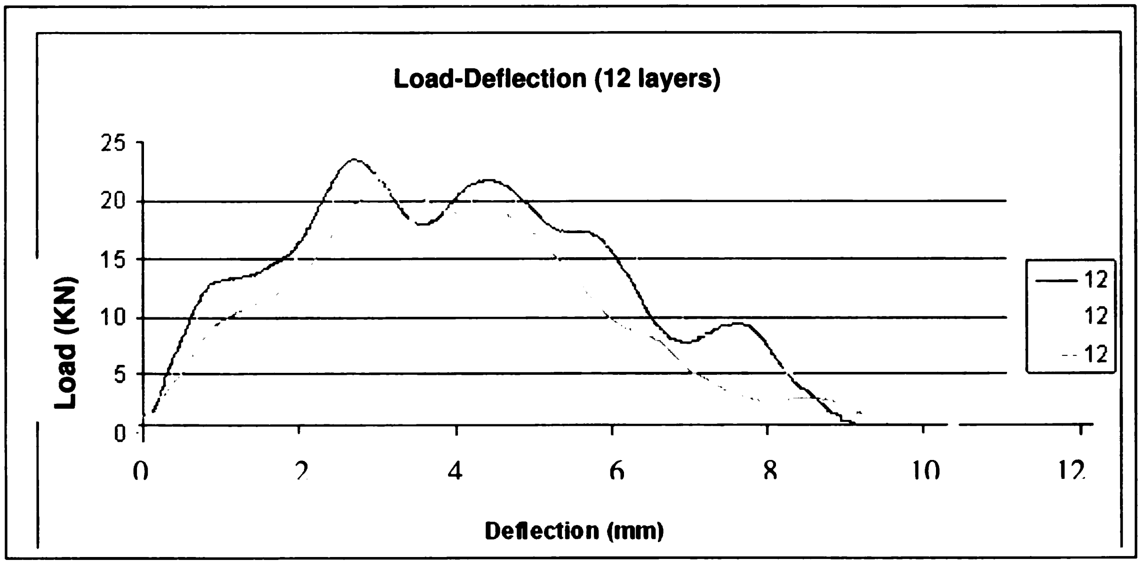


Figure 4.11 12-layer specimens with different batches

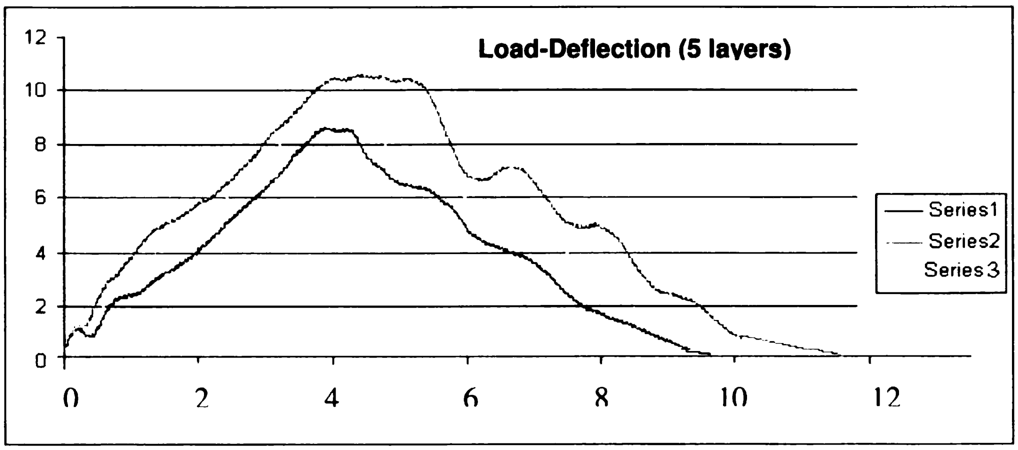


Figure 4.12 5-layer specimens with different batches

Table 4.7 Specimen batches and properties

Batch	Thickness (mm)	Absorbed Energy (J)	Maximum Load (kN)	Slope 1	Maximum Deflection(mm)
3 layer	1.789 ± 3 %	23.68 ± 5 %	3.93 ± 8 %	0.57 ± 4.5 %	11.62 ± 4 %
5 layer	3.46 ± 2.5%	63.25± 7.5 %	9.53 ± 10%	1.93 ± 9 %	11.95 ± 6 %
8 layer	5.727 ± 4 %	107.01 ± 5 %	15.87 ± 2.5 %	2.22 ± 6.5 %	13.64 ± 5 %
12 layer	7.61 ± 2 %	200.58 ± 7.5 %	22.55 ± 5 %	11.34 ± 7 %	9.75 ± 7.25 %

Based on the energy absorption, thickness, maximum load, stiffness and maximum deflection data, it was observed that the variation in most of the sample properties was not large and only differed by a maximum of ± 10 %.

It was deduced that within this range of properties the samples could be fabricated with VARTM in a consistent manner batch after batch.

4.7.3 THICKNESS

The Figure 4.13 below shows the thickness profile of the various samples fabricated with all the setups mentioned in the previous setups.

