2.21

Open Mold Techniques for Thermoset Composites

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2.21.1 INTRODUCTION

In this chapter we will address those techniques in which fibers are placed on to a mold and impregnated with wet resin. The resin may be introduced at the same time as the fibers are placed or may be introduced to the fiber pack subsequently. The basic techniques generally use room temperature low-pressure cure of low-viscosity resins to produce large components for applications where optimum performance is not critical. The adoption of vacuum-bag methods may extend the performance envelope to which these techniques can be addressed. The use of preimpregnated (prepreg) reinforcement/autoclave methods and liquid composite molding techniques are dealt with in Chapters 2.20, and 2.22, this volume.

2.21.2 MOLD TOOLS

The design of the mold tool is a key element in the successful, effective, and efficient manufacture of composite components. The tool should have adequate rigidity to maintain dimensional tolerances, generous curvature at corners to avoid fiber bridging, and a surface finish to reflect that required of the component to be produced.

2.21.2.1 Materials

Mold tools for contact molding (spray or hand lay-up) are often manufactured in-house from a model of the component. The model may be any conveniently shaped material (e.g., balsa-wood, plaster, foam, etc.) which is shaped and sculpted, sealed, and coated with release agent. The tool is usually laid up against the model as a fiberglass-reinforced skin, and supported by a framework (e.g., welded steel section or egg-shell box). The cure schedule of the components to be made in the mold is an important consideration in selection of the mold material. For example, components

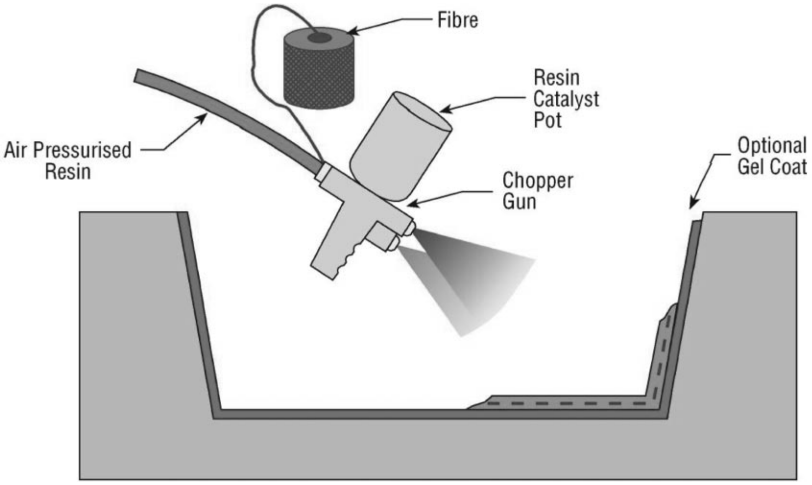

Figure 1 Spray lay-up (Cripps, 1999).

made of unsaturated polyester resins (UPE) are generally cured at ambient temperatures, while vinylester and epoxy resins may be cured at elevated temperatures. Postcure of an UPE mold will improve dimensional stability.

2.21.2.2 Mold Release

Before lay-up/molding commences for any open mold process, it is important to treat the mold surface with a release agent to prevent adhesion of the product to the mold tool and to ease removal of the part. The component may otherwise bond permanently to the mold causing both items to be scrapped! The choice of release agent depends on the surface finish required on the product and on whether subsequent bonding and/or painting will be undertaken. Proper mold preparation is an essential step in the production of good moldings that come cleanly off the mold. The manufacturer's instructions should be followed closely.

2.21.3 GEL-COAT

Before lay-up/molding commences for any open mold process, it is common to coat the mold with a clear/pigmented resin layer. This may act as a cosmetic outer surface and/or as a barrier to prevent environmental attack on the fiber–matrix interface. The gel-coat may be applied by painting, air atomization from a pressure pot, or airless spraying. The gel-coating stage, prior to lamination, may be the major cause of volatile emissions in vacuum bag-molding techniques. It is normal to make the mold surface a different color from the gel coat to clearly determine that a full gel-coat has been applied. Imperfections are more easily seen in a dark gel coat. A "Troubleshooting Guide for Gel Coats" is presented in Wittman and Shook (1982).

2.21.4 SPRAY-UP

2.21.4.1 Basic Processing Steps and Cycle

The spray-up technique uses a hand-held "gun" to feed a stream of chopped fibers into a spray of catalyzed liquid resin (see Figure 1). This stream is projected on to the mold tool. The deposited materials are left to cure under standard atmospheric conditions. The fibers normally settle onto the tool in a random (quasiplanar) orientation and, in consequence, the mechanical properties are limited by the twin constraints of discontinuous fibers and random fiber orientation. The sprayed fiber/resin mix is normally rolled to effect complete wetting of the fibers and to reduce voids and bubbles before resin cure is completed. A sequence of photographs illustrating a typical spray lamination process can be seen on the Web (http://www.goldshield.com/open_mould2.html).

2.21.4.2 Typical Process Window

The process is normally conducted at ambient temperatures and pressures in the interests of comfort of the workforce. The process is usually carried out using glass fibers and unsaturated polyester resin.

2.21.4.3 Process Equipment and Manufacturing Set-up

Safe and comfortable operation is dependent on the selection of suitable spray guns. A typical system will draw resin from the supplier's drum through a filter, inject a controlled amount of catalyst, and spray a fan of resin. The reinforcement strands are supplied into the air stream via a ceramic-coated guide, chopped and carried to the mold surface by the flowing resin.

2.21.4.3.1 Pumps

Pumps used for spray lamination are generally of the air-operated positive displacement type. This permits adjustment of the pressure and rate of delivery by means of an air regulator. Catalyst pumps may be piston (Binks or Venus) or peristaltic (Glascraft). They are designed to maintain a fixed catalyst ratio (for unsaturated polyester this is generally restricted to 0.5–8%). The Venus pump is a true piston pump connected directly to the shaft of the resin pump through a pivot beam. This system provides an accurate catalyst/resin ratio. The Binks pump is of the bellows type driven by an air motor. This does not have the leakage problems associated with the true piston.

2.21.4.3.2 Chopper

The chopper often consists of two air-driven rollers. The cott wheel (rubber or urethane) moves the fibers through the chopper against the cutter wheel (aluminum roller) which has short lengths of razor blade embedded in it to break up the fibers. The exhaust from the air drive is vented to assist in projecting the fibers towards the mold tool.

2.21.4.3.3 Spray head

The whole spray head assembly (often referred to as the gun) integrates the chopper and resin mixing (Wittman and Shook, 1982). The most common forms of mixing are:

(i) *External mixing*: typically four air-driven nozzles are arranged in a square pattern around the chopper with two nozzles dispensing resin and two nozzles dispensing catalyst. This arrangement requires the gun front to be cleaned after use.

(ii) *Airless external mixing*: catalyst and resin are fed from pressure pots such that mixing occurs by stream impingement. This arrangement requires the gun front to be cleaned after use.

(iii) *Air-driven internal mixing*: air, catalyst, and resin are mixed within the head before ejection. This arrangement requires internal flushing after use.

(iv) *Airless internal mixing*: catalyst and resin are fed at high (~5 MPa) pressure and mixed within the head. This arrangement requires internal flushing after use.

(v) *Two-pot system*: two separate nozzles operating at high (2.7–7.5 MPa) pressure are arranged to impinge the resin and catalyst streams around 150 mm ahead of the gun. This is potentially the simplest system and permits close down at the end of shift simply by turning off the fluid flow as catalyzed resin is kept away from the gun.

A recent development is the "flow chopper." This is similar to the resin chopper gun but equipped with a low-pressure, nonatomized resin delivery system and a unique nozzle and glass chute design (Wiley, 1998; Tracy-Adams, 1998). Whereas a spray fan breaks into droplets and atomizes before reaching the mold surface, the flow coat nozzle provides "a series of streams of catalyzed resin continuously flowing onto the open mould." For FlowChop to optimally reduce emissions, the resin flow must be maintained as a stream through low pump pressures. The US National Marine Manufacturers Association (NMMA), sponsored by the US Environmental Protection Agency (EPA), has recently conducted a study of this technique. It suggested that reductions in styrene emissions of 25% (for a 35% styrene content resin) to 43% (for a 42% styrene content resin) were possible on changing from external- to internal-mix spray guns for the fabrication of 5.5 m hulls. The reductions achieved in the Composite Fabricators Association (CFA) Phase 2 study are summarized in Table 1.

The CFA is promoting controlled spraying as a method to increase transfer efficiency in atomized spray application. The goal is to minimize surface area by reduced atomization and reduced overspray. The documentation (*Controlled Spraying Handbook*, 1998; *Controlled Spraying Training: Instructors Guide*, 1998; Lacovara, 1997, 1998, no date) for this approach can be downloaded from the Internet (Composites Fabricators Association Website, 1999). Controlled spraying has three elements:

(i) spray gun pressure calibration,
(ii) operator training, and
(iii) overspray containment flanges.

Lacovara has suggested that film-forming agents (called vapor suppressants or styrene suppressants) may be used in addition to low-styrene resins, controlled spraying techniques,

Table 1 Comparison of styrene emission levels from a standard internal mix spray unit and FlowChop (both Venus–Gusmer machines).

Nozzle : mold distance ⇒	*300 mm*	*610 mm*	*910 mm*
Internal mix spray gun (I)	47.2 ppm styrene	69.2 ppm styrene	91.8 ppm styrene
FlowChop machine (F)	9.6 ppm styrene	9.9 ppm styrene	10.6 ppm styrene
Styrene reduction: (I-F)/I	79.7%	85.7%	88.5%

Source: Tracy-Adams, 1998.

and nonspray application. These resin additives, which are almost as old as the composites industry, are typically based on aliphatic waxes (e.g., paraffin) or proprietary compounds for high-performance formulations. The wax phase rapidly separates from the styrene to form a surface film and thus inhibit styrene evaporation.

