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REVIEWS

A Review on Advanced Out-of-Autoclave Composites Processing

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Abstract | Traditional autoclave curing has been the process of choice for aerospace related composites manufacturing. This technology has been by and large limited to aerospace applications primarily due to high cost. This has motivated many researchers and industries to consider an out-of-autoclave (OoA) alternative for non-aerospace applications, and of late, even for aerospace applications. During the last couple of decades number of autoclave substitutes have been developed and demonstrated by the technologists around the globe. This review provides information on leading OoA technologies that are used for various applications. The theoretical and practical aspects as well as merits and demerits of these processes are presented in this review. Future areas of development are also discussed.

Keywords: *out-of-autoclave composites, VARTM, RFI*

1 Introduction

It is an immense challenge for design and manufacturing engineer to select the right manufacturing process, the reason being many choices are available in terms of processing techniques to fabricate any part. The criteria for selecting a process depends on the production rate, cost, strength, and size and shape requirement of the part. This is true even in case of composites manufacturing. For manufacture of high-end structural composites the techniques used can be categorized as Autoclave Cured (AC) and Out-of Autoclave (OoA) cured techniques.

Most high-performance structural composites for aerospace applications begin as layers of prepreg, or carbon fiber tows pre-impregnated with a catalyzed but uncured resin.[1] Traditionally, prepreg layers are stacked on a tool to form a laminate, enclosed in a vacuum bag assembly, and placed in an autoclave (pressurized oven). The autoclave temperature is then raised, partial or full vacuum is drawn in the bag, and the vessel is pressurized. The consolidation pressure differential compresses the fiber bed, conforms the laminate to the shape of the tool, and in some cases, forces out excess resin. The applied pressure also suppresses porosity, the main manufacturing defect in prepreg-based parts, by driving resin into dry areas and collapsing bubbles often trapped air and/or cure-generated volatiles. Concurrently, the elevated temperature reduces the resin viscosity, allowing resin to flow and wet the reinforcement before curing into a stiff, strong solid.

Autoclave processing is robust and well-understood, having benefited from significant research and experience gained from widespread industrial use, and remains a benchmark for competing processes. However, autoclaves involve significant costs for acquisition, operation, and tooling, particularly for large parts. Autoclaves also impose a relatively inflexible manufacturing environment, in which potential part designs are constrained by available vessel sizes, production rates are restricted by scheduling, large autoclaves must sometimes be used inefficiently for small parts, and subcontractor options are limited.

Advanced composite materials based on carbon fiber-reinforced thermoset polymers have become common in primary aerospace structures, high performance sporting goods, as well as marine and land based wind energy structures. As these composite parts grow in number, size and complexity, the need for faster, more cost effective and more versatile manufacturing comes into conflict with the limitations of traditional OoA processing methods such as hand layup, spray up, filament winding, pultrusion etc. Given the predicted market growth for composites

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and the aforementioned limitations of autoclave processing, advanced out-of-autoclave (OoA) manufacturing techniques, particularly those that yield autoclave-quality parts, are required to meet future demand. Advanced out-of-autoclave (OoA) manufacturing techniques are categorized into two—namely, *(OoA) prepregs* and *(OoA) Liquid composite molding (LCM) processes, where the resin is infused into a fiber structure or preform*.

2 Out of Autoclave (OoA) Prepregs

Recently, a new generation of out-of-autoclave prepregs has been introduced, and experience with these prepregs has demonstrated that it is possible to produce autoclave-quality parts using vacuum bag-only (VBO) consolidation. By avoiding the use of autoclaves, such materials significantly reduce acquisition and operating costs, and are compatible with a diverse range of lower-cost cure set-ups, including conventional ovens, heating blankets, and heated tooling. In addition, the lower cure pressure supplied during VBO cure can eliminate autoclave-induced defects such as honeycomb core crush, thus allowing the use of lighter (and less expensive) cores.[2] As far as manufacturing is concerned, two common methods have been employed to produce VBO prepregs. One method involves the use of a perforated resin film that results in a prepreg with gaps in the resin film; the second involves partial impregnation of fibers/fabric with a resin. The perforated resin film method allows gas to flow out of the laminate in directions parallel and perpendicular to the plane of the prepreg. However, the partial impregnation in practice leaves dry spaces or channels in the prepregs. During subsequent compaction, these channels facilitate airflow in a direction parallel to the laminate plane. Partial impregnation of dry fibers and utilizing an edge-breathing consumable stack during the processing is the more common method of producing VBO laminates.

