Mold filling parameters in resin transfer molding of composites
by Charles William Hedley

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering
Montana State University

Abstract:
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The main focus of this study was to set up a working RTM process and use it for two purposes: (1) to examine the basic aspects of wetting, flow patterns, pore formation, and the effects of mold deflection, and (2) to manufacture specimens for both educational and research purposes. The fiber and resin materials are representative of those used in industry. The equipment, although smaller in scale, utilizes the same principles as in commercial-scale processes.

The results of this study show the relationship between porosity and flow rate; the importance of capillary action to the wetting process; the significance of mold deflection on part thickness and reinforcement permeability; and the flow pattern as the resin actually fills the mold. It can be concluded that the process works well and produces very good quality parts; however, the mold filling process is quite complex. It is determined that small variations in any of the processing parameters can influence the quality of the finished part.

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5/9/94

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Graduate Dean

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ABSTRACT

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CHAPTER ONE

INTRODUCTION

Demand for improved part performance has led to efforts to produce products that are lighter, stronger, and more efficient. This is particularly evident in the automotive and aerospace industries where increased fuel costs have forced manufacturers to increase fuel efficiency without increasing product cost. The area of sporting goods has also seen an increase in the demand for improved performance. This has caused an increase in the use of non-traditional materials of construction such as polymer matrix composites.

Polymer matrix composites are made by impregnating very strong fibers with a liquid polymer and allowing it to solidify. The fibers provide strength and stiffness to the structure while the polymer, or matrix, serves to transfer the load between the fibers, protect them, and keep them oriented in the proper direction so as to maximize the composite properties. These components can combine to give a material with a very high strength and stiffness to weight ratio for aerospace applications. In the automotive industry they are used to provide near net shape products, with little machining or waste, that can replace assemblies of metal parts.

Composites are not a new class of materials, but recent advancements have dramatically improved them and given greater range to their properties. Improvements in the matrix chemistry have allowed composites to move into harsher environments. For instance, some polyimides can be used up to temperatures of around 500-600 °F [1]. Changes in reinforcement types and configuration have yielded improved strength and processing characteristics. Most reinforcements are available in woven fabrics, mats, directional fabrics, and braided structures which allow them to be used with different processes. These improvements in the components in conjunction with lower costs and improved processing have allowed them to penetrate a number of different markets. Sporting goods, tanks and pressure vessels, automobiles, airplanes, and consumer goods are all examples of products that make use of polymer matrix composites. The desire to incorporate composites into these various products has led to the development of a number of manufacturing techniques.

CHAPTER TWO

PROCESSING METHODS

The information contained in the following discussion on processing is summarized from information contained in References 2-4. The main purpose of any composites processing method is to bring the resin and the reinforcement together in the correct shape and in such a way so that little porosity remains in the fiber assembly. This is known as wet-out. It is desirable to accomplish wet-out and maintain performance requirements while still achieving the desired rate of production. The degree of wet-out is subject to the processing parameters of the method employed. Such factors as fiber volume fraction, resin viscosity and kinetics, and product geometry all affect the outcome of the finished part, no matter which processing method is used. By varying one of the processing parameters it is possible to affect one or more of the other parameters. It is only by knowing how these factors relate to one another for a given process that it is possible to successfully produce high quality parts.

The strength and stiffness characteristics in a composite come primarily from the fibers, making a high fiber volume fraction (V_f) very desirable. However, as the fiber volume fraction increases, the porosity of the fiber assembly prior to wet-out decreases, and the ability of the resin to infiltrate the fiber bundles and the spaces between them decreases. This can result in air being trapped and forming pores or in an uneven distribution of resin throughout the part, both of which can affect performance. Proper selection of processing parameters can maximize fiber content for each processing method.

