Forming Processes for Advanced Composites

by

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Abstract

Composite materials are useful in areas where high performance of materials is required. Currently, the common way to make a part out of composite materials is the labor intensive hand lay-up process. Some automated processes have, therefore, been developed. However, defects in the part occur when the part is large and thick or of a complex shape.

This thesis focuses on modeling and developing two new automatic processes to solve the problem of deformation: the Inflated Tool Diaphragm Forming Process and the Vacuum Assisted Single Diaphragm Process. I will also discuss the feasibility of applying the process in industry. In order to find a better process, I compare their forming processes, forming time, numbers of plies formed at one time, cost and the wrinkling effect of the composite parts.

The experiements find out that in the Inflated Tool Diaphragm Forming Process, the lower diaphragm cannot provide full support for the composite material during the forming process. A maximum of 4-plies of composites can be formed at one time, without causing any defects. It is easily operated automatically but is costly and time consuming. In the Vacuum Assisted Single Diaphragm Forming Process, there is little support for the composite materials. It is also difficult to achieve a vacuum state during the process. Compared with the former process, it results in more wrinkles on the surface of the part. As a result, the Inflated Tool Forming Process is a superior process over the Vacuum Assisted Single Diaphragm Forming Process.

Thesis Supervisor: Dr. Timothy. G. Gutowski
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Chapter 1

INTRODUCTION

1.1 Background

Advanced composite Materials are composed of continuous or long discontinuous fibers of graphite embedded in a polymer matrix. Compared with metal, they have higher strength to weight ratio and higher resistance to corrosion and wear.

Advance composite materials are useful in areas where high performance of materials is required. Because of their properties, they have an impact on the aerospace, military, medical, sports and automobile industries. For example, the weight of an airplane wing can be reduced by 30 percent if composite materials are used instead of aluminum; as a result, significant fuel can be saved over the life time of an airplane. Sporting goods such as tennis rackets, bicycle frames and golf clubs are made stiffer and lighter by using composites. In the medical area, scientists have found out that there are many advantages in using composite materials for implanted artificial bone such as the ball joint of the pelvis. They can perform better in supporting the body's weight. Because of their high corrosion and wear resistance, they are also good for shock absorbers in automobiles.

1.2 Problem Statement

Since composite materials have such a great impact in many areas, material scientists and design and manufacturing engineers are focusing on manufacturing composite parts in an efficient and less expensive way. The most common process for making complex composite parts is the hand lay-up process. In this process, prepreg material, which is a combination of fibers and uncured matrix material are placed by hand layer by layer onto the mold. Figure 1-1 shows the way the composite material is laid up. Though flexible, this process is subject to human errors such as the misalignment of ply orientations. This process is also time consuming and costly. In addition, many matrix resins have harmful chemicals. Recent studies have found that many workers have developed carpel-tunnel syndrome from this hand lay-up process.

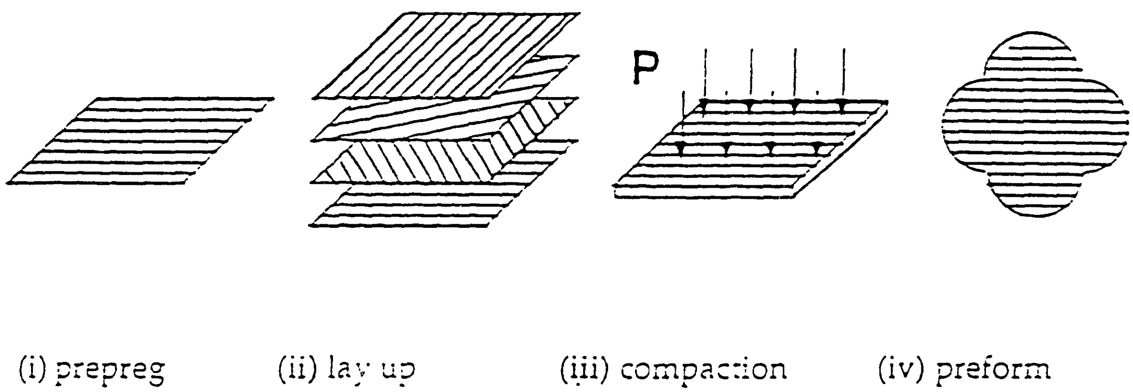

Figure 1-1: Lay-up process of the composite material

Due to the drawbacks of this method, processes for automation and cost reduction have been developed. However, these processes are limited by many factors: composite materials are very sensitive to temperature, pressure and forming rate. Therefore composite materials are difficult and expensive to manufacture, especially in making complex shapes.

There is a great demand for developing new forming methods to form complex shapes while preventing undesirable deformation modes, such as wrinkling on the surface of the part, caused by in ply shear and buckling. Figure 1-2 shows a comparison between good parts and wrinkled parts. The current method of forming for making complex shape is the dual diaphragm forming process, which have the drawback of limitation in the number of plies and the shape of the part. Also the there is a diaphragm between the laminate and the tool; therefore the composite cannot be cured directly on the tool.

1.3 Goals of Research

My research focuses on developing new processing concepts for forming advanced composite material. Experiments were perform on two types of composites: Toray and Hercules. My colleague and I in the Composites Manufacturing Program have developed some new forming processes to solve the above problems by focusing on problem solving, process development and modeling. Two of these processes are the Inflated Tool Diaphragm Forming Process and the Vacuum Assisted Single Diaphragm Forming Process. This thesis describes these two forming processes. In order to find out which is a better process, I will compare their forming rate, the numbers of plies formed at one time, the cost and the wrinkling effect of the composite parts. I will also discuss the feasibility of applying these processes in industry.

1.4 Thesis Overview

The thesis mainly consists of two newly developed processes:

1. The Inflated Tool Diaphragm Forming Process

2. The Vacuum Assisted Single Diaphragm Forming Process

Chapter 2 introduces the Inflated Tool Diaphragm forming process. Detailed information is given about how the process is developed. The experimental results show the advantages and disadvantages of the forming process.

Chapter 3 describes the set up and forming process of the Vacuum Assisted Single Diaphragm Forming Process are illustrated. Using the experimental results, drawbacks and advantages of this process are discussed.

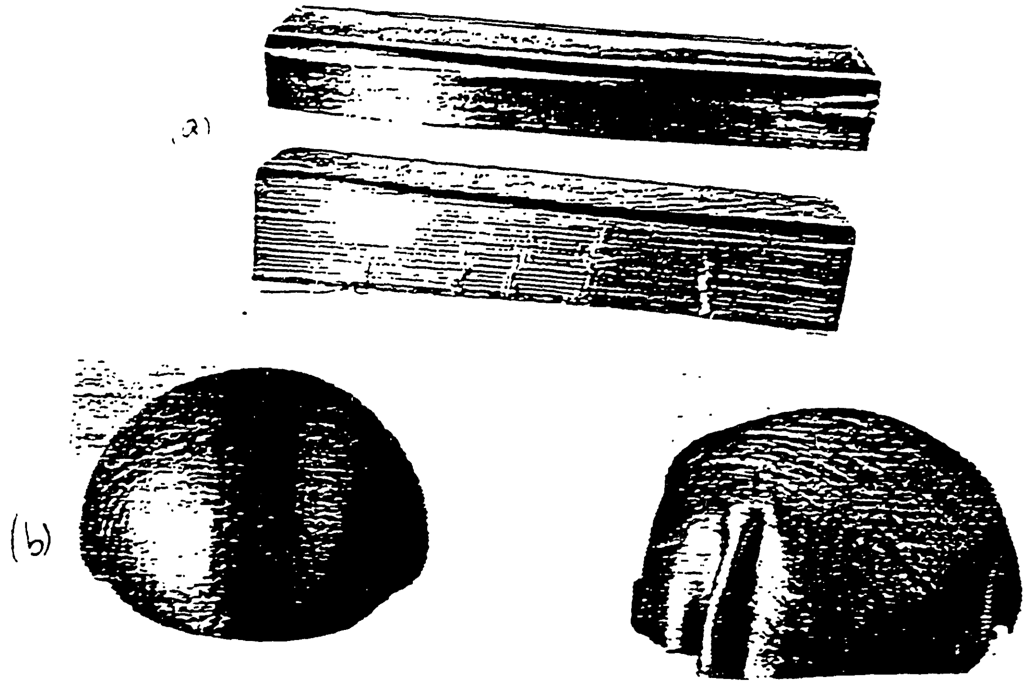

Figure 1-2: Comparison between good parts and wrinkled parts

Chapter 4 presents the comparison of these two newly developed processes. I also discuss their feasibility for industry. Suggestions for the improvement of the forming process are provided.

Chapter 2

THE INFLATED TOOL DIAPHRAGM PROCESS

2.1 Introduction

The Inflated Tool Diaphragm process is developed from the Dual Diaphragm Process which is shown in Figure 2-1. In the Dual Diaphragms Process. sheets of composite materials (called prepreg) are laid layer by layer on a platform and then cut into a preform. They are placed between two rubber diaphragms and placed on top of a mold in a forming machine. By the use of pressure or vacuum. the composite materials together with the diaphragms are pressed against the mold. After the part is completely formed, it has the same shape as the mold and the process is completed. The composite part is placed on top of the lower diaphragm. so the part needs to be carefully removed from the lower diaphragm after the forming process. The formed composite part is hardened by curing. The part is placed on top of a cure tool and put into an autoclave where temperature and pressure can be controlled. The curing process usually lasts for several hours depending on the thickness of the composite part.

