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CHAPTER 7

Liquid Composite Molding

1. INTRODUCTION

The last three chapters have presented a few processes for the manufacturing of composite structures. These have advantages and disadvantages.

The hand-lay-up on open molds provides flexibility and versatility in terms of different configurations; However it does not provide good quality of the part due to the lack of control of compaction and the entrapment of air during the laying-up process. In addition, this process suffers from the evaporation of styrene into the atmosphere, which is an environmental concern.

For the autoclave molding process, even though it also uses laying-up either by hand or by tape laying machine, the environmental concern is not critical because prepreg tapes are used and the evaporation of volatiles is not serious. The quality of the parts is very good due to the fact that the impregnation of the fibers is done off-line. The use of vacuum, pressure and temperature control also gives parts of good quality. However the autoclave molding process has disadvantages as follows:

- Since prepregs have to be used, the cost is high compared to cases where dry fibers are used.
- The prepregs have a shelf life, which imposes time constraint on their usage. This also can produce waste if the prepregs are not used during their shelf lives.
- Since laying up is required, the component cannot have fiber orientations other than in-plane. Having fibers along the thickness

direction of the part can improve properties such as interlaminar strength and toughness.
- The process requires an autoclave, which can be a substantial investment. The autoclave needs to be heated to a certain temperature and sometimes this can be costly as in the case where a large autoclave is heated to cure a small composite part.
- For parts with very large dimensions, such as those of a boat or a wind turbine blade, the use of an autoclave is economically impractical.

The filament winding and pultrusion processes are geared towards parts of special shapes such as those having surfaces of revolutions, or those having constant cross section along their length.

Liquid composite molding (LCM) is a process that may respond to the concerns mentioned above. The main steps of the process are shown schematically in Figure 7.1 and discussed below.

1. *Preforming:* During this step, dry fibers are packaged into a preform having the configuration of the part. The starting materials can be tows, random mats, or woven fabrics. The finished preform is usually woven, compression molded, braided or knitted together. Small amounts of adhesive or small-diameter stitches are usually used to hold the preform in shape.
2. *Tool:* After the preform is made, it is placed inside a tool (mold) for further processing. Usually the mold has two halves. Both of these can be made out of stiff metals (such as the case of SRIM, RTM, VARTM or RFIM) or one-half of the mold can be made out of stiff metal and the other half made out of a flexible membrane (such as the case of SCRIMP or its variations). The surface of the final part

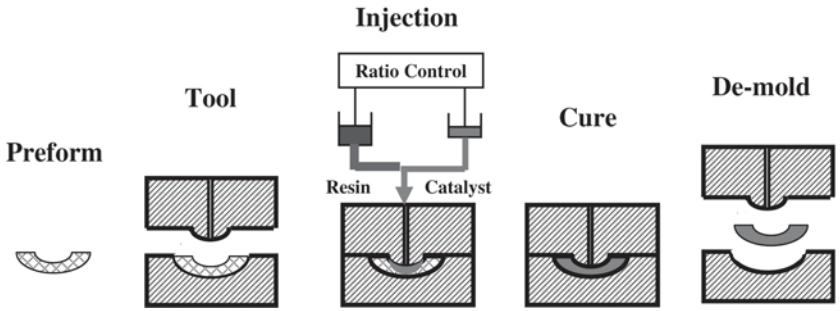

FIGURE 7.1 Schematic of the LCM process.

depends on the quality of the surface of the mold. Also, high pressure can be applied when both mold halves are made of stiff metals. The amount of voids that may be present in the final product depends on the ability of the resin to penetrate into small interstices between the fibers, and this may require high pressure. The type of tool used therefore depends on the required quality of the final part.

3. *Resin infusion:* After the preform is placed inside the mold and the two halves of the mold are closed, resin is infused into the mold. The objective of the infusion is to wet the fibers and to fill up any cavity within the preform. The infusion can be in the form of injection where high pressure [several hundred psi (tens of MPa)] for the case of SRIM, or moderately high pressure (around 100 psi or 6.89 MPa), for the case of RTM, is used. It can also be simply suction created by vacuum (such as the case of VARTM or SCRIMP). The duration of time for the infusion of resin depends on the size of the part and on the reactivity of the resin system. For resin with fast reactivity, such as cyanate for SRIM, the infusion takes place within a matter of seconds; whereas for slower reaction systems such as epoxies for RTM, the infusion time can be on the order of minutes or hours.
4. *Curing:* After the resin has been infused completely into the cavity of the fiber preform, curing takes place. Normally the resin already contains curing agents and catalysts for curing. It is important that the resin does not gel during the infusion process. If the resin gels before the preform is infused, short shots are obtained. Curing can be accelerated by heating.
5. *Demolding:* The part is demolded and removed from the mold.

The advantages of LCM are as follows:

1. The preforms are made using dry fibers and they do not have to contain the partially cured resin as in the case of prepregs (preforms may contain binders, which are small amounts of resin used to hold the shape of the preforms together). Because of this, fibers with different orientations can be built into the preforms. Composites made from the preforms may have reinforcements along the thickness direction in addition to those in-plane. Different techniques such as weaving, braiding, stitching, and knitting can be used to make the preforms.
2. The dry preforms do not have the constraint of shelf life.
3. The process is done in a closed mold. For manufacturing involving

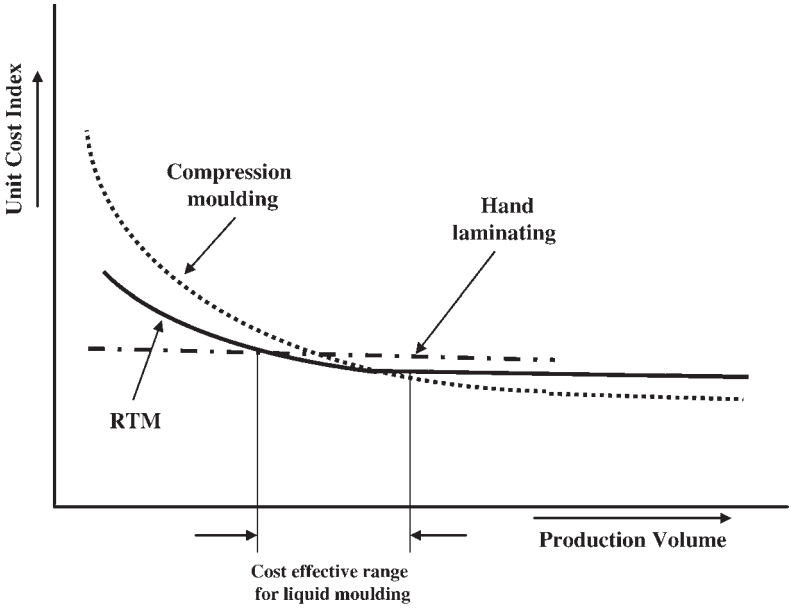

FIGURE 7.2 Cost versus production volume of different manufacturing processes.

polyester and vinyl ester resins, the issue of styrene evaporation into the atmosphere is not a great concern.

4. The cost-effective range for LCM is in the middle range in the production volume. Figure 7.2 shows the relation between production volume and the unit cost index for a few processes. LCM can be more cost-effective compared with the autoclave molding process when the production volume is on the order of 20,000–60,000 units per year [1].
5. The molds required for LCM are generally considered to be lightweight and low cost compared with conventional compression molding and metal forming, resulting in a lower investment to enter production.

Initially liquid composite molding was developed for low-cost applications derived from the injection molding of regular plastic components. Due to its low cost, relatively fast production rate and its ability to provide closed mold conditions that help to address the problem of styrene (in open mold process), LCM has found acceptance for the manufacturing of composites for automotive applications.

The disadvantages of LCM are as follows:

1. Preforms need to be held together by binders. The presence of binders may interfere with the flow of resin to wet the fibers. Binders also need to be dissolved in the resin to avoid the bundling of fibers, which may affect the resulting mechanical properties.
2. Preforms need to fit well into the tool. For the resin transfer molding (RTM) process, if the preforms do not fit well into the tool such that there is looseness at the peripheries of the preform, liquid resin can run quickly along these easy paths resulting in resin rich areas in the final part.
3. The permeability of the preform depends on many factors, such as the volume fraction of fibers, the compression pressure on the preform, the type of fiber form used, and the stacking sequence of the fibers. The variability of the permeability of the fiber preforms makes it difficult to predict the speed of flow of the liquid resin in them. This can result in lack of wetting, voids, and low mechanical properties such as interlaminar shear strength.
4. The quality of the part can be affected by the presence of voids, dry spots or resin rich areas.

Depending on the fiber volume fraction and the end-use applications, there are many variants of the LCM process as follows:

- *Injection molding (IM):* This is a pure plastic injection process where there are no fibers involved, which has been used to make injection molded parts for a long time. The resin is mainly engineering thermoplastics such as polypropylene, polystyrene, and polymethylmethacrylate (PMMA). Sometimes short fibers (such as short glass or carbon fibers) can be incorporated into the thermoplastics to make reinforced plastic components. In this case, the fibers are mixed with the resin and injected together, rather than in the form of fiber preform.
- *Structural reaction injection molding (SRIM):* This is similar to IM above except that in this case a fiber preform is placed inside the mold cavity before injection. Figure 7.3 shows a schematic for this process. Due to the high rate of reaction, the pressure in the mold is usually high and the duration of the reaction is on the order of seconds.
- *Resin transfer molding (RTM):* This is similar to the SRIM process except that the duration of the injection step lasts on the order of minutes and the pressure inside the mold is in less than

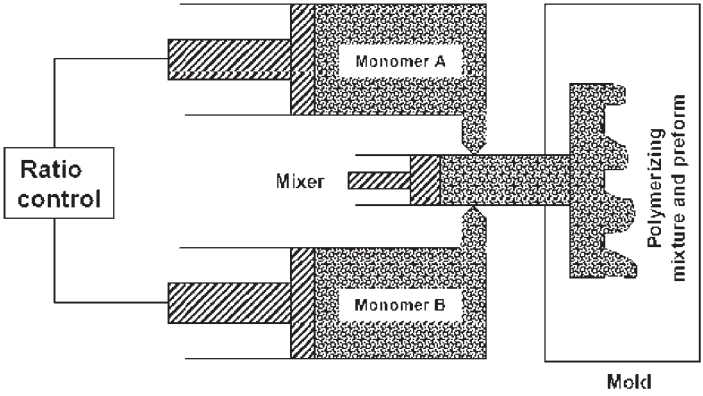

FIGURE 7.3 SRIM process.