The viscosity and the cure kinetics are critical for thermoset resins which are crosslinked (cured) after wet-out and shaping of the part. The lower the viscosity, the easier it is for the resin to flow and saturate the fiber assembly. The cure kinetics are important in that the viscosity increases as curing occurs. Kinetics also affect the efficiency of the process. If cure takes too long, then it takes longer to produce each part. Many resins have been developed specifically for each particular process, not only for their good processing traits, but for desirable physical properties as well. Heat is often used to lower the viscosity. However, there is a trade-off: increasing the temperature also increases the cure rate, which can increase the viscosity.

The part geometry also influences the permeability of the fiber assembly. Each processing technique has an element of matrix flow involved. As the geometry becomes more complicated, it becomes more difficult to force the resin either into or out of certain domains. Ribs and design features with varying thickness can hinder the movement of resin through the part. The geometry of the part can often dictate the best process. The presence of ribs or other uneven surfaces, a constant cross-section, or a hollow center all suggest the use of one process over another.

Although there are variations within each, there are six primary methods used to produce thermoset matrix composites: compression molding, filament winding, hand lay-up, autoclave or bag molding, pultrusion, and resin transfer molding (RTM). Each method has carved out a niche based on the above parameters as well as the desired production rate, and the necessary quality. Each process has strengths and weaknesses which make them suitable for particular applications. Injection molding, another composites processing method, is used mainly with thermoplastic matrices and will not be discussed here.

Compression Molding

A material called sheet molding compound (SMC) is often used in compression molding. SMC is made by sandwiching fibers between two layers of catalyzed resin to form a continuous sheet. The flow of resin into the reinforcement is over a short distance and is aided by compaction rollers. The sheet is rolled up between release films after the matrix thickens. This can be cut into sections and stacked to form a charge. A second element of flow occurs when the charge is placed into a two sided, heated mold; as the mold is closed in a press, the charge is forced to fill the mold. The two-sided mold gives a good finish and allows for varying thickness and the presence of ribs and other variations on both sides.

Increasing the amount of fibers, and thus the fiber volume fraction, decreases the ability to flow. Mold closing speed, temperature, pressure, and the area of the mold base that the charge occupies must be adjusted to insure that the mold fills. It is important to close the mold at a rate that is low enough to allow the material to flow easily. Changing the area that the charge occupies changes the distance that the material must flow. Generally, higher pressures must be used at higher fiber volume fractions and for more complex shapes.

Filament Winding

Filament winding uses a rotating mold called a mandrel to wind up resin impregnated rovings. The process begins by pulling a number of rovings through a resin bath, again utilizing a short wet-out distance. They then are pulled over a roller which helps force the resin into the fiber bundles in the rovings and helps remove the excess resin and porosity. The rovings are then collected together on the carriage, which moves the length of the mandrel. The speed at which the carriage travels, for a given rate of mandrel rotation, determines the angle that the rovings are wound onto the mandrel, giving the desired fiber orientation for a particular layer.

Filament winding uses a resin bath to bring the resin and reinforcement together. After the reinforcement leaves the bath a wiping device is used to control the amount of resin that remains, the amount of resin is also affected by the tension in the strand. The tension can also play a role in the finished piece; if it is too high the resin can be forced out of the first layers on the mandrel as subsequent layers are added, which gives an uneven resin distribution; if it is too low then the fiber content will be low as well.

It is important that the resin not have too high or too low a viscosity. Too low a viscosity will allow the resin to be spun off of the part as it undergoes the winding process. Too high a viscosity will prevent good wetting in the bath, and requires increased residence time so that a slower process results. The resin needs to have a pot life of several hours in order to keep the bath from gelling prior to completion of a large winding.

Filament winding lends itself well to bodies of rotation requiring hollow centers such as tanks and pipes. The structure need not have a circular cross-section, but it is not possible to directly wind shapes with concave surfaces.

It is possible to obtain these shapes with an additional molding operation.