The Dual Diaphragm Process have certain limitations: since the laminate are laid up layer by layer, shearing and buckling between the layers may occur. This results in laminate wrinkles. Lack of control in the curing process is also another reason for

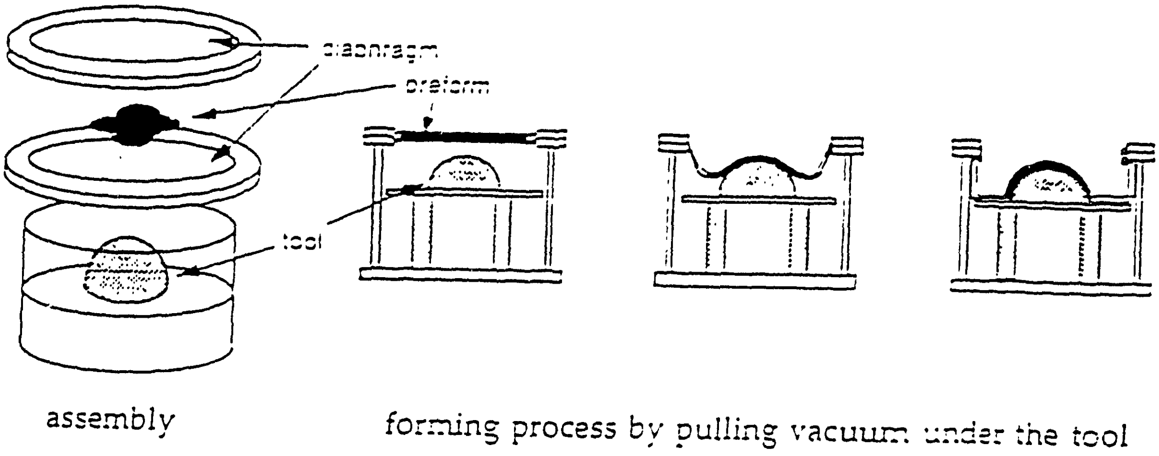

Figure 2-1: Two Diaphragms Forming Process

the wrinkles. The shape and alignment of the parts may be affected as we separate the lower diaphragm from the parts after forming. This process after forming is time consuming. Hence a new process which focused on solving the above problems has been developed.

2.2 Inflated Tool Diaphragm Forming Process

Figure 2-2 and 2-3 illustrate the Inflated Tool Diaphragm Forming Process. During set up, the composite material is placed directly on top of the mold and the upper diaphragm is placed above the composite material. The lower diaphragm is placed below the tool. The lower chamber is made air tight while air can flow freely in and out of the upper chamber. The volume between the upper diaphragm and the cover is also made air tight. Two valves are used to control inflow and outflow of air in each of the air tight volume (four values in all). The first valve system is located on top of the machine to control air flow between the upper diaphragm and the cover so that the upper diapharrgm can press against the composite. The second valve system, which is located at the bottom of the machine, can blow air into the lower diaphragm or pump the air out of the lower chamber to control the second diaphragm. The location of the valve systems is shown in Figure 2-2. The wall of the setup is made of transparent plexiglass for visual control of the process.

To begin this process. the upper diaphragm is put in contact with the composite. Then we open the lower valve to blow the air into the lower chamber at a pressure rate from 10 to 15 psi. pushing the lower diaphragm up. The inflow of air should continue until the lower diaphragm fills in the most of the space in the upper chamber and supports the composite. We then start applying positive presure on the top diaphragm to start forming while gradually letting the air out from the low chamber. We can. therefore perform a forming process in which the lower diaphragm can continuously support the composite during the process while the upper diaphragm is pressing the composite onto the mold. After the composite is completely formed on top of the mold, all the air is let out of the lower diaphragm. as a result: the lower diaphragm is automatically retracted away from the composite and the tool.

The above process can be repeated so that a larger number of layers can be formed sequentially. After the laminate is formed onto the tool. more layers can be formed on top of the formed laminate. This make the forming of thick parts possible.

A picture of the experimental set up is found in figure 2-4. Note that a thermostat and heater assembly is added for forming at higher temperature. (See section 2.4.2 for more detailed discussion.) Figure 2-5 and 2-6 show the plan and side view of a process near its completion. Notice how the lower diaphragm was actually pushed down into the lower chamber by the upper diaphragm and hence have completely retracted from the composite.

2.3 Advantages of the Inflated Tool Diaphragm Process

The major advantage of the Inflated Tool Diaphragm Process over dual diaphragm process is that in the Inflated Tool Diaphragm Process. the lower diaphragm can be retracted automatically from the composite and the mold after the process while