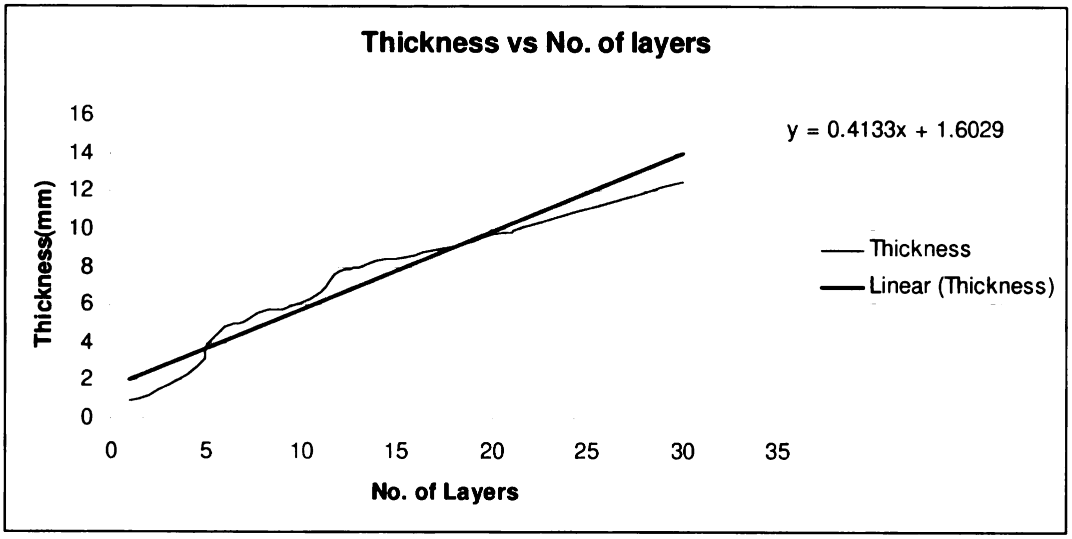


Figure 4.13 Thickness chart for various layers

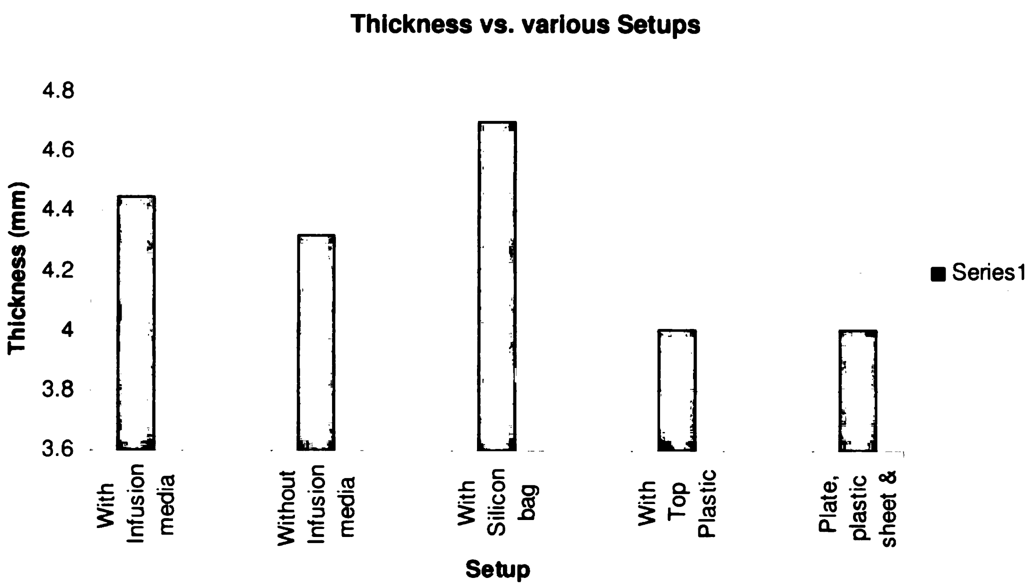


Figure 4.14 Thickness chart for varying setups

Table 4.8 Properties for all the setups

Setup	Thickness(mm)	Standard Deviation	Void (%)	Fiber (%)
With infusion media	4.45	31.7%	4.82	51.78
Without Infusion media	4.32	21.1%	4.13	52.04
With silicone bag	4.74	62.5%	5.25	49.67
With top plastic Plate and dam only	4.00	0.13%	1.72	59.08
With Peel ply, Perforated sheet, Plastic plate and dam	4.00	0.1%	1.96	59.00

It was seen that the variation in thickness decreased as the number of stacking layers increased. Also the variation of thickness was the least with the setup with the plastic sheet on top. The thickness was perfectly controlled by the dam used in this setup. It was also seen that the density increased and the void percentage decreased with the setup with the plastic plate on top. The void percentage reduced to 0.13%and the fiber volume increased to 59.08% overall. Since it was not possible to add all the figures of the samples, only a few edge replicas are shown here.

As shown from Figures 4.15 to Figure 4.18, the sample with the plastic plate had a very controlled thickness, followed by the setup with perforated plastic film, peel ply and plastic plate. The most undulated was the one with infusion media on top of the setup.

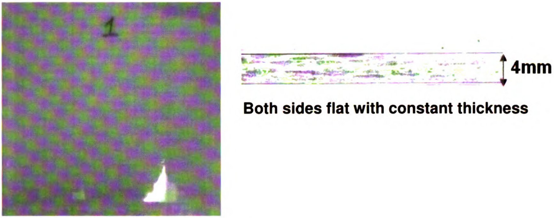


Figure 4.15 Sample with plastic plate setup

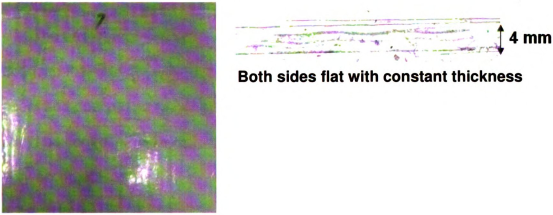


Figure 4.16 Sample with plastic plate, thin plastic sheet and peel ply.

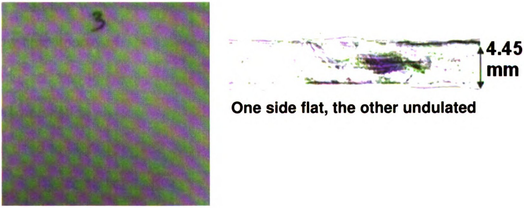
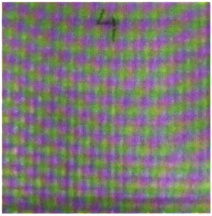
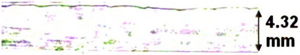


Figure 4.17 Sample with peel ply and infusion media





One side flat, the other undulated

Figure 4.18 Sample with no infusion media or peel ply

The arrows in the above figures indicate the thickness of the sample. It was deduced that with the setup with plastic plate and with plastic plate, perforated sheet and peel ply, constant thickness samples could be fabricated. The variation could be controlled to a value of less than 0.13%, which was considered to be a very acceptable value.

4.7.4 SUMMARY OF RESULTS

The Table 4.9 below summarizes all the tests done and their results. It could be seen that with final setup (perforated film, peel ply and thin plastic plate) the flow time improved, the thickness was uniform and the void percentage was reduced; also the fiber volume fraction improved significantly. The impact characteristics were similar within the batches. This mentioned technique could be used to fabricate composite parts repeatedly.

Large sections could also be manufactured. The next chapter explains the use of the current technique to fabricate large part with controlled parameters like thickness, void percentage, and fiber volume fraction and infusion times. The material properties could also be tailored with the current technique if the parameters involved were controlled.