Early-generation VBO prepregs were designed for low-temperature initial cure (~60°C), followed by high-temperature postcure, and intended for low production runs or load-limited structures.[3–5] The main advantage of these materials were the ability to use lower cost tooling, combined with an increase in dimensional accuracy because of reduced tool thermal expansion. However, these benefits were outweighed by three major drawbacks: (1) relatively high porosity resulting from low applied pressure or inconsistent resin bleed, particularly for high fiber volume fraction reinforcements;[3,6] (2) out-times, or allowable room temperature storage times, of only about a week;[3,6,7] and (3) relatively low mechanical performance, particularly in terms of toughness.[3,7] The wider process window, coupled with developments in resin chemistry and an increasing understanding of optimal matrix properties, enabled the development of a new generation of VBO resins. When properly integrated into appropriate fiber bed architectures and correctly processed, these materials were comparable with autoclave systems on multiple fronts, including porosity, mechanical performance, and out-times.[4,5,8,9] Several such resin systems are shown in Table 1, most of which can be coupled with a range of reinforcements, including woven carbon and glass fiber fabrics and unidirectional (UD) tapes. The key requirement for low porosity VBO-cured parts is the removal of air entrapped during lay-up. To this effect, the VBO prepregs are "breathable", featuring partially impregnated microstructures consisting of both dry and resin-rich areas.[10] The dry areas, sometimes denoted as "engineered vacuum channels" or EVaCs, form a relatively permeable vascular network that allows gas migration towards the laminate boundaries in early processing. When the temperature is increased, resin flows into and infiltrates these channels, leading in principle to a void-free part. To allow gases to escape from the prepreg into the breather, vacuum bag assemblies must include permeable boundaries that connect the laminate to the breather cloth without allowing excessive res in bleed. For in-plane gas evacuation, these boundaries take the form of dry fiberglass strands, cork or other "edge breathing" dams placed around the laminate perimeter. For through-thickness air evacuation, perforated release films or peel plies can be used to separate the laminate from the breather. In summary, for successful cure, VBO prepregs rely on specific material and prepreg properties and appropriate process parameter selections. Furthermore, in the absence of a high-pressure uphold, they are likely to be sensitive to unintended deviations from ideal conditions. In this context, properties and processing must be thoroughly understood.

Out-of-autoclave prepreg systems do not mean faster production rates. As entrapped air extraction is a time-dependent process, OoA cure cycles are typically longer. After debulking, vacuum must be held for an extended period before initiating cure; this hold time period depends on the part size and complexity, ranging from as low as 4 h for 0.4 m^2 to 16 h for a 72 m^2.[11] Furthermore, slow ramp rates are also recommended for the OoA prepreg because fast ramp rates reduce the resin viscosity, allowing the resin to penetrate through the fibers very

Table 1: Current-generation aerospace grade OoA/VBO prepreg resin systems.[2]

Manufacturer	Resin family	Resin type	Description
ACG (now Cytec)	MTM44-1	Epoxy	Medium temperature molding (MTM) toughened epoxy. Qualified by Airbus for secondary and tertiary structure.
	MTM45-1	Epoxy	Lower temperature cure system optimized for compression performance.
	MTM45-1 FR	Epoxy	Variant of MTM45-1 optimized for flame retardation.
	MTM47-1	Epoxy	Variant of MTM45-1 optimized for hot/wet notched performance up to 130°C.
Cytec	Cycom 5320	Epoxy	Toughened epoxy designed for primary structure application.
	Cycom 5320-1	Epoxy	Variation on 5320 system, formulated for increased out-life.
Gurit	Sprint ST94	Epoxy	Single-sided moulding prepreg for parts requiring resistance to impact damage and micro-cracking.
Hexcel	Hexply M56	Epoxy	High performance VBO epoxy system.
Toray	2510	Epoxy	Formulated to meet the requirements of general aviation primary structure.
Tencate	BT250E	Epoxy	Standard VBO system used in Cirrus aircraft and unmanned vehicles. Variations for fatigue and fracture resistance for helicopter rotor blades.
	TC250	Epoxy	Second generation VBO system with increased toughness and higher service temperatures.
	TC275	Epoxy	Third generation system with greater inspectability, resistance to hot/wet conditioning and curable at 135°C.
	TC350-1	Epoxy	Third generation system with increased out-life (45 + days), high toughness, and ability to cure at 135°C with 177°C required post cure.
	TC420	Cyanate ester	High temperature system (service temperatures up to 315°C).
	TC800 BMI+	Bismaleimide	High-temperature, toughened BMI prepreg formulated for cure out-of-autoclave.
Henkel	Loctite BZ	Benzoxazine	VBO prepreg based on a blended epoxy-benzoxazine resin formulation.