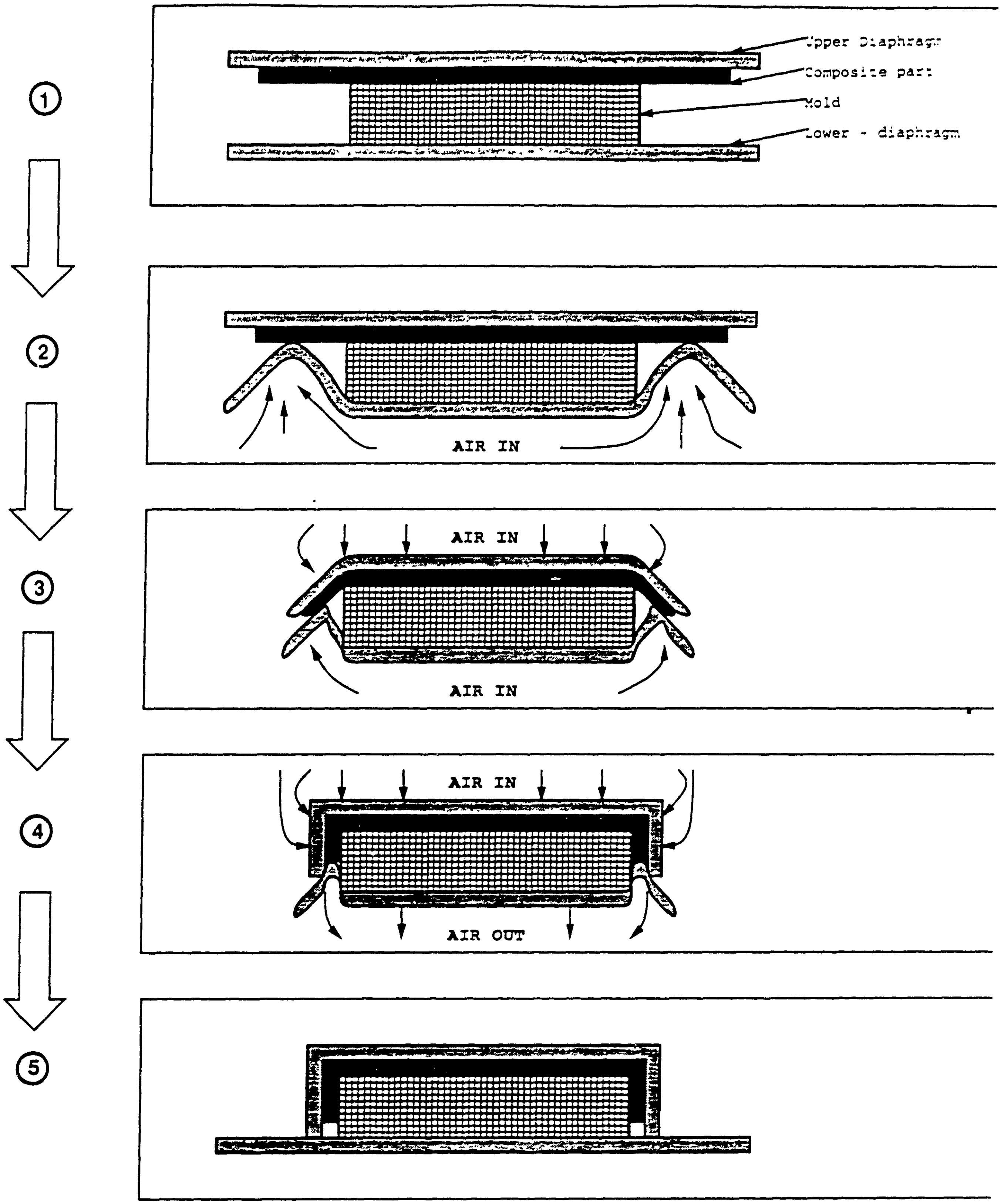

Figure 2-2: Illustration of the Inflated Tool Diaphragm Forming Process

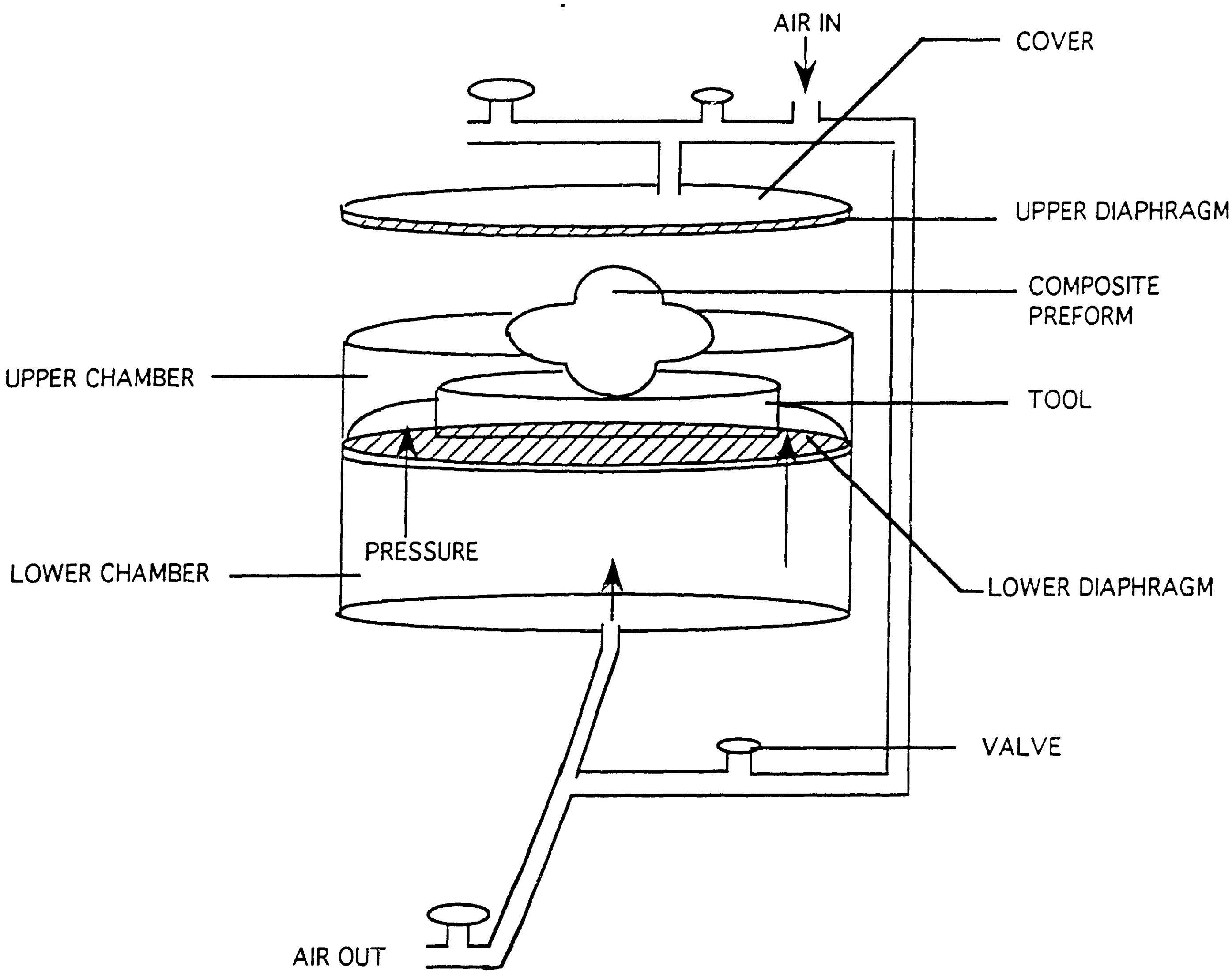

Figure 2-3: Set up for the Inflated Tool Diaphragm Forming Process

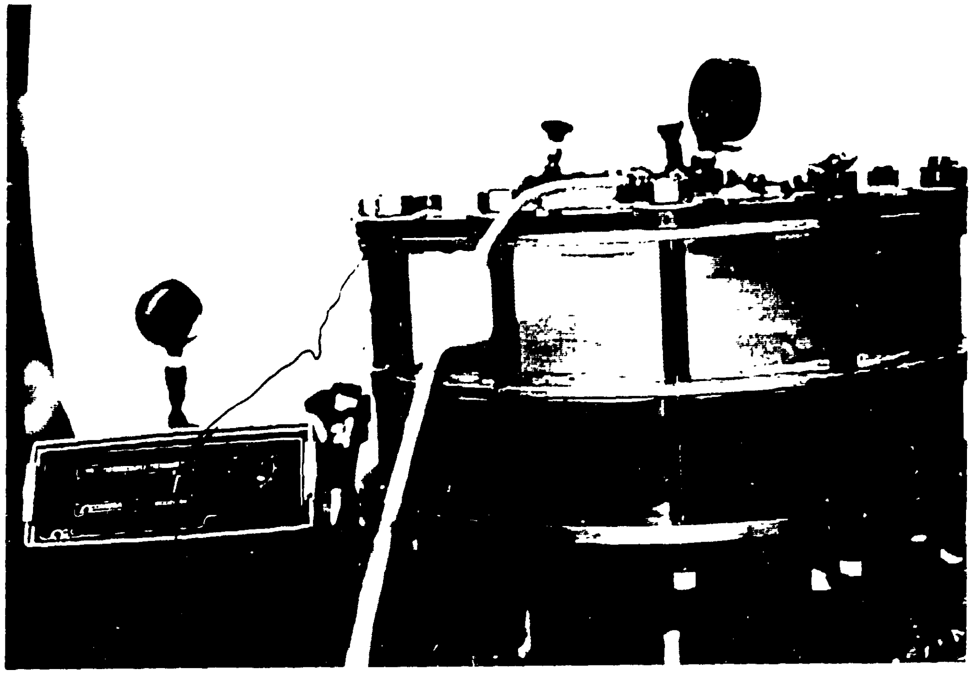

Figure 2-4: Experimental set up for Inflated Tool Diaphragm Forming

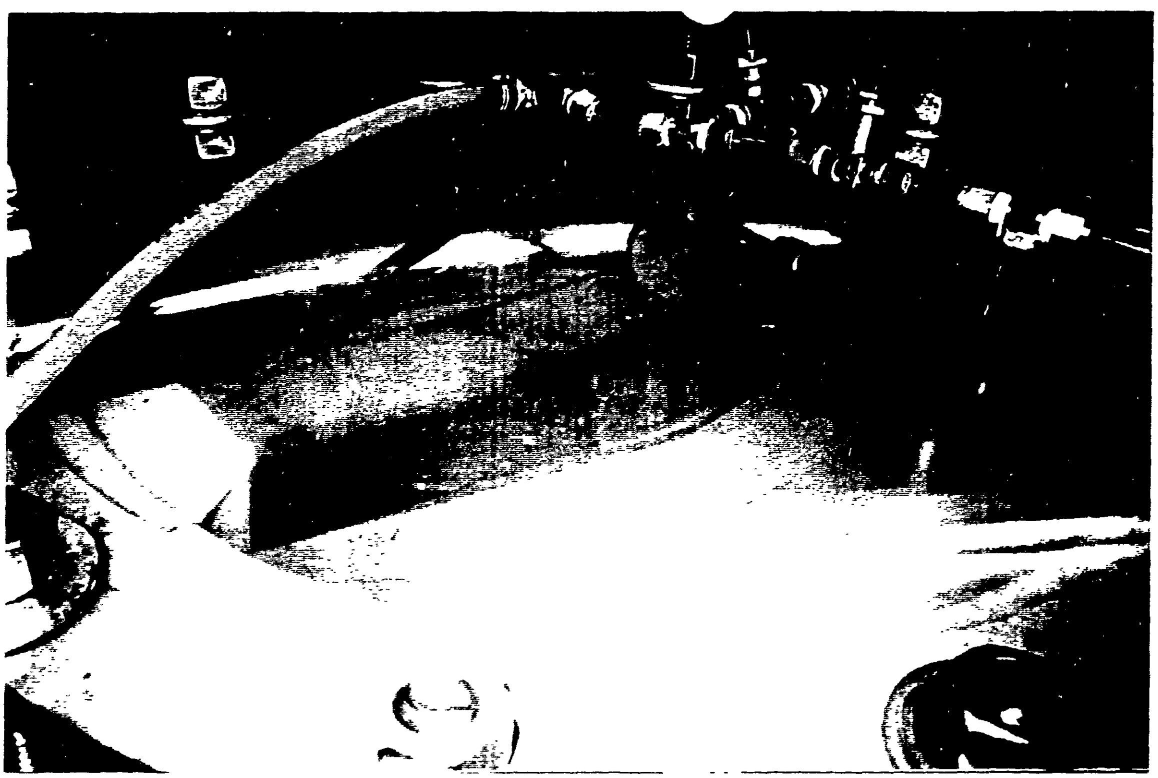

Figure 2-5: A forming process near completion (viewed from above)