Hand Lay-up

Hand lay-up is the least equipment intensive and most labor intensive of the processes. Typically it begins with a one sided mold. The reinforcement is placed in the mold in the proper orientation. Resin is then applied to the reinforcement and a hand roller or squeegee type device is used to distribute the resin and help force it into the fiber bundles.

The processor can control fiber content in hand lay-up by controlling how much resin is applied to the reinforcement as each layer is added. The amount of resin that remains is then determined by the pressure applied by the spreading device. However, as the layers become thick it becomes difficult to force the resin into them. This can result in an uneven resin distribution.

The fact that there is only one mold face makes it difficult to obtain a high V_f, as the laminate cannot be compressed. The single mold face also limits the possible geometries that can be produced. The viscosity is tied to the shape of the part to some extent. If there are steep sides care must be taken to insure that the resin has a high enough viscosity to keep it from running out of the reinforcement.

If the resin is initially applied evenly, the wet-out distances are on the order of the layer thickness. However, if the resin becomes too thick then wetting problems can occur.

Prepreg Molding

In prepreg molding, layers of prepreg tape (unidirectional fibers or woven fabric impregnated with resin which is B-staged or partially cured) are stacked so that they have the proper orientation. Wet-out has already occurred during the manufacture of the tape. The laminate is then surrounded by bleeder material, and release material is applied to the tool to prevent sticking. This assembly is then placed into a bag. The bag is placed into an autoclave or press which provides pressure and heat, usually a vacuum is used to remove the air from the bag. The combination of pressure and heat, specified by the manufacturer, causes excess resin in the prepreg to flow into the bleeder material. The amount of bleeder material determines how much resin is removed once it begins to flow.

In prepreg molding the fiber volume fraction is controlled by how much resin is in the prepreg, and how much is removed in the autoclave. Prepreg contains more resin than is usually desired. The removal of the excess not only affects the fiber volume fraction, but aids in the removal of air and volatiles from the part. This is accomplished by increasing the processing pressure and the temperature in such a way that pressure is applied at the point when the resin is least viscous. This causes the resin to flow, carrying any entrapped air with it, into the bleeder material. As with SMC, the viscosity decreases with the increase in temperature, then increases as the reaction proceeds. The resin in thicker parts cannot move as readily and care must be taken to ensure that gelation doesn't occur on the surface before the resin in the center of the piece begins to flow. Prepreg materials usually have high V_f and excellent control of fiber orientation, but a low production rate. It is generally used in the aerospace and sporting goods industries.

Pultrusion

Pultrusion, like filament winding, uses a resin bath to bring the resin and reinforcement together. The reinforcement, often mat or fabric, is pulled through a vat which contains resin. After leaving the bath it is often pulled through a preformer which gives the general shape of the desired part. It is then pulled through a die which finishes forming. Curing is initiated and completed by heaters. As in the other processes the wet-out distance is short.

High fiber content is obtained by first insuring good wet-out in the resin bath. This is controlled by the resin viscosity and the residence time in the bath. After the fibers leave the bath, the preformers distribute and compact the reinforcement, help force the resin into it, and remove the excess resin. It is this final step, along with the pulling force, that determines the amount of resin in the finished part.

Geometries are long strips, generally have a constant cross-section and are usually solid, although it is possible through the use of some tricks with the die to obtain varying thicknesses and cross-sections. The profiles generally produced are those that are constant along the length.

The viscosity needs to be in a proper range as in the other processes. If it is too low it will drain from the reinforcement prior to entering the die. Too high and the resin won't properly wet-out the fibers unless the residence time in the bath is increased. The pot life of the resin needs to be long, but it must cure quickly in the die at elevated temperatures.

Resin Transfer Molding

Resin transfer molding is not a new process. It has been used in one form or another since the early 1940's [4]. However, its use was limited until the 1970's because of the lack of suitable resins and equipment. In the 1980's fiber preforms and low viscosity resins were developed that allowed the production of more complex geometries and parts for more diverse applications [4]. This, combined with low capital investment and release of volatiles, has dramatically improved the popularity of RTM.