Table 4.9 Summary Chart

Varied Parameter	Type of fabric	No. of samples tested	Type of setup	Average Thickness (mm)	Average Void (%)	Average Fiber Volume (%)	Average Infusion time (sec)
Orientation	U	5	1	2.12	5.14	49.32	961
	U	5	2	1.56	5.052	50.06	2820
Fabric Type	U	2	2	1.76	5.12	49.78	801
	2DC	2	2	2.07	5.32	49.76	356
	2DF	2	2	2.19	4.94	51.95	400
	L	2	2	1.87	4.21	52.00	869
	Q3D	2	2	1.92	3.65	54.87	1731
Various setups	2D	3	1	4.36	4.73	48.33	317
		3	2	4.32	4.12	50.39	549
		3	3	4.00	1.64	59.89	378
		3	4	4.00	1.79	58.33	362
		3	5	4.76	5.32	46.11	371
Stacking Thickness	2D						
	3layer	3	2	1.79	4.78	48.44	546
	5layer	3	2	3.19	4.22	49.33	399
	6layer	2	2	3.95	4.14	50.06	324
	8layer	4	2	5.61	3.98	50.35	297
	10layer	2	2	6.25	3.95	51.00	267
	12layer	4	2	7.84	3.94	52.5	247
	14layer	2	2	8.29	3.65	52.76	239
	22layer	1	2	10.17	3.11	54.00	209
	30layer	1	2	12.65	3.02	54.33	203
Compaction		6	2	3.15	4.65	50.06	347

Legend:

Setup: 1 - Setup Classical VARTM (SCRIMP) - with infusion media and peel ply On top.
Setup: 2 - Setup with no infusion media or peel ply on top
Setup: 3 - Setup with just plastic plate on top
Setup: 4 - Setup with thin perforated plastic sheet, peel ply and plastic plate.
Setup: 5 - Setup with Silicon bag on top
U - Unidirectional Stitched
2DC - 2- Dimensional coarse woven fabric oriented at 0/90
2DF - 2- Dimensional fine woven fabric oriented at 0/90
L - Hand Laid fabric
Q3D - Quasi 3-Dimensional Weave at 0/90

CHAPTER 5

LARGE AND COMPLEX STRUCTURES

To promote the current technique, it is imperative that the recommended technique could be used for large and/or complex structures for a wide variety of applications. This chapter briefly describes the use of the technique (with perforated sheet, peel ply and thin plastic plate on top), mentioned in section 3.9, for the fabrication of some of such specimens. This chapter is divided into two sections. The first section discusses how large parts such as yachts and wind turbine blades are manufactured and how the technique would be implemented. [Such large structures were not manufactured; however the use of this technique is explained]. The second section presents the manufacturing of complex shapes such as arches and sandwich structures.

5.1 LARGE STRUCTURES

Manufacturing large composite structures could be more cost effective than manufacturing large metallic structures, since it does not require fabricating small components and joining them together. There is a great advantage in manufacturing large structures in one infusion. For example the yacht and the wind turbine blade industries are using VARTM as an essential manufacturing technique to produce their structures as it does not require secondary processes and expensive tooling. SCRIMP^{TM} (Seemann's Composite Resin Infusion Molding Process) is a commonly used technique. It uses patented infusion media to manufacture hulls of boats and ships.

Multiple infusion lines are used to inlet the resin. The infusion lines are usually placed parallel to each other and resin is inlet sequentially. When the resin from one infusion line reaches the maximum distance it can travel, that line is clamped back on and the next adjacent line is unclamped simultaneously. This is to ensure that the infusion is continuous and there are no obvious voids and dry spots created during the infusion. The gel time of the resin should be long enough so that it does not start gelling until the resin from the previous line reaches the current infusion line. Otherwise, there would be uneven hardening and properties would be different. Figure 5.1 shows the multiple infusion lines in the process.

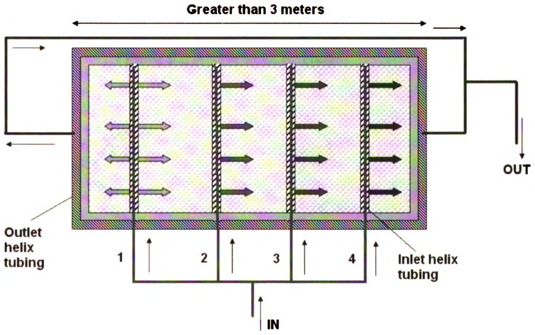


Figure 5.1 Multiple infusion lines used for resin infusion

Most wind turbine blades are also made of composites and they are often manufactured with VARTM. Figures 5.2, 5.3 and 5.4 show the overall structure, details sections and manufacturing process respectively.

