LESSONS LEARNED WHILE DESIGNING LOW-VOLUME CLOSED-MOLD PROCESSES TO REPLACE OPEN-MOLD LAMINATION

Rutz, CT
Cook Composites and Polymers (CCP)

Rutz@ccponline.com
Voice phone (816) 391-6183
Fax phone (816) 391-6254
PO Box 419389
Kansas City, Missouri 64141
United States of America

During the past several years, clean air initiatives have focused on reducing photochemical smog by controlling the release of Hazardous Air Pollutants (HAPs) from the Open Mold Lamination process. These initiatives have prompted using low styrene materials, agents to suppress solvent evaporation and new application processes. These solutions have reached the point of diminished returns, which has contributed towards a renewed interest in low-volume, closed-mold production.

A variety of closed molding systems have evolved as alternatives to open molding. All are variations on resin transfer molding (RTM). Marketing activities have produced a wide array of registered trade names and acronyms. A few examples are:

Vacuum Infusion
Seamann Composites Resin Infusion Manufacturing Process (SCRIMP®)
Shell Laminate RTM (Light RTM)
Closed Cavity Bag Molding (CCBM®)
Multiple Insert Tooling (MIT®) RTM
Zero Injection Pressure (ZIP®) RTM

A trade study is presented to examine the production cost for open molding and four closed molding alternatives. The five basic process features inherent to any RTM process are reviewed and contrasted. Differences in tooling cost and complexity, cycle times, thickness tolerances, design flexibility, production run sizes, tool life, storage requirements and workspace footprint are some of the considerations presented. Fixed and variable costs for a wide range of production run sizes are considered, and trade cost comparisons are reviewed.

The Design and Prototyping methodology is reviewed. The importance of designing the part and ply kit prior to upper mold fabrication is discussed. Mold design details that affect production robustness are presented for consideration. The effects of upstream production processes on process design are presented. Similarly, the effects of process-induced changes in the part design on downstream production processes are described. Lessons learned and Best Practices are described and discussed for four variations of RTM.

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1.0 Closed Molding Processes

Closed molding is a broad category of fabrication processes in which the composite part is produced in a mold cavity formed by the joining of two or more tool pieces. There are many variations of the closed molding process, each having a unique or distinctive aspect. For the purposes of this introduction, these variations are categorized into two types: Compression Molding and Liquid Injection Molding.

Compression Molding processes utilize either Sheet Molding Compound (SMC) or Bulk Molding Compound (BMC). These compounds contain reinforcing fiber, fillers, resin and curing agents. High filler contents result in a higher part density than is typical for open molded parts. Typical cycle times of a few minutes are achieved with a combination of rapid hydraulic mold closure and curing at elevated temperatures. A large number of parts (thousands to tens of thousands) are required to justify the needed capital expenditures. Liquid Injection molding processes include Reaction Injection Molding (RIM), Structural Reaction Injection Molding (SRIM) and Resin Transfer Molding (RTM). The liquid resin injection for RIM and SRIM begin with an empty mold cavity. RIM and SRIM typically use highly reactive resins such as urethanes, and are well suited to high rate production. In general, neither compression molding nor RIM/SRIM are viable alternatives to typical open mold production. This is primarily due to the limited production quantities of typical open molded parts.

The best alternative for open mold production is Resin Transfer Molding. For RTM, the liquid resin injection follows once the mold is first loaded with reinforcement fibers, cores, etc. RTM processes produce parts with strengths, stiffnesses and weights that most closely resemble typical open mold parts. Cycle times can range from a few minutes for small parts, to upwards of several hours for large parts. A wide variety of resin chemistries are used according to the design end-use requirements.

1.1 Resin Transfer Molding Processes

All RTM processes produce a part in a closed cavity. In every variation, the dry reinforcing fiber and cores are placed into the mold cavity, the mold set is closed, and liquid resin is transferred to the cavity. Flow of liquid resin into and through the reinforcing pack is inherent to any RTM process. Flow is achieved with a pressure drop between the supply and vent locations. Without a pressure drop, there is no fluid flow.

Any Resin Transfer Molding process can be described with five process features: Resin Pressure Head; Resin Transfer Scheme; Upper Mold Type; Mold

Clamping Method; Mold Open-Close Method. For each of these process features, there are three or four common variations. These variations are presented in table form, followed by a basic description of each feature variation and examples of commonly known variations.

Resin Pressure Head	Resin Transfer Scheme	Upper Mold Type	Clamping Method	Open- Close Method
Pressure to Vacuum	Discrete Port	Bag Film	Vacuum Clamps	Hand Lift
Pressure to Atmosphere	Edge Manifold	Silicone Multi-Use	Mechanical Clamps	Mechanical Device
Atmosphere to Vacuum	Face Manifold	Shell Laminate	Pneumatic Clamps	Pneumatic Actuators
	Interlaminar Manifold	Rigidized Laminate	Hydraulic Clamps	Hydraulic Actuators

Table 1: Variants of Five Features describe an RTM process.

Resin Pressure Head: The first and most significant feature, this is the generalized state of pressure across the resin from injection point to vent point; it is the driving force that causes the resin to flow through and saturate the fiber pack. The resin pressure head can be described with two words. The first word describes the condition at the injector location and the second word describes the condition at the vent location. Common variations are: Pressure to Vacuum; Pressure to Atmosphere; Atmosphere to Vacuum. These scenarios form the basis for the differences between the common definitions for Vacuum Assisted Resin Transfer Molding (VARTM), Resin Transfer Molding (RTM) and Vacuum Infusion, respectively.

Resin Transfer Scheme: This feature describes the plumbing pathway used to transfer the resin into the fiber pack. The first typical pathway is Discrete Port. Here, the resin is introduced at specific points called ports or injectors. The second pathway is the Edge Manifold. The Edge Manifold is an unobstructed channel that runs along the part perimeter and provides the resin pathway into the fiber pack. The third pathway is the Face Manifold, in which the resin is introduced below or (usually) above the fiber pack using a resin distribution system usually in the form of unobstructed channels. In its simplest form, the Face Manifold distribution system can be nothing more than ordinary bubble wrap packing material. The fourth pathway is the interlaminar manifold. Here, a lamina with a high permeability is placed within the laminate stack.

Upper Mold Type: From a functional standpoint, there are two categories of upper mold. Flexible molds are made from vacuum bagging film or a re-usable silicone elastomer. Rigid molds can be made from any number of materials. They can be thin glass laminates, as is the case for Shell Laminate upper mold.

They can be thick glass laminates that can be further reinforced with steel or wood. The flexible mold types can be used with die locked parts provided the lower mold has provisions to mold the negative draft. The rigid mold types require a properly drafted part.

Clamping Method: Vacuum clamps are a very useful and practical way to clamp molds together. In general, vacuum clamps consist of two rigid shells that come into contact with a rubber seal between them. These shells form the boundary of a cavity. When vacuum is applied to the cavity, atmospheric pressure forces the shells together. The planform size of the cavity and the level of vacuum will determine the magnitude of the clamping force. Full vacuum exerts approximately 15 pounds per square inch on the clamp area. Vacuum clamps are fast acting when properly designed and executed. Mechanical clamps are generally very robust and capable of very high clamping forces. Screw type and break-over type clamps are two common examples. Both require a certain amount of time and labor to actuate. Screw type require more time and labor to actuate than break-over types. Pneumatic clamps generally consist of two horizontal and parallel platens and an air bag. The platens are held a fixed distance apart by a number of large threaded rods with heavy duty nut elements positioned above and below the upper platen. This allows for some variation in the height of the closed mold set. The mold set is shuttled into position between the two platens. There is only a small empty space between the mold set and the upper platen. An air bag built into the lower platen inflates and lifts the mold set upward against the upper platen. Clamping forces of 100 psi are easily attainable. The speed of actuation can be somewhat slow due to air compressibility and supply. There are two types of hydraulic clamping systems. The first is a platen press. The second type uses a number of hydraulic cylinders placed around the mold perimeter. Both are capable of high clamping forces and rapid actuation. Hydraulic clamping systems are costly relative to any other method of clamping.