Reinforced Plastics magazine has recently published a comparison of popular spray guns from different manufacturers (*Reinforced Plastics*, 1999a, Forsdyke, 1999). Further information is available from the supplier companies (e.g., spray and dispensing systems, http://www.gsmfg.com/, 1999; complete line of fiberglass processing equipment, http://www.venus-gusmer.com/Venus-main.html, 1999).

2.21.4.3.4 Automation/robots

The process lends itself easily to automation. Medium volume production can be implemented with "teach and learn" robots. Products may then be equivalent to compression molded sheet molding compounds (SMC) with the potential for more complex component shapes. Such automation may be especially appropriate with the more hazardous resin systems.

2.21.4.4 Possibilities and Limitations

2.21.4.4.1 Advantages

(i) Low equipment and tooling costs.

(ii) Relatively inexpensive materials (fiber is used in the cheapest form: continuous roving).

(iii) Fast deposition rates.

(iv) Labor costs lower than for hand-lamination.

(v) Versatility of part shape and laminate configuration, including local thickness variations.

(vi) Potential for automation with robots.

See Wittman and Shook (1982) and Kelly (1999) for further details on possiblities and limitations.

2.21.4.4.2 Disadvantages

(i) Health and safety legislation/regulations/voluntary codes (meeting standards for levels of volatile organic compounds (VOC, normally styrene) is becoming increasing difficult as permitted levels are reduced).

(ii) Cost of extraction and treatment of VOCs.

(iii) Limited production rates if hand-operator controlled.

(iv) Product quality is dependent on operator expertise.

(v) Difficulty of removing trapped air from the molding.

(vi) Dimensional inconsistency within and between batches.

(vii) Only one molded surface.

(viii) Physical properties limited to those of chopped fiber reinforcement, with consequent high resin contents.

(ix) High levels of waste, especially where overspray is significant.

2.21.4.5 Process Monitoring and Quality Assurance

Process monitoring and quality assurance is generally limited to records of the materials used and to conformity with procedures. There is potential for automated recording of the consumption of materials (e.g., timed records of the weight of materials consumed or flow rates). More comprehensive records including conformity with the intended catalyst/resin mix ratio may be appropriate.

2.21.4.6 Applications and Industrial Utilization

The process is normally used for lightly loaded nonstructural or semistructural panels. By default, the spray process uses discontinuous fibers and there is limited scope for alignment of the reinforcement. For more structural parts, it is possible to interrupt the spraying and hand-place specific (directional) reinforcements

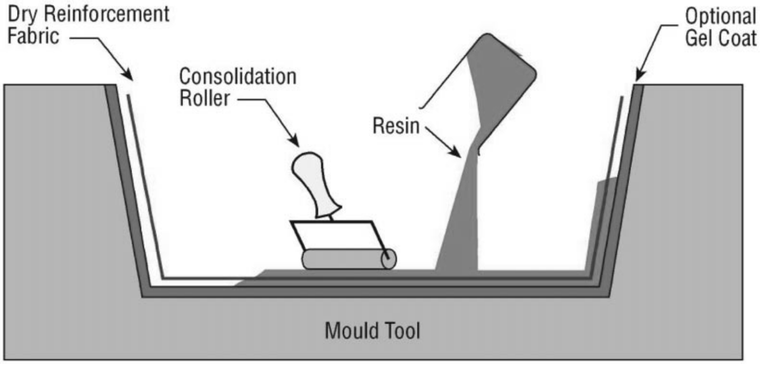

Figure 2 Wet lay-up/hand lay-up (Cripps, 1999).

before restarting spraying. The low cost of tooling makes the process suitable for low-volume production runs. Typical applications include truck fairings, caravan bodies, canoes, low-performance boats, swimming pools, bathtubs, and shower trays.

2.21.5 HAND-LAMINATION (ALSO KNOWN AS CONTACT MOLDING OR WET LAY-UP)

2.21.5.1 Basic Processing Steps and Cycle

In the hand lay-up technique, fibers are positioned on or into the mold and wetted by liquid resin (see Figure 2). The fibers may be of any material (often aramid, carbon, or especially glass) in the form of chopped strand mat, woven-, knitted-, stitched- or bonded-fabrics, either singly or in combination. Brushes are often used to distribute the resin evenly onto the fibers and rollers are employed to work air bubbles out of the reinforcement and to ensure complete wet out. Stippling is used to wet chopped strand mat, while brushing is more appropriate for fabric reinforcements. Nip-roller type impregnators are increasingly used to force resin into the fabrics by means of rotating rollers and a bath of resin. Cure (cross-linking) usually occurs at ambient temperature with no consolidation pressure applied to the molding.

2.21.5.2 Typical Process Window

The process is normally conducted at ambient temperatures and pressures in the interests of comfort of the workforce. Adjustment of catalyst levels (within limits) permits variation of the working time for a range of "ambient" temperatures or for large component sizes. Pressure in the lamination area may be slightly reduced for VOC control and to generate airflow away from the laminator. Lay-up should be continuous with no break of more than 24 h for polyester resin. For extended breaks it may be necessary to clean and/or roughen the surface before continuing. For epoxy resins, this is often achieved through the use of a layer of peel-ply. This has the additional benefit of removing any resin by-product that may have formed at the surface through reaction with the air. The peel-ply is removed from the surface just prior to restarting lamination and leaves a clean textured surface.

2.21.5.3 Process Equipment and Manufacturing Set-up

The normal equipment for hand lamination consists of resin containers and laminating brushes (the process is commonly referred to as "bucket and brush") often in combination with laminating rollers and metal/disk rollers to remove air from awkward corners. Noakes (1992) describes the process in detail in a well-illustrated book.

2.21.5.3.1 Resin roller dispenser

Resin roller dispensers are a method of reducing styrene emissions without major changes in molds and materials. A pump supplies resin and catalyst to a static mixer and application occurs using a roller applicator. The technique minimizes vaporization, fogging, overspray, and bounce-back losses.

2.21.5.3.2 Vibroforming

Devices similar to resin roller dispensers are available with vibrating heads. They encourage air removal and compaction of the laminate leading to lower void contents and higher fiber volume fractions.

2.21.5.3.3 Gantry access with fabric-feed impregnators for large structures

For large structures, such as mine counter measures vessels, it is common for the laminators to work from overhead gantries rather than have to tread on the structure during fabrication. The gantries often carry rolls of fabric which are fed through impregnators within a resin bath prior to application. Impregnators can significantly increase fiber volume fraction and reduce void contents.

2.21.5.4 Possibilities and Limitations

2.21.5.4.1 Advantages

(i) Accumulated experience as the process has been widely used for many years.

(ii) Standardized training exists (e.g., *City and Guilds Hand Laminators Certificate*).

(iii) Short lead times for component production.

(iv) Minimal equipment and tooling costs.

(v) Relatively inexpensive materials.

(vi) Wide choice of suppliers and material types.

(vii) Versatility of part shape, size, and laminate configuration.

(viii) Design changes can be easily effected.

(ix) Cost-competitive for individual items and short production runs of complicated shape.

(x) Fiber volume fractions are potentially higher than for spray lamination.

(xi) Scope for a wide range of physical and mechanical properties in the laminate.

(xii) Resin-rich composites can produce high-quality corrosion-resistant components.

(xiii) Sandwich construction (foam or balsawood core materials) and inserts are readily incorporated.

More information on possibilities and limitations can be found in the following references (Wittman and Shook, 1982; Kelly, 1999; Murphy, 1994, 1998).

2.21.5.4.2 Disadvantages

(i) Health and safety legislation/regulation/voluntary codes.

(ii) Cost of extraction and treatment of VOCs.

(iii) High labor content.

(iv) Product quality and variability is dependent on operator expertise (especially in mixing resin).

(v) Low production rates due to cure times of room temperature resins.

(vi) Resins need to be of low viscosity (low molecular weight) and are hence volatile (especially the styrene in unsaturated polyester resin).

(vii) Dimensional inconsistency.

(viii) High shrinkage and potential exotherm in resin-rich areas, especially for thick components.

(ix) Draining of resin from vertical surfaces may require the addition of thixotropic agents.

(x) Only one molded surface.

(xi) High levels of voids inherent in the process.

(xii) Low molecular weight resin compromises thermal and mechanical properties.

(xiii) Low fiber volume fraction (maxima typically 20% for chopped strand mat or 35% for woven fabrics (Eckold, 1994)) yields poor mechanical properties.

(xiv) High levels of waste.

2.21.5.5 Practical Limitations

In the hand lay-up technique, plant personnel may be exposed to the materials used. Skin contact with liquid resins should be avoided by the use of personal protective equipment (gloves, goggles, and protective clothing). Many of the component chemicals are irritant or hazardous. Other components can be volatile and flammable. Adequate ventilation, and/or fresh air masks, can prevent inhalation of these components.

The cost of extraction and cleaning of air contaminated with volatile organic compounds can be high, most notably where polyester or vinylester resins are used. Legislation varies widely between countries. Open mold processing of unsaturated polyester resins is almost impossible under Scandinavian law. More cost-effective solutions may be a change to a low-volatile content resin (e.g., epoxy) for low-volume production or the adoption of closed mold processing.

Inadequate control of the cure of laminates, especially with thick sections, can result in exothermic reactions. These in turn may result in fuming or even plant fires.

A "Troubleshooting Guide for Hand Lay-Up" is presented in Wittman and Shook (1982).