The RTM process begins by placing reinforcement, in the form of properly oriented mats or fabrics, into a two-sided mold cavity. The mold is then closed and the resin is injected until the fibers are saturated and the mold is full. The resin is allowed to cure and the finished part is then removed from the mold and the process repeated. RTM employs four components: the mold, the reinforcement preform, the resin pump, and the resin (Figure 1).

The fact that this process uses a closed mold offers several advantages. First, complex shapes can be produced. Any variations in the geometry, such as ribs and areas of varying thickness, can be molded directly no matter where they are in the part. Second, the closed mold produces a smooth finish on both sides of the part. Third, emission of volatiles, such as styrene in polyester, is greatly reduced during processing. Styrene is a suspected carcinogen [3], exposure is regulated by OSHA and has been reduced to 50 ppm [5]. Finally, production rates can be high enough for automotive parts. These factors make RTM very attractive from both a production and economic standpoint. Disadvantages are

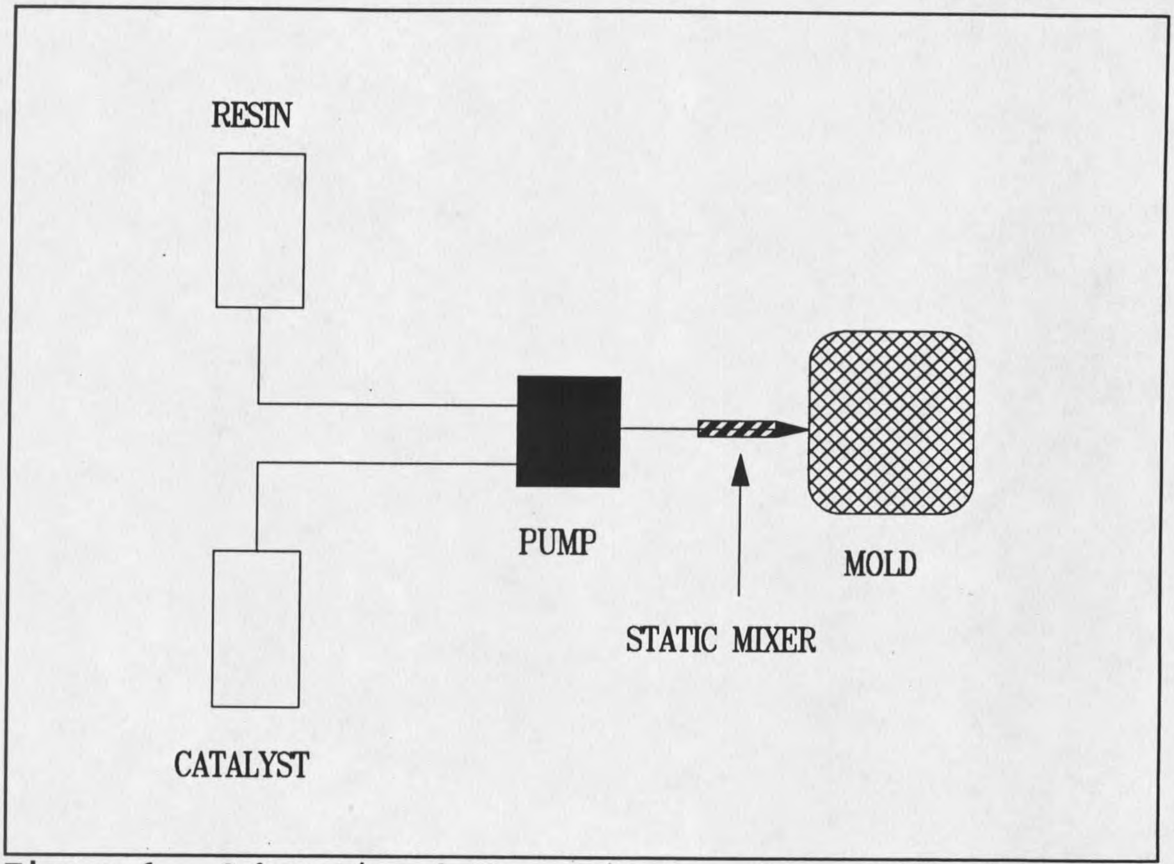

Figure 1. Schematic of the resin transfer molding process.