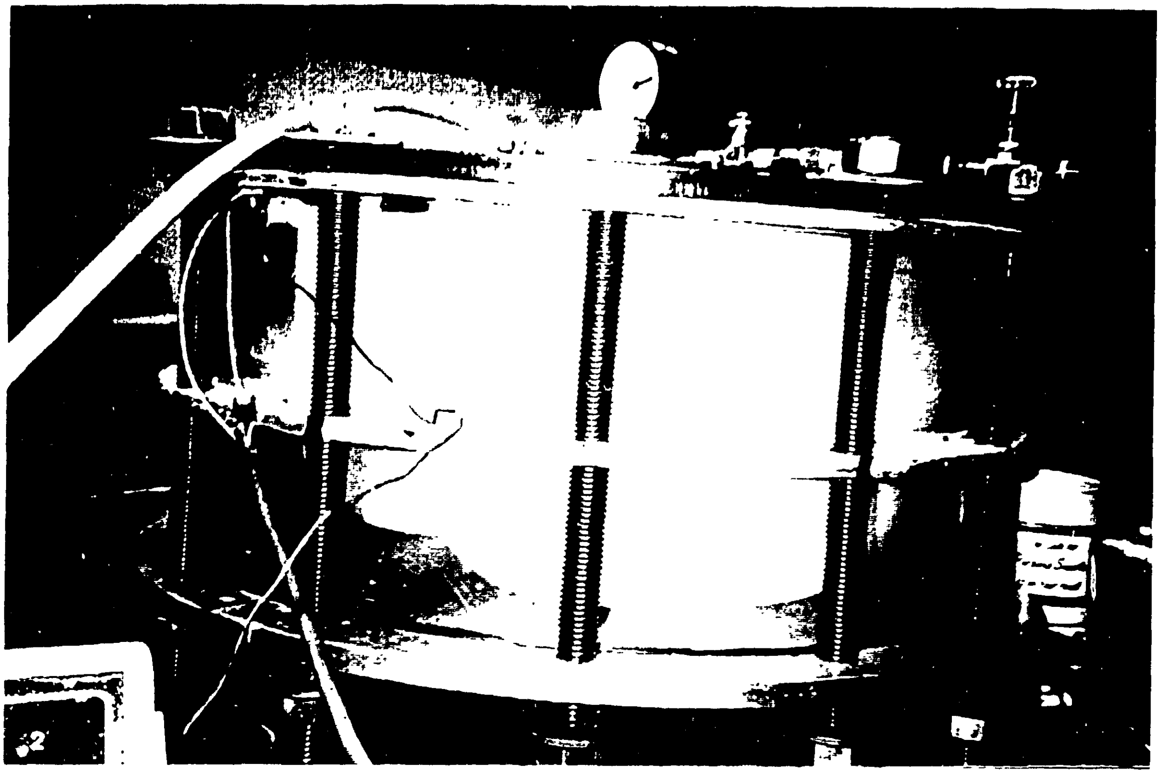

Figure 2-6: a forming process near completion (viewed from the side)

maintaining adequate support of the composite during the process. Consequently, the Inflated Tool Diaphragm Process is superior in the following aspects:

1. The composite is formed directly on top of the mold. We can directly cure the laminate in the same machine by heating up the tool to 350F (170C), the curing tempuature of Toray and Hercules. This eliminates the need to transfer the parts from one machine to another and hence can prevent damaging the composite parts during the transfer process and can save much time.

2. The process allows for sequential forming of many layers. In the dual diaphragm process the lower diaphragm separates the composite from the tool and hence we cannot add new layers to an already formed parts. However in the Inflated Tool Diaphragm Process, the lower diaphragm is retracted away after the process and hence new laminate can be formed on top on already formed parts.

The valves are easy to control during the process. The lid and the body of the machine is made of transparent thick plexi-glass, so the whole process can be observed clearly

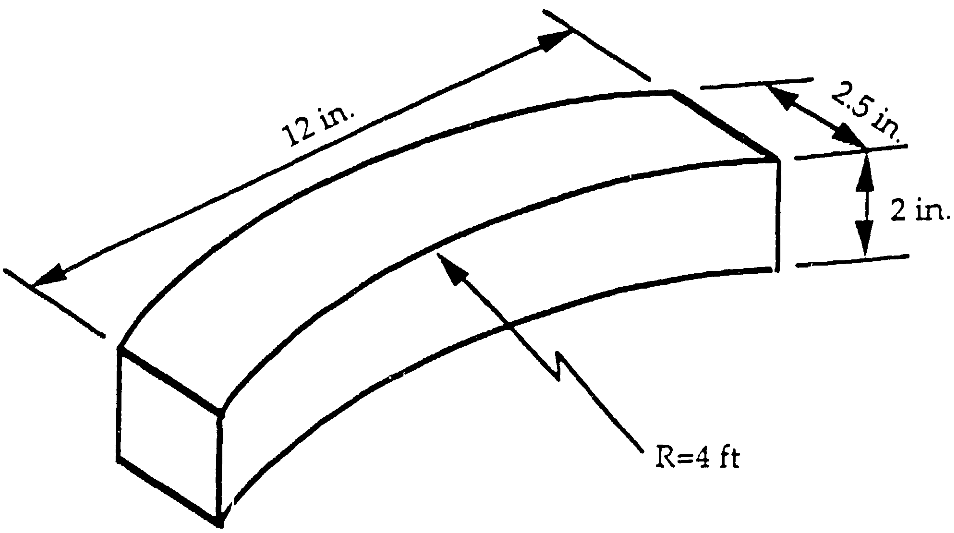

Figure 2-7: The dimension of the tool used in forming C channels

and the process becomes easier to operate.

2.4 Results and Analysis

Experiments were performed using a tool of dimension 12" by 6". C channel are formed on the tool. In the future, we plan to use a tool double that size. The detailed dimension of the tools is shown in figure 2-7.

2.4.1 Diaphrams

We expect a better formed part when a stiffer diaphragm material is used, because when the diaphragm gets stiffer, the stress in the diaphragm will increase. As a result. the presssure supporting the wrinkled areas gets larger. We can therefore expected a better part when a stiffer diaphragm material is used. The type of material used for the diaphragm is a type of silicone rubber. In an ideal case, to suppress wrinkles on the laminate: an extremely stiff silicone rubber should be used. However, the shape of

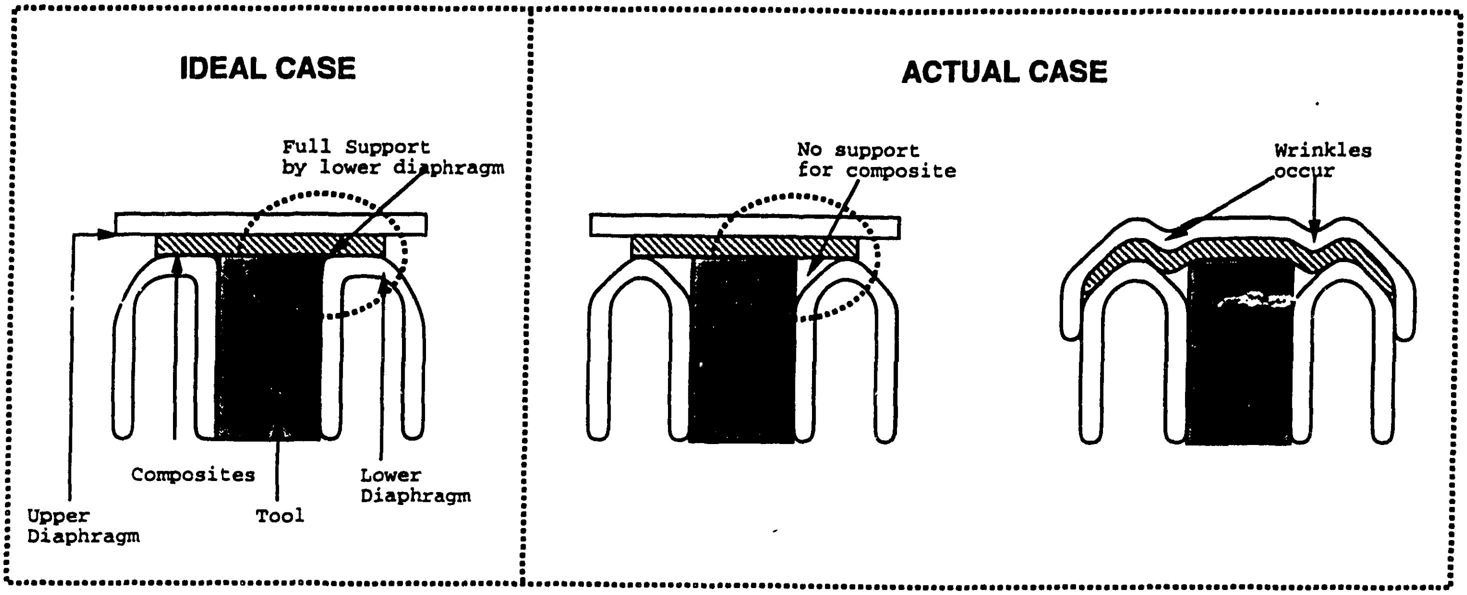

Figure 2-8: Illustration of the cause of wrinkling

the part limites the stiffness of the diaphragm since it is the shape of the part which determine how much the diaphragm needs to be stretched.