Manipulation Method: Mold Manipulation is required to accommodate the process operations of placing the reinforcement into the mold cavity, closing the mold set for the resin transfer operation, and subsequently opening the mold set for removing the finished part. Manipulation can be achieved in a number of ways. For small parts, manual (by hand) manipulation is perfectly adequate. For parts larger than a couple of square feet, manual manipulation requires two persons. Manual manipulation is not practical for parts larger than 10 square feet. Whenever manual manipulation is used, provisions for holding and storing the upper mold are necessary to ensure proper mold handling and care. Mold manipulation can also be accomplished with a variety of mechanical devices. There are many commercially available and relatively inexpensive automobile lifts that use jack-screw actuators. These auto lifts can readily be adapted to serve as large mold manipulators. Chain or wire rope hoists can be used for various mold sizes. Apart from hoists, there are three categories of manipulators that use wire cable: Positioners; Retractors; and Balancers. A Positioner uses a friction break to keep an item in a certain position. Downward movement is easy, but the full weight of the item must be lifted to reposition the item upward. A Retractor uses a coil spring to retract an item upward when no downward force is applied. Minimal effort is required to hold the item at the adjusted position, and effort increases as the item is positioned lower. A Balancer can be adjusted so that objects can be moved up or down with ease, and held at any position within a certain range. A true Balancer features a tapered drum to keep tension constant over the specified travel. The tapered drum reduces the moment arm as the spring tension increases, maintaining a constant tension on the cable. Properly selected, two or more Balancers are an ideal means to effect upper mold manipulation. Balancers are available according to the weight they will support. Common classes are: 5 lbs or less, 5 to 25 lbs, 25 to 100 lbs, and 100 to 200 lbs. Compressed air cylinders provide an inexpensive means of manipulating large molds. Manipulation is somewhat slow due to the compressible nature of air. Hydraulic manipulators provide the fastest actuation at the greatest cost.

1.2 Selection of Specific RTM Processes

For the established open molder who converts to resin transfer molding, there are three process categories that stand out as excellent alternatives. Each provides labor savings that offset the additional tooling costs. Each has certain advantages and disadvantages. The conclusions presented in the following sections pertain to typical part run sizes of several hundred to several thousand units.

1.2.1 Conventional RTM

For parts that are not gel-coated and of small to moderate size, conventional RTM is the process of choice. Resin transfer is achieved with high pressure through a discrete port located at or near the part center. The mold set is robust in order to react the high injection pressures. Venting is usually to atmosphere. Clamping and manipulation utilize hydraulic actuators or mechanical clamps and pneumatic actuators. Tooling costs are relatively high and justified based upon rapid cycle times and relatively large production runs exceeding 1,000 units.

Conventional RTM features the fastest cycle times of any RTM process. This is accomplished by minimizing the fill times, the cure times and the manipulation times. The fill time is minimized by using high pressure to inject the resin. The high pressure injection places stresses on the mold skin that must be reacted with structural elements, which adds to tooling cost. The cure time is minimized with two actions: Heating the mold to drive the chemical reaction ; and de-molding the part “green” (prior to full cure). Because the resin has not fully cured, holding fixtures are sometimes necessary to prevent part warpage. The manipulation times are minimized with hydraulic clamps/actuators. Mechanical

Clamps and Pneumatic actuators can be used at lower cost, but with an associated decrease in speed.

1.2.2 Shell Laminate RTM

For gel-coated parts, the process of choice is Shell Laminate RTM. This uses a low-pressure injection with vacuum venting that utilizes a thin, lightweight shell laminate upper mold. Resin is introduced via an Edge Manifold, the mold is held together with a vacuum clamping system and tool balancers are used for mold manipulation. The low-pressure injection is best facilitated with a converging flow field to vacuum venting. This provides the greatest control over thickness.

Shell Laminate RTM features the lowest tooling cost of any RTM process. It is suitable for production run sizes exceeding 100 units. The lower mold resembles a typical open mold, while the upper mold is a thin, flexible laminate. Inexpensive rubber extrusions form seal elements that facilitate vacuum clamping. The upper mold tooling cost is very low by virtue of the small quantity of material required to fabricate it. Functionality is accomplished by limiting the injection pressures. Low pressure injection requires less structure to maintain mold closure and cavity dimensions. The edge manifold around the entire perimeter allows for the shortest distance for resin flow through the fiber pack. This allows for the lowest injection pressures and the thin laminate construction of the upper mold. Vacuum venting at the part flow center provides thickness control.

1.2.3 Silicone Bag RTM

For parts with die-locked geometries or very deep draws, the process of choice is Silicone Bag RTM. This uses a low-pressure injection with vacuum venting that utilizes a silicone rubber upper mold. For this very flexible upper mold, the injection is best facilitated with discrete ports on the part surface with a flow field that diverges to perimeter vacuum venting. The flexible mold allows the glass pack to become so compressed that its permeability decreases. By pumping the resin through ports on the part surface, the bag is “inflated” with resin, which can quickly travel across the top of the glass pack in the manner of a face manifold.

Silicone Bag RTM features the greatest flexibility with respect to changes in the reinforcement materials. The lower mold resembles a typical open mold, while the upper mold is re-usable silicone rubber with a perimeter shell laminate vacuum clamp. The flexible rubber easily accommodates design changes that increase or decrease part thickness. Silicone Bag RTM is always slightly more costly than Shell Laminate RTM due to the high cost of silicone relative to laminating materials.

1.2.4 Vacuum Infusion

For limited production runs, the process of choice is Vacuum Infusion. Resin transfer is achieved with atmospheric pressure to vacuum venting. The disposable upper mold is constructed from bagging film. The flexible bagging film can be used on parts with certain negative drafts, similar to those that can be achieved using open molding. Vacuum Infusion can also be used to produce a master part when creating the upper mold geometry.

1.3 Presentation of Trade Study Results

The United States Environmental Protection Agency (EPA) has established two rules concerning HAPs emissions from open mold composite processing. One applies exclusively to boat builders while the other applies to the remainder of the industry. The rules are named National Emissions Standards for Hazardous Air Pollutants (NESHAP). For closed molding, there are no requirements to reduce emissions because the processes are inherently low emission processes. With a variety of closed molding systems in use throughout the industry, confusion arises as to which closed mold system is appropriate to replace open mold lamination. Consequently, a trade study was performed to examine these questions and provide solutions.

A small, open-molded part was produced using various closed mold processes. The trade study factors include the cost for producing the part at various production run sizes and rates, the emissions per part, and the part quality results. Four typical, closed mold processes were selected, along with the open mold baseline process. Molds and parts were fabricated to establish task times and materials requirements.

The subject part pictured below is from the deck of a run-about boat.

It is a hinged hatch cover that provides access to an under deck storage compartment or cooler. The step face features a non-skid profile on the external surface. The step face comprises glass skins over a foam filled honeycomb core. The part measures 11”x25” with a 1.5” tall perimeter flange. The design criteria include an impact of 300 lbs from a 3 foot elevation.

1.3.1 Production Plan

Costs were calculated for production run part quantities varying between 10 and 9,000 units. The production run span is 3 years with an equal number of parts produced each year. The shop operates 250 days per year, 16 hours per day over two shifts. Scrap rates were assumed to be similar for each process at 10%.

1.3.2 Equipment Costs

The equipment cost per hour was determined based upon the purchase price, installation costs, maintenance costs and the expected life spans. Only the portion of the equipment cost needed to produce the case study part was charged to the part. This assumption requires that additional equipment capacity would be used for production of other parts.

Equipment Type	Description	Purchase Price	Life Span, years	Installation Costs
Gel Coat Spray Equipment	Non-Atomizing Application Equipment	$8,500	5	$500
Resin Pump Equipment	Displacement Pump with Catalyst Slave Pump	$5,500	5	$500
Vacuum Pump	Continuous Duty with regulator and accumulator	$3,000	5	$500

Table 2: Equipment cost parameters.

Equipment Type	Open Molding	Vacuum Infusion	Silicone Bag RTM	Shell Laminate RTM	Conventional RTM
Gel Coat Spray Equipment	$9,000	$9,000	$9,000	$9,000	$9,000
Resin Pump Equipment	$6,000	$6,000	$6,000	$6,000	$6,000
Vacuum Pump	not reqd	$3,000	$3,000	$3,000	not reqd
Ventilation System	existing	not reqd	not reqd	not reqd	not reqd
Total Capital	$15,000	$18,000	$18,000	$18,000	$15,000

Table 3: Total Capital Cost per process.

Process	Cost Per Part, $
Open Molding	0.14
Vacuum Infusion	0.08
Silicone Bag RTM	0.08
Shell Laminate RTM	0.08
Conventional RTM	0.08

Table 4: Equipment Cost per part

1.3.3 Tooling Costs

The tooling cost per part was determined based upon the number of tools required to meet production rates based upon the process cycle time and mold life span. The first tool purchased includes the cost of the master. Duplicate tools and maintenance costs were included to meet rate or quantity requirements. Unlike equipment costs, all tooling costs, including excess capacity due to residual mold life, were charged to the cost of part production.

Tooling Description	Applicable Processes	First Tool Purchase Price	Life span, parts
Composite female mold with gel coated surface	Open molding Vacuum Infusion (lower mold) Silicone Bag RTM (lower mold) Shell Laminate RTM (lower mold)	$1,200	3,300
Reusable silicone vacuum bag	Silicone Bag RTM (upper mold)	$550	600
Shell Laminate	Shell Laminate RTM (upper mold)	$400	1,000
Rigid composite mold with gel coated surface	Conventional RTM (lower mold)	$1,600	5,500
Rigid composite mold with gel coated surface	Conventional RTM (upper mold)	$1,400	5,500

Table 5: Tooling Cost Parameters

Production Run Size	Open Molding	Vacuum Infusion	Silicone Bag RTM	Shell Laminate RTM	Conventional RTM
100	12.00	21.46	17.50	16.00	30.00
300	4.00	13.46	5.83	5.33	10.00
1,200	1.00	10.46	2.04	1.50	2.50
3,000	0.67	9.86	1.17	0.73	1.73
9,000	0.40	9.77	0.82	0.56	1.56

Table 6: Tooling Cost per part in dollars.