100 psi (680 kPa). Figure 7.4 shows an RTM mold for automotive parts.

- *Vacuum-assisted resin transfer molding (VARTM):* This is similar to RTM except that rather than using pressure, vacuum is used. Because of this, the pressure differential is small. The advantage here is that a rigid mold is used only on one side of the part where on the other side a flexible bag can be used. This can result in significant cost savings. The disadvantage is that due to the low

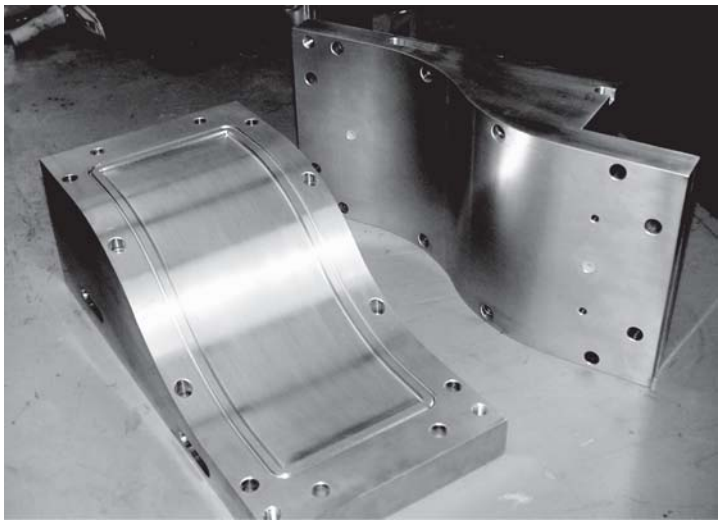

FIGURE 7.4 An RTM mold for a curved piece.

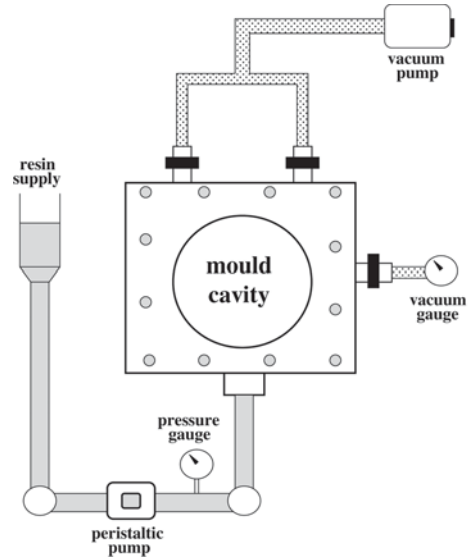

FIGURE 7.5(a) Vacuum-assisted molding arrangement.

pressure, more voids may appear in the part. Figure 7.5 shows schematics of the VARTM.

- *Seaman composite resin infusion molding process (SCRIMP):* This process is similar to VARTM in which only vacuum is used to provide the pressure gradient. In the case of RTM, both mold surfaces are hard, meaning both mold surfaces are made of some sort of metal. In the case of SCRIMP, only one mold surface is hard, the other mold surface is a flexible membrane that is used to contain the vacuum. Figure 7.6 shows a schematic of the process. In SCRIMP, the liquid resin flows in between the flexible membrane and the fiber preform. This type of flow is rapid since

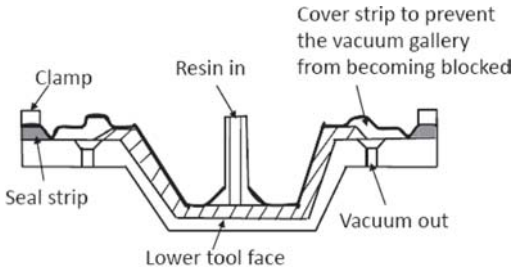

FIGURE 7.5(b) Cross section of a VARTM set up.

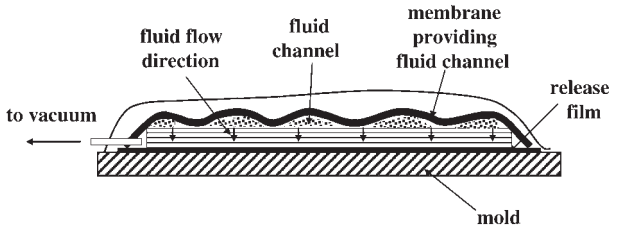

FIGURE 7.6 Schematic of the SCRIMP process.

the resin does not have to flow through the dense fiber preform along the planar dimensions of the part. To wet the fibers, resin only needs to flow through the thickness of the part. The distance *dx* in Darcy's law is therefore small and one does not need to have high pressure difference (*dp*) to get the resin to flow through the fiber beds. The advantage of this process is that it allows the ability to manufacture very large components on the order of several tens of meters (such as boat hulls or large turbine blades). One disadvantage of this method is that good surface finish is only provided on one side (the mold side). The other disadvantage is that the percent void content may be high. For critical applications such as aerospace, the amount of void content needs to be very small.

- *Resin film infusion molding (RFIM):* In this process, instead of injecting resin into the mold, thin films of resin are placed at the bottom of the fiber beds or between different layers of the dry preform. Upon heating and application of pressure, the resin film melts and the liquid resin permeates into the dry fiber preform. Figure 7.7 shows a schematic of the process.

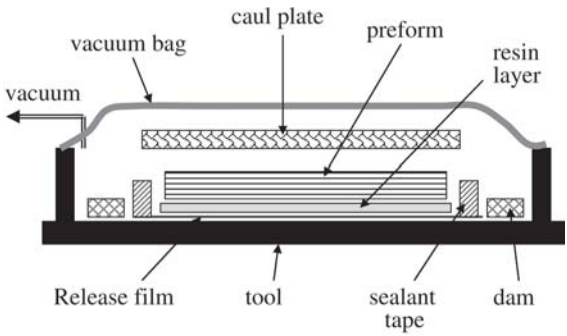

FIGURE 7.7 Schematic of the RFIM process.

2. MATERIALS

2.1. Fibers

Fibers used for LCM are usually glass or carbon. Discussion on fibers was presented in Chapter 3. In addition to the fiber forms presented in Chapter 3, there are other forms of fibers that are specifically applicable to the LCM process.

2.1.1. Flow Enhancement Fabrics

The macroscopic permeability (permeability referring to the fabric as a whole rather than the individual filaments) can be increased by creating effective flow channels between fiber bundles. This can be achieved by fiber clustering, which may still allow high volume fraction to be attained but with a less uniform fiber distribution. Commercially available flow enhancement fabrics are said to offer a number of advantages over the aligned fabrics, in particular, reduced injection times, which may make possible the production of relatively large parts at high volume fractions. The main disadvantage of these materials is the potential reduction in mechanical properties caused by less uniformity in the fiber distribution.

For VARTM or SCRIMP, a layer of impermeable plastic with flow channels can be placed on top of the fiber preform to facilitate fast penetration of the liquid resin. Flow of the resin will only need to go through the thickness of the preform (Figures 7.5 and 7.6).

2.1.2. Surface Veils

Surface veil is a random reinforcement with low superficial density and is produced from a fine (low tex) glass fiber. This material is used in LCM to provide a high quality surface finish by eliminating fiber strike-through and creating a resin rich surface layer, or alternatively where chemical resistance is required (where a C-glass tissue may be used). The use of a surface veil may eliminate the need for a gel coat. A number of materials are commercially available based on either chopped or continuous filaments held together with either a polyester or PVA binder and having superficial densities in the range of 30–100 g/cm^2.

2.1.3. Binder

Binder is applied to the fibers during the preform manufacturing stage

to provide cohesion to the fiber architecture during subsequent handling and processing operations. Binding can be achieved mechanically by needling or stitching with a light yarn or roving, but it is more usual to use a chemical adhesive binder. This may be either a thermoplastic or thermoset in the form of a powder, an emulsion or a solution. For systems using polyester of vinyl ester, binders may be categorized by their solubility in styrene. A dissolution time of less than 60 seconds corresponds to high solubility, between 60 and 200 seconds indicates medium solubility, and over 200 seconds represents low solubility. Relatively low solubility binders result in improved flow characteristics at the expense of prolonged fiber wet-out times. One potential consequence of binder dissolution is a change in resin viscosity. It has been suggested [2] that the viscosity of a vinyl ester resin may be doubled by the addition of 5% by mass of thermoplastic polyester binder.

2.2. Preforms

Preform is an assembly of fibers having the configuration of the part. Once the preform is wetted by the liquid resin and after the resin is cured, a composite part is obtained. Figure 7.8 shows an example of a preform.

There are several good reasons to preform the reinforcement before loading it into the mold.

- Preforms speed up the process and free the mold from everything except loading, injection, in-mold cure, and demolding.