that wet-out distances are long, requiring lower fiber volume and the use of low viscosity resins which may have less desirable mechanical properties. These limitations are being overcome by continued advancements in equipment and resin chemistry.

The Mold

The process requires a two-sided mold in the shape of the part. The fact that RTM is a low pressure process, typically less than 100 psi, allows molds to be constructed of materials other than tool steel, often composites and aluminum; the molds are often heated to lower the viscosity and increase the cure rate. The use of these alternative mold materials allows lower tooling costs compared to compression and injection molding, and allows manufacturers to have their tooling made in-house.

Molds are the most critical aspect of the process. As the shape of the part becomes more complex the position of the resin inlets and the outlets can determine whether the mold will fill correctly. Experience has shown that injecting the resin into regions with higher fiber content aids the wet-out. Placing vents in areas where air is likely to become trapped can eliminate dry spots.

The Reinforcement

The second component of the RTM process is the reinforcement. There are many types of fibers available, such as E-glass, C-glass, S-glass, carbon, and aramids. These come in a variety of styles, such as woven roving, chopped strand mats, continuous strand mats, unidirectional rovings, and woven fabrics. These reinforcements can be layered and combined in such a way that the strength properties of the different fibers and configurations are best utilized.

Fiber contents of 5-55 wt% are not uncommon [6]. At the higher values of V_f the location and the number of the inlets and the outlets become very important due to the difficulty of forcing the resin through the preform. It is also beneficial to have a low viscosity resin to help keep the pressures down and to assist wetting.

At a production level, reinforcements are typically made into preforms. A preform is merely reinforcement in which the fibers have been properly oriented, formed, and held in the final shape with a binder. One technique to make a preform is to stitch together layers of fabric or mat. Another technique, used for non-structural parts, blows a combination of chopped fibers and binder onto a screen in the shape of the part. When the binder hardens the fibers are held together in that shape. The use of preforms greatly facilitates the handling of the reinforcement and its placement in the mold, which in turn speeds up production.

The Pump

Most commercial RTM injection equipment centers around a positive displacement pump. There are usually two tanks, one for the resin and one for the catalyst. Metering capabilities are built into the equipment to correctly proportion the two components. The components are then brought together and mixed in a static mixer located just upstream of the mold inlet. In some cases the holding tanks can be heated in order to lower the viscosity. Solvent tanks are usually included to rinse the catalyzed resin out of the lines between shots.

The Resin

Once the reinforcement is in place the mold is closed and the resin is injected into the mold cavity. RTM requires the use of a low viscosity resin. This assists in wetting out the fiber strands and in flow of the resin through the assembly. RTM relies heavily on capillary forces to get the resin into the fiber bundles. The lower viscosity also permits the use of lower injection pressures and higher injection rates, which in turn allows for the use of smaller pumps and lighter tooling. Resin viscosities range from 100 cP for some polyesters up to 2500 cP for some epoxies.

When the mold is full it is sealed and the resin is allowed to cure. Care must be taken to insure that the resin kinetics match the part being produced. If the cure rate is too fast then the mold will not be full prior to gelling and the part will be ruined. If the cure rate is too slow then the production rate decreases. After the resin is cured the part can be removed from the mold and the process can be repeated.