1.3.4 Material Costs

Material cost per part is the sum, for each material used, of the product of material quantity times material cost.

Process	Cost per Part, $
Open Molding	5.51
Vacuum Infusion	5.27
Silicone Bag RTM	5.27
Shell Laminate RTM	5.07
Conventional RTM	5.01

Table 7: Material Cost per part in dollars.

1.3.5 Labor Costs

Labor cost per part is determined based upon the task time required and the labor and overhead rate of $20.00 per hour. The labor rate was chosen to be representative of small to medium sized production facilities.

Process	Cost Per Part, $
Open Molding	9.08
Vacuum Infusion	10.75
Silicone Bag RTM	5.75
Shell Laminate RTM	5.75
Conventional RTM	5.75

Table 8: Labor Cost per part in dollars.

1.3.6 Total Part Cost by Process

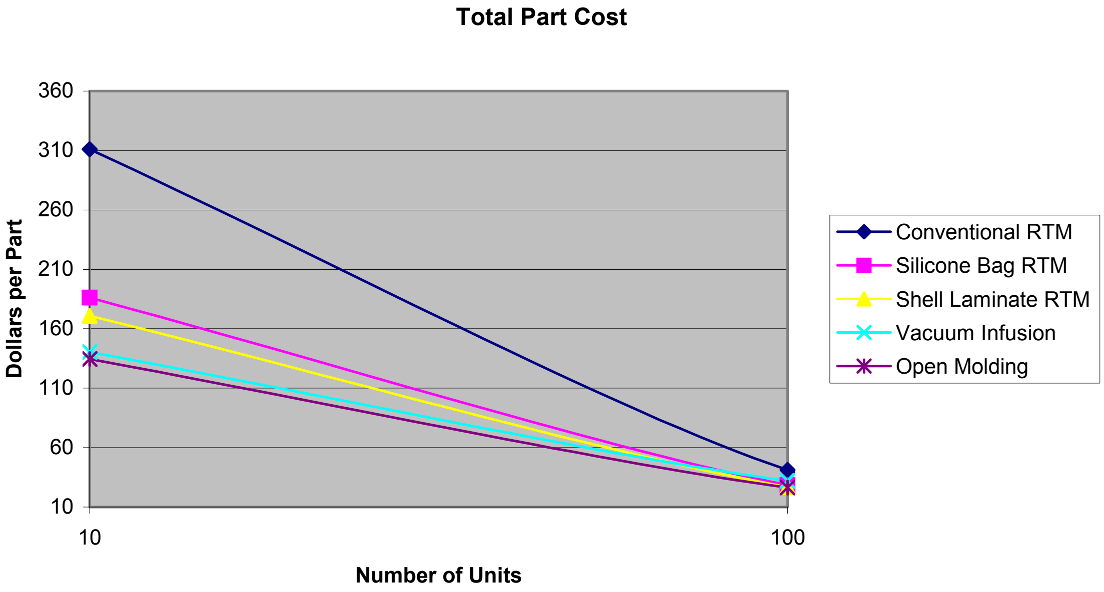

Figure 1: Total Part Cost Comparison by Process from 10 to 100 units.

At very low production rates, open molding is the low cost process. Vacuum infusion is slightly more costly, although almost negligibly so. Shell Laminate and Silicone bag, respectively, are increasingly costly, while conventional RTM is considerably more expensive than any other process.

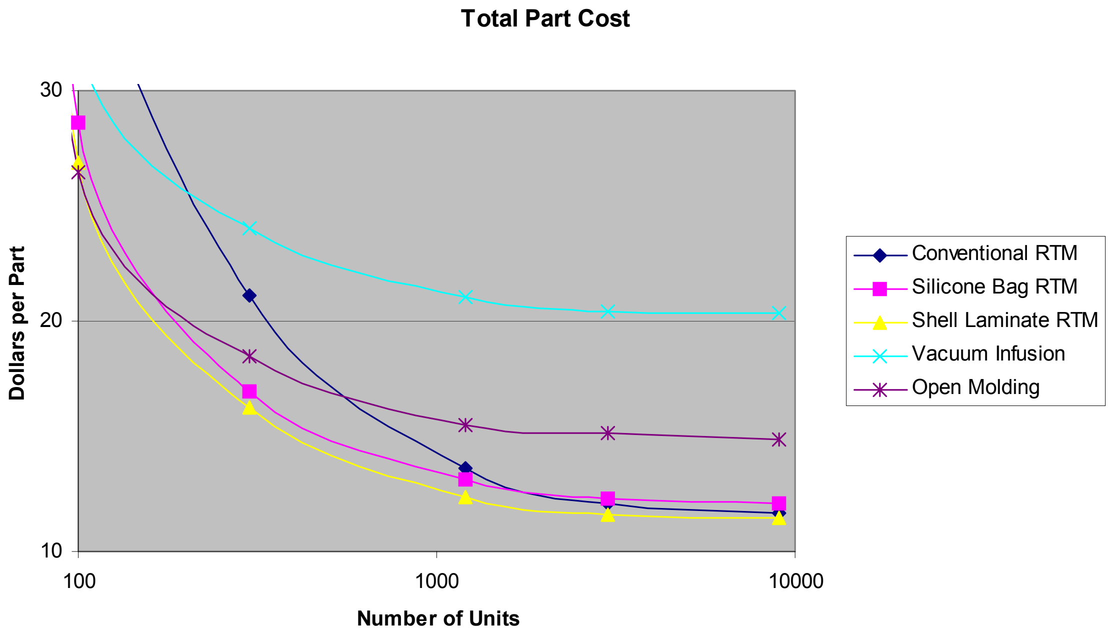

Figure 2: Total Part Cost Comparison by process from 100 to 9,000 units.

Above 200 units, vacuum infusion becomes the highest cost process. This is due to the high cost of vacuum bagging film and sealant tape, and the need to purchase them for each part produced. Above 100 units, Shell Laminate RTM becomes the lowest cost process. Silicone Bag RTM is always slightly more costly than Shell Laminate RTM due to the high cost of silicone materials relative to tooling laminating materials. At roughly 1,100 units, Conventional RTM approaches the cost of Shell Laminate RTM, but doesn't appear to provide savings even at 9,000 total parts when the part design features an in-mold gel coat surface.

These results are calculated based upon production experience for the subject part. Minor variations in the results can be expected based upon individual part designs. For non-gel coated parts, these results may be different.

1.3.7 Emissions calculations

Emissions per part were calculated according to the procedure outlined in the Boat Builders National Emissions Standards for Hazardous Air Pollutants (NESHAP). This is a point value system with tabulated values of emission rates by material and process. The tabulated value multiplied by the mass of resin used estimates the mass of hazardous air pollutants (HAPs) released into the atmosphere.

HAP=[(PVr)(Mr)+(PVpg)(Mpg)]

Where

HAP = Hazardous Air Pollutant emissions, kilograms
PVr = resin point value, kilograms/megagram
Mr = Mass of resin, megagrams
PVpg = point value of pigmented gel coat, kilograms/megagram
Mpg = mass of pigmented gel coat, megagram

Component	Open Molding Conventional Materials	Open Molding Low HAP Materials	Closed Molding
HAP Content Of Resin, % Mass Of Resin, Pounds	45 1.39	35 1.39	Not applicable
Hap Content Of Gel Coat, % Mass Of Gel Coat, Pounds	42 0.3	26 0.3	26 0.6
HAP Emissions Per Part, Pounds	0.334	0.126	0.064

Table 9: HAP emissions calculated per the Boat Builder's NESHAP

1.3.8 Case Study Results Summary.

Property	Open Molding	Vacuum Infusion	Laminate Shell RTM	Silicone Bag RTM	Conventional RTM
Part Weight	2.7	2.3	3.5	3.7	2.4
Part Appearance	Part back side is rough	Part back side is matte	Part back side is smooth	Part back side is matte	Part back side is smooth
Strength	Acceptable	Comparable to open molding	Comparable to open molding	Comparable to open molding	Comparable to open molding
Cost Effective Production Run Size	<100 parts	<200 parts	100 to 9,000 parts	100 to 9,000 parts	>1000 parts
Emissions	0.126 to 0.334 lbs/part	0.064 lbs/part	0.064 lbs/part	0.064 lbs/part	0.064 lbs/part

Table 10: Comparison of RTM Processes

Each study process produced a part that was comparable to the open molded part. Emissions were reduced by 80% compared to conventional materials, and 50% compared to low VOC materials.