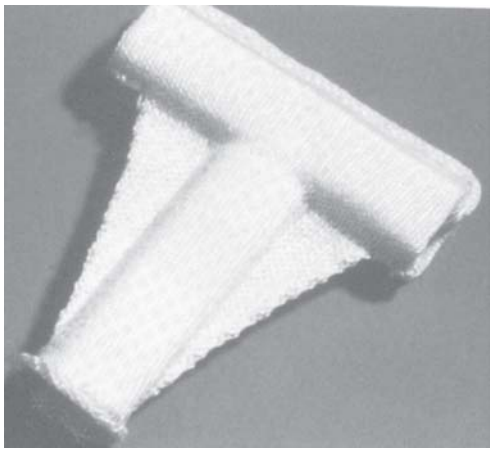

FIGURE 7.8 Knitted glass fiber preform for a stiffened T joint (courtesy of Preform Technologies Ltd.).

- Preforms improve quality and reduce part-to-part variations. For fast cycle times, the ideal is to make the preform so stiff that it becomes self-locating in the production mold. In other cases, when the mechanical properties are of paramount importance, one often wants to minimize the preform binder since the mechanical properties can be adversely affected by the binder.

In general, a good preform is required to be inexpensive to make and stiff enough to be stacked and handled before injection. The fibers must stay in the direction in which they have been placed both during handling and injection. To achieve all these goals it is common to apply some form of preforming agents (binders). Both thermoplastic and thermosetting powders are commonly used for this purpose.

The compaction behavior of the preform differs a lot depending on the performing method and the type of reinforcement that has been used. An important observation is that the fiber volume fraction at zero compaction pressure can differ significantly between different fabrics. A lower nominal fiber volume fraction can result in movement of the reinforcement during filling and incomplete impregnation. Another typical feature of the compaction behavior is that all fabrics behave like nonlinear (stiffening) springs and that the possible increase in fiber volume fraction from the value at rest is limited.

In practice, most molds are flexible and will deform when the fiber volume fraction becomes too high (which corresponds to a high compaction pressure). The forces associated with the compaction can be so high that the mold surface becomes deformed or even that the entire mold breaks (if the clamping force is powerful enough). High compaction pressure is a particularly difficult problem when the thickness of the laminate in a part varies in different positions (stepping of the thickness). In this case, even a small error in the placement of the fabric with a corresponding increase in local fiber volume fraction can lead to a dramatic increase in compaction pressure. Both thermosetting and thermoplastic powders are commonly used to stiffen the preform. Ideally, the preforming agent should not decrease the permeability, the wettability, or the mechanical properties of the finished part, but it should still stiffen the perform so that it can be handled. In practice, however, this compromise is difficult to achieve. For example, the mechanical properties can be significantly reduced by the preforming operation, but they can also be close to the value without preform binder with a judicious choice of preforming agent. The raw material suppliers can usually recommend suitable preforming agents for a given matrix system or provide pretreated reinforcement with binder.

It should be noted that the permeability of the resin in the fiber preform depends to a great extent on the fiber volume fraction. Since the compaction pressure has great influence on the fiber volume fraction, this pressure therefore has important influence on the flow of the resin through the preforms.

2.2.1. Preforming Methods

The preforming methods can roughly be classified into five basic types: (1) cut and paste, (2) spray-up of chopped fiber on preformed models, (3) thermoforming, (4) weft knitting, and (5) braiding.

2.2.1.1. Cut and Paste

In this technique, sheets of fabrics are cut to simple shapes and these pieces are fit together with an adhesive or by stitching to make up the configuration of the part. It should be remembered that an adhesive can adversely affect the mechanical properties.

2.2.1.2. Spray-up

In this technique, continuous rovings are chopped using a chopping device. These rovings are deposited on a perforated former having the shape of the perform. Binder solution is sprayed on the chopped fibers to provide adhesion. After spraying, hot air is allowed to circulate for about 1 minute so that the thermoplastic binder melts. After melting, the air stream is switched to cold and the preforming powder solidifies. Figure 7.9 shows an example of a preform made by spray-up.

2.2.1.3. Thermoforming

In thermoforming, the fiber bed along with binders is compression molded at the proper temperature. The formability of woven fabrics is limited and only moderately double-curved shapes have been formed commercially. Wrinkles and folds formed by draping of woven fabrics can to some extent be predicted with computer simulations. There is a possibility that the fiber orientation may change during forming.

2.2.1.4. Weft Knitting

There are two kinds of knitting operations: weft and warp. Both of these produce interlooped structures. These methods differ in that weft

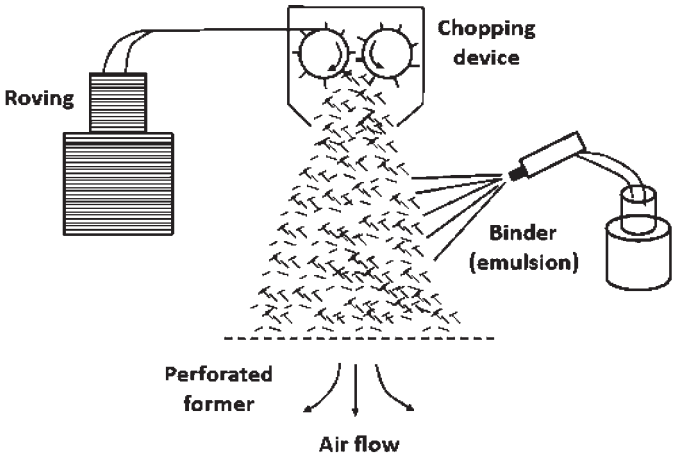

FIGURE 7.9 Preform by spray-up.

knits are formed in the weft or horizontal direction, whereas warp knits are formed in the warp or vertical direction. The weft-warp knits have the advantages of conformability and can be automated easily. The disadvantages are that high fiber volume fraction is difficult to achieve and the knit is anisotropic.

2.2.1.5. Braiding

Braiding is a good technique for forming tubular structures. Braiding is available in diameters up to about 300 mm and with different types of fibers. Figure 7.10 shows an example of a braided perform.

2.3. Matrix

Common requirements for resin systems for LCM processes are:

- Sufficiently low viscosity (about 500 cP) and long gel time to permit complete impregnation, mold filling and fiber wetting
- Appropriate curing characteristics to provide acceptable cycle times
- Adequate mechanical properties and physical characteristics to meet the performance requirements

RTM processes rely heavily on polyesters, vinyl esters and (for aerospace applications) epoxies, while SRM is almost exclusively based on polyurethanes.

2.3.1. Polyester and Vinyl Ester

In common with the hand-laminating industry, RTM has been dominated (in tonnage) by the use of polyester resins. Unsaturated polyesters are produced via a condensation reaction of organic acids (maleic and phthalic anhydride) with ethylene or propylene glycol to produce esters (Chapter 2). The styrene content of an unsaturated polyester is important in that it controls the resin viscosity and thereby the impregnation process. Increasing styrene content will decrease the viscosity but will increase the heat of reaction and peak exotherms at the expense of the final mechanical properties. Excessive styrene content may be detrimental to product quality since any residual monomer following curing or post-curing may continue to be lost in service with dimensional changes in the finished part.

2.3.1.1. Shrinkage Control Additives (Low Profile Additives or LPA)

Polyesters and vinyl esters exhibit a significant amount of shrinkage

FIGURE 7.10 Preform made by braiding.

upon curing (about 8%). This shrinkage can produce undesirable effects such as poor surface finish, out-of-dimensions, residual stresses and cracks. Shrinkage control additives or Low Profile Additives (LPAs) have been added into the resins to reduce the shrinkage. LPAs in the form of thermoplastic additives, have been widely used in molding compounds to produce molded parts requiring smooth surface and dimensional stability. A variety of thermoplastics include: polyethylene, polystyrene, polymethyl methacrylate, and polyacetate. The precise mechanism whereby shrinkage control is achieved is the subject of debate. However, it is generally agreed that during the curing reaction the shrinkage control additive and cross-linked unsaturated polyester phases must separate. The micro-voidage that arises from this compensates for the bulk shrinkage and reduces the effects of any dimensional changes or surface defects.

Although the major and desired effect is the reduction of surface shrinkage for cosmetic reasons, thermoplastic additives can have a number of effects on the processing characteristics of the resin and on the properties of the final composite as follows:

- Modified resin viscosity
- Reduced heat of reaction due to the dilution of the reactive mass
- Modified reaction rate
- Reduced laminate strength and modulus

2.3.2. Epoxies

Discussion on epoxy resin was presented in Chapter 2. Typically epoxy resins cost about four times as much as general purpose polyester and two times as much as vinyl ester resins. Epoxies have major performance advantages over general purpose unsaturated polyesters including higher strength, modulus and fracture toughness. The good adhesion of epoxies to substrates generally leads to a stronger interface with fibers, which, in turn, determines the performance of the composite. Epoxies generally have shrinkage of about 5%. For RTM applications, the most common hardener is a low viscosity (cycloaliphatic) amine. Gel times in the range of 2 minutes to several hours are possible by correct matching of the hardener and mold temperature. Cure times are typically 6 times the gel time and a secondary post-cure is usually required. Anhydrides are used almost exclusively for elevated temperature curing and provide extended pot lives at room temperatures with several days being practical.

3. MOLD FILLING

The objectives of mold filling in LCM are to fill the mold completely, to wet the fibers well, to avoid dry spots and voids, and to avoid modifying the fiber orientation during the filling process. The discussion on mold filling will be divided into two parts. In the first part, ideal filling conditions are assumed where flow through porous medium is examined. In the second part, problems and issues arising from the practice of filling will be discussed.

3.1. Part I. Theoretical Considerations

The flow of resin through a fiber preform is usually assumed to be equivalent to that of an incompressible fluid through a porous medium. Therefore, the physics of the fill phase during liquid composite molding is based on in-plane incompressible mass conservation and uses Darcy's law as a momentum balance.

The equation of mass conversation for the fluid phase can be written as:

$$\nabla.\bar{u} = 0 \tag{7.1}$$

where $\bar{u}$ is the superficial fluid velocity vector (that is the velocity at which the fluid actually travels, rather than the observed or macroscopic velocity).