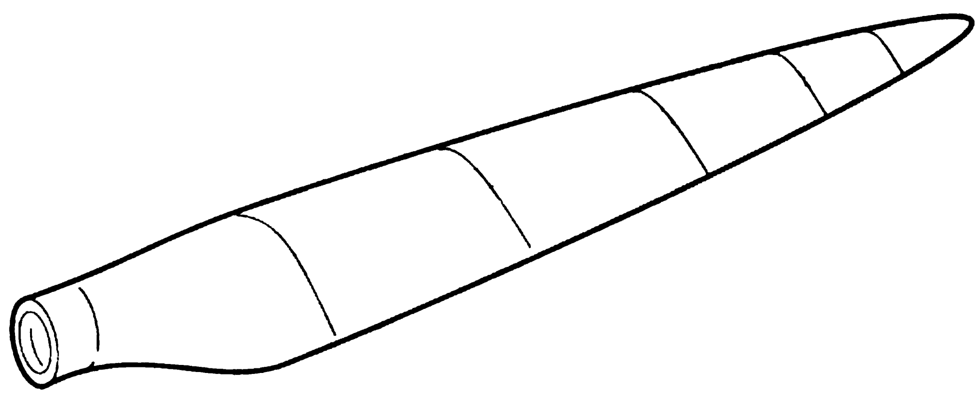


Figure 5.2 A typical wind blade

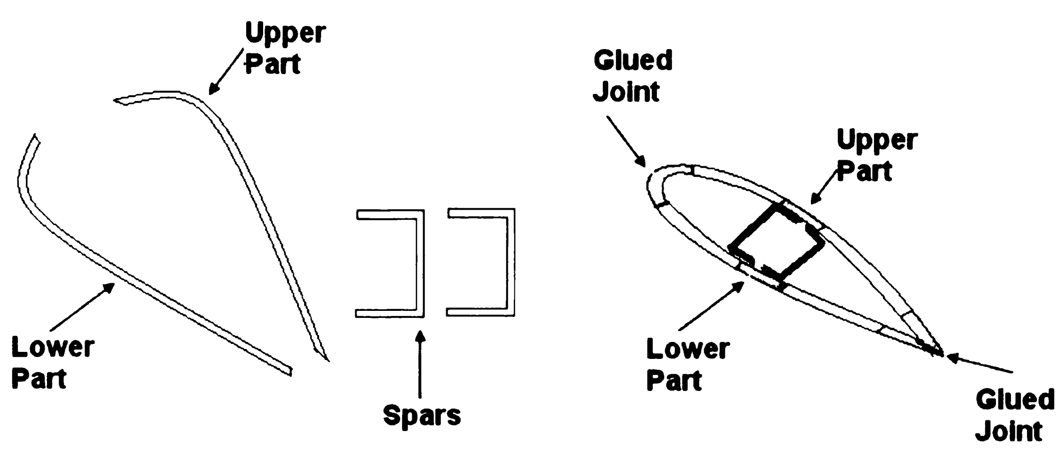
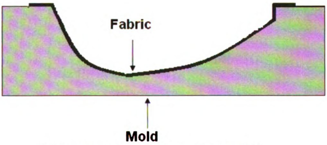


Figure 5.3 Parts of the wind blade

The first step is to place a layer of the reinforcing material (fabric), which is large enough so that it fits the mold and some of it exceeds the side of the mold. The mold is then polished with wax and sealant tape is applied to the edges of the mold. The fabric is then placed on the mold, shaped in the mold of one half of the wind turbine blade. Next, a layer of peel ply and infusion media are placed on top of the fabric. Then the inlet and outlet piping is placed. A vacuum bag is placed on the very top and sealed with the sealant tape on the periphery of the mold, resulting in a completely sealed setup. Vacuum is drawn thereafter and left for a long duration such as three hours so that all the excess air is drawn out. Next the resin is infused and the lay-up is left overnight to infuse. Once the resin has cured the part is then demolded. Both the top and the bottom parts are manufactured in this manner. The supporting spars are then placed in between the two parts and they are bonded together. Figure 5.4 (a) to (f) show the entire manufacturing process.

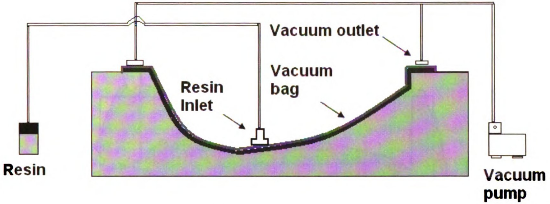
(a) Fabric



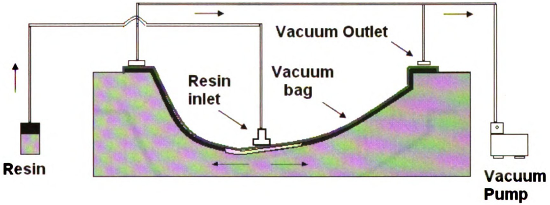
(b) Layup of fabric on the mold

Figure 5.4 Manufacturing process

Figure 5.4 Manufacturing process continued

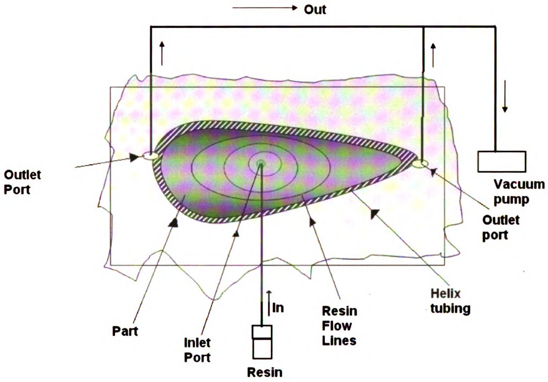


(c) Drawing Vacuum



(d) Resin infusion

Figure 5.4 Manufacturing process continued



(e) Top view of the resin infusion process

(f) Demolding and final processing

VARTM is used to manufacture wind turbine blades in the above shown Figure 5.4

There are four independent parts in the blade section, the upper and lower section and two web spars. These parts are manufactured separately and then joined together with adhesive bonding. The use of infusion media on the outlet side causes air bubbles in this process towards the outlet ports. This leads to the removal of the end sections. Therefore, the infusion sections are always made bigger than the desired size. Besides "bubble trap" technique, mentioned earlier could be used so that the voids are trapped in the peel ply and do not retract back.

Since the vacuum bag side is not smooth, it may lead to structural instability due to the thickness variation throughout the part. A stiff plastic sheet made in the shape of the structure could be used to match with the mold so that constant thickness parts could be manufactured. This would improve the properties of the part produced.

5.2 COMPLEX AND SANDWICH STRUCTURES

In this section arched structures and sandwich composites are discussed.

5.2.1 ARCHES

With the current technique, some complex shapes like arches and domes could also be manufactured. The idea for this experiment was to demonstrate the feasibility of the technique for complex structures.

The mold prepared for this specimen was an arched shape made of steel and polished with wax so that the tool side is smooth. Figure 5.5b shows the setup. Eight layers of 2D fabric of dimension 203 mm x 203 mm (8 in x 8 in) were placed on the tool after waxing and the rest of the procedure was done in the similar manner as explained earlier. The vacuum was drawn and the bag conformed to the shape, leaving no race-tracking channels. The part was infused in approximately 4 minutes.

It was observed that the resin accumulated on the edges where the arch began. This was due to the fact that the fabric did not completely conform to the shape of the arch, leaving some gap filled by resin. Overall the part thickness was around 5.65 mm with a standard deviation of 0.85%.