2.21.5.6 Process Monitoring and Quality Assurance

Process monitoring and quality assurance is generally limited to records of the materials used and to conformity with procedures. There is limited potential for automated recording of the consumption of materials. The criti-

Figure 3 SEAT rally car built using SP Ampreg 20 epoxy laminating resin and dry reinforcements with hand lay-up techniques.

cality of resin component mix ratios (especially for stoichiometric systems such as epoxy) can be protected against by the use of mixing machines. Correct operation of mixing machines needs to be regularly verified by disconnecting the mix-head and weighing the component streams.

The degree of cure of the component can be assessed by the use of portable Barcol impressors (British Standard BS2782 method 1001, Europaïsche Norm EN59) on the shop floor, backed up by thermal methods (e.g., DSC, DMTA) in the laboratory.

2.21.5.7 Applications and Industrial Utilization

The ability to incorporate continuous fibers/fabrics permits hand lay-up to be used for higher performance applications than spray techniques. Reinforcements, notably unidirectional tapes, can be specifically placed for optimum reinforcement of the component. Chopped strand mat (CSM) can be used to produce similar components to those made by spray-up, although the hand laminated component will generally have better properties because of the higher fiber lengths and the lower resin and void contents. There is considerable potential for the production of pre-prototype components by hand lamination prior to making a commitment to the expenses involved in molds for other techniques.

Typical applications include boat hulls, storage tanks, swimming pools, chemical plant, agricultural containment, architectural panels, garden furniture, wind-turbine blades, car and truck bodies and fenders (see Figure 3), furniture, and equipment housings. Component size is virtually unlimited. Mine counter measures vessels are produced in the UK (Royal Navy Hunt class: 60 m overall length), Sweden (Landsort class: 47.5 m), and Italy (Lerici/Gaeta class: 51 m). The Italian vessels, also adopted by the US Navy, are of monocoque construction with laminate thickness up to 300 mm.

2.21.6 VACUUM-BAGGING

For thermoset prepregging and autoclaving, see Chapter 2.20, this volume.

2.21.6.1 Basic Processing Steps and Cycle (Temperature and Pressure, etc.)

This is basically an extension of the wet lay-up process described above with pressure applied to improve consolidation of the laminate by extracting excess resin and included air. This is achieved by covering the hand-laid laminate with peel-ply, release film, breather/bleeder fabric, and vacuum bagging film and sealing the film to the edges of the tool (see Figure 4). The air under the bag is extracted by a vacuum pump and thus up to 1 atm of pressure can be applied to consolidate the laminate. The peel ply is porous and permits resin to be bled from the laminate. The size and spacing of the perforations in the release film gives an element of control to the degree of bleed. The breather/bleeder fabric plays a dual role:

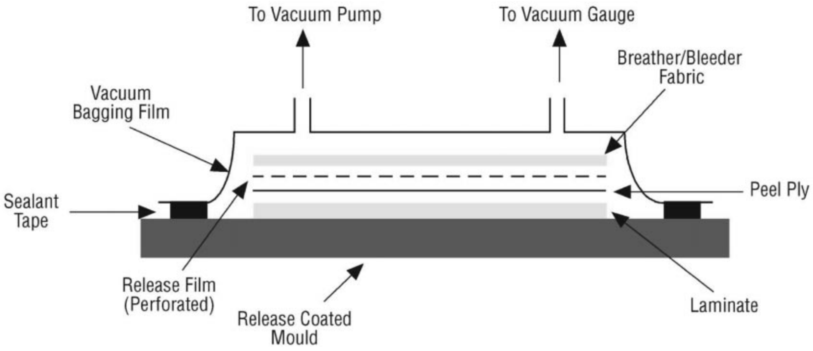

Figure 4 Schematic representation of the vacuum-bagging configuration (Cripps, 1999).

(i) the breather permits uniform pressure to be applied by providing an air path over the whole laminate;

(ii) the bleeder (absorption fabric) soaks up excess resin bled from the laminate.

Epoxy resins are most commonly used due to the potential problems that may occur due to styrene extraction from unsaturated polyester resins.

2.21.6.2 Typical Process Window

Lamination and bagging are performed at ambient temperature and pressure. The vacuum is applied once the resin has reached a sufficiently high viscosity to avoid excess resin bleed and is maintained until no further flow is anticipated (i.e., when the resin has progressed through gel and acts as an elastic solid). Cure of the bagged laminate may take place in an oven. A temporary enclosure with space heaters may be used for very large structures.

The same techniques can be used to locate and bond core materials in sandwich panels. Bagging is especially useful for curved components where hand placement can be difficult because of the need for a uniform pressure. Vacuum is maintained until the adhesive has formed a bond that is strong enough to retain the core. Cores are usually scored or perforated to permit extraction of air from underneath the core. Such prepared cores are supplied commercially.

2.21.6.2.1 Autoclave quality without prepreg

Stringer (1989) considered the optimization of the wet lay-up/vacuum bag process for the fabrication of XA-S carbon fiber composites in two different epoxy resins. Laminates were consistently produced with fiber volume fractions up to 58% and void contents below 2% provided that the resin viscosity at the time of application of bagging pressure was within the limits 75–165 poise (1 poise = 10 Pa s). A dwell time "window" exists between the same limits "regardless of the resin system and temperature being used" and can in principle be derived for any resin system from the viscosity–temperature–time characteristics.

2.21.6.3 Process Equipment and Manufacturing Set-up

The process is essentially the same as for hand-lamination with a requirement for additional consumable materials and labor. The mold must have a flange wide enough to permit attachment of the bag and must be vacuum tight. The additional consumable materials and equipment required for vacuum bagging are summarized in Table 2.

It is essential to ensure that uniform vacuum pressure is drawn. For large structures, a perforated tube and extra breather may be used to this end to provide a network of air paths. Various permutations of the consumables may be used, e.g., extra perforated release film between the bleeder and the breather or the use of double bagging (see Figure 5). The laminate *and* the mold may be enclosed in a tubular bag where smaller components are being produced. Bagging times and consumable costs can be reduced by the use of tailored reusable silicone bags.

2.21.6.4 Possibilities and Limitations

2.21.6.4.1 Advantages

(i) As for hand-lamination, with potentially higher fiber volume fractions and lower void contents.

(ii) Better fiber wet-out due to the pressure and resin flow.

Table 2 Consumable materials and equipment required for vacuum bagging.

Peel-ply	A sacrificial open weave fiberglass or perforated heat-set nylon ply placed between the laminate and the bleeder/breather to provide the textured and clean surface necessary for further lamination or secondary bonding
Bleeder cloth	A nonstructural fabric designed to absorb excess resin and reactants from the laminate. This may also act as the breather cloth
Breather cloth	A loose weave or nonwoven porous material use to provide a gas flow path over the laminate both to permit the escape of air, reactants, moisture, and volatiles and to ensure uniform vacuum pressure across the component. This may also act as the bleeder cloth
Release film	A (perforated) sheet of material placed between the laminate and the mold surfaces to prevent adhesion
Edge dams	Profile used to define the edge of the component
Caul plate	A mold or tool placed on top of the laminate inside the bag to define the second surface
Intensifiers	Generally hard rubber profiles incorporated in the bag to consolidate the laminate at sharp radii
Bagging film	The membrane which permits a vacuum to be drawn within the bag
Tacky tape	Adhesive strip used to bond the bag to the tool and provide a vacuum seal
Breach unit	A connector through the bagging film to permit a vacuum to be drawn
Vacuum pipes	The link between the breach unit and the vacuum pump
Resin trap	A container in the vacuum line to collect any excess resin before it can damage the vacuum pump
Vacuum pump	Generally a high-volume pump (absolute vacuum is rarely required) suitable for continuous running. For some slow-curing epoxy resins 24 operations may be needed
Pressure gauges	Generally clock-type gauges attached via a breach unit connection

(iii) Heavier fabrics (than for hand-lamination) can be wet-out.

(iv) Volatile organic compounds are largely contained during the curing stage.

(v) The additional consolidation pressure can help the reinforcement to conform to tight curvatures.

(vi) Improved mechanical properties consequent upon the higher fiber volume fraction.

2.21.6.4.2 Disadvantages

(i) Health and safety legislation/regulation/voluntary codes during lamination.

(ii) Cost of extraction and treatment of VOCs during lamination/prior to fitting the vacuum bag.

(iii) Additional (higher skilled) labor needed for the bagging stage.

(iv) Product quality and variability is dependent on operator expertise (especially in mixing resin).

(v) Low production rates due to labor required for bagging.

(vi) Resins tend to be of low viscosity (low molecular weight) and are hence volatile (especially the styrene in unsaturated polyester resin).

(vii) Dimensional inconsistency.

(viii) High shrinkage and potential exotherm in resin-rich areas, especially for thick components.

(ix) Usually only one molded surface is produced.

(x) Low molecular weight resin may compromise thermal and mechanical properties.

(xi) Bagging film is available in limited widths and sealing adjacent pieces can be difficult.

(xii) The mold tool must be vacuum tight.

(xiii) Additional costs for equipment (tool/vacuum pump) and consumables.

(xiv) The vacuum pump may strip volatile components from the resins, especially polyester and vinylester resins.

(xv) Consumable materials need to be compatible with the resin system and it's volatile components.

(xvi) The consolidation pressure is limited to 1 atm.

(xvii) High levels of waste, especially consumables.

2.21.6.5 Practical Limitations

The size of the components that can be produced by wet lay-up with vacuum bagging is limited by the following factors:

(i) The extra stage of bagging must be allowed for in the working time of the resin.

(ii) Working times must be carefully calculated to achieve the correct viscosity at the application of vacuum.