CHAPTER THREE

LITERATURE REVIEW

An understanding of how all of the processing parameters interact is necessary for accurate predictions of mold filling behavior in RTM. There have been efforts by researchers to model the RTM process and examine some of the factors that affect it. The goal is to ultimately assist in the design of molds and produce better quality parts. Presently, mold making is more of an art than a science and relies heavily on past experience and trial and error [7]. Prediction of flow fronts can lead to faster cycle times, reduce waste, and lead to more efficient placement of inlets and outlets. There is a delicate balance where the pressure drop, the flow pattern, and the resin properties are suitable for good wet-out and a quick cycle time. Too high of a pressure drop in the mold can cause the mold to leak or the reinforcement to be displaced. If the pressure drop is too low the mold may not completely fill [8]. The proper resin processing properties are equally important. If the cure cycle is too slow there is a loss of efficiency. If it is too fast the result can be incomplete mold filling. If the viscosity of the resin is too high then poor wet-out can result.

Much of the work in this area has been done empirically. Many researchers have built molds with which to compare results of their models [7,9-25] and to observe the actual filling behavior. In some cases the molds are also used to determine the values of processing parameters for use in models, such as the processing pressures and permeability of the reinforcement.

Permeability

The importance of the permeability of the reinforcement has made this parameter the subject of much study [7-10,14,22,27]. The permeability of the reinforcement determines the resistance to resin flow and is a necessary component of all models. Permeability is usually measured in units called darcys, where one darcy is equal to 9.87×10^{-9} cm^2 [28]. This property affects resin wet-out of the fibers as well as the pressure necessary to force the resin through the mold.

The method used by Molnar et al. [8], Fraccia [14], Gauvin [15], Li and Gauvin [20], Martin and Son [21], and Trevino et al. [22] for measuring the permeability of a particular reinforcement was based on Darcy's Law. The reinforcement is placed in a mold and saturated with resin. After saturation, more resin is forced through the mold from one end to the other. Once steady state has been reached, the pressure drop across the length of reinforcement is measured. This value, with the dimensions of the mold cavity, the viscosity of the resin, and the volumetric flow rate can be substituted into Darcy's Law, and a permeability can be calculated.

Darcy's Law is generally used in the 1-dimensional form of

$$Q = -\frac{KA}{\mu}\frac{\Delta P}{\Delta L} \quad (1)$$

where Q is the volumetric flow rate, K is the permeability of the porous media, A is the area available for flow, μ is the viscosity of the fluid and $\Delta P/\Delta L$ is the pressure drop per unit length of the medium. This form of the equation can be used in cases where the permeability is isotropic. However, because not all fabrics are isotropic, Darcy's Law is sometimes modified in order to account for anisotropy in the permeability. In the 2-dimensional case a permeability tensor is substituted into the equation and after some manipulation results in

$$\begin{bmatrix} u \\ v \end{bmatrix} = -\frac{1}{\mu}\begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix}\begin{bmatrix} \frac{\partial P}{\partial x} \\ \frac{\partial P}{\partial y} \end{bmatrix} \quad (2)$$

Adams et al. [9,10] used a different approach in their study. A square mold with a central injection site, which allowed for radial flow, was constructed. The porous media took the form of various woven fabrics. A hole was cut through the fabric to prevent compression of the fabric over the injection site, which could allow for uneven distribution of resin. Once the injection was started, the movement of the flow front was timed. Models were developed that allowed the prediction of the permeability in both isotropic and nonisotropic fabrics. Results obtained from these experiments were in accordance with Darcy's Law.

Miller and Clark [27] developed an apparatus to determine the flow resistance of resin normal to the plane of a fabric. This device amounted to a cylinder in which a specimen of the fabric could be mounted. Liquid could be forced through the thickness of the fabric at different rates and the pressure monitored.