Closed molding is a broad category of processes that includes many options. Each option has specific advantages in different applications. Each process can produce parts with quality that is equal to or superior to the quality obtained via open molding. Closed molding processes are inherently low emission processes. Closed molding processes can be lower cost than the open mold part due to labor and material savings.

2.0 Lessons Learned while Implementing RTM in the Open Mold Factory.

The term "Best Practices" describes the actions and considerations that produce a sort of optimum set of results. Many times, these actions are arguable depending upon which "optimum" is desired. Some things are going to depend upon the specific part design and production plan. For the purposes of this presentation, the "Best Practices" are those actions and considerations that contribute to successful production of gel-coated cosmetic parts with high as-molded quality for production runs of hundreds to thousands of parts.

If the term "Best Practices" has an obvious meaning, its antonym would probably be "Bad Habit". Sometimes, a bad habit can be described as a worthwhile short-cut. Judgments from different perspectives can result in situations where one person's "best practice" is another person's "bad habit". Certain features of the open mold process allow bad habits to be developed and accepted as routine. Some bad habits can become entrenched in the product development cycle such that successful closed molding seems impractical. These bad habits are the subject of this discussion.

Successful product development and production can be achieved in spite of bad habits. To demonstrate this point, consider the act of driving an automobile without functional brake lights. This act can be accomplished in apparent safety for a considerable period of time. Sooner or later, however, you will brake suddenly, and the car following behind will not have sufficient warning to stop before colliding with your automobile. One argument relishes the money saved by not buying replacement brake lights, while another argument contrasts the small certain cost of light bulbs against the potential high cost resulting from an easily preventable accident. In this case, driving an automobile with functional brake lights has become universally accepted as a best practice.

2.1 Design and Prototyping

A prototype is a necessary step in a product's development. The prototype serves to validate the design's fit, form and function. Many times, the process is abbreviated by not addressing function. Fit and form are evaluated for the prototype, but function is not evaluated until further down the product development cycle where it is usually discovered via a product failure. In open molding, the solution manifests itself in changes to the laminate schedule. A part is designed, a pattern is prepared, a mold is constructed and a part is produced. The part is evaluated for fit and form and the design is certified as acceptable. If function is later found to be lacking, additional reinforcement materials can be added to an open molded part without much concern for the mold design.

When the upper mold comprises vacuum bag film or silicone rubber, adding additional plies of material to increase part strength and stiffness is equally nonconsequential. But, when the upper mold is rigid, adding additional plies of material becomes problematic. The part cavity remains the same. Thus, the plies must be compressed to a greater extent, with a corresponding decrease in their permeability. At some point, the plies become so compressed that they don't wet out properly and don't exhibit their normal strength. White fiber bundles visible at the part surface are evidence of inadequate wet-out. Further ply compression can even prevent resin from flowing through the region, resulting in dry spots.

Many variables work towards or against proper and consistent mold filling. The biggest factor is the consistency of the glass fiber pack. Best results are achieved by controlling the type and amount of reinforcement, as well as the location and extent of ply overlaps. This is achieved by designing the ply kit before the mold cavity is designed. This requires material selection prior to ply kit design, and includes not only the type of glass reinforcement, but the specific form (usually width) for that glass type. The benefits of this approach are two-fold: Minimizing material waste; and, ensuring consistent mold-fill performance.

2.2 Designing the reinforcement package

There are various methods of preparing the reinforcing pack. One method produces the reinforcing pack in a upstream operation known as pre-forming. This pre-form is then placed dry in the empty mold, the mold set closed, and the resin injected. The most rapid cycle times are achieved using the pre-form approach. The reinforcement pack can also be assembled in the empty RTM mold. The lower mold is engaged during this process, which adds directly to cycle time.

The most common fibrous raw materials are broadgood roll materials. Continuous Filament Mat (CFM) is the most common and least expensive reinforcement. Its architecture results in resin-rich and fiber-rich areas that result in more fiber print than other materials. It is not very conformable and requires cutting and darting for complex geometries. CFM is the most commonly used reinforcement for conventional RTM processes.

Stitched Chopped Strand Mat (Stitched CSM) offers much greater conformability that CFM. The polymer fiber cross-stitches prevent the fiber wash that you would see during the fill process with ordinary Chopped Strand Mat.

Other stitched materials are used as structural materials. These are available in a wide variety of configurations, often with three or more distinct layers. A common example is 1708 / 1808 material. This is a three layer material. The first layer is aligned glass fiber in the warp direction, the second layer is aligned glass fiber in the weft direction, and the third layer is chopped mat.

Special constructions are also available. One interesting product comprises two layers of glass reinforcement separated by a layer of polymer fiber core. The polymer fiber core adds thickness, and thus bending stiffness, without the full weight of a glass ply. Available from several sources, these materials tend to be very conformable and provide good cosmetics. They do suffer from reduced inter-laminar shear strength due to the low strength of a polyethylene or polypropylene fiber ply.

A spun-bound polymer fiber ply works effectively as a print blocker when placed against the gel coat layer. With this approach, there is a trade-off between the cosmetic quality and the tendency of the gel coat layer to crack.

In vacuum infusion, the flexible bag film upper mold tends to compress the glass reinforcement so much that the permeability becomes very low, and therefore, the resin flows very slowly. Certain materials have been designed that resist compression and provide a ready flow path for the resin. These can be placed within the laminate thickness, or above the laminate for subsequent removal.

The ply kit must be designed and proven before designing the mold cavity. Material types and forms are selected by fiber architecture, areal weight and width, respectively. The ply kit is designed by determining the minimum number of lineal feet required of that width material to build the part thickness. This usually requires ply splices to be located somewhere on the part. Any overlap areas are designed in the part cavity in the form of additional thickness. This approach ensures consistent filling during the resin transfer operation by eliminating highly compressed areas in the reinforcement pack that serve as flow restrictions.

Nesting plies in a ply kit is another method of minimizing material usage. Nesting refers to the operation of orienting different ply details such that the greatest fraction of material is utilized. Plies from different parts should never be co-mingled in a single nest for the same reason that different parts should not be ganged together in a single mold; it leads to higher material usage. Replacing any one scrap part requires production of all the parts nested or ganged together. Nesting is common for aerospace designs in which individual ply details are precisely designed. Nesting is not the low cost approach to minimizing material usage unless the design is a minimum weight design. For a minimum weight design, ply splices must be precisely controlled in order to ensure design integrity. Ply splices are weak spots that must be accounted for in strength analysis. Seldom are glass fiber polyester resin composites designed to