(iii) A good understanding of the time–temperature–viscosity (degree-of-cure) relationships is required for an optimized process. Instantaneous resin viscosity typically halves for a 10 °C temperature rise. The time to a specific viscosity is roughly halved by a 10 °C temperature rise due to progress of the cure.

(iv) Bagging film is available in limited widths and joining pieces for larger components incurs additional labor and consumable costs. For large structures, postcure is common at up to 60 °C in a tent with space heaters (rather than using a purpose-built oven). Boat hulls up to 60 m in length have been produced in this way. The cost of consumables may be a significant part of the component costs for fiberglass structures.

2.21.6.6 Process Monitoring and Quality Assurance

Barcol hardness is less useful as a means of monitoring the degree-of-cure for bagged laminates due to the higher fiber content (less resin) achieved in the process relative to hand lamination without bagging. The thermal techniques (DSC and particularly DMTA) remain appropriate.

Ciriscioli and Springer (1990) have presented process models and an expert system applicable to autoclave curing of thermosetting matrix composites. This may also be appropriate for vacuum bagging without autoclave consolidation for high value components.

2.21.6.7 Applications and Industrial Utilization

Due to the higher costs incurred in bagging, the process tends to lend itself to structures where performance is more critical and often where the raw materials are of higher value (e.g., carbon fiber/epoxy). The process is used for higher quality hand-laminated components, especially large one-off cruising boats, racecar components, and core-bonding in production boats (see Figure 6).

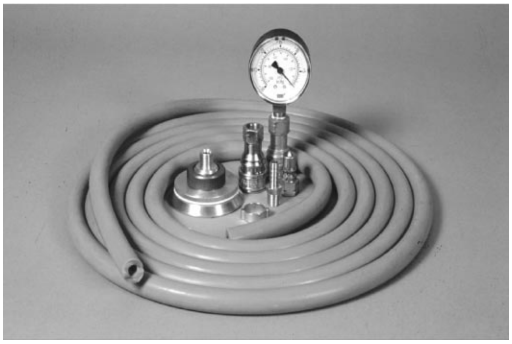

Figure 5 Breach unit, pressure gauge, and hose (Cripps, 1999).

2.21.6.8 Process Simulation

The models appropriate for process simulation of prepreg manufacture should be applicable to wet lay-up with vacuum-bagging (see Chapter 2.20, this volume). However, it may be more difficult to determine accurate rheological characteristics for the mixed resin system and the extent of resin bleed will normally be higher.

2.21.7 RESIN INFUSION

2.21.7.1 Basic Processing Steps and Cycle

Resin transfer molding (RTM) involves the long-range flow of resin into a dry fiber pack that is preloaded into a defined mold cavity. This topic is covered in Chapter 2.23, this volume, by van Harten (1993), and various books (Potter, 1997; Rudd *et al.*, 1997; Kruckenberg and Paton, 1998; Benjamin and Beckwith, 1999). Resin infusion under flexible tooling (RIFT) is a variant of RTM in which one tool face is replaced by a flexible film or a light splash tool (see Figure 7). The flow of resin results only from the vacuum drawn under the film and any gravity effects. In RTM the dimensions of the component are defined by the separation of the mold faces, while in RIFT processes the thickness of the part is a function of the pressure history during the process.

The basic process has been known for some 50 years, being patented by Marco Chemicals Inc. (Muskat, 1945). In the original Muskat patent, "The method of the present invention contemplates the handling of the fibrous base

Figure 6 100′ cruising yacht built using SP Ampreg 26 epoxy laminating resin, impregnated with a nip-roller wet-out machine and consolidated under a vacuum bag.

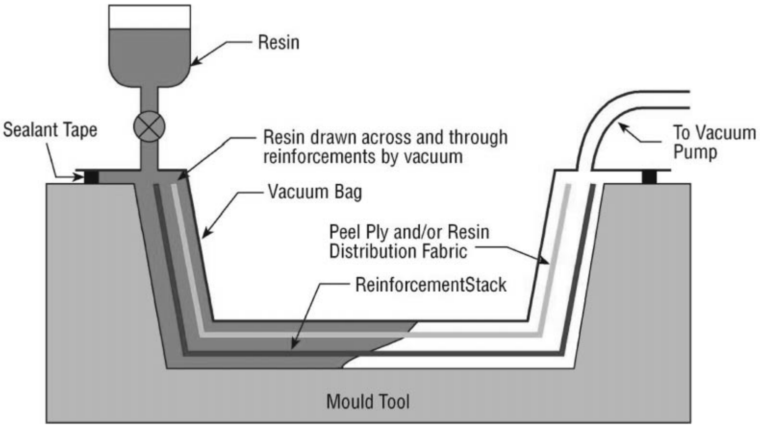

Figure 7 Schematic representation of the resin infusion process (Cripps, 1999).

to be impregnated... preferably in a substantially dry state, and the subsequent impregnation of the base in a mold with a liquid or liquefied resinous material by an applied force which serves to drive the resin into the base to impregnate it and at the same time drive from the base all air entrapped therein. The applied force is obtained by applying an outside pressure differential between the inside and outside of the mold.” Further, “impregnation of the fibrous base may be obtained by providing tubes in each of the complementary molds or in only one of the molds, one tube being connected to a source of resin and the other to a vacuum pump, and sucking the resin up through the tube and into the mold until it is filled.” The patent implies that the “complementary molds” are solid rather than bag materials, but the two mold halves appear to be free to move together under the applied vacuum. The process was introduced to the UK by Scott Bader in 1946 (Coniff, 1999) when molders had to use closed molds in order for the resin to cure properly because of chronic air inhibition.

Similar solid mold techniques have been used commercially for car bodies (Chapman, 1972; Adams and Roberts, 1985), railway rolling stock (Gotch, 1978, 1980, 1985), ferries on inland waterways (le Comte, 1982), and aircraft propellers (McCarthy, 1981, 1984). Preliminary experiments on high fiber volume fraction composites were conducted in the early 1980s (Allen *et al.*, 1982; Bacon *et al.*, 1984; Gurtan *et al.*, 1987).

In RIFT processes, the dry fabric is positioned on/in the mold tool and enclosed in a vacuum bag. A peel ply and a flow medium (carrier layer: usually a knitted nonstructural fabric) are often placed between the laminate and the bagging film. The vacuum removes air from the dry laminate stack (hence minimizing trapped air) and then draws resin from a container (usually at atmospheric pressure) into the reinforcement pack. The resin flows into the carrier layer, floods one surface of the component, and impregnation then proceeds by through-thickness flow more or less simultaneously across the whole component. The flow front in the reinforcement also pushes any residual air towards the vacuum port. Flow is usually stopped when there is no evidence of air being flushed from the reinforcement into the outlet pipes. For short flow distances and high permeability fabrics it may be practical to use flow within the plane of the fabric without resorting to a flow medium.

The many variants of the process are known by a wide variety of names, including:

(i) CIRTM (co-injection RTM) (CIRTM, 1998; Beckwith and Hyland, 1998):
  (a) injection of more than one resin into soft-sided tooling and vacuum bag mold.
  (b) separation of flow between multiple resins through the thickness of the part.
  (c) eliminates the need for secondary bonding.
(ii) Crystic VI (vacuum infusion) from Scott Bader (Coniff, 1999)
(iii) DRDF (double RIFT diaphragm forming) (Channer *et al.*, 1999):
  (a) dry fabric is placed between two elastomeric membranes.
  (b) resin is infused into the fabric.
  (c) the "sandwich" is vacuum-formed over the mold shape.
(iv) Plastech VM vacuum molding system (Plastech, 1999): a hybrid RIFT/RTM system.
(v) Quickdraw (Lazarus, 1995).
(vi) RIFT (resin infusion under flexible tooling) (Williams *et al.*, 1996):
  (a) generic term for all vacuum driven resin infusion processes under soft tooling.
(vii) RIRM (resin injection recirculation molding) (Beckwith and Hyland, 1998):
  (a) combination of vacuum and pressure infusion.
  (b) resin recirculated until satisfactory wet-out achieved.
(viii) SCRIMP^{TM} (Seeman Composites Resin Infusion Manufacturing Process) (Beckwith and Hyland, 1998; SCRIMP, 1999a, 1999b; Welcome aboard, 1999):
  (a) patented process involving vacuum bag resin distribution.
  (b) resin quickly distributed across large part surface area.
  (c) resin then saturates through the preform thickness.
  (d) vacuum bag, soft-sided tooling required.
  (e) (SCRIMP Systems LLC has recently been acquired by True North Partners: the investment company behind the molder: TPI Plastics) (Reinforced Plastics, 1999b).
(ix) UVRTM (ultraviolet cure RTM) (Beckwith and Hyland, 1998):
  (a) SCRIMP^{TM}-like process with ultraviolet cure through UV-transparent vacuum bag.
(x) VARI (vacuum assisted resin injection):
  (a) vacuum (typically 0.34–0.95 bar) used to pull resin into the preform.
  (b) process may use pressure to push resin at the same time.
(xi) VARTM (vacuum-assisted resin transfer molding), see VARI.
(xii) VIM (vacuum infusion molding).
(xiii) VIMP (vacuum infusion molding process) (Beckwith and Hyland, 1998):
  (a) resin fed by vacuum or gravity.
  (b) resin transfer occurs from preform interior within the mold.
(xiv) VIP (vacuum infusion process) (Beckwith and Hyland, 1998), see VARI:
  (a) proposed as a generic term for "resin introduce at lower than atmospheric pressure" by Bob Lacovara of CFA (USA).

The flow media can be applied either outside the laminate (any feeder material separated from the laminate by peel ply) or within the laminate (e.g., balsa, Rovicore, or Multimat) (Hoebergen, 1999). The carrier layer may be interleaved with the fabric layers (Åström, 1997).