quickly, which hinders the removal of air from the laminate. However, by utilizing slower ramp ups, additional evacuation time is achieved allowing for the maximum extraction of air and generated volatiles. External parameters such as relative humidity also play a very important role in void content in the laminate. Generally, epoxy resin tends to absorb moisture in the air and the trapped moisture is very difficult to remove under VBO processing. Influence of relative humidity on void content of VBO processed laminate has been systematically studied by Nutt et al.[12]

Various researchers suggested the possibility of using different heating methodologies to make the heating more efficient compared to convection ovens. Among these liquid heated moulds, Quickstep,[13] induction, infrared, microwave and radio frequency heating are thoroughly studied.[13] Despite the numerous advantages of OoA prepreg for VBO and its claimed cost effectiveness, the work based on OoA is primarily R&D oriented. In fact, the OoA materials available right now cost same as the autoclave primary structure materials in use. But considering the reduced tooling costs and manufacturing costs of these OoA laminates, OoA prepregs could win over the existing standard prepregs.

3 (OoA) Liquid Composite Molding (LCM) Processes

The basic idea behind this group of processes is the integration of formally two production processes in one step. Fibers are no longer pre-impregnated or cut and applied before curing, but rather, the fiber fabrics are cut or manufactured to fiber performs, and within the curing process infused or injected and cured to the final part. Most scrap is, therefore, produced only by the dry fiber fabrics and not pre-processed fibers and resin. In principle, there are three physical approaches or basic categories for how the resin is actually transported through the fiber structure: applying pressure, using vacuum, or both, by over- and under-pressurizing the fiber structure. From these basic principles many different process types have originated, with various names all over the world and differing from industry to industry (Table 2).

These processes are considered to be very cheap for several reasons. The main cost advantage is quite often based on the use of preforming processes which are on one hand the basis of one-shot solutions for complex structures and on the other hand designed with a high level of automation. Other benefits can be achieved by using vacuum based methodology and single sided tools, integral and large structures (less bonding and/or assembly), faster material layup, no debulking steps, and of course a lower material cost. This not only originates from lower scrap costs (mostly only fibers without resin and no out life restrictions that exist for prepregs) and cheaper direct material cost (single components vs. semi-finished products), but also lower storage cost (most prepreg materials need a controlled cold storage at −18°C and less). Among various processes mentioned above a brief discussion on RTM, VARTM and RFI will be discussed presented in the forthcoming sections as these processes have gained popularity in recent years.

3.1 *Resin Transfer Moulding (RTM)*

Resin transfer molding (RTM) was adopted for composite manufacturing in the mid-1980s. The driving force was the automotive industries that were looking for high volume production net shape structural parts. Injection and compression molding of discontinuous fibers could fabricate net shape structures at high volumes, but the structural performance could not be achieved by short fibers. Hence, the idea emerged to have a woven or stitched fiber preform structure inside a net shaped mold and then inject the resin under high pressure to cover the empty spaces between the fibers. Only low viscosity resins were possible candidates due to the resistance to flow because of the micron level empty spaces between the fibers. Hence, the resins of choice for this process are thermosets, although there has been some recent activity in bringing to market thermoplastic resins with low viscosity.

The RTM process begins with a dry fiber preform. The preform is placed into a matched metal mold, and the mold is closed resulting in the compaction of the preform to the specified fiber volume fraction. A liquid thermosetting resin is then injected into the mold (typically at high pressure, such as 5–7 bar). The mold and resin can be preheated before injection, or the mold can be heated after injection to cure the resin. Due to the high injection pressures and often high temperatures involved, RTM tools are bulky and costly to manufacture and to process. One should design the preform by selecting adequate fiber and fabric types, and fiber volume fraction (i.e. the number of plies in the preform) considering the (a) mechanical performance, (b) permeability to resin flow, (c) fiber wet out, (d) formability and (e) cost.

3.1.1 Issues that influence manufacturing with RTM: The part quality in composite manufacturing processes suffers from the effects of inherent variations in materials and process

Table 2: Selection of different liquid composite molding processes by category.