We first used the same material for the upper and lower diaphragms. This material is a strong silicone rubber with 1/16 inch thickness. This material was so thick and strong that its flexibility was very low. As shown in Figure 2-8, the lower diaphram is very stiff that it could not stretch large enough to maintain a full contact with the tool and the composites. After many experiments, we chose to use a thinner material for the lower diaphragm so that it can be stretched easily. As a result, we chose to use latex sheet with 1/50 inch thickness for the lower diaphragm. Latex sheet is a very thin and flexible material – it can be stretched a great deal without developing any cracks. Latex sheet can be inflated very close to the ideal case shown in figure 2-8. It can therefore provide a better support to the composite part. Figure 2-9 shows how the latex lower diaphragm fills up the upper chamber and provide support for the part much like the ideal case in figure 2-8.

One of the disadvantage of the latex sheet is that it is very thin and that it will start to soften at temperature above 165F. At room temperature, the lower

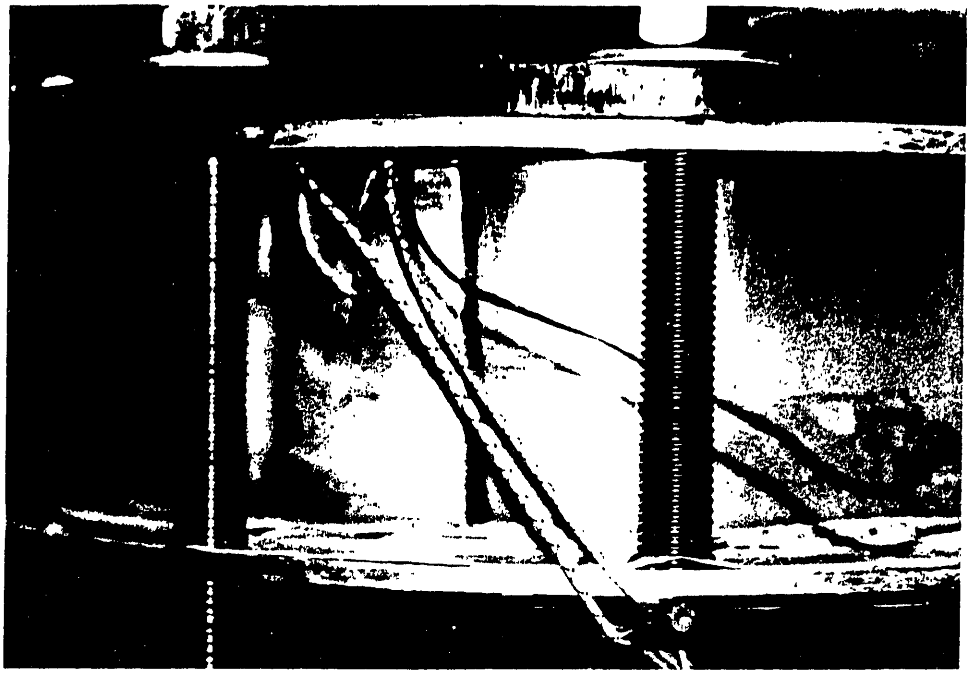

Figure 2-9: The lower diaphragm providing support for the composite part by filling the upper chamber.

diaphragm made out of latex can perform the forming for many times, usually more than 10 times, before cracks or small holes develop on it. However, when we heated up the tool to about 135F, defects developed on the latex sheet much more rapidly. The latex lower diaphragm can only last for 1 or 2 experiments, after 2 experiments, tiny holes will appear on the diaphragm, causing air leakage.

2.4.2 Temperature

Temperature affects the viscosity of the epoxy resin matrix as shown in figure 2-10. Temperature also reduce the shear stress which will be built up due to the deformation generates compressive force that wrinkles the laminate. Toray can form best under the temperature where the resin has the lowest viscocity.

The prepreg manufactured by Toray does not form well at room temperature. I did some experiments on heating up the composites during the process at different temperature. I drilled a 6.5" deep hole inside the 17" long tool and placed a electrical heater inside the tool. I found out that the composite parts have a smoother surface at a higher temperature. However, the temperature cannot be too high to start the chemical reaction. From table 2.1, we can clearly see that the good parts were formed

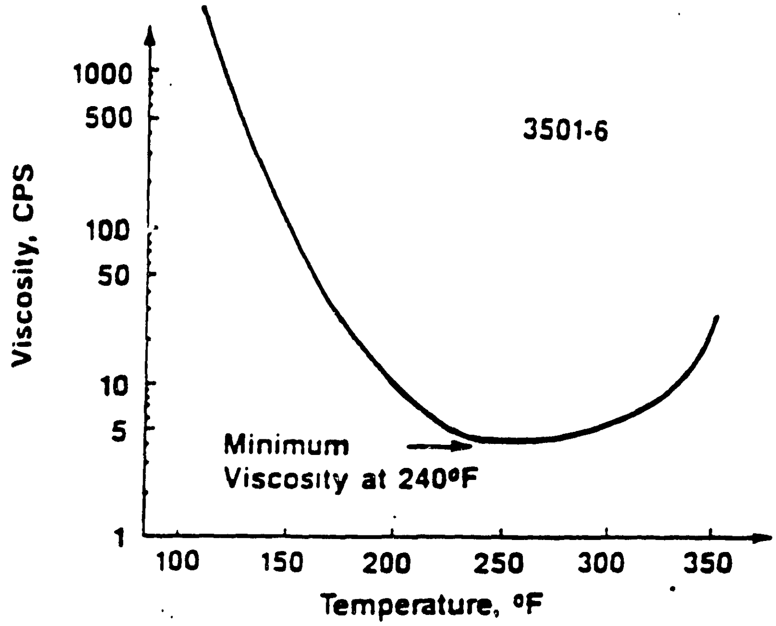

Figure 2-10: Change in viscosity during cure (Adapted from [1, p.43])

at temperature around 125F. The wrinkled parts were formed at room temperature. A higher temperature can make the parts softer and easier to form. A maximum of 8 plies of composite materials can be formed without any major wrinkles at about 135F while at the room temperature, a maximum of only 2 plies of composites with some wrinkles can be formed (See table 2.1).

In general, Hercules is easier to form than Toray. As a rule of thumb. if we can successful form a part in Toray there will be no problem forming the same part in Hercules. Therefore Toray is used in our experiment to find the upper bound.

2.4.3 Wrinkling on the Composite parts

No major wrinkle is found if only 4 plies of composites are formed at one time at room temperature. Since the upper diaphragm can be taken away from the part easily. more plies can be laid on top of the composite part. Hence a seqential forming process can be use to solve the problem of wrinkling on the parts in making a thick part. Table 2.1 showed the data for the Toray Composite part at different temperatures. The two parts that are formed from 8 plies of Toray with heating are shown in figure 2-11 and figure 2-12.

Number of plys and orientation	Without Heating	With Heating
$\|0/90\|$ 2plies	No Wrinkle	No Wrinkle at 123F
$\|45/-45\|$ 2plies	No Wrinkle	No Wrinkle at 125F
$\|0/90\|s$ 4plies	No Wrinkle	No Wrinkle at 123F
$\|45/-45\|s$ 4plies	Minor Wrinkle	No Wrinkle at 125F
$\|0/90/+45/-45\|$ 4plies	Major Wrinkles on the web or on the flange	No Wrinkle at 134F
$\|0/90\|2s$ 8plies	Major Wrinkles on the web and the flange	Minor Wrinkle with smoothe surface at 132F
$\|0/90/+45/-45\|s$ 8plies	Major Wrinkles	minor wrinkles at 135F

Table 2.1: Data for Toray composite parts in Inflated Tool Diaphragm Process

2.4.4 Forming Process

During forming, as the upper diaphragm pressed down onto the part, wrinkles would occur if the lower diaphragm gets trapped in between the part and the mold and is not extracted in time as shown in Figure 2-8. We therefore need to control the rate of the air flowing out of the lower chamber, and also at the same time control the compression rate of the upper diaphragm. During the forming process, we need to make sure the lower diaphram can support the laminate and have a good contact with the upper diaphragm.

Forming rate of the process need to be controlled carefully during the forming process. Slower forming rate (increase the forming time) will result in a better part with less wrinkles. Experimental data showed that longer forming time will resulted in a better part. More wrinkles appeared on the composite parts if formed in less than 5 minutes. For parts which were formed for more than 15 minutes, they will have less wrinkles on the surfaces.

During the forming process, the laminate sticks to the lower diaphram at higher temperature. A great amount of friction exists between the laminate and the lower diaphragm. As the lower diaphram was retracting away form the laminate, the friction of the lower diaphragm tore the fibers out of the laminate. This is called *tow splitting.*

Tow splitting caused by the lower diaphragm is shown on figure 2-13.