While most resins formulated for hand lay-up can be used for this process, there are resins of lower viscosity specifically formulated for liquid composite molding processes which are suitable for RIFT techniques (Table 3).

Table 3 Comparison of hand-lay and LCM resins.

Property	*Resin units*	*SP AMPREG 20/slow hand lamination*	*SP PRIME 20/slow infusion*
Mix viscosity (at 25 °C)	Pa s	447	188
Glass transition temperature (after 50 °C postcure)	°C	85	86
Tensile strength of casting (after 50 °C postcure)	MPa	83	74

Source: Cripps, 1999.

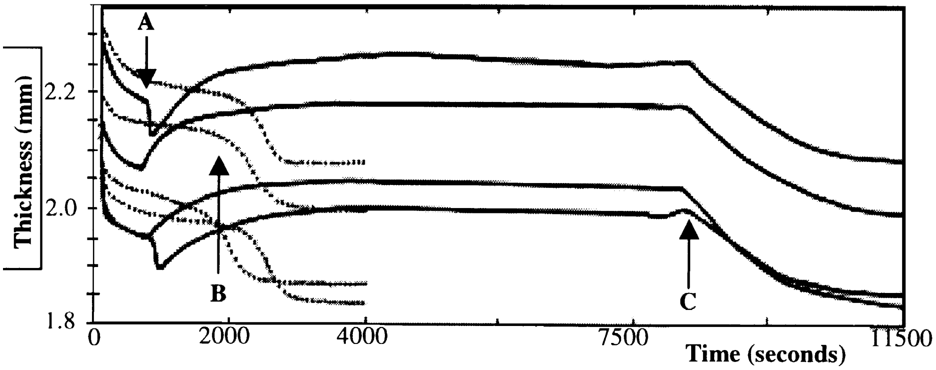

Figure 8 Thickness variation during the RIFT process for four separate moldings. Solid lines are for a transducer at 30 mm from the inlet, dotted lines are for a transducer at 180 mm from the inlet. A is resin arrival at first transducer, B is resin arrival at the second transducer, C is the time at which inlet and outlet pipes are clamped (after Williams *et al.*, 1998).

2.21.7.1.1 *Effect of vacuum on resin*

A potential problem in RIFT processes is often described as "boiling" of the volatile components. Lundström *et al.* (1993) state that styrene is evolved at 0.01 bar at 40 °C. Poor laminate quality, normally attributed to the volatile components, was suggested to be an indication of air permeability of the mold.

2.21.7.1.2 *Fabric compressibility*

The application of vacuum pressure to the laminate stack results in fabric compaction which, in turn, limits the pore space and results in slow in-plane flow rates in the fabric. Fabric compaction is briefly considered in Appendix A. The thickness of the reinforcement stack changes during the resin infusion process. A brief analysis, based on the application of Kozeny–Carman–Blake theory to resin transfer molding, is presented in Appendix B to illustrate the effect of such thickness changes on the permeability of the reinforcement.

2.21.7.1.3 *Thickness change during RIFT processes*

Williams *et al.* (1998) have presented results of a preliminary experimental study of the effects of changing pressure consequent upon the flow during RIFT processes (see Figure 8). Compaction of the reinforcement is complex. The application of vacuum causes an initial reduction in thickness. The arrival of the resin front appears to have a lubricating effect and may result in further compaction. As the flow front progresses beyond the monitored position, the net pressure on the laminate is reduced and the fabric relaxes. To produce a laminate of uniform thickness it may be necessary to seal off the bagged wetted laminate and allow the pressure within the bag to equilibrate.

2.21.7.2 Typical Process Window

Preparation of the bagged laminate is normally conducted at ambient temperatures and pressures in the interests of comfort of the workforce. Flow may be undertaken at elevated temperatures to reduce the resin viscosity and hence fill-time.

2.21.7.3 Process Equipment and Manufacturing Set-up

The capital equipment required for the RIFT process is simply the mold tool and a vacuum pump. The mold tool may be that used for contact molding (spray or hand lay) although extension of the mold tool to permit attachment of the bag may be needed. The tool should also be vacuum tight as any route for the ingress of air will result in tell-tale void trails in the laminate.

The consumables applicable to RIFT processes are similar to the peel ply and bagging film required for vacuum bagging. Additional components are the flow medium and perforated pipes. The flow medium is usually an open-weave fabric which is laid over the laminate to promote rapid flooding of one face of the laminate with resin. The pipes (often lightweight steel coil channel) promote "race-tracking" and hence minimize the distances that the resin flow front travels in the flow medium.

Equipment developed for RTM may find applications in RIFT. Plastech have developed the Autosprue®: an automated injection sprue (Plastech, 1999; Moore and Bland, 1999), and MPG™: mold pressure guard (Plastech, 1999; Moore and Bland, 1999) for their VM vacuum molding system. They also offer both catalyst flow monitoring (Moore and Bland, 1999) and an AGC (arrival, gel, and cure) sensor (Moore and Bland, 1999). The latter provides a signal indicating electrolytic activity and temperature.

2.21.7.4 Surface Finish

Hetron Resins, in combination with SCRIMP™, have developed a resin capable of producing class A finish in the vacuum infusion process (Weaver, 1998).

2.21.7.5 Resin Infusion for Autoclave Consolidation

The use of resin infusion techniques to prepare laminates for autoclave consolidation may result in considerably less expense in the acquisition of raw materials. This advantage must be set against the potential increase in both labor and quality costs for the fabricator due to the extra stages of production in-house.

2.21.7.6 Possibilities and Limitations

2.21.7.6.1 Advantages

(i) Can be used for polyester, vinylester, and epoxy resins and most conventional woven or stitched fabrics.

(ii) Large structural components can be fabricated.

(iii) Relatively low tooling costs for high-performance components.

(iv) More consistent than wet-laid components with minimal modification of the tooling.

(v) Heavy fabrics are more easily wetted than by hand lamination.

(vi) Higher fiber volume fraction leads to improved mechanical performance.

(vii) More uniform microstructure and minimal void content relative to hand lamination (Figure 9).

(viii) Cored structures can be produced in a single flow process.

2.21.7.6.2 Disadvantages

(i) The process is relatively complex and requires different skills to hand-lamination.

(ii) Greater emphasis is placed on premolding preparation than on the actual molding process.

(iii) Process is sensitive to leaks (air paths) in the mold tool and the bag.

(iv) Requirement for very low resin viscosity may compromise thermal and mechanical properties, especially for polyester and vinylester matrix composites.

(v) Uneven flow may result in unimpregnated areas and thus very expensive scrap parts.

(vi) Cannot easily be implemented for honeycomb core laminates.

(vii) Only one side of the component has a molded finish (cf. resin transfer molding).

(viii) Thinner components have lower structural moduli.

(ix) Patenting of aspects of the process in the USA, and associated licensing costs, have caused potential users to be wary of adopting the process for fear of legal action.

2.21.7.7 Practical Limitations

In some circumstances, easy flow paths can result in some areas of the component being starved of resin. Barnes and Galbraith (1995) proposed the following options for practical situations:

(i) block the flow of resin over the reinforcement to force resin to flow through the reinforcement before reaching the vacuum pump.

(ii) incorporate 5–10% high permeability layers within the laminate to achieve wet-out of thicker laminates.

(iii) use of a flexible former (intensifier) between the bag and the laminate to maintain consolidation pressure during the process especially on large vertical or overhead surfaces.

For large products, it is often beneficial to employ a "grid-like" injection strategy of one major channel with several branches (Hoebergen *et al.*, 1999). The quality of the tooling is critical with maintenance of vacuum integrity becoming increasingly problematic as the component size increases.

2.21.7.7.1 *Cosmetic finish/print-through*

There is some concern, particularly from the boat-building industry, that the RIFT processes produce laminates with a surface that echoes the topology of the reinforcement fabric. This is due to resin shrinkage in the resin-rich region in between the points at which tows cross. It is mainly a problem with polyester and vinylester resins formulated with high styrene contents to achieve a viscosity appropriate to the infusion process. Finer fabrics adjacent to the surface can help to minimize this effect, but further research is needed to optimize materials and processes to eliminate the effect. Avoiding "print-through" is of commercial importance for all components where good surface finish is required and especially for producers of boat hulls.

2.21.7.7.2 *Effect of thinner section on scantlings*

The use of vacuum to drive the RIFT process causes fabric compression and results in reduced resin content in the laminate. The laminate produced is therefore thinner than for a comparable number of layers of reinforcement made by hand-lamination (in our experience the RIFT panel is $<75\%$ of the thickness of the hand laminated panel). Some of the classification societies for boat building have scantlings (standard dimensions for parts of a structure) in which the thickness assumes manufacture by hand lamination. To meet these requirements with RIFT manufacture would require additional layers of fabric. The use of RIFT processes produces thinner parts with a higher elastic modulus. However, loss of thickness may compromise the structural modulus due to the effect on second moment of area, so the panel stiffness may be reduced.