Vacuum based	Vacuum and pressure based	Pressure based
VARI	VARTM	RTM
VAP (vacuum-assisted process)	LRTM (light resin transfer molding)	Inflatable tubeprocess
SCRIMP (Seeman composite resin infusion molding process)		GAP impregnation
RFI		TERTM (thermal expansion resin transfer molding)
RST (resin spray transfer)		URTRI (ultimately, reinforced thermosetres in injection)

parameters that result in variations in mechanical properties of the parts. Important issues that manifest themselves either during fiber preforming or mold filling stages of RTM have been identified. Research was focused on overcoming them with process modeling, control and automation.[13] Basic outcome of this research was designing the mold and process parameters to achieve two key goals: (1) to fill the mold cavity completely without the presence of either macro or micro voids and (2) to reduce the cycle time and total cost.

Usually, a process simulation can be used to design the injection and vent locations with the input parameters of geometry of the mold and the permeability of the fabric. The vents are usually placed at the locations where the resin arrives last, so voids can be prevented. This will produce void-free parts if these conditions are replicated from one part to the next. However, material placement and variability will change the permeability of the fabric in certain locations from one part to the next altering the resin flow pattern which will not ensure that the resin will arrive at the vents for all the parts. Hence, it is important for the designer to anticipate disturbances in the flow due to material placement, variability, developing optimization and control approaches to address them. Various micro and macro issues that may cause variation in the flow pattern are summarized below:

a. Racetracking channels

(i) When a fiber preform is placed and compacted in the mold cavity, regions in contact with the mold walls or inserts placed in the mold usually will have lower fiber volume fraction than the bulk. These regions have lower resistance (thus higher permeability) to resin flow than the bulk preform, and the resin races along the path of the highest permeability. This phenomenon is known as 'racetracking', and the path is called 'racetracking channel'.[14–16] Usually, *racetracking channels are formed: Along the mold edges*: The fiber volume fraction may be lower along the mold edges due to (1) missing fiber bundles which may have dislodged from the plies during cutting and placement and (2) smaller in-plane perform dimensions than the mold dimensions.

Along the ribs or bend sections: If the inner and outer bend radii of the mold are not carefully machined, the fiber volume fraction will be lower there as compared to the bulk regions, providing resin with low resistance to flow paths which will alter the flow. On the other hand, if the bend radii create smaller mold gap than the bulk regions, the fiber bundles may be highly compacted in in-plane and thickness directions and fiber volume fraction may be higher here than the bulk regions. In this case, the preform will have higher resistance (lower permeability) to resin flow than the bulk regions. The effect of these cases on the mold filling has been investigated.[17,18]

(ii) Along line injection gates: Although the above racetracking channels are formed unintentionally, racetracking channels may be formed intentionally to create line gates and vents, and also along other paths to intentionally race the resin flow and thus reduce the mold filling time and/or reduce the required maximum resin pressure. This is usually accomplished by machining in the mold plates. However, the designer should be careful that it does not lead to multiple flow fronts that can entrap air between them as they approach each other.

b. Deformation of fiber structure during draping

When a fiber preform is draped over a tool surface, the orientation of the fibers in the preform will also change. This will change the fiber volume fraction and hence the permeability to resin flow. Depending on the type of fabric and radius of the mold curvature, the deformation and permeability may vary spatially. Rudd et al.[19] discussed four different mechanisms of fiber deformations:

- Inter-fiber (intraply) shear: Occurs when the fibers rotate about the stitches or weave centers.
- Inter-fiber slip: Occurs when the fibers move relative to each other.
- Fiber buckling: Occurs due to the in-plane compression of the fibers which causes fiber wrinkling.
- Fiber extension: May occur under high tensile stress during draping. However, this mechanism is not as common as the other three listed previously due to the high stiffness (modulus of elasticity) of fiber materials.

Rudd et al. developed a kinematic drape model. Its numerical solution with constrained fiber paths predicts fiber shear deformations and their effect on the fiber volume fraction. Bickerton et al.[20] modeled the draping of a compound curved preform and its effect on the resin flow. They validated the model results with mold filling experiments. There are commercial programs available such as FiberSIM, LaminateTool[21] that provides the draping angles due to the layup. One can use that information to update the permeability and fiber volume fraction values to access the changes in the flow patterns and the time to fill due to the draping of the fabric.

c. Macrovoid formation
Macrovoids (macro size dry regions in the preform) are formed under the conditions—

- if the resin flow front reaches the vents before impregnating the perform completely,
- if air is present in the dry region (i.e., no perfect vacuum is applied before the resin injection),
- if the resin pressure around the dry region is not sufficiently high to shrink and collapse the void or move the void toward the vents.