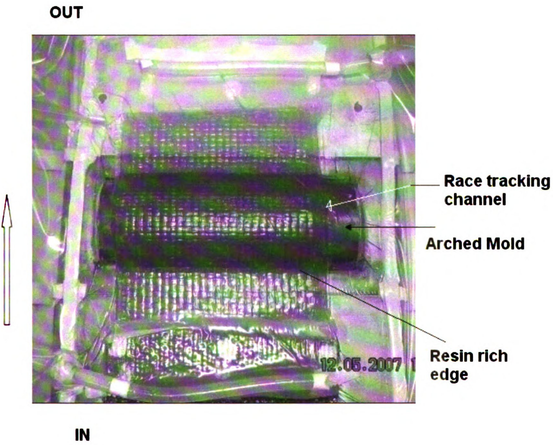


Figure 5.5a Manufacturing arched specimens

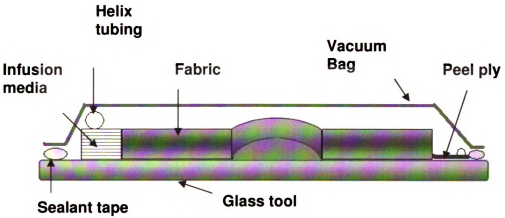


Figure 5.5b Schematic for arched specimen setup

It was observed that the resin flowed very uniformly thereby impregnating the entire part and leaving very little visible voids. Figure 5.6 shows the manufactured part.

Figure 5.6 Arched Specimens

5.2.2 SANDWICH STRUCTURES

When materials with high energy absorption-to-weight ratio are mentioned, the first thing which comes to the foreground is composites. Sandwich composites enhance this property. As the name suggests, they are made of materials which have lightweight core, such as Styrofoam, which separates fiber composite faces. The sandwich structure can absorb significant amount of energy. Some sandwich composites were manufactured with the technique presented in this study.

5.2.2.1 DESIGN I

The first design for the sandwich composite is shown in Figure 5.7 .The top layer, bottom layer and the two intermediate layers were made of 2D coarse woven glass fabric cut into 127 mm x 127 mm (5 in x 5 in) dimensions. Circular open-celled Styrofoam balls were cut into semicircular with a diameter of 65.5 mm (2.5 in) and height of 9.5 mm (0.37 in) and painted with Styrofoam paint to make the surface smoother and completely closed. Open-celled means that the individual cells are permeable and allow materials to pass through it, just like sponge. The need to make the Styrofoam complete closed, was that the infusion resin would not seep through the pores of the foam thereby creating a specimen rich of resin which would increase the overall weight of the sandwich composite. Also, fiber rich of resin would render the composite, brittleness.

The setup for making the sample is same as shown in the Figure 3.19b (Chapter 3). The inlet side infusion media was stacked into layers so that it matched the height of the specimen which was 19.05 mm (0.75 in). This was necessary because the resin flow in the specimen would be uneven otherwise.

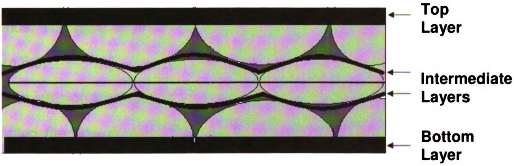


Figure 5.7 Schematic of the sandwich structure

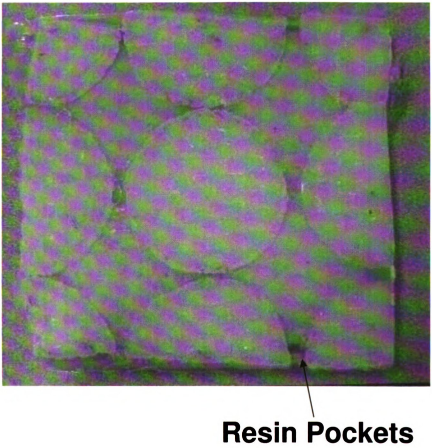


Figure 5.8 Manufactured sandwich composite

The infusion time for the sample was 159 seconds as there were huge passage gaps between the domes. The resin flow within the fabric was 194 seconds. The gaps between the domes formed resin pockets as shown in the Figure 5.8.

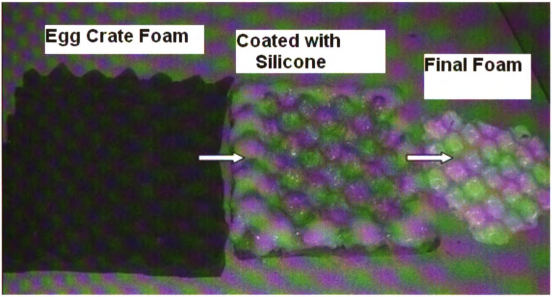
The infusion took place the same way as explained in section 3.9 .The gaps promoted the flow of resin and the peel ply at the outlet trapped air bubbles, leaving the sample with minimum voids. The voids, however, were more as compared to the rest of the materials used in the previous setups. The cause of the voids was attributed to the gaps between the domes.

5.2.2.2 DESIGN II

To reduce the amount of gaps between the domes, perfectly matched domes were made. This would ensure the reduction of the gaps between the two layers of foam. Polyurethane expanding foam manufactured by US Composites was used for this. It is available in densities from 0.000064 g/cm^3 (2lb per cubic foot) to 0.00254 g/cm^3 (16lbs per cubic foot). It is available as a two part expandable liquid. The liquid is a 50/50 mixture and is sold in the following kit sizes of 1.8 kg, 7.2 kg, 36.2 kg and 45.4 kg (4 lbs, 16 lbs, 80 lbs and 100 lbs).

Egg crate foam (usually made from polyurethane or poly ether) was used as a base mold for making the final foam. It was coated with silicone rubber. This was to give the egg crate foam a fine finish, so that the foam made could be easily demolded. The setup is shown in the Figure 5.9 below. Two equally sized containers were taken and each part of the components of the expandable foam was poured into it. Then they were mixed and stirred for approximately 20 seconds. It was then poured into the silicone rubberized mold and a glass plate was placed over it, as one-sided flat foam was to be made.

Some weight was placed on top of the glass plate to make the surface uniform. It took about 10 to 15 minutes for the foam to fully expand to about 15 times the original volume. Once made, it was cut to desired shape. Fabrics were placed in similar manner as the above mentioned setup and infused with VARTM



. **Figure 5.9 Making the foam**

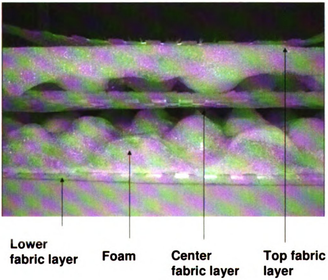


Figure 5.10 Side view of the sandwich structure before infusion

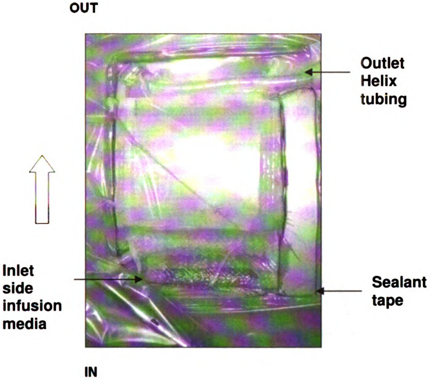


Figure 5.11 Infusion process

The dimensions of the fabric were 165 mm x 203 mm (6.5 in x 8 in).This setup took about 290 seconds to infuse. It was longer than the previous setup. This was attributed to fewer gaps available for the resin to flow in between the foam and the fibers. The manufactured parts had visibly fewer resin pockets than the setup shown in Figure 5.7.