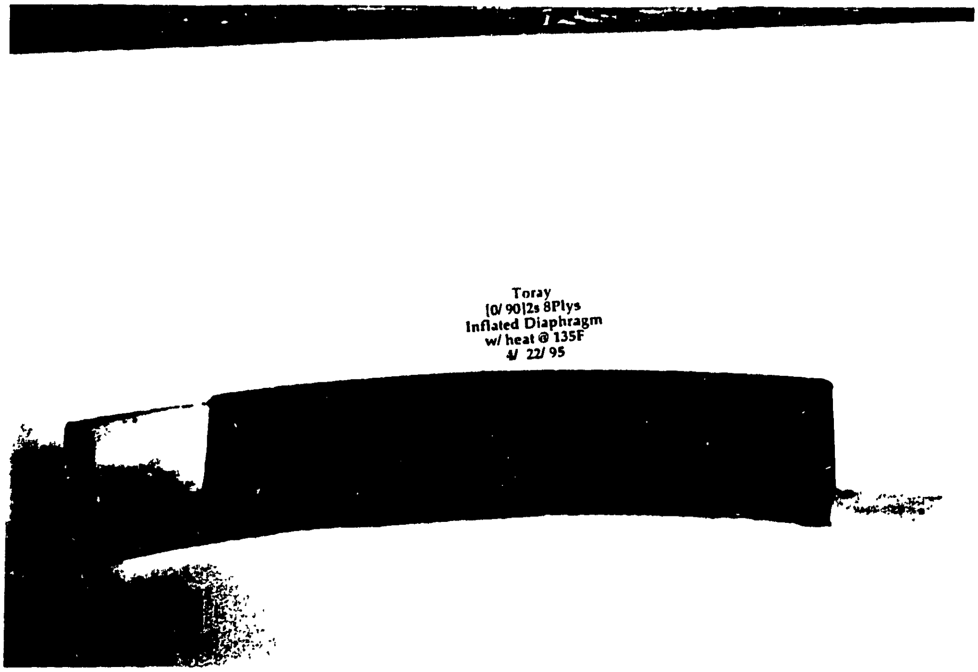

Figure 2-11: Toray [0/90]2s 8 plies, 135F.

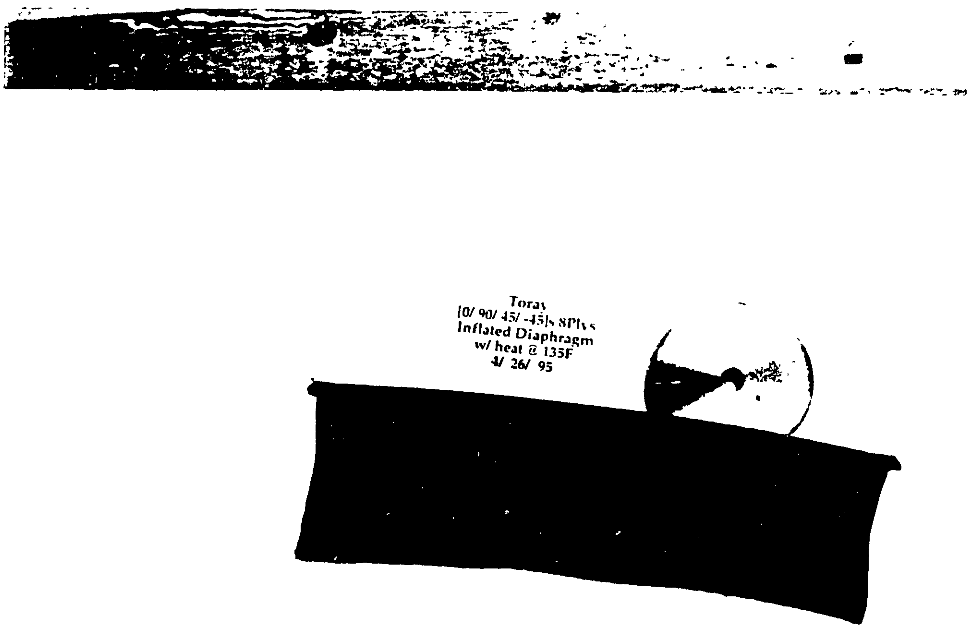

Figure 2-12: Toray [0/90/45/-45]s 8 plies, 135F.

Figure 2-13: Tow splitting caused by friction between lower diaphragm and laminate

Chapter 3

THE VACUUM ASSISTED SINGLE DIAPHRAGM FORMING PROCESS

3.1 Procedure

There are many advantages in forming and curing the parts in the same machine. Without removing the lower diaphragm from the formed composite part, we can prevent the deformation of the composite parts and save time. We therefore have focused on developing a process where the lower diaphragm is not placed between the composites and the mold. Beside the Inflated Tool Diaphragm Forming Process, we have developed a new process named the Vacuum Assisted Single Diaphragm Forming Process.

As shown in Figure 3-1, the lower diaphragm is cut into ring form so that its inner edge can support the outer edge of the laminate and its outer edge has enough area to attach itself to the upper diaphragm. Since it is not a complete sheet of material anymore, we will call it the rubber ring. The rubber ring will not affect the composite part in the curing process. Its function is to maintain a vacuum between the upper diaphragm and the composite preform. Hence in this process the support

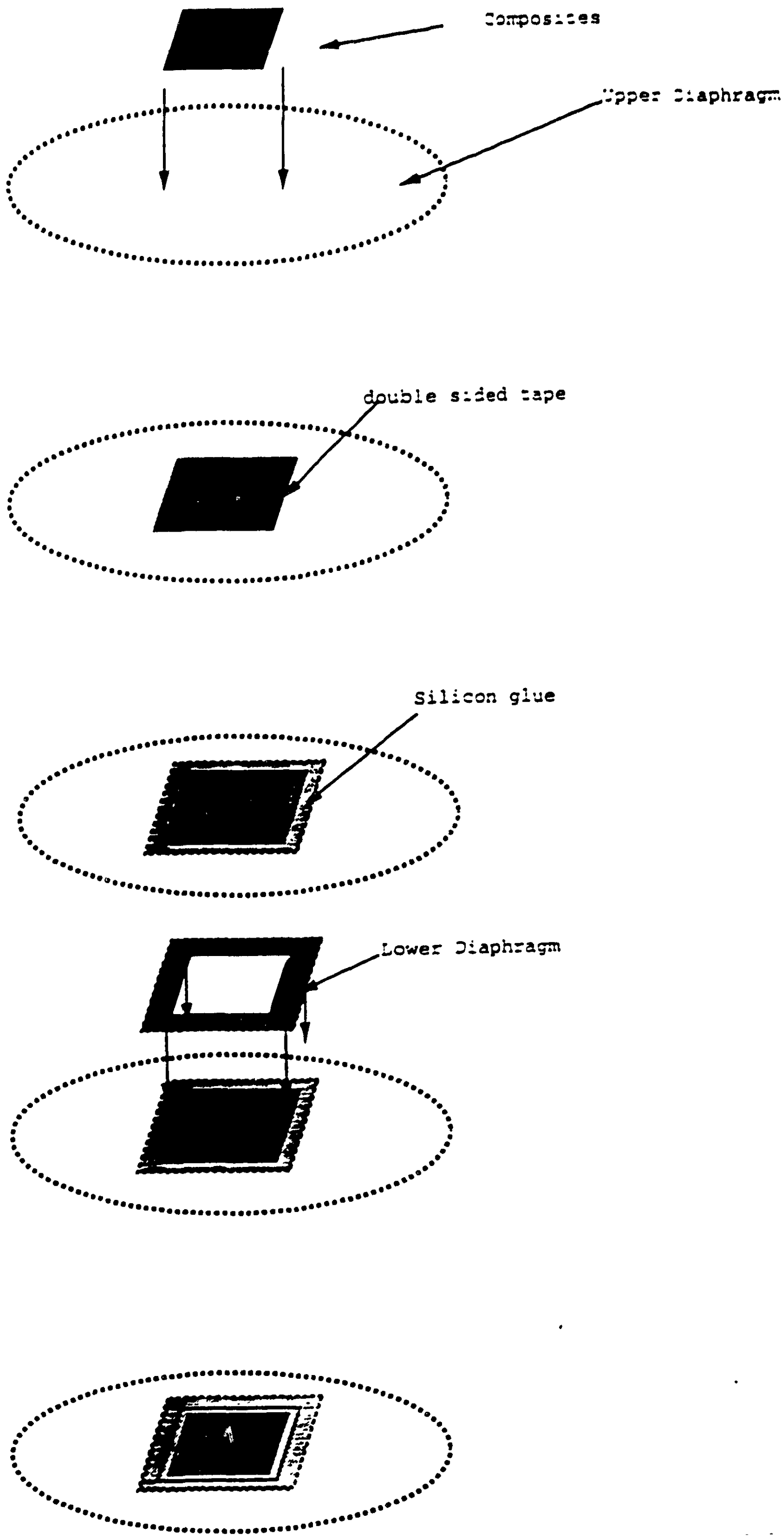

Figure 3-1: Set up procedure for the Vacuum Assisted Single Diaphragm Process.

of the composite comes from air pressure.

The composite part is placed on the top of the rubber ring. Vacuum tape is used to stick the outer edge of the composite part to the inner edge of lower diaphragm. A silk cloth is then placed in between the composite and the upper diaphragm to ensure a uniform evacuation on the composite. Vacuum tape is used to stick the lower diaphragm to the upper diaphragm. A plastic tube is placed inside the edge of the composite part and other end of it is connected to a vacuum pump; therefore, the air between the top diaphragm and the composites is extracted by the pump. The composite-diaphragm assembly is placed directly on top of the mold.