Some studies [8,22] have examined the effects of the stacking order of different reinforcement types on the overall permeability of a laminate. The permeability of random mat, bidirectional mat, and unidirectional mat were each determined separately. It was found that the unidirectional mats had a higher permeability in the fiber direction. However, the pressure drop was higher as well for these mats. This was attributed to the unidirectional mats having a lower permeability in the thickness direction because of their packing characteristics. The study also found that a combination of random and unidirectional mats made for a short transition to a stable, steady state flow pattern. This was due to the unidirectional mat allowing the resin to move in the thickness direction and into the random mat which kept the front smooth. Adams and Rebenfeld [9] also found that the addition of a layer with high in-plane permeability aided the movement of the resin in the thickness direction. This allowed the flow front to remain uniform through the entire thickness.

There has been some disagreement as to whether the fluid behavior is actually described with Darcy's Law in RTM. This has stemmed from the fact that Darcy's Law is based on a saturated, isotropic porous medium. The fluid is assumed to be Newtonian, have a particle Reynolds number less than 1, and not undergo any chemical or physical changes [28]. Because the RTM process has both a saturated and unsaturated region where flow is taking place, involves a chemical reaction, and may use non-Newtonian fluids, some researchers have shown that permeabilities obtained experimentally deviate from Darcy's Law predictions [8,15,21,22]. This has led to the suggestion that there is a transition that takes place where the permeability changes with advancement of the flow front and saturation [29].

On the other hand, several studies have shown that permeabilities based on Darcy's Law in fact are consistent in both saturated and unsaturated porous media [9,10,14].

It should be noted that there are no clear sources of error in these studies. Some of the confusion is due to the lack of detail reported in most of these experiments. Fraccia [14] and Martin and Son [21] both mention that deflection of the mold faces is either a minimal factor or is somehow known not to be a factor. Martin and Son found a deviation from Darcy's Law while Fraccia found there to be agreement. Furthermore, with the exception of the studies done by Adams et al. [9,10] and Gauvin et al. [15] all of these studies used fluids known to be Newtonian instead of resins. Adams et al. used epoxy with a viscosity of 94.4 poise and stated that the behavior was Newtonian. Good agreement was found between plots of experimental data and predictions from a Darcian-based model. Gauvin used a polyester with unknown viscosity which was assumed Newtonian. Plots of pressure drop *versus* flow rate showed that permeability was a function of flow rate.

In addition to the use of Darcy's Law a number of non-experimental approaches have been taken in order to determine and predict the permeabilities of the reinforcement used in RTM. One type of permeability model is the conduit type. The Bundle of Capillaries Model is one of these. This model attempts to relate the pore structure of the reinforcement to the permeability. It assumes that the reinforcement can be represented by a system of straight, parallel capillaries. This was used by Chan et al. [30] as a basis for a mold filling simulation.

Another conduit type permeability model is the Kozeny-Carmen Equation [28]. This is similar to the capillary model except that it is assumed that there is only one very tortuous conduit of roughly constant cross section through which the fluid flows.

Pore Formation

Pore formation is an important aspect of composites processing. Pores cannot transfer stresses and can serve as stress concentrators. This strongly influences some mechanical properties and the mobility of liquids through the finished part. The interlaminar shear strength and also the compressive strength are adversely affected by the pore content [31]. Pores near the surface can cause flaws in the appearance of the part such as blisters or holes. Pore contents of less than 1% are considered to be acceptable [32].

Broutman and Krock [31] state that pores are commonly caused by the inability of the resin to displace all of the air within the strands. This is affected by the viscosity of the resin, the contact angle, and the rate at which the resin and the reinforcement come together. Pores can also be caused by bubbles, which are entrained in the resin and transported into the mold. It is also possible for volatiles and dissolved air in the resin to form pores, particularly during curing. Broutman and Krock make a distinction between small spherical pores that form in the resin and interstitial pores which form in the strands. The interstitial pores tend to have sharp corners which act as places of stress concentration.