Mold filling (i.e. resin flow) simulations help the design engineers to determine the last point(s) of resin arrival under vacuum, and then place the vents at those points to avoid macrovoid formation. There are two approaches to eliminate the macrovoids:

1. Allow the resin to bleed out of the vents for sufficient time (usually of the order of minutes), so that any potential macrovoid (along with the air inside) is pushed toward the vents and/or it shrinks.
2. Apply process control by (a) monitoring the flow front position by using sensors, (b) predicting if any macrovoid is likely to be formed at the end of the resin injection and (c) adjusting process parameters (resin pressure or flow rate, opening/closing inlet gates) if necessary.

The disadvantage of item (1) is that flushing of the extra resin increases both waste and cycle time. Item (2) is powerful, but it requires process modeling and control and embedding of robust sensors in the mold.

In typical RTM applications, in-plane part dimensions are much larger than its thickness. Thus, many resin flow models in literature are based on the assumption that there is no significant transverse flow, thus simplifying the modeling to a 2D flow in the in-plane directions, and only a shell mold cavity is used for the solution domain.

2D flow assumption is violated when—the part thickness varies significantly, the in-plane permeabilities of the multiple plies of the fiber perform change by orders of magnitude or core materials such as foam are embedded between the plies. In that case, significant transverse flow develops, and macrovoids may be entrapped. From the solution procedure point of view, fully three-dimensional flow modeling and simulations are not much more difficult than the two-dimensional version; however, one needs (1) to discretize the solution domain in 3D instead of 2D (which takes much longer CPU time to solve the pressure distributions and advance the flow front in a time marching scheme), and (2) to measure the transverse permeability of the perform, which is much more difficult than measuring in-plane permeability components.[23–25]

d. Dual scale fiber structure
A typical RTM fiber preform has two scales of permeabilities to resin flow:

- Inside a fiber bundle, the porosity (volume fraction of empty spaces) is low. Thus, its permeability to resin flow is low.
- The empty spaces between the woven or stitched fiber bundles are relatively larger than the empty spaces in the fiber bundles. Thus, its permeability to resin flow is high.

Typically, a fiber bundle has thousands of fibers in an elliptical cross-section with a width of a few millimeters. Considering that a glass or carbon fiber has a diameter of 10 microns approximately, and if all the fibers are densely packed in a bundle, the gap between the fibers is of order of as small as microns (i.e., 10^{-6} m). This is much smaller empty space than the empty space between the fiber bundles, which is typically of the order of millimeters (i.e., 10^{-3} m). These two types of empty spaces give rise to two scales of permeabilities encountered by the resin flow, and they may result in microvoid entrapment inside the fiber bundles.

e. Microvoid formation
Due to the dual scale permeabilities in a fiber preform (as explained previously), two types of microvoids may be entrapped in a composite part during resin injection:

- Intra-bundle microvoid is the most common microvoid type that occurs due to the lower permeability of the fiber bundles than the permeability of the empty spaces between the bundles. The resin flow is faster between the fiber bundles than inside the bundles, and the resinen circles itself when it reaches a stitch or another bundle perpendicular to the flow direction, and entraps a microvoid inside the bundle. To avoid this type of microvoid, the common practice is to slow the resin flow down by decreasing the injection pressure/flow rate boundary condition. This allows sufficient time for the encircled microvoids to shrink and collapse due to the higher resin pressure around the microvoids than inside the voids.

- Inter-bundle microvoid is formed if the dual scale permeabilities are formed such that the resin flows faster inside the bundles along the fiber direction due to the capillary forces than in between them. Microvoids are entrapped between fiber bundles when it gets drawn due to the capillary action across a stitch.

3.1.2 Process modeling: Mathematical modeling of different stages of the RTM process has been applied for the last several decades to design the process. Flow models have been developed that allow the user to control the process parameters (resin injection pressure/flow rate) and design the mold (locations of the gates and vents). The details of the process modeling have been studied in many books and book chapters.[26–29]

3.2 *Vacuum Assisted Resin Transfer Moulding (VARTM)*

The vacuum assisted resin transfer molding (VARTM) process, which has been developed during the past two decades, is now a widely used process for manufacturing fiber reinforced polymer (FRP) composite laminates. The VARTM process, which is a closed-mold process with reduced volatile organic compounds (VOC) emission, combines the benefits of high quality, repeatability and clean handling of the resin transfer molding (RTM) process with the advantages of flexibility and scalability of open-mold hand layup processing. The VARTM process plays many important roles in promoting the quality, affordability and part complexity of large closed-mold FRP composite structures. VARTM processes are widely used in marine, energy, infrastructure building, aerospace and defense industries. Many variations of VARTM have also been developed recently for manufacturing more complex composite parts with improved quality and lower cost.