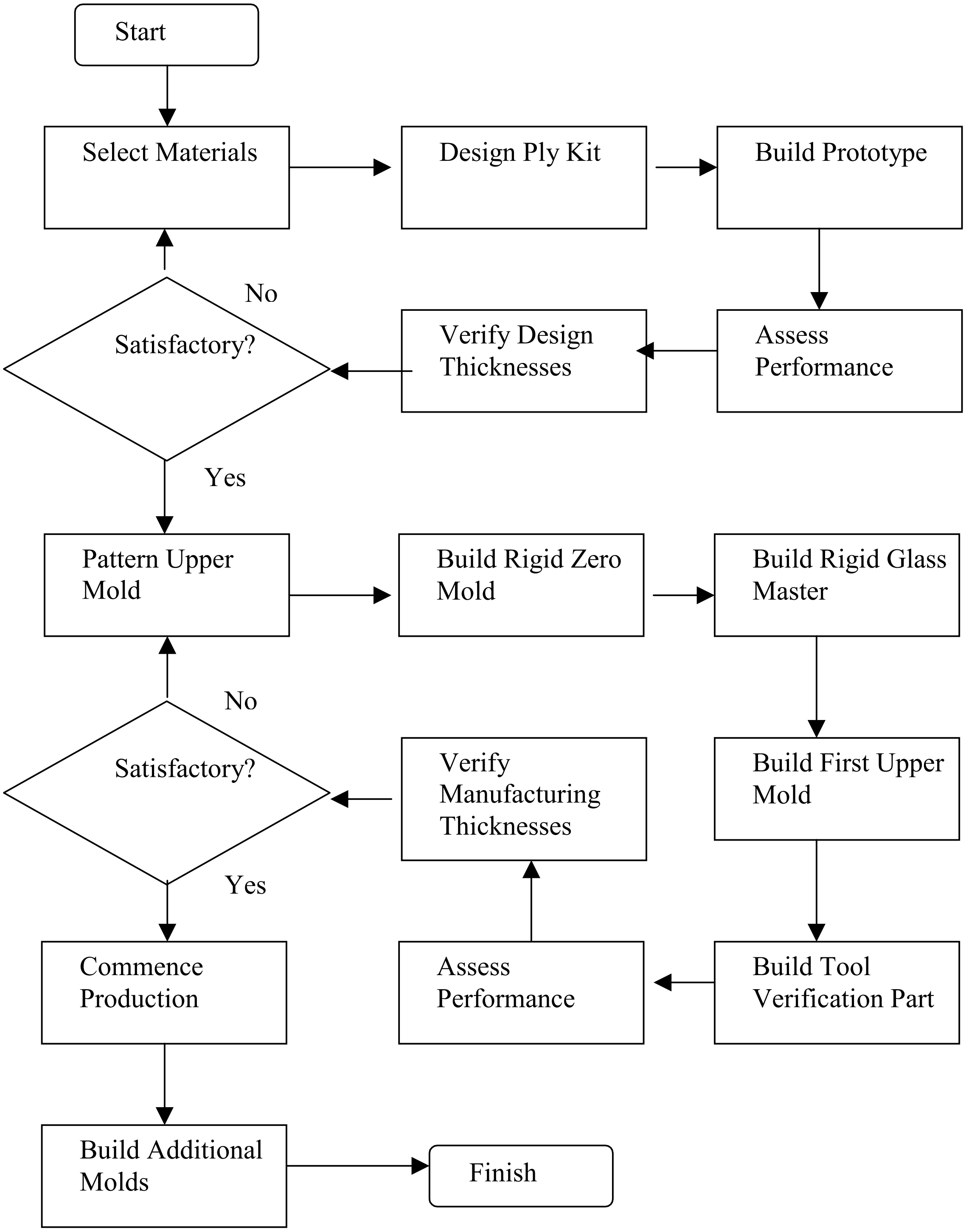

Figure 3: Best Practices Product Development evaluates a prototype prior to mold fabrication and verifies manufacturing thicknesses prior to production.

minimum weight. More likely, they are designed to minimum cost. Usually, ply splices can be located with concern for assembly fit tolerance and without regard for part strength provided that basic splice rules are followed. Above all, splices should never be superimposed through the thickness.

There are two types of splices. Butt splices and Overlap splices. A Butt splice comprises two ply details oriented such that the edge of one ply is adjacent to the other. A butt splice should be avoided when the ply constitutes a significant fraction of the part thickness. Since the reinforcement is discontinuous across the splice, the joint is significantly weaker than the area away from the splice. An Overlap splice comprises two ply details oriented such that some portion of the end of one ply lies on top of the other. Overlap splices provide greater strength than butt splices. Overlap splices almost always require additional part thickness to accommodate the extra reinforcement material. Butt splices are preferred when assembly fit tolerance requirements preclude additional part thickness.

Once the ply kit is designed, the materials should be used to hand laminate or vacuum infuse a part for prototype testing. This testing should evaluate part functionality and verify that the part thicknesses and reinforcements are adequate for the design. Careful attention to glass content and part thickness is imperative to a successful structural evaluation. Once the laminate schedule is proven, the prototype part should be cut into pieces to verify design thicknesses. Then and only then should the part cavity be designed and patterned.

2.3 Mold Design Details

Certain design details can greatly impact the performance of a mold set on the factory floor. While they are not critical for success, they can contribute to the robustness of the process on the factory floor.

2.3.1 Mold Features that add robustness

The mold set should be designed such that the upper mold cannot accidentally be installed at the wrong clocking relative to the lower mold. If the lower mold is oriented at 12 o’clock, it should not be possible to close the mold at any orientation other than 12 o’clock.

The mold halves should separate with a true vertical motion. Many times, open mold parts are designed with some negative draft that requires the part to be pulled somewhat horizontally prior to being moved vertically out of the mold. This should be avoided in closed molding unless a device is fashioned to align and move the mold pieces into the mated configuration. This will also require special seal extrusions for proper functioning.

For both the Shell Laminate and Silicone Bag RTM processes, the mold assembly procedure should require only moderate hand pressure and the vacuum clamps, without resorting to mechanical clamps.

2.3.2 Mold Framing and Thickness

For the three process variations, laminate thickness, structural reinforcement and construction materials vary considerably. A conventional RTM process minimizes fill times with high injection pressures. Its mold frame must not only support the weight of the mold laminate, but also the injection pressures. The frame itself must be structurally tied to the mold laminate. Both the lower and upper mold must be held to shape, and clamped together. The highest pressures are at the injection point, which is usually at the part center. This area needs to be adequately reinforced to prevent mold cavity deformation.

In contrast, an open mold frame only serves to support the weight of the mold laminate. The open mold frame acts as a cradle to support the mold laminate, with flexible glass laminate ties that don’t couple the mold and frame structurally. This cradle design is much more tolerant of thermal shock than is a structural RTM framing system because thermal expansion differences between the steel reinforcement and glass laminate are absorbed by deflections of the light ties.

The shell laminate upper mold must be thin to resist cracking. Being very thin allows the mold to bend and flex without generating a lot of interlaminar shear stress. The laminate schedule should include one 20 mil layer of tooling gelcoat, a 10 mil conformable glass veil directly against the gel coat, a chopped mat skin coat and one layer of a structural material such as 1708 or 1808. These are non-crimp fabrics with chopped mat stitched into a three layer assembly. Additional thickness should be used over the vacuum clamps, edge manifold and alignment devices. Vinyl ester should be the minimum grade resin material.

2.3.3 Alignment Devices

Problems with aligning the mold halves can show up in various ways. The simplest feature is a thickness variation in the part’s vertical walls. One side is thinner while the opposing side is correspondingly thicker. In other cases, certain geometric features work to align the molds after the outermost vacuum seal is established. When this happens, the mold is not free to float into position. The interference that occurs at these geometric features can cause stresses that fracture a shell laminate upper mold. The resulting vacuum leaks will introduce air into the mold cavity, displacing resin and resulting in voids and/ or dry spots in the part.

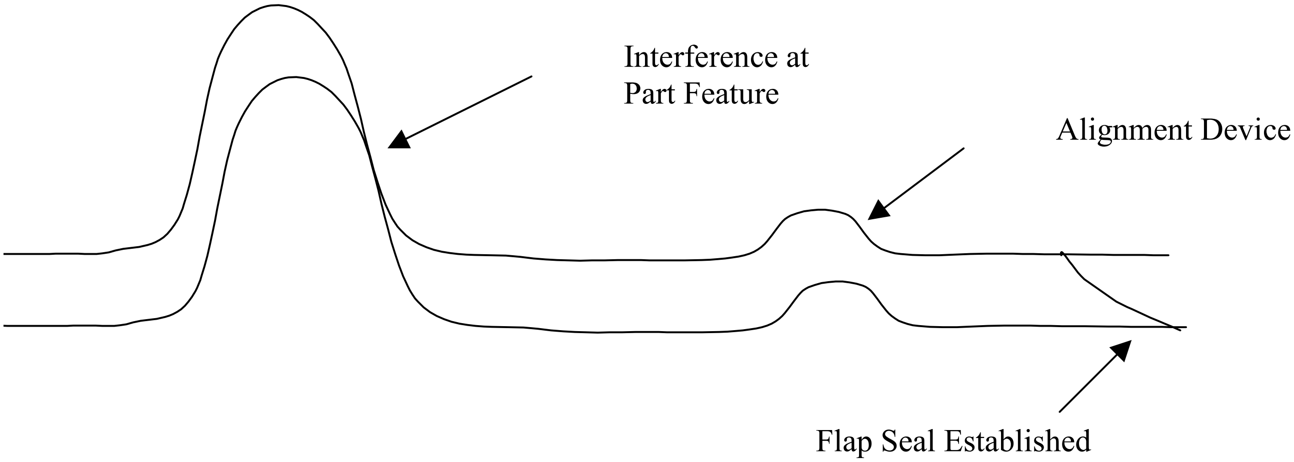

Figure 4: In the upper and lower mold line sketch above, the alignment device is ineffective. For clarity, not all mold features are depicted.

Any alignment device must engage itself prior to those features on the part. Extending the lower mold flange beyond the outer seal provides a simple alignment feature. In the following sketch, the height of the diagonal surface is slightly greater than the height of the part features that otherwise would align the molds.