Darcy's law in three dimensions can be written as:

$$\bar{u} = -\frac{1}{u}[K]\nabla p \tag{7.2}$$

In which $[K]$ is the permeability tensor, taking the form of a $[3 \times 3]$ matrix, as:

$$[K] = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

If the flow is predominantly one-dimensional, the above two equations can be significantly simplified. This is shown for the two cases of rectilinear and radial flows below.

Rectilinear flow. If the flow is rectilinear (such that the fluid velocities

in both the y and z directions are zero), then Darcy's law is reduced to the following equation:

$$u_x = \frac{Q_x}{A} = -\frac{K_{xx}}{\mu}\frac{dp}{dx} \tag{7.3}$$

where A is the cross-sectional area of the cavity. Figure 7.11 shows a schematic of rectilinear flow. The mass conservation equation is reduced to:

$$\frac{du_x}{dx} = 0 \tag{7.4}$$

Combination of the above two equations gives:

$$\frac{d}{dx}\left[\frac{K_{xx}}{\mu}\frac{dp}{dx}\right] = 0 \tag{7.5}$$

The Case of Constant Pressure at the Injection Gate

If the pressure at the injection gate is constant, and if the permeability and viscosity remain constant throughout the mold, then this equation implies a linear pressure distribution between the injection gate and the flow front. For example, if the resin pressure at the injection gate is P_o and the pressure at the flow front is 0 gauge, then the pressure distribution can be written as:

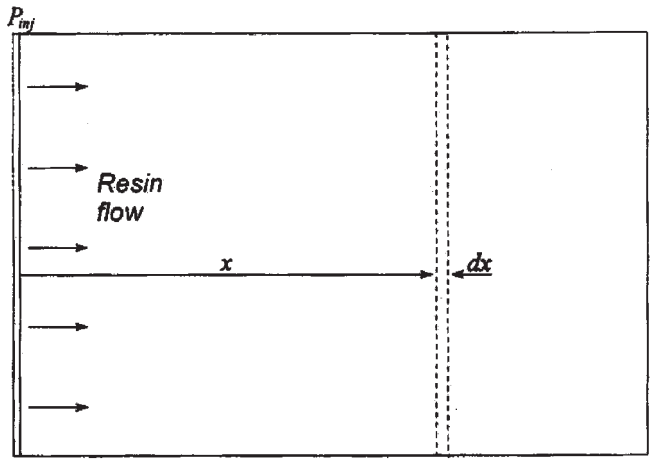

FIGURE 7.11 Schematic of rectilinear flow.

$$P = P_o\left[1 - \frac{x}{x_{ff}}\right] \tag{7.6}$$

where x_{ff} is the position of the flow front. The resulting pressure gradient can be substituted into Darcy's law to obtain an expression for the macroscopic flow velocity. Note that the superficial flow velocity is defined by Equation (7.3) where the macroscopic flow velocity is defined as:

$$v_x = \frac{Q}{A_{\text{cavity}}} = \frac{Q}{A\phi}$$

$$v_x = \frac{u_x}{\phi} = \frac{K_{xx}P_o}{\phi\mu x_{ff}} \tag{7.7}$$

where,

φ = the porosity and is equal to $(1 - V_f)$
v_x = the macroscopic flow velocity
u_x = the superficial flow velocity

It can be seen that the macroscopic flow velocity is independent of the distance from the injection gate. Equation (7.7) can be expressed as:

$$\frac{dx}{dt} = \frac{K_{xx}P_o}{\phi\mu x} \tag{7.8}$$

which can be written as:

$$xdx = \frac{K_{xx}P_o}{\phi\mu}dt \tag{7.9}$$

If the injection pressure is constant, integrating this equation from 0 to x_{ff} and from 0 to t_{ff} we have:

$$t_{ff} = \frac{\phi\mu}{2K_{xx}P_o}x_{ff}^2 \tag{7.10}$$

By substituting the mold length x_{ff}, this expression can be used to calculate the maximum fill time for the rectilinear flow under constant injection pressure. The above equation can also be arranged to determine the permeability:

$$K_{xx} = \frac{\phi\mu}{2KP_o t_{ff}}x_{ff}^2 \tag{7.11}$$

where the position of the flow front x_{ff} is determined at the corresponding time t_{ff}.

The Case of Constant Flow Rate at the Injection Gate

Alternatively if the injection flow rate is held constant, then it can easily be shown that:

$$t_{ff} = \frac{\phi A x_{ff}}{Q_o} \tag{7.12}$$

where Q_o is the constant injection flow rate.

It can be seen that now the fill time is directly proportional to the distance from the injection gate, and is independent of the resin viscosity and reinforcement permeability.

The pressure at the injection gate can be found by using Equation (7.7) as:

$$P_o = \frac{u_x \mu x_{ff}}{K_{xx}} = \frac{Q_o \mu x_{ff}}{A K_{xx}} \tag{7.13}$$

Equation (7.13) suggests that, for constant flow rate injection, the pressure at the injection port will increase as the flow front progresses.

Radial flow: If the resin is injected at the center of the mold from a point source, then flow will proceed radially until the resin reaches the mold wall. Figure 7.12 shows the schematic of radial flow. Darcy's law can be applied in radial coordinates:

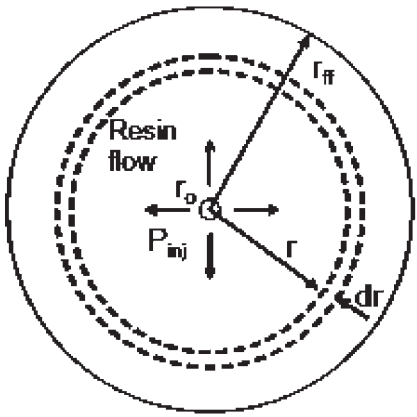

FIGURE 7.12 Schematic of radial flow.

$$Q_r = -\frac{K_r A}{\mu}\frac{dP}{dr} = -\frac{K_r}{\mu}2\pi rh\frac{dP}{dr} \tag{7.14}$$

where h is the thickness of the preform. Note that the volumetric flow rate is used as this allows the change in cross-sectional area of the flow front to be considered.

Assuming that the reinforcement permeability and resin viscosity remain constant throughout the mold, Rudd et al. [3] obtained the following equation for the pressure.

$$P = P_o \frac{\ln\left[\dfrac{r}{r_{ff}}\right]}{\ln\left[\dfrac{r_o}{r_{ff}}\right]} \tag{7.15}$$

where r_o is the radius of the injection port. This equation shows that the pressure decays rapidly as the distance from the injection gate increases. Equation (7.15) can be substituted into Equation (7.14) to obtain the macroscopic fluid velocity in the radial direction as:

$$v_r = \frac{Q_r}{A\phi} = \frac{K_r P_o}{\phi\mu r \ln\dfrac{r_{ff}}{r_o}} \tag{7.16}$$

If the injection pressure is held constant, then the time required to fill a region of radius r_{ff} is:

$$t_{ff} = \frac{\phi\mu}{2K_r P_o}\left[r_{ff}^2 \ln\frac{r_{ff}}{r_o} - \frac{1}{2}(r_{ff}^2 - r_o^2)\right] \tag{7.17}$$

For constant flow rate injection, the fill time is given as:

$$t_{ff} = \frac{\phi h\pi(r_{ff}^2 - r_o^2)}{Q_o} \tag{7.18}$$

and the resulting pressure at the injection gate is given as [from Equation 7.16)]:

$$P_o = \frac{Q_o\mu}{2\pi hK_r}\ln\left[\frac{r_{ff}}{r_o}\right] \tag{7.19}$$

3.1.1. Coefficient of Permeability

The coefficient of proportionality k (k_{xx} or k_r) is called the permeability of the reinforcement. According to theory, k is only dependent on the geometry between the fibers in the reinforcement (the pore space). Several models for the dependence of k on the fiber volume fraction have been proposed. The most cited is the Kozeny-Carman model, which predicts the quadratic dependence on the fiber radius r in addition to the dependence on V_f.

$$K = \frac{r^2}{4k_o} \frac{(1 - V_f)^3}{V_f^2} \tag{7.20}$$

The constant k_o is called the Kozeny constant and it attains a value of 0.7 for well-ordered reinforcements with uniformly distributed fibers (e.g. unidirectional prepreg). The effective values for the Kozeny constant for angle ply laminates at $\pm\alpha$ (Figure 7.13) are shown in Table 7.1.

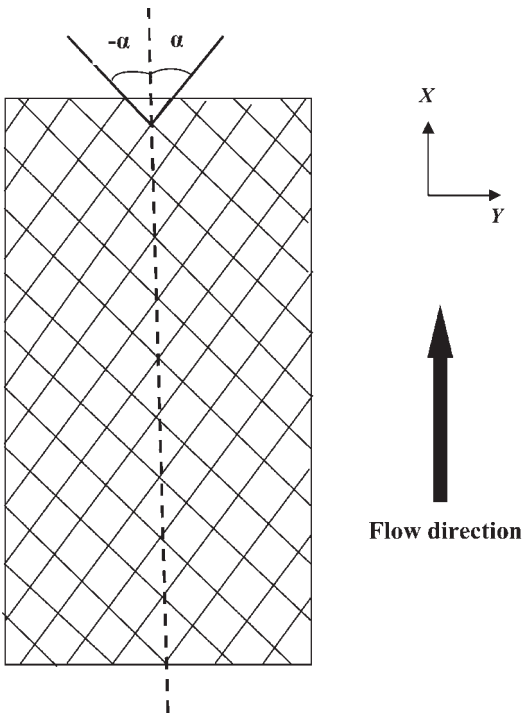

FIGURE 7.13 Flow in angle-ply laminate.