The experimental procedure can be carried out after the set up is completed. Air between the upper diaphragm and the composite part is pumped out during the whole forming process to achieve the vacuum state. Positive pressure is applied on top of the top diaphragm to press the composite part until the composite part is completely formed into the shape of the mold. The lower diaphragm can be trimmed away from the composites without destroying the part. The formed composite parts can later be cured while remaining placed in the machine. The whole machine is heated up to 350F for curing.

3.2 Advantages of the Vacuum Assisted Single Diaphragm Process

The function of the lower diaphragm (rubber ring) is changed in this forming process from providing support to the whole preform to providing support for the edge of the preform and maintaining a vacuum seal. The composite part is pressed against the upper diaphragm by air pressure. The rubber ring can be trimmed away from the composite part without removing the part from the machine. We can also save material because only a small piece of lower diaphragm is needed. Sequential forming in which layers of composites materials are laid on top of the formed parts to form a thick composite part is also possible.

3.3 Result and Analysis

3.3.1 Sealing by the vacuum tape

The vacuum tape, used to seal the upper diaphragm to the composite part cannot provide a perfect seal. The seal broke during the forming process, vacuum could not been maintained between the top diaphragm and the composite part. There are leaks in the area where the tube is placed between the inside edge of the composite part and the diaphragms. Experiments are performed to find out a better way to provide an air-tight seal in the forming process. First, a double side tape is stuck on the composite: then silicon glue is applied on top of the double side tape: lastly, the rubber ring is placed on top of this assembly to achieve an air-tight seal. However, it took a long time to complete the above process.

It is very difficult and time consuming in achieving the vacuum state between the upper diaphragm and the composite parts. It usually takes 30 minutes to achieve an air tight seal between the rubber ring and upper diaphragm with composite laminate in between. Silicone glue is used to stick the diaphragms together which helps to achieve the air tight seal. However, Silicone glue needs 1 day of curing under room temperature. In comparison with the actual forming process which take about one hour; this sealing process is obviously consuming too much time. Although the new taping combination described above is used, the air tight seal may still fails during the forming process.

3.3.2 Diaphragms

Just as I described from Chapter 2, we expect a better formed part when a stiffer diaphram material is used. We choose to use a strong silicone rubber with 1/16 inch thickness. It is strong enough that it can help to suppress the wrinkles on the laminate. We use the same silicone rubber for the lower rubber ring. Silicone rubber can withstand high temperature up to 300F.

3.3.3 Temperature

Toray is very sensetive to temperature which can dramatically affect the viscosity of the resin matrix. As described from Section 2.4.2 of Chapter 2. we found out that the state of the resin of the composite changes as temperature changes. As shown in Table 3.1 , we can clearly see that the prepreg of more than 2 plies of Toray does not form well at room termperature. Wrinkles will formed on the part unless higher temperature is used. When compaing experiments in which all the other forming parameters except temperature were kept the same. we see that the part was formed well with higher temperature. while the part formed at room temperature has wrinkles.

A new setup for heating up the process is shown in Figure 3-2. The top diaphragm. the laminate. and the lower ring diaphragm remain as an air-tight seal. They were placed on top of the tool in the upper chamber. Hot air was blown into the chamber through the hollowed lower chamber of the machine. The steel poles were used to support the steel plate which held the tool.

3.3.4 Supporting the laminate

Buckling occurs since there is not enough support of the composite in the absence of the lower diaphragm. In plane buckling and shearing will occur. As the number of plies of the laminate increases, the problem of in plane buckling and shearing becomes more serious. As a result. wrinkles may occur on composite part. This method cannot form many plies at a time.

3.3.5 Wrinkling on the Composite parts

As seen in table 3.1. at room temperature, only 2 plies ($|0/90|$ or $|45/-45|$) of Toray can be formed without major wrinkles. Parts with 4 or more plies developed many wrinkles in this process at room temperature. As temperature increases. 4 plies can be formed without major wrinkles.

Since Hercules are easier to form. 8 plies ($|0/90/45/-45|s$) can be formed with

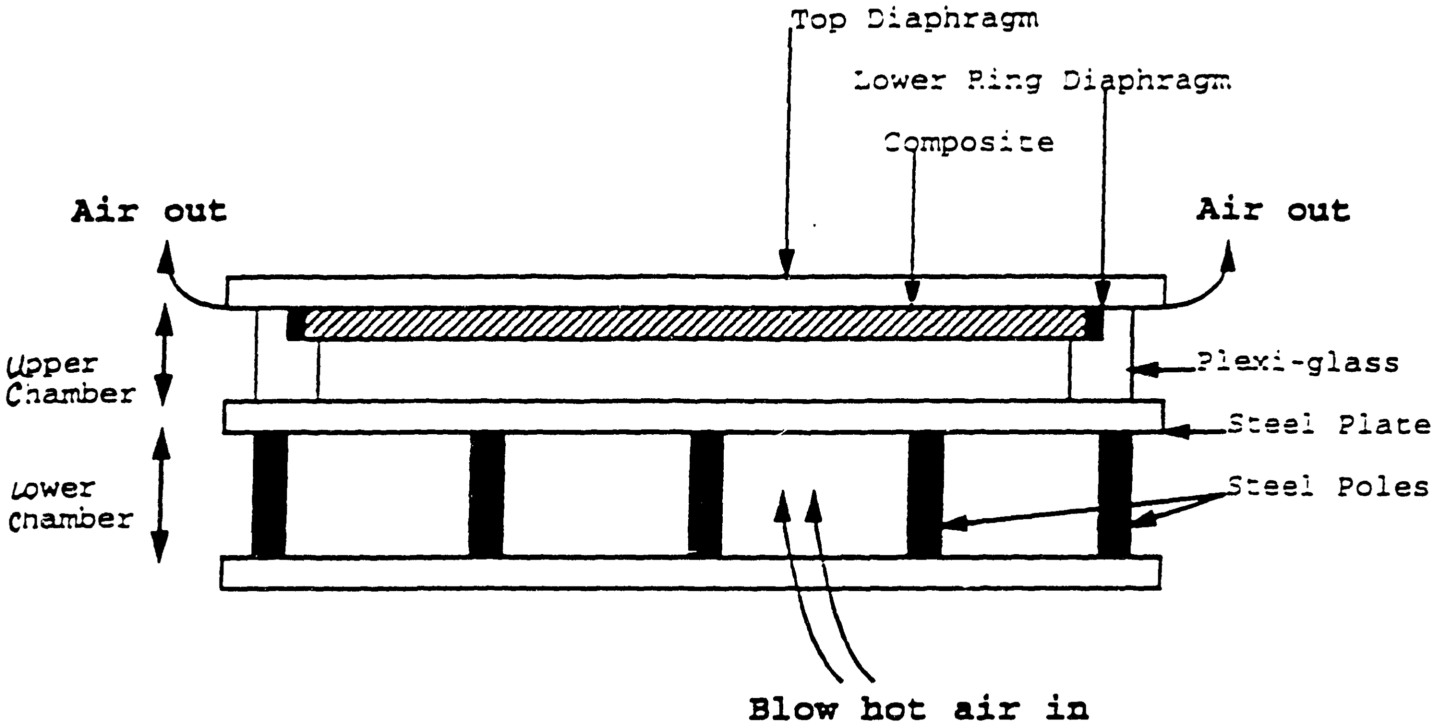

Figure 3-2: Set up for the heated Vacuum Assisted Single Diaphragm Forming Process

Number of plys and orientation	Without Heating	With Heating
[0/90] 2plies Toray	No Wrinkle	No Wrinkle at 130F
[45/ − 45] 2plies Toray	No Wrinkle	No Wrinkle at 130F
[0/90]s 4plies Toray	Major Wrinkles on the web and the flange	Minor Wrinkles at 140F
[45/ − 45]s Toray 4plies	Major Wrinkles on the web and the flange	Minor Wrinkles on the web and the flange at 140F
[0/90/ + 45/ − 45]s Toray 4plies	Major Wrinkles on the web and on the flange	Minor Wrinkles on the web and the flange at 145F
[0/90]2s Toray 8plies	Major Wrinkles on the web and the flange	Major Wrinkles on the web and the flange at 150F
[0/90/45/ − 45]s Hercules 8plies	Major Wrinkles	Wrinkles on the side with heat at 120F

Table 3.1: Data for Toray and Herculescomposite parts in Vacuum Asisted Single Diaphragm Forming

heat at one time without major wrinkles.

3.3.6 Forming Rate

Forming rate is a critical factor in determining the quality of the composite parts. In this process, we found out that the longer forming time. the better the parts formed. In addition to that. a well controlled. slower forming process can reduce the chance of breaking the vacuum seal between the upper and lower diaphragm.

Chapter 4

DISCUSSION

4.1 Introduction

In the previous chapters. I have discussed the design. process and experimental results of the two newly developed forming processes. I have also discussed briefly their advantages and possible failures. In this chapter. I will compare the two processes and discuss about the feasibility of applying the processes in industry. I will also suggest future work and possible improvements in composites forming processes.