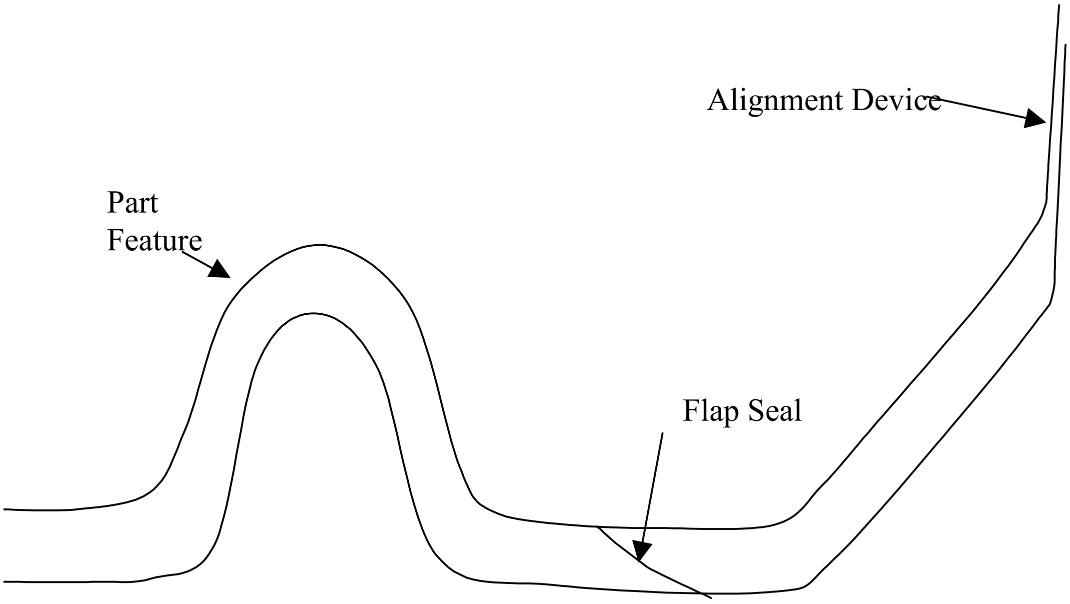

Figure 5: In the upper and lower mold line sketch above, the alignment device engages prior to flap seal contact or part feature interference. For clarity, not all mold features are depicted.

Three or four of these details are required to provide mold alignment. These details also serve as wedge points when the upper mold needs additional force to effect release, without causing damage to the rubber seal extrusions.

2.3.4 De-mold Devices

A common problem when converting from open mold lamination to closed molding occurs when one designs a lower mold according to the criteria “simply an open mold with a wide flange”. For the open mold, the part edge is located on often a vertical but drafted surface. The open molded part is commonly laminated with the glass reinforcement lapping over the flange inside edge, extending sometimes beyond the outside edge. This “flange laminate” is subsequently trimmed from the part. However, this material provides a convenient de-molding tab. Wedge tools are inserted between the mold flange and this offage, producing a lifting force that serves to begin the de-molding event.

When the newly designed closed mold system features reinforcement that ends at the flange inside edge, there is no longer a “flange laminate” that can be used as a de-molding tab. When mold release requires mechanical assistance, wedges placed between the mold flange and the resin that filled the edge manifold easily break off the un-reinforced resin without generating adequate lifting force to effect the part removal. Then, when wedges are placed between the mold sidewall and part, the forces are mostly in the horizontal direction, not in the vertical lifting direction. Although de-mold can be achieved in this manner, the more common result is gel coat scarring near the boundary of the edge manifold. This becomes progressively worse throughout the mold service life.

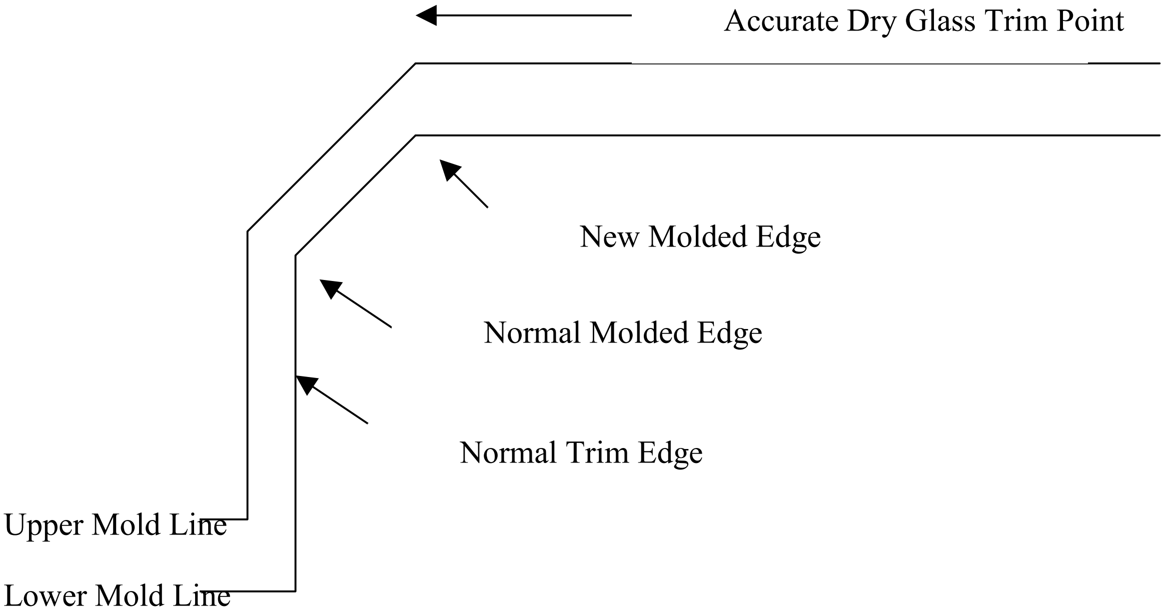

Figure 6: Extend the part so that there is a 1” long bevel at 45 deg. This replaces the open mold flange laminate with a reinforced tab that assists in de-molding when wedges are used.

A fiber reinforced de-molding tab can be incorporated in the molded part by extending the part surface upwards and outwards. A simple bevel at 45 deg from vertical accomplishes this with little added cost to tooling and part manufacture. The upper transition, from the diagonal to the horizontal, also provides an accurate guide for cutting the dry glass. This provides for consistency in the perimeter edge manifold width, with resultant increases in fill consistency.

2.3.5 Sealing Issues

A rubber extrusion seals against a physical surface by being compressed against the surface. One method to achieve this is to use a solid rubber profile that is compressed by moving the mold pieces together. This contact is best achieved by moving the surfaces together in purely a perpendicular fashion. The initial contact occurs before the mold pieces are completely together. As the mold pieces are brought into contact, the seal is compressed.

When two mold pieces come together, there are two components to the motion. One is perpendicular to the surface while the other is parallel to the surface. Problems arise when bringing the surface and the extrusion into contact by motion that includes a parallel component. From the time when contact is first established until the seal is compressed, the parallel motion serves to drag the seal extrusion. Best results are obtained when the contact surfaces move together in purely a perpendicular fashion. Another method uses a hollow rubber profile that fits in a seal groove and is expanded by pressure once the mold pieces are assembled. Tucked inside the seal groove, the parallel motion cannot drag the seal extrusion.

2.3.6 Resin transfer ports, manifolds and vents for Shell Laminate RTM

Proper, symmetric mold filling is almost always best achieved with two injectors and one vent. These injectors will be called the “primary” injectors. The resin is supplied to the entire part perimeter via the edge manifold. The resin flow will converge on the vented flow center. The flow center depends on the planform and the thickness. For a single cavity thickness, the flow center is in the planform center. If half the part is twice as thick, the flow center is skewed towards the thick area, because it takes more resin to fill up the greater thickness. The vent should always be located at the flow center.

The injectors are positioned by finding the “longest straight line distance across the part”. For certain odd part shapes, this “straight” line may be “bent” at one or more locations. Measure a path across the part with a cloth tape measure (available in sewing aisle at grocery store) until you identify the longest straight line path. The vent is almost always along this path. If the thickness is not constant, or if there is more part to one side of this line, the line will move in a parallel sense towards the “thicker” or “bigger” area. Thicker is like longer when it comes to the path because it takes more resin to fill up the thicker cavity. The two primary injectors are positioned at the part perimeter at these points.

For large parts, or extremely odd shapes, two secondary injectors may be used. These injectors are located midway between the primary pair of injectors. A constant thickness part would have them exactly between the two primary injectors. For parts with varying thickness, the secondary injector would be skewed towards the thicker portion of the part.

If parts are much longer than wide, the secondary injectors are not used until later in the fill process. The delay time depends on the length to width ratio. The longer it is to wide, the longer the secondary injectors are delayed.

Certain part designs require a second resin manifold, a portion of the way from the edge manifold to the flow center. The edge manifold is used to fill the part until the resin reaches the inner manifold. Then, resin flow is directed through the inner manifold until the part is completely full. This is necessary for large parts, parts with high glass contents, or parts with heavy filler loadings and thus, higher viscosity matrix material.

2.3.6.1 Examples of injector and vent locations:

Part #1 is a perfect square of uniform thickness. The longest straight-line path across the part is on the diagonal. Two injectors are located on opposite corners. The vent is located midway between the injectors, at the center of the square. Most people mistakenly choose to place the injectors at the middle of a side.

Part #2 is a long rectangle of uniform thickness. The longest straight-line path across the part is on the diagonal. Two injectors are located on opposite corners. The vent is located midway between the injectors, at the center of the rectangle.

Part #3 is a perfect circle of uniform thickness. The longest straight-line path is any one of the diameters. The injectors are located at both ends of the diameter and the vent is in the center.