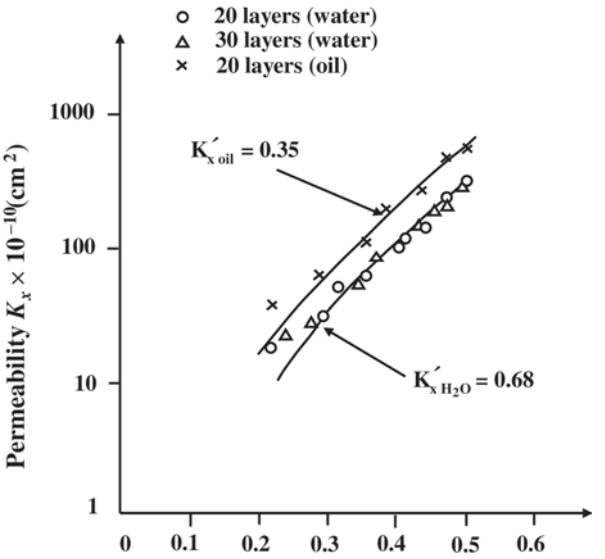

FIGURE 7.14 Axial permeabilities for a uniaxially aligned graphite fiber bed [5].

For flow along the fiber direction in unidirectionally aligned fiber beds, Lam and Kardos [5] show that the Kozeny-Carman equation predicts the permeability well with a Kozeny constant of $k_o = 0.68$ for water and $k_o = 0.35$ for silicone oil as permeants for the liquid volume fraction range of 0.25–0.5 (Figure 7.14).

For flow transverse to the fiber direction, using $k_o = 11$, Lam and Kardos [5] found that the data points fit well to the Kozeny-Carman equation for liquid volume fraction range of 0.25–0.5, as shown in Figure 7.15.

Lam and Kardos [5] found that for unidirectionally aligned graphite fiber reinforced resin prepregs, the ratio of the transverse to the axial fiber bed permeabilities is K_z/K_x =1/19 whereas Gutowski et al. [6] found a similar ratio of 0.7/17.9.

TABLE 7.1 In-plane Kozeny Constants for ±α Preform [4].

α	$k_{ox}(0°)$	$k_{oy}(90°)$
0	0.68	11.0
15	1.18	10.1
30	1.49	6.65
45	2.70	2.70

3.1.2. Effect of Off-Axis Fiber Orientations on Axial Permeability

Following the suggestion of Scheidegger and Marcus, the anisotropic axial permeability K_x can be represented by:

$$\frac{1}{K_x} = \frac{\cos^2 \alpha}{K_{x\,uni}} + \frac{\sin^2 \alpha}{K_{x\,90}} \tag{7.21}$$

where $K_{x\,uni}$ is the axial permeability for a unidirectional fiber bed, $K_{x\,90}$ is the axial permeability for a 0–90 bed of fibers, and α is the angle between the fibers in successive plies. Equation (7.21) can be written in terms of the Kozeny constants as:

$$k_x = k_{x\,uni} \cos^2 \alpha + k_{x\,90} \sin^2 \alpha \tag{7.22}$$

Figure 7.16 shows a comparison between experimental results and those determined from Equation (7.21).

For commonly used fabrics in LCM (e.g., with continuous strand mat or weaves), $r^2/4k_o$ should be seen as an adjustable model parameter with only weak coupling to the fiber or fiber bundle diameter.

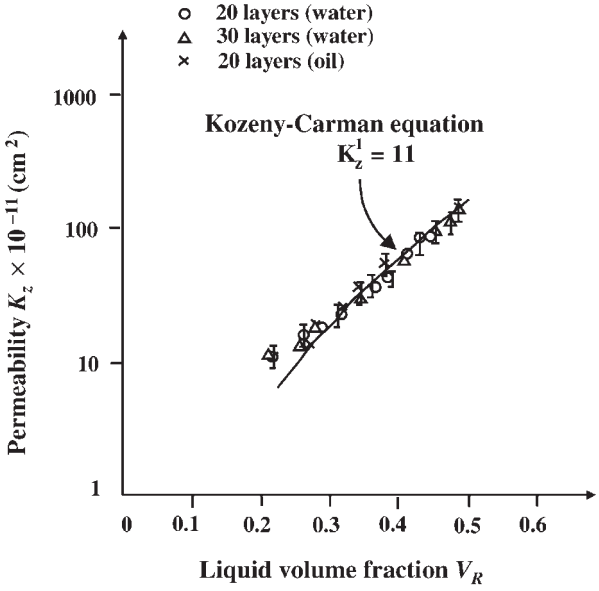

FIGURE 7.15 Transverse permeabilities during consolidation for a uniaxially aligned graphite fiber bed [5].

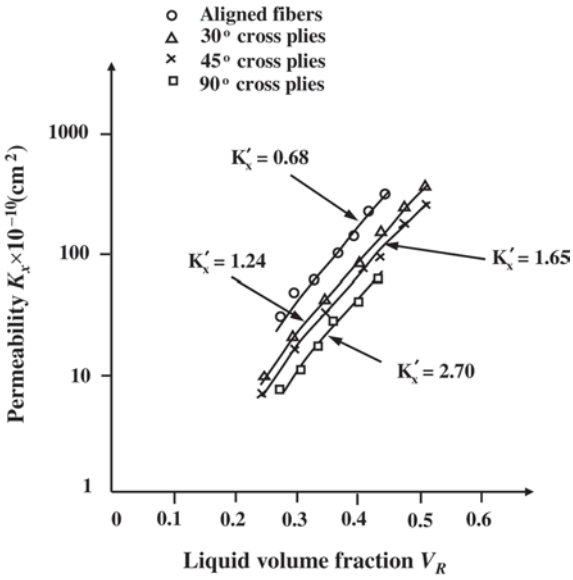

FIGURE 7.16 Axial permeability during consolidation as a function of ply orientation for a water permeant [5].

Continuous strand mats are approximately isotropic and have almost the same permeability in all directions (in the plane of the fabric). Many other fabrics, however, are strongly anisotropic and have different permeability in different directions.

The best way to use the Kozeny-Carman model is to use it as an interpolation formula for intermediate volume fractions between known values. Extrapolation should be done with extreme caution because the models are developed for idealized reinforcements. Table 7.2 shows typical values for the permeability of different types of reinforcement.

TABLE 7.2 Typical Permeability Data for a Few Reinforcement Materials [7].

Type of Material	Fiber Volume Fraction	Permeability (m^2)
Continuous glass strand mat	0.25	1×10^{-9}
Unidirectional glass (along fiber direction)	0.59	7.1×10^{-11}
Unidirectional glass mat (transverse to the fiber direction)	0.59	1.2×10^{-11}

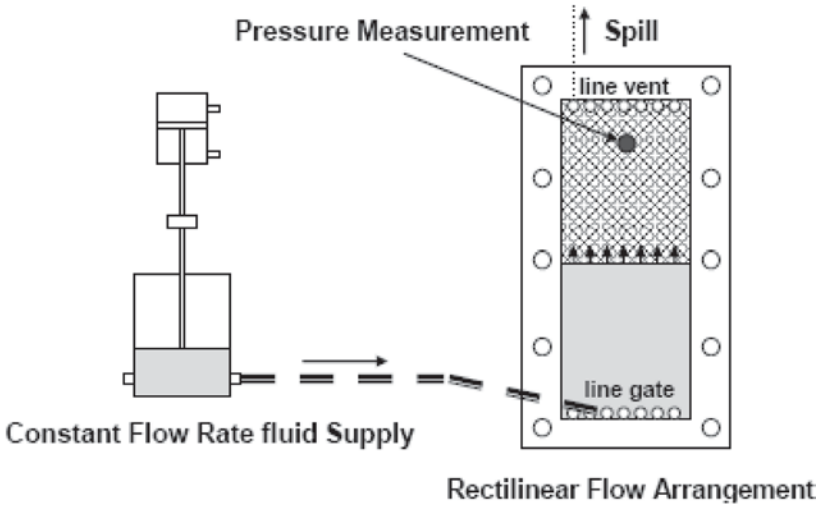

FIGURE 7.17 An experimental setup to determine the permeability of fiber preforms using rectilinear flow.

The permeability can be determined experimentally in several different ways (e.g., in a radial flow or unidirectional flow experiment). The experiments can also be done with either an advancing flow front (wetting flow or unsaturated) or a fully saturated reinforcement under steady-state conditions.

A convenient way to estimate the permeability is to use a rectangular mold where the resin is injected from one of the sides unidirectional to the opposite side. The other two sides are sealed tightly against the reinforcement so that the tow front becomes a straight line. Experimental setups to determine the permeability are shown in Figures 7.17 and 7.18.

One of the major sources of errors in permeability measurements is mold deflection, and it is a particular nuisance in the radial flow method because the smallest in-plane dimension of the mold (which governs the mold deflection) has to be larger than that of the unidirectional flow method. The major difficulty with the unidirectional flow method is preventing leakage at the edges.

3.1.3. Injection Strategies

The mold filling time and the quality of the part are affected by the mold-filling strategy (the way in which the resin is introduced and air is

vented out of the mold). The mold filling strategies can be divided into three main types:

1. *Point injection.* The resin is introduced through a port in the center of the part, the resin flows essentially radially into the reinforcement, and air is vented at the periphery of the part. Figures 7.12 and 7.18 show the schematic of the point injection.
2. *Edge injection.* This is accomplished by injection through an inlet at one edge of the part. The flow is more or less unidirectional over the part, and air is vented at the opposite side. Figures 7.11 and 7.17 show the schematic of edge injection.
3. *Peripheral injection.* The resin is introduced in a resin distribution channel around the periphery of the part. The flow is radially inward and air is vented at the center of the part. Figure 7.19 shows a schematic of the peripheral injection.