3.2.1 VARTM process: In VARTM process, the environmental pressure (e.g., the atmospheric pressure) is typically utilized to provide the pressure against the fiber perform that is sealed in a vacuum bag and the mold. The VARTM mold looks identical to the open mold of a hand layup process, can be constructed with much larger dimensions than an RTM mold. After securing the dry preform against the mold resin is drawn into the preform. A flow distribution media is used to enhance the resin infusion speed; the flow distribution medium layer is connected to the resin injection port, and must not directly contact the vent port. Note that depending on the resin system used in VARTM, the mold temperature may need to be elevated during the curing cycle of the VARTM process. For a large or complex composite part (with inserts, hybrid fabric systems, co-cured parts, etc.), multiple injection lines and vents could be used to improve the resin infusion. The flow distribution medium layer could also be placed in different patterns to create versatile resin infusion paths that can promote the resin infusion quality of a large or complex composite part.

a. Salient features

Advantages:[13]

- Flexible mold tooling design and selection of mold materials.
- Able to manufacture large and complex composite parts with good quality.
- The resin and the catalyst can be stored separately and mixed just before the resin infusion.
- With a transparent plastic vacuum bag, a visible dry spot occurring during the resin infusion process can be removed by inserting a vacuum needle at the dry spot and drawing the air out.
- Low VOC (i.e., VOC) emission. The resin mixing process is the only step with major VOC emission.

Disadvantages:

- Vacuum bag, flow distribution medium, peel ply, sealing tape and resin tubing may not be reusable. These consumables will need to be prepared for each individual VARTM process every time.
- Chance of air leakage is high, and this strongly depends on the worker's skill, experience and the consumable (sealing tape, vacuum bag, etc.) quality of each VARTM process. The air leakage can cause dry spot and incomplete resin infusion. A careful and frequent inspection for the air leakage is necessary before the resin infusion, during the resin infusion and during the curing cycle as a leakage can be initiated at any time during these three processing stages and ruin the composite part.
- The resin injection pressure is limited between the environmental pressure (e.g., the atmospheric pressure) and the vacuum. The resin injection pressure of a VARTM process is much lesser than the pressure applied during a typical RTM process or an autoclave/vacuum bagging process, and can limit the air void compressibility.

- The compressive pressure on the preform is limited between the environmental pressure (e.g., 1 atmospheric pressure) and the vacuum. A lower compressive pressure on the fiber preform can limit the fiber volume fraction of the composite part. Typical fiber volume fraction achieved by VARTM is within the low 40% to high 50% range, and mainly depends on the fiber preform used.

b. Fundamentals

1. Resin Flow phenomenon

The resin flow within the distribution medium layer and fiber preform can be treated as flow through anisotropic porous media[30] and described by the generalized Darcy's law:

$$\vec{U}_D = -\frac{[K]}{\mu}\cdot \Delta P \tag{1}$$

where $\vec{U}_D$ is the Darcy velocity (which is the volume averaged velocity with respect to a small control volume containing both the solid phase porous medium and the fluid inside it), μ the dynamic viscosity of the fluid (i.e., the liquid resin or air), P the fluid pressure, and K is the permeability tensor for the stationary porous media. Equation 1 can precisely quantify the relation between the Darcy velocity and the pressure for a resin saturated porous medium. For the liquid resin in the solid porous medium, it further requires the mass flow continuity for the incompressible fluid and solid system as:

$$\nabla \cdot \vec{U}_D = 0 \tag{2}$$

Combining Eqs. 1 and 2 for a resin saturated porous medium, one obtains

$$0 = \nabla \cdot \left(\frac{[k]}{\mu}.\Delta P \right) \tag{3}$$

By specifying the boundary conditions of the pressure for the resin filled porous medium domain, the pressure distribution inside the resin filled porous medium domain can be solved by using Eq. 3. Then the Darcy velocity $\vec{U}_D$ distribution in the resin saturated porous medium domain can be solved using Eq. 1.