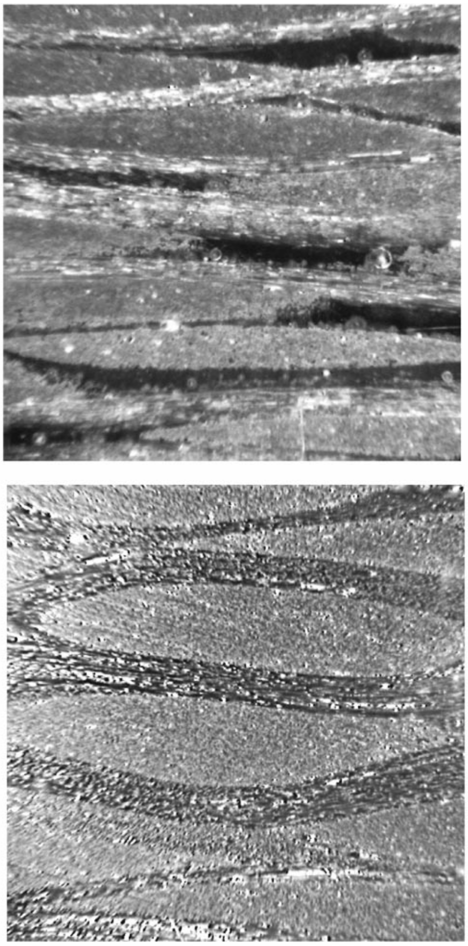

Figure 9 Typical microstructures for hand laminated (top) and resin infused (bottom) composites: both composites are nine layers of 764 gsm plain woven E-glass in epoxy resin (the tow width based on the number of tows per meter is approximately 5 mm) (Summerscales, 1998).

2.21.7.8 Process Monitoring and Quality Assurance

The position of the flow front may be monitored visually through the bag or by using galvanic cells (Moore and Bland, 1999) or fiber-optic sensors (Bernstein and Wagner, 1997). The state-of-cure of the component within the mold may be monitored using dielectric methods (Senturia and Sheppard, 1986; Summerscales, 1990) or chemical spectroscopy via embedded optical fibers (Parnas *et al.*, 1999).

2.21.7.9 Applications and Industrial Utilization

2.21.7.9.1 *Marine applications*

Le Comte (*Ship and Boat International*, 1986a, 1986b) produced a series of simple versatile reinforced plastic landing craft up to 22 m long using vacuum-assisted injection molding (VAIM) and proposed that the 5 ton hulls of 34 m surface effect ships will be produced using the VAIM technique.

Vosper Thornycroft has progressively increased the extent to which components manufactured by the SCRIMP^{TM} vacuum infusion (VI) technique are incorporated in the *Sandown* class single role minehunter for the Royal Navy (Weaver, 1997; Reinforced Plastics, 1997, 1998a, 1998b, 1998c). The 55.2 m 470 tonne displacement craft is $\sim 30\%$ reinforced plastic, largely molded by VI. The benefits of SCRIMP^{TM} are:

(i) resin infusion into the tows is independent of fabric weight.

(ii) reduced costs and greater efficiency in production: fewer layers of a heavier ($6000\,g\,m^{-2}$) fabric are needed compared to the 35 separate plies of $800\,g\,m^{-2}$ woven roving glass used in hand lamination.

(iii) reduced component weight (up to 72% fiber by weight).

(iv) void content is reduced from 5% by hand lamination to $<1\%$ by SCRIMP^{TM}.

(v) increased laminate strength (due to the higher fiber fraction and reduced void content).

(vi) cleanliness (reduced styrene emissions and waste resin).

SCRIMP^{TM} is now used for the entire superstructure and some internal structures. Laminates up to 100 m^2 in area and up to 20 m long have been made. The superstructure is molded on two 10 m × 50 m vacuum tables with two vacuum ring mains and resin delivery systems capable of delivering $50\,kg\,min^{-1}$. The use of epoxy resins specially formulated for infusion processes (e.g., SP PRIME 20) has been found to reduce fill times by 10% compared to equivalent polyester or vinylester resins.

Hoebergen (1998, 1999) has described the use of vacuum injection techniques for the production of the hull (16.4 m long × 4.5 m wide × 2.5 m high) of the Contest 55 sailing yacht (Conyplex shipyard, The Netherlands) in a female mold. The injection strategy chosen for the glass fiber skin balsa core molding was a main channel running from the stern via the keel to the bow with branches from the main channel running up to the deck flange. The balsa core was used as the flow medium. A second injection was used to fabricate monolithic stiffeners for attachment of the keel. A two-stage sequential injection strategy has been implemented (1999) for the deck in order to overcome fill problems around the wheelbox. Injection was simulated using π-7 software (developed by TNO during BRITE/EurAM II grant BE5477) and subsequently RTMworx (POLYworx, NL).

Leenders *et al.* (1999) conducted a study to improve the repeatability and quality of large load-bearing secondary ship structures such as removable bulkheads and hatch covers. They concluded that higher absolute pressures and an increased pressure difference (from 650 to 860 mbar) solved the problems of voids appearing in large structures.

Other vessels constructed using SCRIMP^{TM} techniques include the 27.4 m North End Composites deep-vee power boat hull (Lazarus, 1997), J/Boats J/32 sloop (http://www.jboats.com/j32/j32gen.htm; http://www.jboats.com/j32/default.htm; http://www.jboats.com/j32/j32scrimp.htm) and J/125 (http://www.jboats.com/j125/j125construction.htm) and Projection Yachts Sundeer 64 (Pittman, 1993) and Projection 762 (Thomas, 1996) (see Figure 10).

2.21.7.9.2 Land transport applications

One of the most successful examples of the application of RIFT processes is 21 m long railroad freight cars for the transportation of refrigerated goods. The units use glass-fiber reinforced vinylester resin skins over a polyurethane foam core. Payload is increased to 135% of that for conventional steel freight cars, while the insulation is so good that the cargo can be loaded cold and transported for week-long journeys with no refrigeration unit required. The cars are assembled from two sections: the roof and an integrated floor and walls (Anon, 1996; Dawson, 1999).

Vosper Thornycroft have used SCRIMP^{TM} to produce the Strasbourg tram bumpers (fenders). The process can meet the high impact and low weight requirements which are not possible with hand lay-up, yet is less expensive than RTM (Weaver, 1997).

Weinhold and Wozniak (1998) have described the use of SCRIMP^{TM} for the fabrication of compressed natural gas integrated storage system (ISS) for light duty vehicles. The two mating shells, when assembled, contain three high-pressure filament-wound cylinders. Labor for lay-up was significantly less than for prepreg fabrication methods, although labor for vacuum bagging was about the same.

2.21.7.9.3 Armor applications

French (1999) (also see Gilby, 2000) has reported that the hull moldings for an advanced composite armored vehicle platform (ACAVP) demonstrator have been manufactured by

Figure 10 O/D 48′ racing yacht built using SP Prime 20 epoxy infusion system and the SCRIMP process at TPI.

vacuum-assisted resin transfer molding (“VARTM also known as SCRIMP”). The reinforcement is E-glass as a quasi-isotropic noncrimp fabric. The bare hull weight is around 6000 kg. The moldings will probably be the thickest components made by an RTM-like process. The following advantages were identified for the VARTM process:

(i) similar materials costs to hand lamination or compression molding.

(ii) more consistent higher quality product than produced by hand lamination.

(iii) superior dimensional and quality control relative to hand lamination.

(iv) thicker fabrics can be processed than is possible with hand lamination.

(v) manufacturing costs below those associated with prepreg manufacture.

(vi) VARTM materials do not have the limited storage/shelf-life problems associated with prepreg.

(vii) greater flexibility and lower process equipment costs than compression molding.

Kelkar and Vaidya (1999) have described the use of vacuum-assisted resin injection molding (VARIM: essentially a RIFT process) for the manufacture of the thick load-bearing laminate in integral armor for the upper hull of the Composite Armored Vehicle-Advanced Technology demonstrator (CAV-ATD) for the US Army. Thirty-eight layers of S2-glass twill weave fabric were infused with vinylester resin to produce a laminate of 25.4 mm thickness with full wetting achieved within 20 min of fill time. The properties (tensile strength, modulus, and fatigue) were comparable for VARIM and similar RTM panels.

2.21.7.9.4 Offshore applications

Devonport Management Limited (DML, Plymouth, UK) have developed RIFT techniques for the reinforcement of existing structures with carbon fiber composites manufactured *in situ*. These have been applied to fire and blast protection systems for offshore oil and gas production platforms (Barnes and Galbraith, 1995; Barnes, 1994). The substrate to be strengthened is used as the mold. The requirement for adhesion between the composite and the substrate eliminates the need for release agent on the mold. The system has been used for blast strengthening of the Mobil Beryl B and BP Cleeton platforms and for strategic strengthening of the Chevron Alba North platform.

2.21.7.9.5 Civil engineering infrastructure applications

Fiberlite injects resin through gaps and channels in the sandwich core to produce composite manhole covers for service station forecourts. Their process is known as network injection molding (Marsh, 1997).

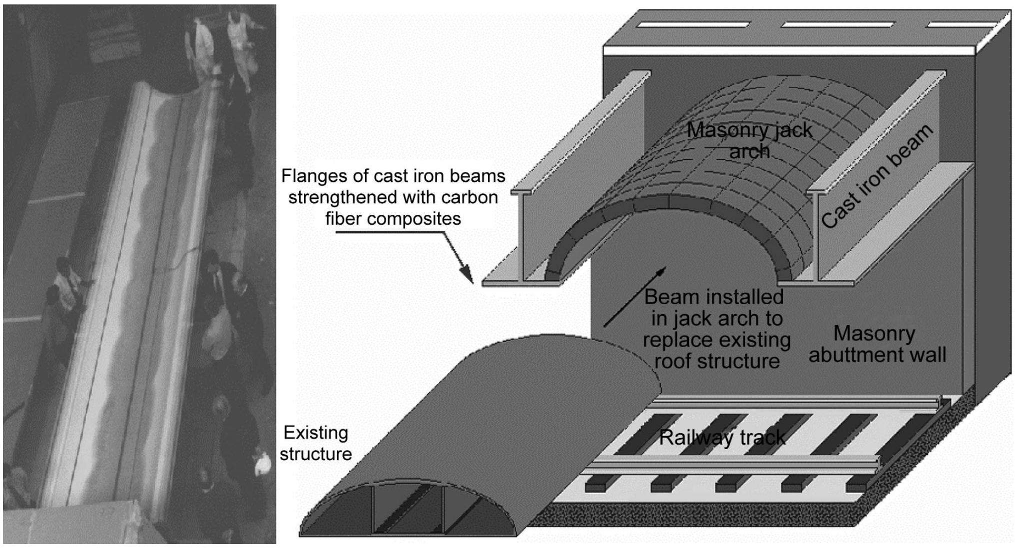

Figure 11 Structural beam for strengthening of London Underground tunnels. The carbon beam is 8 m long, 1.5 m wide/deep, and up to 25 mm thick. It is composed of a mixture of high-strength and ultrahigh modulus carbon fibers (courtesy of Devonport Royal Dockyard, Plymouth, UK).