The mold filling time differs considerably between the different strategies, with peripheral injection being much faster than the other two. Depending on other problems that may occur, however, all three alternatives are commonly used. The three basic strategies can also be combined, as in multipoint injection, to obtain faster filling or better impregnation. The position of the inlet(s) and outlet(s) is crucial with all three strategies because dry spots or areas of high void content will result if the gates are improperly positioned.

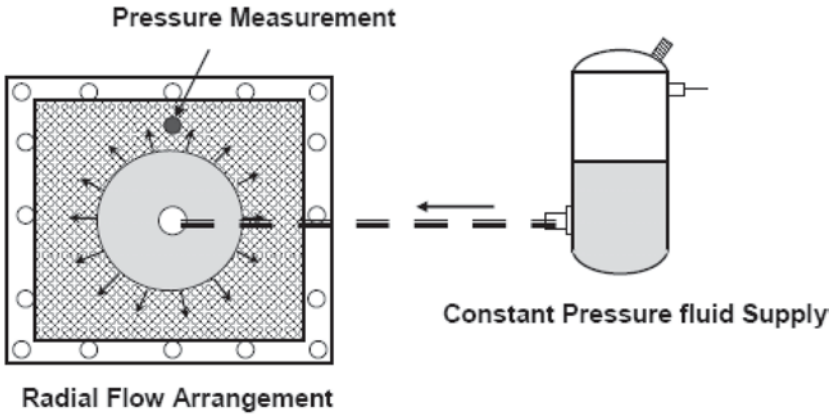

FIGURE 7.18 Experimental setup to determine the permeability of fiber preforms using radial flow.

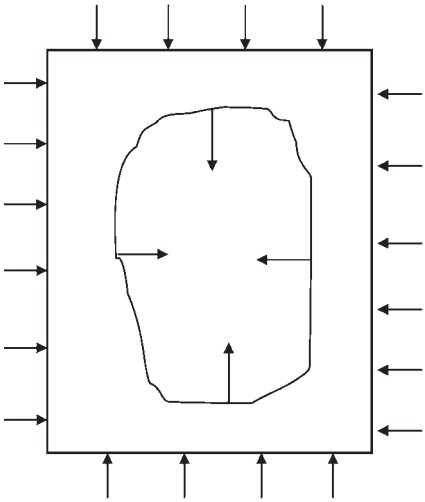

FIGURE 7.19 Peripheral injection.

3.1.3.1. Estimation for the Required Filling Time

The fill time can be estimated using the equations derived earlier. This is illustrated in the following example.

Example 7.1: Estimation of Fill Time for a Large Composite Part

It is desired to fill a plate made of glass fiber perform using epoxy resin. The dimension of the plate is 1 m × 1 m. The injection pressure at the gate is kept constant at 500 kPa. The viscosity of the resin is 800 cP. The permeability of the fiber preform is 1×10^{-10} m^2. Fiber volume fraction is 0.50. Determine the estimated time to fill the mold using the different techniques as follows:

a. Point injection with a 3 cm diameter of the injection port. Assume that the equation is valid over the whole domain of the plate.
b. Edge injection
c. Peripheral injection

Solution

a. Point injection
The time required to fill the space is given by Equation (7.17) previously as:

$$t_{ff} = \frac{\phi\mu}{2K_r P_o}\left[r_{ff}^2 \ln\frac{r_{ff}}{r_o} - \frac{1}{2}(r_{ff}^2 - r_o^2)\right] \quad (1)$$

The equation is valid for the region of radius r_{ff}. However the statement of the problem assumes that the equation is valid over the whole domain of the plate. Since the plate is a square 1 m × 1 m, the effective radius r_{ff} can be taken to be half the square root of (1 + 1) = (0.5)(1.414) m = 0.707 m. The injection port has a diameter of 3 cm giving r_o = 1.5 cm. Substituting the values as given in the problem statement and above information into Equation (1) yields:

$$t_{ff} = \frac{(0.5)(800\times10^{-3}\ \text{Pa - sec})}{(2)(10^{-10}\ \text{m}^2)(500\times10^{3}\ \text{Pa})}\left[(0707\ \text{m})^2 \ln\frac{0.707}{0.015} - \frac{1}{2}(0.707^2 - 0.015^2)\ \text{m}^2\right]$$

$$t_{ff} = 6{,}700\ \text{sec} = 1.86\ \text{hrs}$$

b. Edge injection

The characteristic dimension in this case is the length of the plate, or L = 1m. Equation (7.10) gives:

$$t_{ff} = \frac{\phi\mu}{2K_{xx}P_o}x_{ff}^2 = \frac{(0.5)(800\times10^{-3}\ \text{P.sec})}{(2)(10^{-10}\ \text{m}^2)(500\times10^{3}\ \text{Pa})}(1\ \text{m})^2$$

$$= 400\times10^{1}\ \text{sec} = 4000\ \text{sec} = 1.11\ \text{hrs}$$

c. Peripheral injection

For the peripheral injection, the distance is equal to half that of the edge injection. The time would be 1/4 that of the edge injection for the theoretical method.

For theoretical method, t_{ff} = 1000 secs.

The fill time for a given injection strategy can be reduced by:

- Decreasing the viscosity (raise temperature or change resin)
- Increasing the pressure (beware of fiber washing and mold deflection)
- Changing the reinforcement

The most dramatic change in fill time, however, can be achieved by a reduction of the flow length through:

- Additional inlets
- Resin distribution
- Other changes in the injection strategy

The simplest way to estimate the fill time more carefully is to guess the flow path during filling. The longest flow distance is then estimated from the guess and the fill time can be computed from the formula for unidirectional filling. This method is surprisingly powerful, at least in cases where it is easy to guess the flow path. A useful method to guess

the path is to try to imagine how a heat wave from a sudden temperature rise at the inlet would propagate through the part. In the preceding example and point injection the flow front will develop as a circular front, starting at the inlet, until it meets the closest side. From then on, the front will tend to move unidirectionally in both directions toward the far side (if there is no leakage at the sides). A reasonable estimate of the fill time is somewhere between the time to fill radially and the time to fill unidirectionally to the far side (flow distance 1.5 m). However, the estimate of the fill time shows that a more detailed study of injection strategy and process parameters is necessary because it is difficult to reach an acceptable production economy with a fill time of about 1 hour. An obvious action would be to choose a more efficient resin distribution method than a one-point inlet (e.g. peripheral injection or a multipoint injection). In addition, it would be worthwhile to try to lower the viscosity and increase the pressure.

There are several phenomena that occur in practice that invalidate the assumptions that lead to the fill time formula. Examples of such phenomena are:

- Fiber washing
- "Race tracking" at edges or on top of the reinforcement
- Significant mold deflection
- Significant cure during injection
- Significant pressure drop in resin distribution channels
- Non-Newtonian behavior of the resin
- Binder dissolution in the resin (increases the viscosity)
- Preform variations

The preceding formulas are useful for rough estimates but can sometimes yield significantly shorter fill times than in reality. More accurate predictions can be obtained through computer simulations based on Equations (7.2) and (7.3), and this is the recommended method when sufficient time and resources are available.

One problem with computer simulations is to obtain realistic values for the material parameters, particularly the permeability. As presented before, permeability depends on many parameters and it is difficult to have an accurate prediction for this property at all locations along the flow path at different temperatures and wetting conditions. These depend on the preforming step (fiber orientation) and to some extent on the loading step (improper location that leads to locally high- or low-fiber volume fraction). However considerable progress has been made on this problem and it seems likely that the accuracy of simulations will increase further as more progress is made.

3.2. Part II. Problems and Issues Related to Mold Filling

The discussion in part was based on the assumption that the flow behaves normally and that there are no deviations from the ideal situation. However, in reality, there are many issues and problems associated with mold filling. These include: different types of permeability, race tracking, fiber washing, occurrence of voids, limited fiber wetting time, and dry spots.

3.2.1. Different Types of Permeability of the Fiber Perform

Permeability can be defined as the compliance to the flow, i.e., the ability of the preform to let the flow go through it. This definition is simple but permeability of the fiber preform is probably one of the most challenging aspects in LCM. Permeability is influenced by the physical characteristics of the reinforcement; type of fabrics used; and thickness of the preforms, including pore size, roughness, tortuosity and channel lengths. These factors, in turn, are likely to be influenced by the compaction pressure, fiber volume fraction, orientation of the fibers, fiber architecture, history of compression of the preform, temperature, wetness or dryness of preforms, part thickness, and stacking sequence.

When a liquid is forced to flow through a simple layer of fiber perform with fibers all oriented along one direction, two types of flow front are observed: macro flow front and micro flow front, as shown in Figure 7.20. The reason for this is because, inside a fiber bed, there are two types of flow channels. One is the large channel that arises from the gaps between the tows. The other is the small channels that arise from the space between fibers within a tow. When the flow is dominated by the applied pressure gradient rather than capillary effects, the resin proceeds faster outside the fiber bundle than within and creates voids as the faster flowing resin enters the fiber bundle. Unless the voids can be flushed from the fiber bundles they are retained and the final void content depends on the cavity pressure. At low flow rates, the flow front is able to progress more rapidly within the fiber bundle than outside it. At moderate flow rates the capillary and viscous flow rates are approximately equal which results in more or less simultaneous impregnation of the small and large gaps between the fibers. At high flow rates the viscous forces dominate and only the large capillaries become infiltrated.

The permeability also depends on whether the fibers are dry or wet. In the case of advancing flow front (unsaturated permeability), the permeability is different from the case of saturated flow when the fibers are already wet (saturated permeability).