Figure 5.12 shows the manufactured sandwich composite. It was observed that due to the fabric (coarse woven $[0/90]_2$) in the center portion was not flexible enough it could not take the exact shape of the domes on both the upper and lower side even though the domes matches very closely independently. Due to this there was resin pockets developed in the places where the fabric did not conform to the shape as shown in Figure 5.12.

These resin pockets were potential weak points as the resin deposition would give brittleness to the composite as a whole. These resin pockets would also result in additional weight of the composite. Due to the resin-rich pockets, the fiber percentage of the composite would decrease significantly. Also void content was higher.

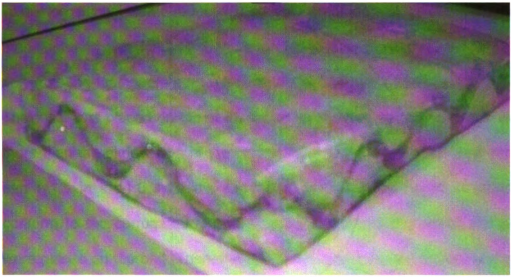
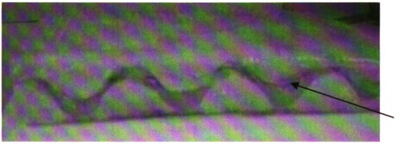


Figure 5.12 Sandwich composite



Resin rich Areas

Figure 5.13 Side view

The top, bottom and center fabrics were impregnated completely as observed which meant that the infusion process was feasible for these structures. The foam was closed celled so the resin did not impregnate the foam and thus the weight of this structure was comparable to the previous setup where foam domes were used. Also the thickness was 36.83 mm (1.45 in) with a standard deviation of 0.93%. It was concluded that the setup could be used for sandwich composites also.

5.2.2.3 DESIGN III

To minimize the gaps and reduce the resin pockets so that the probability of void formation was reduced, another method of sandwich structure manufacturing was used. First, the lower fabric layer (coarse woven [0/90]) and a polyurethane foam were cut to dimensions of 254 mm x 254 mm (10 in x 10 in). The foam was placed on top of the fabric layer. Next, two fabric layers were cut more than the dimensions of the bottom layer and the foam, i.e. 292 mm x 292 mm (11.5 in x 11.5 in). This was done so that these layers of fabric could conform to the corrugated foam uniformly. Perforated thin sheet and peel ply were placed on top of it. Then, the vacuum bag was sealed on top, and vacuum pressure was drawn. This setup was then infused with resin. The schematic of the setup is shown in Figure 5.14

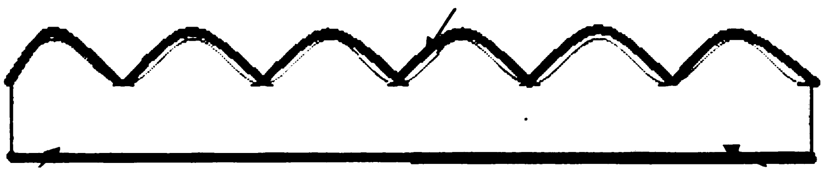


Figure 5.14 Cross sectional view of the 1st step

After the infusion was completed and the setup was fully cured, it was demolded. This setup was placed on a glass plate and freshly prepared foam mixture was poured on the already infused structure. This was to ensure that the foam took the shape of the structure below, thereby significantly minimizing the gaps between the top foam layer and the intermediate fabric. This would reduce the resin pockets as the top foam layer would perfectly match the intermediate fabric. A glass plate was then placed to maintain a smooth finish on the top surface of the foam.

After the foam took the shape, the structure was removed from between the two plates. Another layer of coarse woven fabric ([0/90]) was placed on top of the top foam layer. Perforated thin sheet, peel ply and thin plastic sheet were placed on top of the fabric and the setup was sealed under a vacuum bag. This setup was again infused. Since the intermediate layers were already infused and the foam was closed celled, the resin only traveled through the top fabric layer, completely impregnating it.

Once the resin had cured completely, it was demolded. It was seen that the weight of the sample was comparable to the samples produced by the methods mentioned above. This proved that even though this specimen was larger, it had comparable weight to the other. It could be concluded that this was due to the reduction of the resin pockets which were formed earlier. The thickness was also comparable; it was 36.6 mm (1.44 in) with a standard deviation of 1.03%

Since the top and the bottom fabric layer were clear, the foam beneath them could be easily seen. However due to the foam not being transparent it was not possible to observe the intermediate layers and the resin pockets. Figure 5.15 shows the manufactured sample.

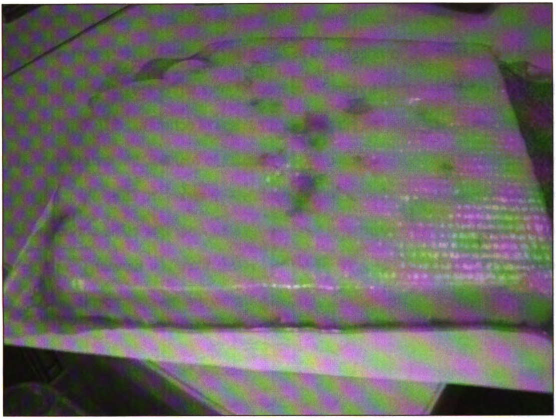


Figure 5.15 Manufactured sample with matching domes

The motivation for making these composites was the impact testing of the domed structures. It was found out that the domed structures were capable of absorbing more energy and thus the center core was made in the shape of domes so that the center layer could absorb more impact energy with the help of the domed structures.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

From this study, a number of conclusions were reached upon.