During the mold filling process, the resin flow front is indeed a moving boundary. At the resin flow front, there are two significant velocities, that is, the Darcy velocity, $\vec{U}_D$, and the flow front velocity, $\vec{U}_F$. The flow front velocity is the phase-volume averaged velocity of the liquid resin (with respect to the control volume of the liquid phase only) and is related to the Darcy velocity as

$$\vec{U}_F = \frac{\vec{U}_D}{\phi} \tag{4}$$

where ϕ is the porosity of the porous medium. The porosity can be related to the fiber volume fraction V_f of the fiber perform.

Once the Darcy velocity is obtained at the flow front from Eq. 1 for a given time step, one can use Eqn. 4 to project the expansion of the resin saturated porous medium domain for the next time step and reiterate the pressure, Darcy velocity and flow front velocity solutions for the next time step using Eqs. 1, 3 and 4, respectively. For the numerical modeling, one can also perform the finite element-control volume (FE-CV) numerical simulation to fill the control volume of the mesh of a numerical finite element model and update the resin flow front and the pressure distribution for each time step until the resin front reaches the vent of the VARTM mold.[30] More details and improvements regarding the numerical solution methods have been reported by many researchers.[31–35] Since the VARTM parts are usually very large (long and wide) and relatively thin, the numerical simulation method such as the FE-CV usually encounters the element aspect ratio limitation issue and the numerical compatibility issue between the flow distribution medium layer and the fiber preform. As a result, a numerical simulation of a large and thin VARTM part can be very costly and challenging in terms of mesh generation; number of elements used and mold filling computation. Various studies such as ratio between in-plane flow and through thickness flow, distance of a resin flow front travels during a period from the initial time t_0 till an arbitrary time t, resin flow front region length (lag length), fiber perform compaction effects, resin viscosity effects in modeling, composite cure behavior.[14]

c. Critical elements of VATRM process design

Following are the design elements of a successful VARTM process:

- Mold temperature selection: The mold temperature control is very critical for (1) resin curing management, (2) resin gel time control, (3) resin viscosity control, (4) material selection of vacuum bag, sealing tapes, flow distribution medium layer, flow distribution tubes, resin flow inlet and outlet tubes, peel ply, mold release agent and the construction material of the mold itself.

- Flow process design: after the mold temperature has been decided, the resin viscosity and the resin gel time can be determined or measured. Then one can work on designing the flow process parameters: (1) locations of vacuum ports (vents) and injection gates, (2) locations and sizes of flow distribution lines, (3) type, number of layers and locations of flow distribution medium, (4) timing to open and close gates and vents, (5) in some cases, one may like to control the vacuum pressures of vents to steer the resin flow during the resin infusion stage.[31]
- Fiber preform compaction and fiber volume fraction control: The fiber performs compaction is very important for the part thickness control. To have a more uniform part thickness, it is preferred to close all injection gates and leave the vents on after filling the mold. The pressure gradient as well as the non-uniformity of fiber preform compaction will gradually relax as the liquid resin redistributes itself inside the fiber preform. The relaxation process is related to the resin viscosity, the mold temperature, the pressures and location of vents, the flow distribution medium and the fiber preform.

d. Defects and challenges

(i) Air Entrapment

In a VARTM process, the vacuum pressure inside the fiber preform can never be the true zero pressure. As a result, there is a considerable chance of air entrapment inside the final composite part if the air cannot be completely displaced by the resin during the mold filling. One of the major reasons for dry spot formation is an improper mold filling design that causes the resin flow to reach the vent before all the air inside the fiber preform is fully displaced by the resin. In this scenario, although the entrapped air can still be slowly washed out by a continuous resin flow with the inlet and vent opened, the limited resin gelation time and the increased cost to supply the extra resin for the air washout process make this approach unpopular in general VARTM processes. On the other hand, an optimized mold filling design or an active mold filling control technology can mitigate the dry spot issue effectively. For complex mold geometry, one can use the optimization method such as the artificial genetic algorithm and the molding filling simulations to optimize the arrangement of flow distribution medium layers, flow lines and vent locations or even control the on/off timing of the gates and vents.[37–39] Johnson and Pitchumani[40] reported an active VARTM flow control method by heating the resin locally during the VARTM mold filling stage to reduce the resin viscosity and accelerate the VARTM flow locally. The local flow acceleration can be utilized to control the resin flow front motion during the mold filling process to minimize the dry spot in a VARTM part. However, they also point out that the heating may accelerate the curing reaction of the resin locally, and one has to take this factor into consideration while using this local heating flow control technique.