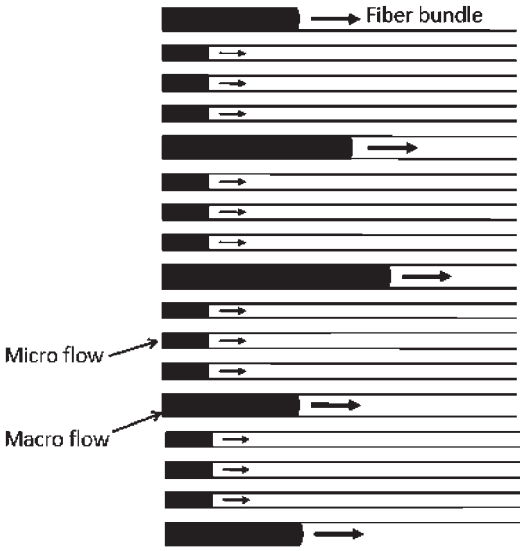

FIGURE 7.20 Macro flow front and micro flow front.

3.2.2. Race Tracking

In LCM, particularly RTM, where two solid mold surfaces on both sides of the preforms are used, it is essential that there are no large gaps between the preform and the mold wall. The existence of the large gaps will provide easy paths for the resin to flow. One example of areas of large gaps is shown in Figure 7.21. In this case, the preform has a tendency to follow the "inner lane" around corners so that the fiber content

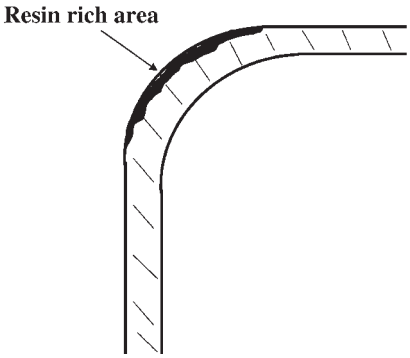

FIGURE 7.21 Race tracking due to a large gap between preform and mold wall.

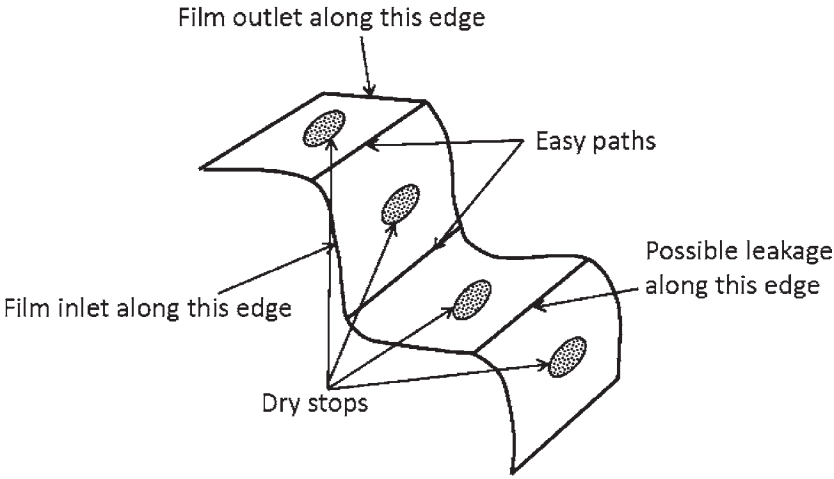

FIGURE 7.22 Race tracking and dry spots.

becomes low or negligible at the outer lane. One way of reducing the problem is to "compensate" the preform tool and modify the geometry so that the preform fills the real mold well at corners. The problem with varying fiber content at the comers is less pronounced for high fiber volume fractions.

Another example of race tracking is shown in Figure 7.22. In this case, the regions of large gaps occur at the bend lines. The flow will follow these gaps along the edge and along the bend lines. The flow then follows along radial directions. If air pockets are not completely removed, the flow cannot enter into the central part and these become dry regions. The dry region will decrease in size during the rest of the injection due to the increasing pressure around it, but a permanent dry spot will usually result if the enclosed region is large enough. The best solution to address this problem is to adjust the preform by increasing the volume fraction at a race track or by compensating the preform geometry. It is also worth considering a change in the injection strategy that makes the formation of dry spots less likely.

3.2.3. Fiber Washing

The reinforcement can be displaced significantly by fluid forces if injection velocity is too high or equivalently if the injection pressure is too high compared with the friction forces between the mold and the reinforcement. The problem will be less pronounced at higher fiber volume

fractions when the compaction pressure is higher. As a consequence, it is harder to hold the reinforcement in place. The optimum fiber volume fraction depends on the type of reinforcement used. One way of estimating suitable processing conditions is to measure the "bulk factor" of the fabric (i.e. the fiber volume fraction when the fabric is uncompressed). Fiber volume fractions below this level are completely unacceptable because they will result in fiber washing, flow on top and so on. On the other hand, too high of a fiber volume fraction will make it difficult to close the mold and also reduce the permeability so much that it will be difficult to fill the mold in an acceptable time. Fiber washing changes the orientation of the fiber and this has detrimental effects on the final properties. Fiber washing usually occurs at locations close to the inlet of the resin.

3.2.4. Occurrence of Voids

One of the fundamental problems to be addressed during the impregnation phase is the removal of air from the mold cavity. This is necessary to produce high quality components with low void content. Air is present both within and between the fiber bundles and the displacement of each is necessary for minimum voidage.

Low pressure processes such as vacuum impregnation are best operated with the mold inclined so that the flow can proceed vertically upwards. This ensures that the effective pressure gradient is controlled by the suction pressure and minimizes race tracking effects.

Due to the dual flow mechanisms discussed earlier, where low void contents are critical, it is important that care is taken to control the resin flow rate such that it proceeds with a speed that is comparable with air removal from within the fiber bundles. This may need to be determined empirically since the micro-scale flow depends upon the resin properties and fiber architecture. Flow front velocities between 0.1 m/min and 0.6 m/min were found to be successful for a glass/polyester system, where typical resin viscosities of 300 cP are common. For vacuum driven processes, it is also important to avoid any air ingress following the mold filling phase which can be done conveniently by maintaining a positive pressure in the mold between mold filling and resin gel.

3.2.4.1. High Void Content at Outlet

Voids are usually formed at the flow front during mold filling. The voids move with the resin, but there will always be a region close to the flow front where the void content is higher than it is in the rest of the part.

To solve the problem, one can either use vacuum assistance during filling or allow a longer time for resin flow (resin flushing) after complete mold filling. Optimization of the process parameters, particularly injection pressure and temperature, can also reduce the problem.

3.2.4.2. High Void Content and Vacuum

Vacuum assistance during mold filling will usually reduce the void content significantly. The void content will be approximately proportional to the absolute pressure in the air inside the mold during mold filling. The mold, the sealings, and all gates, however, must be vacuum tight for this to be true. Even small leaks may be sufficient to give a very high void content. The sensitivity to leaks depends on the injection strategy. Point injection is usually the most robust method and peripheral injection the most sensitive method (air is "sucked" into the molding). Another cause for this problem can be the presence of volatile components in the resin. This can be tested by placing a beaker with resin inside a transparent container that is evacuated to the desired vacuum level. It is normal for some dissolved gas to come out of solution, but if gas bubbles continue to form after a long time they are most likely the result of evaporation of volatile components. For some resins this effect can be so strong that the resin "boils over." The best solution in this case is to change to a resin that can be processed at the desired vacuum level. An alternate solution is to reduce the vacuum level until the problem disappears.

3.2.5. Fiber Wetting

One of the limitations of the liquid molding processes compared to those based on preimpregnated materials is the relatively short length of time that elapses between the macroscopic impregnation of the preform and the rapid viscosity rise that accompanies the curing reaction. One of the consequences of this is the limited time available for the wetting of the individual fibers and development of the fiber-matrix interface. High speed processes such as SRIM involve such rapid gel of the resin system that the time available for fiber wetting may be limited to a few seconds. Conventional RTM almost certainly provides a greater window for wetting over the majority of the area of the mold but in a limiting case, i.e. adjacent to the vent, the wetting time may be limited to 1 minute or less in extreme cases. Because of the limited time available for wetting and bond formation the compatibility of the fiber surface (imparted by the sizing) and the resin system is of critical importance.

3.2.5.1. Effect of Fluid Surface Tension

It was presented in Chapters 1 and 2 that surface tension of the fluid plays an important role for the wetting of fibers. It is essential that the surface tension of the fluid resin be less than that of the fibers so that wetting can occur. The value of the fluid surface tension may also have an effect on the speed that wetting takes place. This is because the capillary action of the fluid in small channels has influence on the micro flow. By using different permeants with a range of viscosities and surface tensions and by changing the flow rate, the effect of the capillary number on void formation and retention was studied. The capillary number C_a is defined as:

$$C_a = \frac{\mu v}{\gamma} \tag{7.23}$$

where,

μ = the Newtonian viscosity.
v = the interstitial velocity.
γ = the fluid surface tension.

It was established [8] that a critical value of capillary number exists. Figure 7.23 shows the void content versus capillary number for a number of glass fiber preforms and oil. It shows a critical capillary number of 0.0025, below which the void content increases exponentially with decreasing capillary number. Above the critical value the void content was found to be negligible. Equation (7.23) shows that for a certain fiber network, the capillary number is inversely proportional to the surface tension of the fluid. The existence of a critical capillary number therefore means that there is also a critical surface tension of the fluid above which a large number of voids may occur.