a) Resin flow was affected by the angle of orientation of the fabric. The fabric oriented in the largest angle with respect to infusion direction required the least infusion time. The difference in flow-path of resin did not vary even when the flow was accelerated with the use of infusion media placed on top. The fast resin flow changed the overall thickness in the large angled fabrics. The thickness was the highest on the sides and the inlet side as there was accumulation of resin due to quick flow. The void volume fraction increased and density decreased with the increasing angles.

b) Among hand laid unstitched, stitched unidirectional, 2D fine woven, 2D coarse woven and Q3D woven fabrics, the flow of resin was fastest in the 2D coarse woven fabric as it provided the least resistance to flow because of large fiber tows which caused large interstices (the gaps between the tows which act as the flow channels) in the fabric. The Q3D was the slowest to impregnate as the nesting of the fibers was dense and fine flow channels were diminished.

c) Use of infusion media on the outlet side resulted in the retracting of the displaced air bubbles, causing infused parts with high void percentage (8%). Elimination of infusion media from the outlet side and placing peel ply instead trapped the bubbles and did not let them retract back into the sample. This was named “BUBBLE TRAP ” technique. This reduced the void percentage and increased the overall fiber volume fraction in the sample.

d) In the setup with 2D coarse woven fabric laid in $\underline{[0/90]_3}$, using no infusion media and peel ply on the top side, reduced the overall flow of resin tremendously (29% and higher), but reduced the thickness variation (upto 22%). The void percentage also decreased from 4.8% to 4.1% and the fiber volume fraction increased from 48.3% to 52%. The elimination of the infusion media improved the transparency of the specimen as the finish was smoother than the setup with peel ply and infusion media on top.

e) The increase in the stacking thickness of the fabric improved the flow in the through thickness direction, thereby improving the overall resin flow from 546 sec to 203 sec. It also decreased the thickness variation from 3% to 1.82% and void percentage from 4.78% to 3.1% of the sample.

f) Silicone rubber sheet of thickness 6mm was used as a flexible second mold which was used to give the specimen uniformity and smoothness on the vacuum bag side, i.e. the top side. Race-tracking, *a phenomenon where the infusion resin follows the easiest path (path of lowest resistance) either through the side of the setup or the fabric where there is a gap to pass,* was observed and it made the resin to move faster through the sides parallel to the flow and caused the specimen to increase in overall thickness by 8.7%. The flow of resin was faster than the setup without the infusion media. The void percentage was higher (5.23%) among all setups used. This silicon bag was a good method to obtain fine finish on the vacuum bag side; however, it increased the thickness, increased the void content and decreased the fiber content of the sample.

g) Increasing the compaction time of the setup decreased the flow time of resin in the fabrics by 15%. It also decreased the void percentage from 5.23% to 4.29%

h) Degassing of the resin improved the overall density, decreased the void percentage and increased the fiber percentage in the specimen.

i) The use of thin plastic plate on top, instead of the peel ply and infusion media, improved the surface quality of the specimen and thereby the transparency of the specimen. It also improved the flow time of the resin (faster than the setup with no infusion media by 4.5%). The use of control dams helped manufacture constant thickness parts with standard deviation of 0.13%. This setup decreased the void content from 4.8% to 1.7% and increased the fiber volume content to 59%.

j) The use of thin perforated plastic sheet, peel ply and plastic plate on top improved the overall flow close to that with the infusion media (16% slower). The use of dams controlled the thickness and the variation was 0.13%, similar to that with the plastic plate. The void content decreased to 1.7% and the fiber volume content increased to 59%.

k) By looking at the overall properties such as absorbed energy, stiffness, maximum deflection, peak load, void percentage, fiber percentage, resin flow, and thickness variation, it could be concluded that the specimen produced with the VARTM setup using perforated sheet, peel ply and thin plastic plate on top, were consistent and would give a better batch-to-batch repeatability to the process, making it a more repeatable, cost effective and easy to use process for composite fabrication.

l) Complex structures such as arches and sandwich composites could be manufactured with the similar technique. The flow time for the 2D coarse woven ($[0/90]_8$), 203 mm x 203 mm, arched specimen was 238 seconds. The thickness was 5.65 mm with a deviation of 0.85%. For the sandwich composite the flow time was 194 seconds and the thickness was 19 mm with a deviation of 2.1%.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Based on the observations made and lessons learnt, the following recommendations are made for future work on this topic.

a) All the procedures including fabric lay-up, peel ply placing, vacuum bag sealing, resin mixing and degassing, in short all the procedures which have human error involved should be eliminated. To produce repeating samples these procedures should be automated so that there is no room for human error.

b) The thickness variations during the flow of resin through the fabric should be monitored using LVDT's so that run-time monitoring of the thickness can be observed and resin flow controlled.

c) Since this technique can produce clear samples, and the bubbles traveling from the inlet to the outlet can be monitored, the void distribution can be monitored and can further be controlled. The transparency of the samples produced can be further used for analyzing the damage area in different layers of laid fabric. Other resin types can be used to improve the transparency of the specimen

d) Resin flow can be monitored using various types of infusion resin with varying viscosities. Desired properties can be achieved by varying the resin type.

e) Using a thinner silicone sheet (< 2.5 mm) can eliminate the race-tracking effect and two sided finish can be achieved for the sample with controlled thickness. It can also be used for complex structures without difficulty as it is flexible and smooth.

f) A very sensitive camera could be used to monitor the flow front on the sides so that the flow pattern can be understood more accurately.

g) Multiple infusion lines can be used to produce large structures so that the resin moves uniformly throughout the structure without creating any loss of vacuum pressure and develop any void formation.

h) Use of uniform pressure on top, likely air pressure, could be used to eliminate the control dam, the top plate and the dead weight so that uniform thickness can be maintained for complex structures