DML have also applied RIFT techniques to rehabilitation of the London Underground Limited (LUL) railway system infrastructure (Moriarty and Barnes, 1998; Barnes, 1999) (see Figure 11). This has included temporary strengthening of the District/Circle Line tunnel at Sloane Square station. Permanent strengthening solutions for LUL will be implemented during 1999.

Hardcore Composites (DE, US) (Anon, 1999) designed and constructed a one-piece bridge deck using the SCRIMP^{TM} technique. The deck, supported on six steel girders, is 11.9 m long, 5.2 m wide, and 254 mm at the deepest section. It achieved the American Association of Highway and Transportation Officials (AASHTO) H25 load rating, confirmed by loading with a 30 tonne truck.

2.21.7.10 Process Simulation

The models appropriate for process simulation of resin transfer molding techniques (see Chapter 2.23, this volume) should be applicable to resin infusion under flexible tooling. However, these models will not normally take account of the thickness variation during the process due to the compression characteristics of the fabric.

Hammami and Gebart (1998) have presented a one-dimensional model for the "vacuum infusion molding process." The rough first formulation showed fairly good agreement with experimental results. The experimental investigation clearly showed that the process was governed by complex relationships "The fiber volume fraction and permeability of the laminate stack depend upon the vacuum level achieved. The problem is further complicated by the flexible top surface. In addition, the lubrication effect introduced by the resin impregnating the fibers adds to the complexity of the problem." Their good agreement between the model and experimental results indicates that Darcy's law is still valid if an additional equation for the vertical equilibrium of the cavity height is added.

Sun *et al.* (1998) used a three-dimensional (3-D) control volume/finite element method (CV/FEM) to solve the flow governing equations for the relative flow in the flow medium, peel ply, and a stitched fiber mat reinforcement. The flow front lead-lag (flow medium, reinforcement) was "not very large and remained nearly constant through the entire mould filling process." A simplified 2-D CV/FEM model was proposed using two assumptions:

(i) the permeability of the fiber preform is much less than that of the flow medium, and

(ii) the length along the flow direction is much greater than the thickness of the composite part.

In consequence, there is only flow through the thickness direction in the peel ply and the fiber preform. The models appear to assume constant cavity height. Ni *et al.* (1998) have also presented similar results for SCRIMP with grooves acting as flow channels.

Han *et al.* (2000) have developed a flow model to simulate resin infusion processes for composites manufacturing. A hybrid 2.5-D and 3-D modeling technique is introduced with some assumptions to simplify the complex problem of fluid flow through compressible porous media. The model was used to simulate different injection strategies for a quarter-scale model of a 5 m (16 foot) boat hull. The simulation results for flow pattern and filling time agreed well with the experimental SCRIMP infusion.

2.21.8 HEALTH AND SAFETY

It would be impractical to fully review safe practice for handling the materials used in composite manufacturing processes in the context of this chapter. The following short section draws attention to some key points. It is written from the viewpoint of UK users. Legislation and voluntary codes can differ quite markedly between countries. Users should consult the suppliers for safety information and the national regulatory bodies for the latest standards.

In the UK, the principal legislation is the Control of Substances Hazardous to Health (COSHH) Regulations 1988. This is not a bureaucratic exercise, but a route to reduce pain and suffering caused by ill health. Before committing to any manufacturing process, the manufacturer should satisfy themselves (in the order given) that:

(i) they cannot substitute a safer material,

(ii) they are using appropriate engineering solutions to minimize exposure, and

(iii) that appropriate personal protection equipment is provided.

2.21.8.1 Hazardous Chemicals

The chemical components of resin systems are potentially hazardous to the health of composite fabricators, but need not be problematic if treated with due respect. Appropriate precautions should be taken to prevent undue exposure. Appropriate action would be to change to a less problematic resin system or to adopt a closed-mold process in line with the COSHH requirements. A brief list of documents providing guidance is included (Mattli *et al*., 1987; Approved Codes of Practice, 1988; Safe Handling of Advanced Composite Materials Components: Health Information, 1989; British Resin Manufacturers' Association, 1992; GPRMC, 1994; Envirosense, 1999).

PERA International (Mould, 1998) has designed a system to reduce styrene emissions during the manufacture of GRP products. The two-stage system is based on the use of a carbon absorption medium followed by catalytic oxidation. The absorption system can run for 10–12 h before being switched to regeneration mode with the styrene then oxidized to water vapor and carbon dioxide.

2.21.8.2 Fibers

The UK Health and Safety Executive considers dust of $<3\,\mu\text{m}$ to be respirable and sets a limit of $<5\,\mu\text{m}$ particle size to reduce the risk. It is generally accepted that carbon (typical diameter 7–8 μm) and glass (typical diameter 10–30 μm) fibers do not normally fracture to lengths shorter than the diameter. As such they are not classified as respirable dusts, but should still be treated as nuisance dusts. The Health and Safety Commission (1979) considered precautions in the manufacture and use of man-made mineral fibers (MMMF). They concluded that there was "no evidence of a long-term risk to the health of people working with MMMF, although it is acknowledged that animal experiments are interpreted by some authors as indicating a possibility of such risk. In view of this and the fact that transitory irritation to the skin and upper respiratory tract may occur, precautions should be taken against any possible effect of contact with or exposure to MMMF." The Health and Safety Executive (1979) recommends that the nuisance dust threshold limit value (TLV) of $10\,\text{mg}\,\text{m}^{-3}$ be applied for carbon fiber.

Aramid (Kevlar/Twaron) fibers have a more complex microstructure than carbon/glass fibers and may split parallel to the fiber axis. Phillips (1990) has suggested that the "main bulk of the [aramid] fibrous material is far too long and thick to be respirable but it has been found that abrasion can cause fibrils to peel from the surface of large fibers. These fibers may be within the respirable range and diameters may be less than 1 micron." DuPont (1991) "believes that Kevlar in normal use represents minimal risk to human health and the environment."

2.21.8.3 Personal Protective Equipment (PPE)

Exposure to hazardous chemicals should be minimized by the use of laboratory coats/overalls, safety glasses, gloves, and barrier creams. Respirators are manufactured by a number of suppliers (e.g., 3M Occupational Health Group, 1994). They will advise on appropriate systems both for protection against dust and against volatile organic compounds. Respirator systems are available which can address both problems in a single face-mask.

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The use of tradenames/trademarks in the text of this chapter does not imply endorsement by the authors of any specific product. Such descriptions are provided simply in the interest of traceability.

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2.21.10 APPENDIX A: FABRIC COMPRESSIBILITY

The fiber volume fraction (V_f) within a composite with parallel faces can be calculated from the number of layers (j), the areal weight of the fabric (A_f), the thickness of the product (d), and the fiber density (ρ_f), such that

$$V_f = jA_f/d\rho_f$$

It is essential for the prediction of the thickness of products manufactured by the RIFT process that the compression response of the reinforcement fabric is known. Data reported for the compressibility of textile reinforcement fabrics and empirical equations have been derived for several individual data sets (Peirce, 1947; Hoffman and Beste, 1951; Bogaty *et al.*, 1953; Bartlett and Bloechle, 1978; Gutowski *et al.*, 1986; Hou, 1986; Gauvin and Chibani, 1988; Batch and Macosko, 1988; Quinn and Randall, 1990; Kim *et al.*, 1991). The stiffness of a fiber bed can be related to the fiber volume fraction by a power law. Quinn and Randall (1990) proposed that the fiber volume fraction (V_f) is related to the square root of the applied pressure (P) by the equation below where K_1 and K_2 are constants (see Table A.1)

$$V_f = K_1 + K_2\sqrt{P}$$

Toll and Månson (1994) have presented a micromechanical analysis which confirms the values of the exponent (3 for 3-D wads, 5 for the random planar case) and suggests that the power law may also be applied to aligned fiber bundles (exponent is 7–11 for weaves and 7–15.5 for rovings). Pearce and Summerscales (1995) confirmed the exponent for a dry glass fiber fabric and extended the response data to repeated compression cycles for the same fabric stack.

Saunders *et al.* (1996) have conducted compression tests on assemblies of 546 g m^{-2} plain weave glass fiber cloths both dry and resin (catalyzed Crystic 471PALV polyester resin) impregnated. The power law index for dry cloths was 11 for 5, 10, or 20 layers of cloth. The response of wet cloths included a viscous resin pressure component. This viscous component decreased with a decrease in the compression speed.

Craen *et al.* (1998) have monitored the compression response of two different ~300 g m^{-2} glass fiber (plain weave and stitched biaxial) fabrics both dry and lubricated with (Jotun Polymer 42-10 polyester) resin. The overall thickness for both fabric styles was shown to reduce with the number of cycles in both compression and relaxation. In spite of a marginally higher initial areal weight, the stitched fabric

Table A1 Characteristic constants for the compliance of typical reinforcement materials.