A large body of work in this field has been collated by Lundstrom [9], which concludes that the architecture of the preform influences both the formation and the transportation of voids and that the following steps should be taken to minimize their occurrence in RTM laminates:

- Resin degassing
- Vacuum assistance during impregnation
- Positive pressure following mold fill and during heating and curing
- Purging the cavity with an excess of resin following first fill

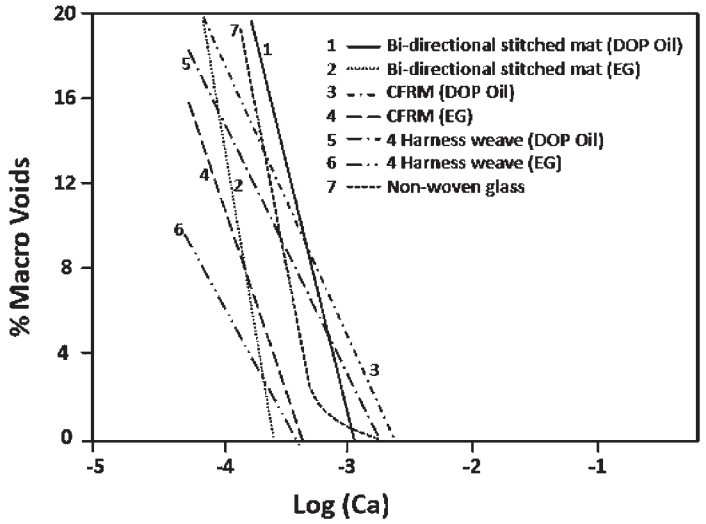

FIGURE 7.23 Void content versus capillary number (reproduced from Patel N., Rohatgi V. and Lee L.J. "Influence of processing and material variables on resin/fibre interface in liquid composite moulding," *Polymer Composites,* April 1993, Vol. 14, No. 2, pp. 161–172, with permission).

3.2.6. Dry Spots

Large spots with unimpregnated reinforcement can occur, even without race tracking, due to improper position of the injection or ventilation gates. The severity of the problem can vary. A longer time for resin flow out of the outlet gate (resin flushing) may be sufficient to solve the problem of the dry spot close to an outlet. In other cases, it may be necessary to move the outlets in the mold. If the mold is made from composite material (e.g. mass cast or laminated), then this may require making a completely new mold. With steel molds, new holes can be drilled and old ones can be filled if necessary.

3.3. Maximum Mold Filling Time

The mold filling time depends both on the permeability of the reinforcement and on the viscosity of the resin. As a rule of thumb, the catalyst system of the resin and the processing temperature can be chosen so that the gel time is about three times longer than the fill time. The time when the viscosity increases so much that no flow can occur is sometimes called the noninjection point or NIP time. The NIP time is related

to the gel time of the resin, but it occurs considerably earlier because a moderate increase in viscosity (compared with gelation) will already make further flow impossible.

Most resin systems that have viscosity below 1 Pa·s (1000 cP) can be resin transfer molded. Even higher viscosity can be accepted, but the price for this is usually a very long injection and cure time. High viscosity systems can often be preheated before injection so that the viscosity is reduced sufficiently. A fairly low temperature increase can already be sufficient to reduce the viscosity to the recommended level because the viscosity dependence on temperature is exponential.

4. IN-MOLD CURE

4.1. Fundamentals

The resin cure must proceed in such a way that the curing reaction is slow or inhibited in a time period that is dictated by the mold fill time plus a safety factor. Otherwise, the increase in viscosity will reduce the resin flow rate and prevent a successful mold fill. On completion of the mold filling, the rate of cure should ideally accelerate and reach a complete cure in a short time period. There are limitations, however, on how fast the curing can proceed set by the resin itself, and by heat transfer rates to and from the composite part. An ideal resin processed in optimized conditions should have:

- A suitable and low resin viscosity during mold filling
- A short cure time from completed mold filling to demolding
- No material defects
- No shrinkage

4.2. Optimization of Cure

The most common objective for cure optimization is to minimize cycle time. Other factors to be considered are:

- Residual stresses
- Warping
- Void formation
- Surface quality
- Special knowledge of design work for composites

The parameters for cure optimization are: variations of the resin cure

system, temperature control during cure, and time. Although the parameters cited here are limited to three there is a large number of degrees of freedom within these high-level parameters. First, it is necessary to identify the primary function in the system we aim to control. From a theoretical point of view, the key function is the reaction rate.

Figure 7.24 is a schematic illustration of the dependence of gel time and complete cure time on resin reactivity. Resin reactivity can be changed by altering the temperature or changing the resin formulation. In this figure, the process window is formed by the common part of the rectangle formed by dashed lines and the lines indicating the time to gelation and complete cure. The rectangle is formed by the horizontal lines for fill time and required maximum cycle time and the vertical lines by the requirement for complete cure and no thermal degradation.

Several choices exist to optimize cure. The most straightforward and obvious are:

- Use of existing knowledge from similar material combinations
- Use of guidelines from resin manufacturers
- Small-scale tests to guide in the choice of parameters
- Fundamentally based calculations
- Full scale tests in the production mold

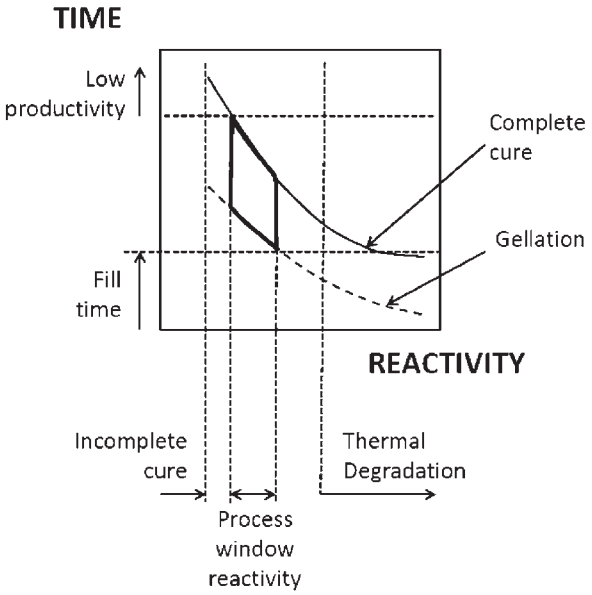

FIGURE 7.24 Processing window.

The use of simulation tools (e.g. computer programs) to calculate curing conditions is an area of great interest and is increasingly used to optimize cure for several processes, including LCM. However there are several obstacles to this advanced route, such as the need of:

- Skill to use computers
- A computer and a suitable program
- Accurate material properties for all constituents
- Accurate kinetic model for the resin

In addition to the above, experience and a good knowledge of processing is needed to evaluate the results from the simulation. The key problem today is often the last point (i.e., to obtain a sufficiently accurate kinetic model). Because these models are different for all resins and also different when the curing system is changed, the option is often only one: to obtain the model by one's own measurement. Hence, skill, knowledge, instrumental capacity, and quite a lot of experimental work are needed just to obtain a model. In addition, fiber sizing can influence the cure significantly, adding one more factor to take into account.

4.3, Cure Problems

Cure problems can be divided into two types: problems that give material defects and problems that make the process inefficient. Some examples of common problems of the first type are discussed below.

4.3.1. Delaminations

Delaminations can occur during cure as a result of high internal stresses. Those stresses develop due to resin shrinkage and thermal volume changes. The level of stresses depends on several material properties, such as Young's modulus, Poisson ratio, and thermal coefficient of expansion for both the resin and fibers. The level of stresses also depends on several conditions, such as fiber orientations, fiber volume fraction, and part geometry. The strength of the matrix plays a primary role for delaminations to occur, but the solution to delamination problems is usually not to increase matrix strength. In addition, the matrix material is changing during the curing process, and all matrix properties vary with the degree of cure. At low degree of cure, therefore, both modulus and strength are low regardless of matrix type.

Important parameters that affect delamination are:

- Thick composite parts

- Geometrically complex parts (varying thickness and closed parts)
- Resin with high shrinkage
- High temperature variation during the cure process

Possible actions to solve delamination problems are:

- Reducing temperature and, hence, prolonging cure
- Controlling cure propagation in thick parts by curing from inside to outside (hollow parts) or curing sequentially along the part, which can be done by partial heating of the mold
- Changing the resin system to one with less shrinkage or using additives that reduce shrinkage (this will create micro voids)
- Increasing pressure during cure

4.3.2. Surface Finish

The surface finish can be good in LCM but is usually good on one side of the laminate. A prerequisite for a good surface finish is to have a high gloss mold surface finish. The mold material and the release agent can also influence the surface finish indirectly. The primary cause of rough surface is resin shrinkage, provided the mold surface has a high gloss. Hence, if a good surface is required some action must be taken to reduce the resin shrinkage.

Possible actions to obtain a good surface finish are:

- Using high temperature on the mold side, where high surface finish is required, combined with internal mold pressure during cure
- Using LPA (low profile additive) resin systems

4.3.3. Porous Areas

Porous areas in LCM are often caused by mold filling problems. However, other causes also exist (e.g., high temperatures during cure may evaporate resin monomers or dissolved gas that form voids). Actions to be taken to optimize cure for minimum void content are:

- Degassing of resin before injection
- Reducing temperatures during cure

4.3.4. Incomplete Cure

The reactions are seldom allowed to go to completion in the mold. The

usual practice is to let the part cure until it is sufficiently stiff to de-mold and then to perform a post cure either in an oven or at room temperature. If the degree of cure is too low at de-molding, then a number of problems can occur:

- Inability to de-mold without damaging the part
- Permanent deformation of the part

Solutions to these problems are to increase the cure temperature, to let the part cure for a longer time in the mold or to change the resin formulation. It is a good idea to make a serious effort to optimize the cure cycle and resin formulation if incomplete cure should occur.

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6. HOMEWORK

1. It is desired to fill a plate made of glass fiber preform using epoxy resin. The dimension of the plate is 1 m × 1 m. The injection pres-

sure at the gate is kept constant at 500 kPa. The viscosity of the resin is 800 cP. The permeability of the fiber perform is 1×10^{-10} m^2. Fiber volume fraction is 0.50. Determine the estimated time to fill the mold using the different techniques as follows:

a. Point injection with a 3 cm diameter of the injection port. Assume that the equation is valid over the whole domain of the plate.

b. Edge injection

c. Peripheral injection