2.4 Patterning the Upper Mold

There are three methods of patterning the Upper Mold geometry. Each can produce the necessary upper mold, although with varying results.

2.4.1 Machining from Tooling Block

The highest degree of accuracy is achieved with a computer controlled cutting machine. Solid modeling techniques are used to produce a computer aided design (CAD) / computer aided manufacturing (CAM) data file that is used to control a numerically controlled (NC) cutting machine. A plug blank is first constructed from tooling block or other pattern materials.

2.4.2 Calibrated Sheet Pattern Materials

The lower mold can also provide the basis for the upper mold geometry. Pattern materials are placed into the lower mold to simulate the part thickness. Calibrated thickness sheet wax provides a high degree of accuracy. Other pattern materials can be used, particularly in thick areas. Mold features such as the edge manifold and vacuum clamps are also patterned upon the lower mold. This master plug then provides the surface definition for the upper mold.

2.4.3 The Master Part

A master part can be constructed using either hand lamination or vacuum infusion. The lower mold is used for this method. Careful attention to glass content is required to ensure accurate mold cavity thickness. Inside edges tend to be thicker than intended for hand laminated parts. Some amount of grinding may be necessary to achieve back side radius requirements. The entire part surface must be coated with a filler type primer material and finished smooth for molding the upper mold. This method does not provide the same accuracy as the other methods presented.

2.5 Mold Fabrication

Most patterns are not durable and are suitable for only one pull. The de-mold process usually imparts sufficient forces to destroy the pattern. As a result, two options present themselves for consideration. One can either build one accurate upper mold from the pattern, or one can build a robust master with accurate upper mold geometry that can yield any number of high accuracy upper molds.

In almost all cases, a Zero mold should be made from the pattern. This Zero mold is so named because it is used as a step in the production of tooling. It has the geometry of the upper mold, but is not the same construction. The Zero mold should be constructed in a manner similar to a conventional open mold. Steel framing is preferred but wood is acceptable when encapsulated in glass laminate. A Glass Master is made from the Zero mold. The production molds are made from the Glass Master. In this method, accurate upper mold geometry has been maintained through the successive moldings.

A common mistake is to forgo the master building step and build the upper mold directly from the pattern. The shell laminate upper mold can easily be warped or cracked during use as an RTM mold. When this happens, geometric accuracy is lost. Any master produced from a warped/cracked shell laminate upper mold will not have the correct geometry, consistent mold fill performance and accurate part thicknesses and weights. The only recourse is to re-pattern the upper mold using the lower mold as a basis. This requires that the lower mold be taken out of production for 1 to 2 weeks for the mastering process. With a high quality fiberglass master, a new shell laminate upper mold can be produced in two days time while the current mold set is still in production.

2.6 Upstream Processes

Processes that occur upstream of the liquid injection procedure reduce lower mold productivity when the mold is engaged in that activity. These processes can include taping / masking, applying and curing gel coat and loading the reinforcement materials. Multiple lower mold pieces can be used to address the need for Work In Process (WIP) at each operation.

For conventional RTM, the lower mold tooling cost becomes prohibitive when gel coat is an upstream operation. The benefits of rapid cycling disappear, and the need for high pressure injection wanes.

2.7 Executing the Process

During the course of building parts, certain actions can have undesirable effects. These effects can go unnoticed, or their causes can be unknown. Regardless, bad habits during process execution usually adds production cost.

2.7.1 Resin Transfer

The proper amount of resin must be transferred to the closed mold cavity. This is best accomplished with a resin pump that automatically shuts off after pumping the desired quantity of resin. For both the Shell Laminate RTM and Silicone Bag RTM processes, the mold cavities are full before they appear to be full. Resin pressure lifts the upper mold slightly as the mold fills. When the proper amount of resin is transferred, the vent vacuum causes the upper mold to return to its design height as the resin reaches the vent location. Properly executed, very little resin exits the mold cavity at the vent location.

Transferring the proper amount of resin is particularly important for Shell Laminate RTM. The resin flows from the perimeter edge manifold and converges on the vacuum vent at the flow center. As the fill process begins, there is no hydrostatic pressure on the resin flow front in the unobstructed flow channel. As the resin begins to move into the glass pack, the pressure increases according to the distance traveled through the glass pack and the rate of resin delivery. The pressure is highest at the edge of the part and lowest at the flow front. The pressure forces the upper mold to move upwards, producing a thicker mold cavity that requires more resin to fill. If resin pumping continues until the resin enters the vent trap, the pressures rise very quickly due to the small vent diameter relative to the large injector diameter. Usually, the higher exotherm temperatures experienced in the greater mass will cause the upper mold to take a permanent set. When this occurs, part thickness is permanently impacted for this mold set.

2.7.2 Vacuum Leakage

The mold set must be vacuum tight. Minor vacuum leaks are the root cause of most problems encountered when developing a closed mold system that features vacuum venting. These problems produce parts with dry spots and air voids. Vacuum integrity is one of the more difficult concepts for open mold technicians to appreciate, particularly when the vacuum leakage is through the mold laminate. On the other hand, technicians working with high pressure (i.e. autoclave) lamination processes quickly learn to respect leakage through the mold laminate.

2.7.2.1 Measuring Vacuum Leakage for the Mold Set

A vacuum gauge is required to determine minor vacuum leakage rates. First, vacuum is applied to the mold set. The level of vacuum is noted. The vacuum source is interrupted and the time interval is measured. After a prescribed time, the level of vacuum is again noted. The difference between the initial vacuum and the vacuum after 5 minutes corresponds to the overall vacuum leakage rate.

For a very tight mold, vacuum will hold steady during the entire 5 minute test. A leak-down of 0.5 to 1.0 inches of mercury is consistent with a well sealed mold. Even this level can make part manufacture difficult for high vacuum processes. For leak-down rates from 1 to 2 inches of mercury, most parts can be successfully fabricated. For a leak-down exceeding 5 inches of mercury in 5 minutes, successful part manufacture is difficult, if not impossible, even if vacuum is vented before resin gellation.

It is vitally important to have a leak-free mold. To ensure the vacuum integrity, a leak down test must be performed on every new mold set. Since there are two separate cavities in the Light RTM mold, the leak down test should be performed twice: once on the clamp chamber, and; once on the part cavity.

First, ensure that both molds have a serviceable coating of release agent. Load the glass and cores into the lower mold. Prepare the upper mold by installing a new injection tube. Position the upper mold upon the lower mold. Install the resin trap at the vent location. Clamp off the injection tube. Apply a full vacuum to the clamp chamber via the clamp fitting. Apply half vacuum to the part cavity via the resin trap. If the mold set does not close and seal, apply a manual force to the upper mold until the flap seal contacts the lower mold flange. Once the flap seal is established, the upper mold will draw towards the lower mold until the inner seal comes into contact with the lower mold flange.

Vent the vacuum connection to the part cavity by disconnecting the line to the resin trap while maintaining the vacuum connection to the clamp chamber. The inner seal should allow the clamp to maintain a closing force between the mold halves.

Interrupt the vacuum supply to the clamp cavity without venting the clamp to atmosphere. Monitor the level of vacuum present in the clamp cavity as time passes. The clamp should maintain enough vacuum to remain clamped for 30 minutes or longer. If the clamp does not maintain vacuum very long, there is a leak. It may be necessary to find and repair this leak.

Once vacuum integrity has been established for the clamp chamber, apply vacuum to the part cavity. At this point, both the clamp and the part cavity are under vacuum. After a few minutes, interrupt the vacuum supply to both the clamp and part cavity. Monitor the level of vacuum present in the part cavity as time passes. The part cavity should maintain vacuum for 30 minutes or longer. If the part cavity does not maintain vacuum very long, there is a leak. It is probably necessary to find and repair this leak.

Some leaks are not harmful. If the clamp leaks, and if that leak is NOT across the inner seal, and if the vacuum system can keep ahead of the leak, successful molding is possible. If the part cavity leaks, and if that leak is right at the resin trap vent location, successful molding is possible.

If, however, the part cavity leaks, and if the leak's location is away from the vent location, the vent vacuum will draw air into the part, and the displaced resin will accumulate in the resin trap. A large leak will allow most of the resin to exit the part via the vent fitting. If the resin trap overflows, resin will enter the vacuum system and require immediate removal.

2.7.2.2 Vacuum Leakage through Laminate Porosity in the Mold Skin

All laminates contain some amount of porosity or micro-porosity. When this porosity is great enough, atmospheric air will leak into the mold cavity by traveling through the porous laminate.

Of all the possible leakage paths, this one is the most difficult for process engineers to comprehend. A simple experiment can be performed to show this phenomenon. The experimenter should build two vacuum bags. One vacuum bag should be on the mold side of a porous laminate. The other vacuum bag should be on a glass plate. Each vacuum bag should be equipped with both a vacuum gauge on the resin feed line, and on the vent line, a vacuum source that can be interrupted without venting the bag to atmosphere.