Material	K_1	K_2	V_f (%) at 157 kPa
E-glass continuous strand mat	9.7	0.37	24
E-glass chopped strand mat	20	0.46	38
E-glass roving	32	0.75	62
E-glass woven fabric	40	0.45	58
E-glass woven roving	21	0.60	45
Kevlar fabric	47	0.51	67
Unidirectional carbon fiber cloth	34	0.80	66
±45° carbon fiber fabric	35	0.51	55

Source: Quinn and Randall, 1990.

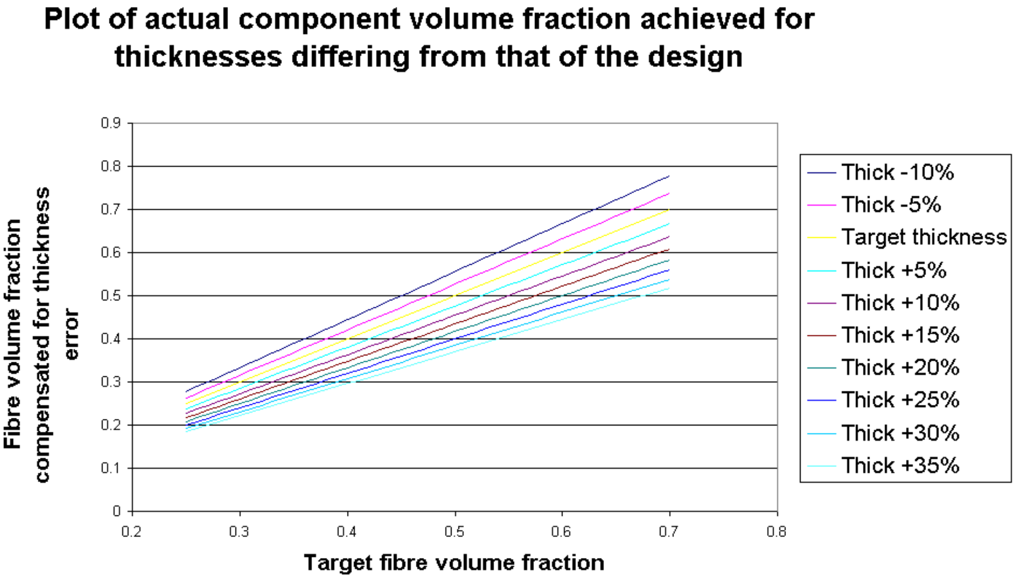

Figure B1 Variation of fiber volume fraction with changing mold cavity depth.

achieved a higher fiber volume fraction. The increase in fiber volume fraction on cycling will result in a decrease in the permeability of the fabric to resin and thus any pressure cycling before flow could extend the fill time for the process. Pressure cycling after fill might enhance the achievable fiber volume fraction.

2.21.11 APPENDIX B: FABRIC PERMEABILITY

Simulation of the resin transfer molding process usually assumes that the mold cavity is infinitely stiff (see Chapter 2.23, this volume). In practice, there is usually some flexibility in the mold structure. This flexibility may result in the part not being produced with accurate dimensional tolerances. Where very low fiber volume fractions and vacuum-only injection is used without mold closure stops, the component may be undersized. Where very high fiber volume fractions (fabric compression force curves obey a power law relationship) and high injection pressures are used the mold may be subject to ballooning and the component will consequently be oversize. Typical variations achieved in real moldings may range between −10% and +35%. Figure B1 plots the variation of fiber volume fraction achieved against target volume fraction for the above range of thickness deviations in 5% increments.

However, the mold thickness cannot be neglected in the RIFT process since one mold face may be very flexible. Any modeling of the flow and pressure must account for the consequent changes in laminate thickness.

The one-dimensional form of Darcy's equation (1856) relates volumetric flow rate (Q) to process parameters

$$Q = K.A.\Delta P/\mu.L \tag{1}$$

where K is a constant of proportionality known as the permeability, A is the cross-section of the porous medium normal to the flow direction, $\Delta P/L$ is the pressure gradient driving the flow, and μ is the fluid viscosity. For simulation of the process, modeling should use the tensor form of Darcy's equation.

Kozeny (1927) and Carman (1937) developed an expression to relate the volumetric flow rate of fluid to the microstructural features of the porous bed

$$Q = \varepsilon.A.m^2.\Delta P/k.\mu.L \tag{2}$$

where ε is the porosity (one minus volume fraction of fibers), m is the hydraulic radius, and k is the Kozeny constant. Blake (1922) defined the hydraulic radius as the volume in which fluid actually flows, εV (where $V = AL$), divided by the wetted surface area (S). Substituting $m = \varepsilon V/S$ into Equation (B2) yields

$$Q = \varepsilon^3.A.V^2.\Delta P/k.\mu.S^2.L \tag{3}$$

Clearly, if all other parameters remain constant, the flow rate is proportional to the cube of the porosity of the porous bed. From Equation (B1), permeability is proportional to the flow rate. The dependence of permeability on change in mold thickness for this relationship is presented in Figure B2.

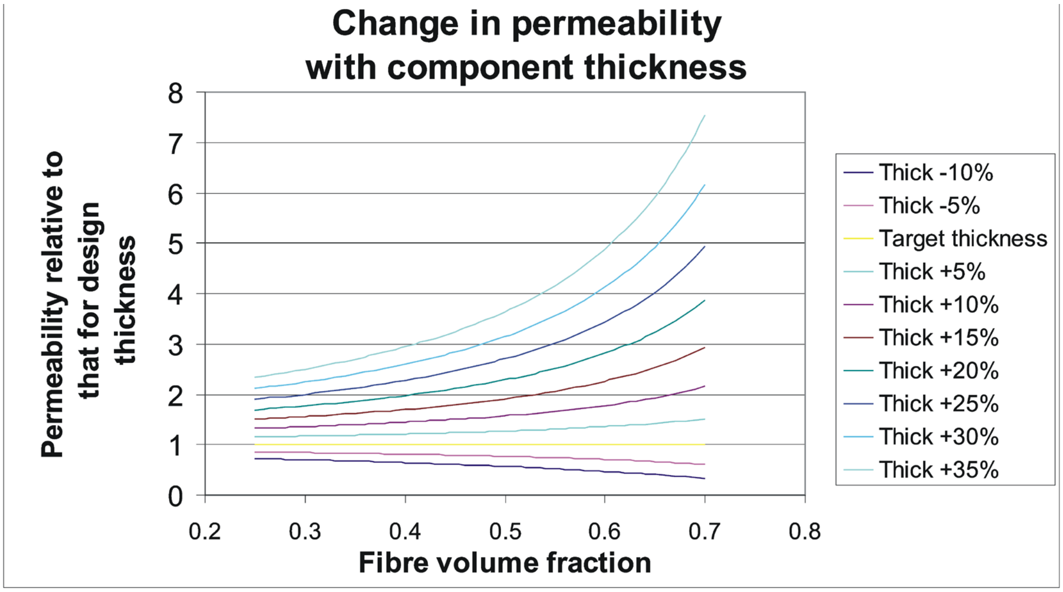

Figure B2 Variation of permeability with cavity depth as predicted by Equation (B3).

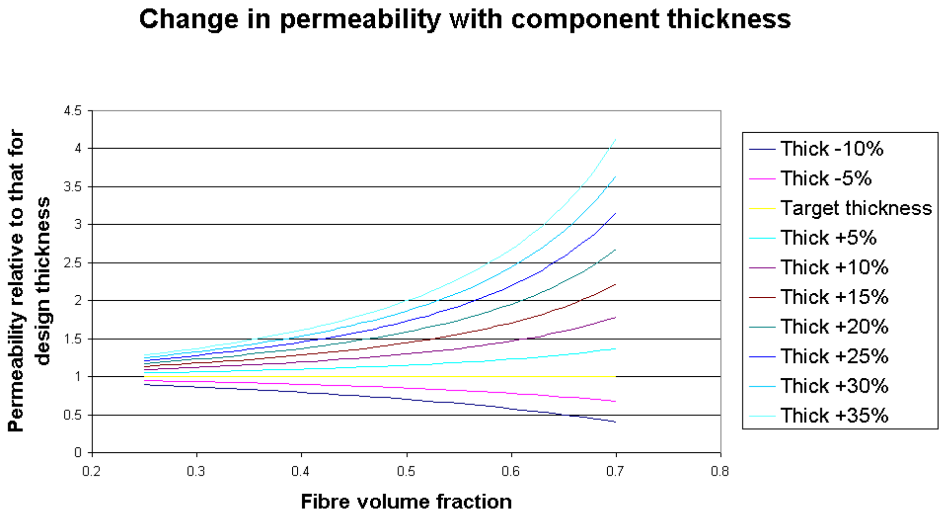

Figure B3 Variation of permeability with cavity depth as predicted by Equation (B4).

However the assumptions above are oversimplistic. The introduction of further fibers to increase the fiber volume fraction will inevitably increase the wetted surface area. This will have a limit when the fibers touch. The introduction of further fibers will then reduce the wetted surface by denying access to some of the pore space. The increase in surface area will be linear with volume fraction before the above limit. The dependence of permeability on intermediate fiber volume fractions (V_f) therefore becomes the relationship below, when V_f^2 is substituted for S^2

$$K \alpha (1 - V_f)^3/V_f^2 \quad \text{or} \quad \varepsilon^3/(1 - \varepsilon)^2 \qquad (4)$$

The dependence of permeability on change in mold thickness for this relationship is presented in Figure B3.

An increase in the deviation from nominal component thickness causes an increasingly significant change in the permeability of the fabric reinforcement. Note that a doubling of permeability is predicted when a part with a nominal 54% fiber volume fraction is produced at 15% overthickness.