APPENDICES

APPENDIX A

Pictures of impacted specimens (backlit) top and rear face

NOTE: Nomenclature on samples is to be ignored

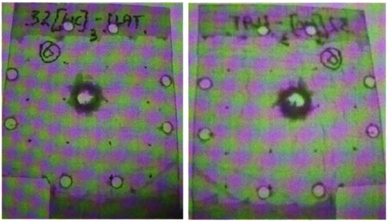


Figure A1 3 layers

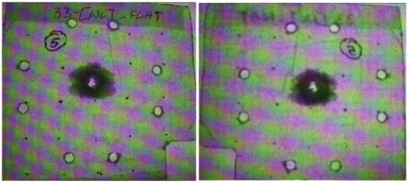


Figure A2 5 layers

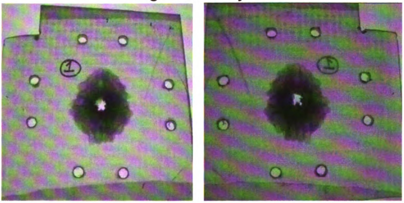


Figure A3 8 layers

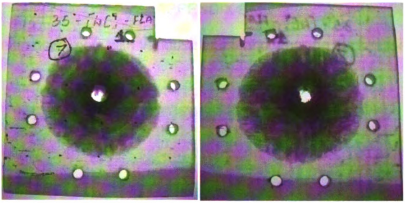


Figure A4 12 layers

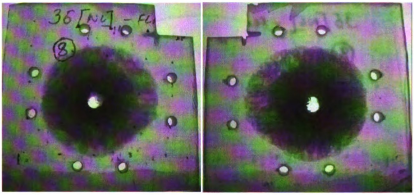


Figure A5 14 layers

APPENDIX B

Resin flow fronts with various setups and stacking thicknesses

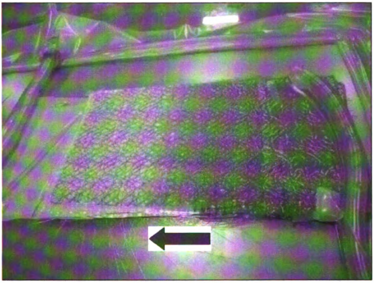


Figure B1 Resin flow with peel ply and infusion media on top

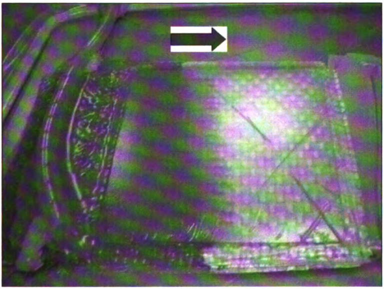


Figure B2 Resin flow with only plastic plate on top

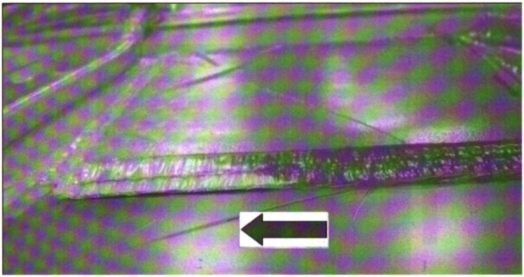


Figure B3 Side view of setup with only plastic plate on top

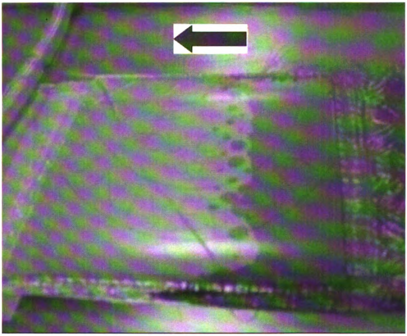


Figure B4 Resin flow using perforated sheet, peel ply and plastic plate

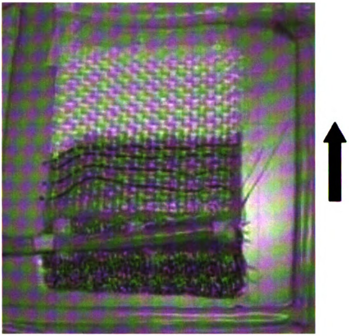


Figure B5 Resin flow with no infusion media or peel ply

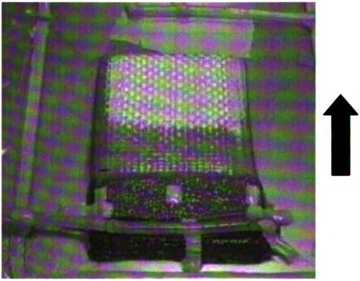


Figure B6 Through thickness flow through a thick stacking sequence

APPENDIX C

Properties charts

Table C1 Gougeon Brother's Inc., PRO-SET Epoxy Technical and Handling Data

PRO-SET Epoxy Technical and Handling Data					
Property	117LV/224	117LV/226	117LV/229	117LV/237 *	117LV/ 239*
Density g/ml	1.114	1.09	1.114	1.078	1.102
Viscosity cP	800	350	310	360	290
Mix Ratio Weight	100:33	100:30	100:31	100:30	100:31
Mix Ratio Volume	100:34	100:35	100:37	100:36	100:35
Pot Life 100 g sample in min					
65° F	29	85	110	281	465
72° F	21	44	61	190	360
80° F	15	25	40	105	219
Working Time @ 72° F	20 min	1 hr	2 hrs	4 hrs	7 hrs
Gel Time @72° F	2.25 hrs	3 - 3.5 hrs	5 hrs	7 - 8 hrs	10 - 12 hrs

* Requires at least 125° F Post Cure

Table C2 Various available mold release wax

Mold Release	
Wax	**Non-wax**
TR Reg Temperature	Polyvinyl Alcohol (PVA)
TR High Temperature	Silicone Mold Releases
Honey Carnuba Wax	Urethane Mold release
Meguiar's Mirror Glaze	Zinc Stearate Mold Release
	Naphtha-based Releases

APPENDIX D

Darcy's Law

$$Q = \frac{-\kappa A}{\mu} \frac{(P_b - P_a)}{L} \quad \text{...(1)}$$

Dividing both sides by area and writing in general notations

$$q = \frac{-\kappa}{\mu} \Delta P$$

Here q is the flux (discharge per unit area, with units of length per time, m/s) and $\nabla P$is the pressure gradient vector. This value of flux, often referred to as the Darcy flux, is not the velocity which the water traveling through the pores is experiencing.

Deriving from 3 D:

$$\mu \Delta^2 u_i + \rho g_i - \partial_i p = 0 \quad \text{...(2)}$$

$$\frac{\mu \phi}{k_i} u_i + \rho g_i - \partial_i p \quad \text{...(3)}$$

Where φ is the porosity. This gives the velocity:

$$u_i = -\frac{k_i}{\mu}(\partial_i p - \rho g_i) \quad \text{..(4)}$$

This gives the Darcy's Law:

$$q_i = -\frac{k_i}{\mu}(\partial_i p - \rho g_i) \quad \text{..(5)}$$

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