4.2 Comparison of the forming processes

Both forming processes allow the forming of additional plies of composite material formed on top of the formed composite parts. They also have the advantage of allowing the forming and curing of the composite part to take place in the same machine. In this respect. both of these processes are superior to the dual diaphragm process that is currently in use in industry.

Furthermore, the experiments suggest that the Inflated Tool Diaphragm Process has the following advantages over the Vacuum Assisted Single Diaphragm Process:

1. The Inflated Tool Diaphragm Process is easier to control. and has a shorter set up time. Hence the cost of operation is lower.

2. The Inflated Tool Diaphragm Process produces fewer wrinkles on the surface of the parts then the Vacuum Assisted Single Diaphragm Process

3. More plies of composite materials can be formed in the Inflated Tool Diaphragm Forming Process at one time. Our experiments showed that under similar conditions at room temperature, the Inflated Tool Diaphragm process can form 4 plies at one time without major wrinkles, while Vacuum Assisted Single Diaphragm Process can only form 2 plies.

One of the major problems in Vacuum Assisted Single Diaphragm Process is the difficulty in achieving vacuum between the upper diaphragm and the composite part. In addition, the lack of support of the composites without the lower diaphragm can cause buckling between the layers of the composites.

4.3 Industry Feasibility

Our experiments are in general successful in forming part with complex shape (C-channel) with multiple curvature. Hence, the prospect of implementing these forming processes in industry is promising. There are several aspects of the set up that can be changed in an industrial setting to improve productivity of the process and quailty of the formed parts. This section will focus on such improvement of an industrial set up over our experimental set up.

4.3.1 Forming Machine for the Inflated tool Forming Process

All the experiments that I did for the two forming processes were on the small pressure chamber with 18 inch diameter. The composite preform have a dimension of 12" by 6". There was only 3 inches apart from the edge of the chamber to the part during forming. As a result, the force distribution by the diaphragm on the part was not even and become one of the reason for minor wrinkling on the part (see figure 4-1).

Figure 4-1: Force distribution by the diaphragm is not even near the edge of the chamber

In industry, the size of the presure chamber should be larger compared to the size of the parts form.

In our experimental set up, screws are used to clamp the various air seals tight. In order to achieve good seals in the pressure chambers of the forming machine, I have to tightened up 8 screws on the lid of the forming machine. It is time consuming. In industry where time is of critical concern, I suggest using a locking lever system for achieving the air seals.

In the Inflated Tool forming process, I applied positive pressure (about 10 psi) to inflate the upper and the lower diaphragm. This is adequate for forming a small part (12"x 6") in a small machine. Industrially, a larger part, a larger machine and a higher pressure might be required. First of all, the plexi-glass that I was using in the small machine may not be able to withstand high pressure in a large machine. In addition, a larger volume of air at high positive pressure poses a risk of explosion. For industrial applications, it is better to use negative pressure for these processes. The basic forming processes can remain the same, only some changes in design of the machine are needed.

4.3.2 Diaphragm for the Inflated Tool Forming

As discussed in section 2.4.4 for the Inflated Tool Forming process, we need to adjust the friction between the lower diaphragm and the laminate to prevent the tow splitting. Another way to prevent two splitting is by a better control of air flow for both the upper and lower diaphragm. A better control can also reduce wrinkling. Another problem we experienced is that the latex rubber can only withstand heat upto 160F. In forming a larger and thicker part, a higher temperature to heat up the tool and the part is needed. Therefore, we cannot use latex rubber to form a big part in industry. New material for the lower diaphragm which has high flexibility and can withstand higher temperature need to be used.

4.3.3 The Vacuum Assisted Single Diaphragm Forming

In this process, we used positive pressure for forming the composite. With the same reasons as section 4.3.2. it is better to use negative pressure for forming.

The main problem of Vacumm Assisted Single Diaphragm Forming is in maintaining the vacuum seal between the part, the upper diaphragm and the lower ring diaphragm. The sealing procedure to achieve the above vacuum state is time consuming and complicated. This is not applicable in industry unless a new faster and stronger sealing system can be developed.

4.3.4 Conclusion

As a conclusion, the Inflated Tool Diaphragm Forming Process is more feasible for use in industry than the Vacuum Assisted Single Diaphragm Forming Process. The Inflated Fool Diaphragm Forming Process is easy to control and can be done through automation.

4.4 Future work for the forming process

4.4.1 Changes in the Set up

Many of the improvements suggested in section 4.3 can be incorporated in our experimental set up. One of the suggested improvements is to build a larger pressure chamber to form a bigger part with dimension of 12"x 24". The force distribution in the machine need to be studied and analysed so as to come up with a new design for the forming machine with force evenly distributed on the part. In the future, we can also design a machine forming at negative pressure for the reasons described in section 4.3.2.

4.4.2 More Experiments

More experiments are needed to develop a more precise description of the effect of forming speed on the wrinkling of the parts. Right now the control of the process speed depends on the experience of the operator. In order to automate the process, we have to develop a quantitative description of such effects.

We should also continue to search for better diaphragm materials. A good diaphragm need to be flexible, durable (especially at high temperature), and have proper frictional behavior to prevent tow splitting.

One of the major advantage of the processes discussed is the possibility of sequential forming of more plies of composite over already formed parts. However this possibility has not been experimented. Experiments in this direction will provide us with better understand of the processes.

Appendix A

PHOTOGRAPHS OF FAILED PARTS

The photos selected here aims at illustrating different failure modes encountered during the experiments. Reasons for the failures are also given.

These attempts are not included in the analysis of table 2.1 and table 3.1.

A.1 Parts Formed by Inflated Tool Diaphragm Forming

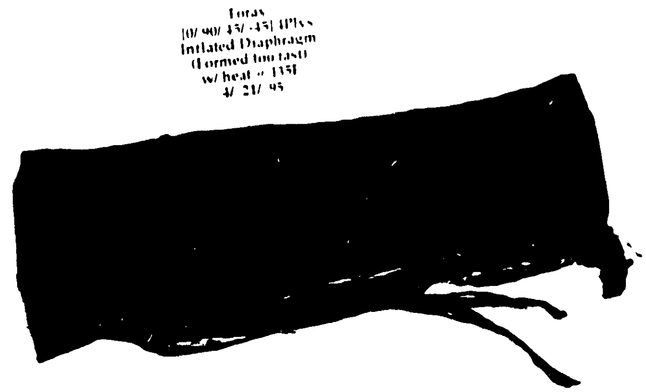

Figure A-1: Toray, [0/90/45/-45] 4 plies, 135F. Failure: severe tow splitting. Reason: formed too fast

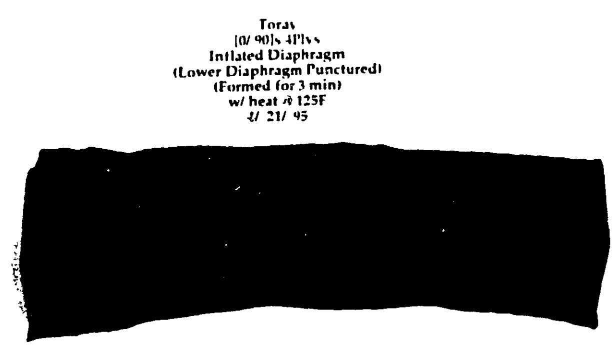

Figure A-2: Toray, [0/90]s 4 plies, 125F. Failure: major wrinkles. Reasons: Lower diaphragm punctured, formed too fast

A.2 Parts Formed by Vacuum Assisted Single Diaphragm Forming

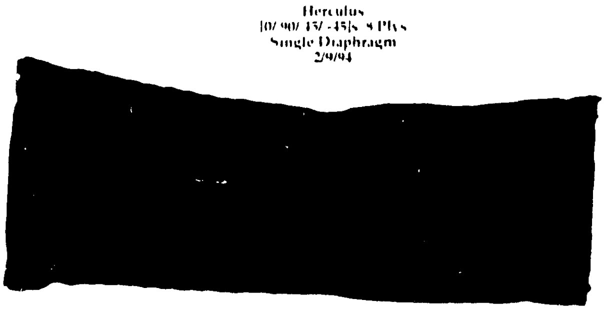

Figure A-3: Hercules, [0/90/45/-45]s 8 plies, 120F. Failure: incomplete forming. Reason: seal broken 6 mins into forming

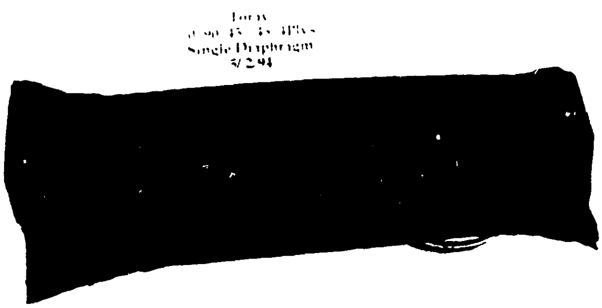

Figure A-4: Toray, [0/90/45/-45] 4 plies, 135F. Failure: incomplete forming. Reason: seal broken 7 min into forming

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