Most of the models examined in this work neglected the contribution of pores in the RTM process; however, there were several exceptions. Chan and Morgan [33] modeled the impregnation of unidirectional reinforcement with pore formation. It was assumed that the contribution of the capillary pressure was small compared to the injection pressure. The model was based on the assumption that two types of flow were present. One was a macroflow which moved parallel to the strands. The second was a microflow which moved radially into the strands. Furthermore, it was assumed that Darcy's Law described both of these levels of flow. The numerical technique used to solve the equations used in this model was not specified.

Kurematsu and Koishi [17,18] characterized the behavior of epoxy resin impregnating non-woven polyester fabric. In an initial study [17] it was found that the distance that the resin impregnates the fabric increases with an increase in temperature at atmospheric pressure. A modified version of the Carmen-Kozeny equation was used to measure the time dependence of the impregnation. The modification was in the form of a theoretically determined capillary force which was introduced in order to account for the contribution of the fibers. A continuation of this study by Kurematsu and Koishi [18] looked at the kinetics of pore formation. It was found that the interface between the impregnated region and the non-impregnated region was not uniform. Differences in the distribution of the fibers caused variations in the velocity of the resin in very localized areas. Pores were also found to form during this process and a theoretical model was developed to estimate the pore volume. Martin and Son [21] also suggested that the formation of pores are the result of air being trapped by flow fronts recombining.

Parnas and Phelan [29] modeled the flow of resin at both a macro and microscopic level. Pores inside the fiber bundles were also examined as part of this study. Pore size was determined as a function of what was referred to as the sink strength, the ability of the fibers to remove resin from the macroflow. It was also predicted that the pore diameter would be largest at the outlet end and smallest at the inlet end due to the pressures in the mold. As the flow front continued to move through the mold, pressures increase and fiber bundles behind it continue to wet-out, which reduces the size of the pores in the bundles.

Modeling

Most of the research that has been performed in the RTM area has centered around the development of models of mold filling behavior [7,9-26,29,30,33,34]. These models attempt to predict various aspects of the mold filling such as fill times, mold pressures, and flow front positions.

The complexity of solving the partial differential equations that describe the flow of fluids through porous media is greatly eased by the use of numerical techniques. These equations are solved in an effort to predict the position of the flow front [7,9-15,20-22,26,29,30,33,34], mat deformation [16,17], or the pressure distribution in the mold [7,12,13,21,26,29,30]. Crotchet et al. [35] state that for modeling non-Newtonian fluids, finite difference methods are easier to understand and require less processing time than finite element methods. However, finite element methods have a distinct advantage over finite difference methods when it comes to modeling complex geometries. These and several other techniques have been used to model the RTM process. For instance, the finite element method was used by Ref. [7,11,16,21,23,29]. The finite difference method was used by Refs. 22 and 34. A technique using the numerical generation of a boundary fitted coordinate system was used by Li and Gauvin [20]. Coulter and Guceri [12,13] used a boundary-fitted curvilinear coordinate system. Parnas and Phelan [29] used an explicit Euler algorithim. Um and Lee [25] used a boundary element method. No clear choice seems to have emerged as a superior technique. The accuracy of results obtained from these models has varied from good to bad.

The method for verifying results of models used by most of the previous researchers [9,10,12,13,21,22] has been to construct a square or rectangular mold. One side is usually made of a transparent material, such as glass or Plexiglass® (polymethyl methacrylate), to observe the advancing flow front. These molds use a sandwich design where some sort of gasket material is clamped between a base plate and the clear material plate. A low viscosity, Newtonian fluid is selected to simulate the resin. In many instances the mold is also used to determine the value of the permeability of the reinforcement, which is used in the model. The actual flow front positions are recorded for comparison to the predictions of the model. In several cases [7,11,12,20,22,25] the models that are subsequently developed are run on different mold geometries. Material properties of the reinforcement and the resin are incorporated into the models. Results of the simulated mold filling such as pressures, flow fronts, mold filling times, and permeabilities are then compared to what has been observed experimentally. In some cases these models have been run for a number of different reinforcement types.