Perform a vacuum leak-down test on both vacuum bags. The vacuum bag on the glass plate serves to demonstrate that the student can successfully build a good vacuum bag which maintains vacuum for a long time.

If the mold skin porosity is resulting in vacuum leakage, successful part manufacture may not be practical.

2.7.3 Resin Outgassing

During resin manufacture, air is introduced into the resin during blending operations. This air dissolves into the resin in the same way that carbon dioxide dissolves into water to form the fizz in carbonated beverages. Reducing the pressure above the solution and increasing its temperature provides a driving force which forces the dissolved gases out of solution in the form of bubbles.

During the resin transfer operation, applied vacuum first acts to degas the resin, pulling dissolved air out of the resin solution. It is normal for bubbles to form at the resin flow front. Many times this is mistakenly attributed to “styrene boil”. Instead, these bubbles are largely due to degassing.

Vacuum does not draw air bubbles “through” the resin. On a sealed system, vacuum will cause the air bubbles to become larger in accordance with Boyle’s Law. Applying vacuum to the vent merely increases the pressure head that forces the resin to flow through the mold cavity. Air bubbles move through the mold cavity by virtue of being carried by this resin flow. Any air in the system must exit during the resin transfer operation. Problems arise when air enters the system late in the fill process. There must be enough resin flow to carry the bubbles to the vent. This requires that more resin enters the mold cavity.

2.8 Down Stream Impacts

Operations that occur downstream from the closed mold process can be affected by changes in the part that directly result from the change to closed molding.

2.8.1 Open Mold Tabbing

Open mold tabbing is the process of affixing a secondary structural element to a previously laminated part using open mold laminating techniques. This is a secondary lamination process. Secondary lamination requires that the underlying surface is not fully cured and not extremely smooth. Timing is the key parameter. The underlying part is allowed to gel and cure to some extent. To achieve a good secondary bond, the secondary laminate must be applied before the part cures too much.

If too much time elapses, then the part surface must be mechanically abraded prior to applying the secondary laminate. This procedure removes contaminates as well as provides a mechanical “keyway” for the secondary laminate adhesion. An alternative to mechanical abrasion is the use of a peel ply. The peel ply produces a textured fracture surface when it is removed from the cured part.

There are two components to secondary laminate adhesion. One is a chemical bond with resin unsaturation in the underlying part. The second is a mechanical bond due to the surface roughness on the underlying part.

To understand the importance of mechanical bonding, consider the following scenario. Select a well-cured substrate comprising a molded surface with exterior gel coat. On one half of the substrate, do not perform any sanding; this will be called the smooth substrate. On the other half of the substrate, lightly sand the gel coated surface with an aggressive sandpaper, such as 60 grit, until the gloss is removed and the surface is covered with sanding scratches; this will be called the sanded substrate. Solvent wipe the surface to remove all traces of dirt and contaminates from both halves of the substrate. Apply a nominal thickness (1/4 to ½ inch thickness) of catalyzed polyester bonding putty to each half of the substrate. Allow the bonding putty to cure. Evaluate the bond quality by using a putty knife to pry the bonding putty from each half of the substrate. The putty on the smooth gel coat substrate will release with much less effort than the putty on the sanded gel coat substrate. The difference is due entirely to the mechanical keyway provided by the sanding scratches. In this case, both pieces were equally well cured and not subject to oxygen inhibition as is the case with a back side open mold laminate.

2.8.2 Adhesive Bonding

The substrate surface features will determine the appropriate type of adhesive to use for successful bonding. Some adhesive types contain an etching agent that enhances the adhesion on smooth, gel-coated surfaces. Alternatively, some adhesive systems use a primer wipe to soften the substrate prior to bonding. Methacrylate adhesives are becoming increasingly popular as a replacement for open mold tabbing.

2.9 Conclusions

Variations of the RTM process are suitable to replace open mold lamination. Attention to detail is a key ingredient to the success of transitioning. Building an accurate mold cavity that is free from vacuum leaks is the pertinent challenge for Shell Laminate RTM and Silicone Bag RTM processes.

For rigid upper mold types, the fabrication of the upper mold must follow successful prototyping to include the ply kit and lamination schedule not just in regards to fit and form, but also function. Designing the ply kit prior to the upper mold provides for the most economical part material usage. The upstream process of gel coating has a distinct impact on the economics of conventional RTM due to the time involved with applying and curing the gel coat. The downstream processes of secondary lamination and adhesive bonding must also be visited for suitability with a given closed mold process due to the different nature of smooth, molded surfaces.

2.10 Appendices

The following sections provide additional information that many consider useful.

2.10.1 Flow Theory

Flow through porous media can be described mathematically. A French civil engineer in the mid 1850s formulated a relationship known as Darcy's Law. This relationship is:

$Q=-KA\ dh/L$ Rate of Fluid Flow

Q is the rate of fluid flow
K is the hydraulic conductivity
A is the cross sectional area of the porous medium
dh is the change in pressure over the length L
L is the path length

This equation shows that which is intuitively obvious. The flow is quicker when the hydraulic conductivity is greater, when the flow area is greater, when the pressure drop is greater and when the fill path is shorter. Rapid fluid flow requires greater hydraulic conductivity, larger flow area, larger pressure drops and shorter fill lengths. The flow is slower when the hydraulic conductivity is lower, the flow area is smaller, the pressure drop is lower and the path length is longer.

The hydraulic conductivity is also known as the permeability. This permeability is greater when the fiber is less compacted. Conversely, when the fiber is highly compacted, the permeability is low, and flow is reduced. The orientation and arrangement of fibers in the reinforcing pack will also affect the permeability. These features are referred to as the fiber pack architecture.

To expand on Darcy's Law further and define the hydraulic conductivity K:

K=(Intrinsic permeability)*(fluid density)*(Acceleration due to gravity)/(fluid viscosity)

The intrinsic permeability of the porous media is the property determined by the reinforcement form and its degree of compression. A lower fluid viscosity causes an increase in the hydraulic conductivity with a corresponding increase in the rate of fluid flow.

The two resin properties of interest, density and viscosity, are both functions of temperature and degree of cure. As a mold fills, the viscosity increases until gellation occurs.

2.10.2 Shell Laminate Mold Design Checklist:

Lower Mold:

Does my lower mold have features that allow me to wedge out a stuck part without causing damage to the mold surface?

Is the boundary of the edge manifold easily identified to enable accurate material trimming?

Is my flange design appropriate for my seal rubber extrusions?

Will the upper mold fit in only one clock position?

Does my mold set come together and separate with a pure vertical motion?

Upper Mold:

Have I designed and proven my part?

Have I designed my ply kit so that I know where my overlaps will be?

Have I chosen cavity thicknesses that correspond to the materials and glass contents specified by the proven design?

Have I identified the flow center and injector locations?

Does my mold set have alignment devices that align the mold set before the part features force the molds to align?

Does my mold set have features that allow me to wedge the upper mold off the part/lower mold without destroying my rubber seal extrusions?

2.10.3 Shell Laminate RTM: The Process on One Page:

Mask the lower mold flange at the flap seal for gel-coating. Apply Gel-coat.

Load the cavity with specified glass and core.

Trim reinforcement at the edge manifold.

Place Upper Mold approximately in position.

Install and clamp the injector tube(s).

Install the vent line or resin trap.

Apply vacuum to the part cavity at the vent first. Apply hand pressure to bring the outer flap seal into contact with the lower mold.

Apply vacuum to the clamp cavity once outer seal integrity is established.

Vent the part cavity to check the inner seal.

Reapply vacuum to the part cavity. Perform Leak-down Test.

Transfer the proper amount of resin into the part cavity. Clamp off the injector tube.

Maintain vacuum on both the part cavity and clamp cavity until the resin gels.

Once the resin gels, remove the resin trap and clean immediately.

Maintain vacuum on the clamp chamber until the part cures sufficiently to meet the part and process design requirements

Remove the upper mold. Perform Mold Maintenance Immediately.

Allow the part to continue curing sufficiently to meet the part and process design requirements. Remove the part.

2..10.4 What makes a good Shell Laminate RTM mold design?

A properly designed and built Light RTM mold has certain features:

The mold set is vacuum tight.

The upper mold cannot accidentally be installed at the wrong clocking relative to the lower mold. If the lower mold is oriented at 12 o'clock, it is not possible to close the mold at any orientation other than 12 o'clock..

Alignment devices align the mold set before the part's geometry does.

The mold can be assembled and sealed using only moderate hand pressure and the vacuum clamps, without resorting to mechanical clamps.

The fill is consistent from part to part.

The glass is not so compressed as to prevent fiber wet-out.

A known amount of resin is transferred to the part cavity and very little (tablespoons) makes its way into the vacuum trap.

The molds separate with a true vertical motion.

It's easy to wedge the upper mold off the lower without damaging the rubber seal extrusions.

It's easy to wedge the part off the lower mold without damaging the lower mold gel coat surface.