The second cause for dry spot formation is that the filling process could be too slow to completely fill the mold before the resin becomes too viscous to flow. To accelerate the infusion speed, one may consider using more flow distribution layers, injection ports and vents. Alternatively, one may also consider slowing the resin curing process by using fewer curing accelerators or by changing the mold temperature, etc. A modeling based mold filling analysis can also be helpful to prevent early resin gelation before the VARTM mold is completely filled.

The leakage in the vacuum bagging system is also a common cause of dry spots. The leakage may include but is not limited to (1) vacuum bag damage, (2) leakage in tubing, connectors or resin supply lines, (3) leakage near the sealing tapes, and (4) newly formed leakage due to vacuum bag shrinkage or the composite part deformation during the VARTM process. The leakage may be prevented by carefully selecting the bagging and related materials and paying attention to mold tool cleaning and layup process.

Besides the visible dry spots, microvoids are another type of air entrapment in VARTM processes. The cause of microvoids is different from that of dry spots. The microvoids are formed due to the incompatible dual scale flow behavior of the wetting process inside a fiber tow (or fiber bundle), which is used to form the fiber mat, and the resin flow process in the gap between fiber tows as explained earlier in the section on RTM. The resin flow in the gap between two fiber tows is governed by the Darcy's law (i.e. Eq. 1). However, the resin filling inside a fiber tow is driven by the capillary effect if air/resin interface is involved. The relationship between the microvoid formation in VARTM processes and the dual scale effects of the Darcy's flow and the capillary flow has been investigated by many researchers.[41–46] Generally, at the resin flow front, small amounts of air could be trapped and form microvoids if the capillary flow front velocity is significantly faster or slower than the Darcy's flow front velocity during a mold filling process. For a given resin viscosity and flow velocity, the microvoids

larger than a certain critical size can be mobilized and washed away by the resin flow according to the void mobilization model proposed by Chen et al.[42] Since the resin viscosity, the fiber preform compaction, the Darcy's flow behavior and the capillary flow behavior (resin surface tension and the contact angle between resin and fiber) strongly depend on the temperature and the pressure used in a VARTM process, Kedari et al.[47] demonstrated that it is possible to reduce the microvoid content as well as to achieve high fiber volume fraction by optimally controlling the mold temperature and the resin inlet pressure (assuming the environmental pressure is fixed and the vent vacuum is maintained ata constant level) during a VARTM mold filling process. Their experimental results suggest that a higher mold temperature and a stronger vacuum level (i.e., lower absolute pressure) at the vent are useful in increasing the fiber volume fraction and enhancing the fiber volume fraction consistency due to the reduction in resin viscosity and the increase in thickness-direction compression. However, their experimental data also show that a higher mold temperature may sometimes increase the void content if the injection pressure is not modified accordingly. Since the capillary pressure of polyester/E-glass system is reduced at a higher temperature, they utilized a compatibility model to predict that a reduced pressure difference between the inlet and the vent of a heated VARTM process must be used so as to enable one can obtain the same low void content of the part infused at a room temperature. By using a dual pressure control VARTM configuration with a heated mold, they experimentally validated this prediction by applying a reduced inlet pressure and an elevated mold temperature to fabricate a VARTM part with enhanced fiber volume fraction and reduced void content. In their study, Kedari et al.[47] concluded that the flow compatibility and the thermal pressure coupling effects have significant influence on both the microvoid formation and the fiber volume fraction control and should be considered for optimizing the flow and thermal control of a heated VARTM process.

(ii) Thickness and fiber volume fraction

The fiber volume fraction distribution of the final composite part is determined and locked during the post-filling compaction relaxation process. The post-filling compaction relaxation process depends on many parameters, such as (1) the preform and the fiber system, (2) the resin viscosity and the cure kinetics, (3) the mold temperature, and (4) the type and the arrangement of the flow distribution network. Currently, the compaction relaxation can only either be measured from experiments or predicted by numerical simulations.[48–51] For a practical VARTM process, one should try to have the resin stay at a low viscosity for enough time and close all injection gates during the post-filling stage. Generally, increasing the VARTM mold filling speed and using a resin with longer gel time will benefit in the part thickness control.

e. Advances in VARTM process

Fan et al.[52] introduced an injection and double vacuum-assisted resin transfer molding (IDVARTM) process. The IDVARTM process adds a rigid vacuum chamber outside the vacuum bag of a regular VARTM setup and utilizes the chamber vacuum pressure to increase the fiber preform porosity. In addition to using the VARTM process for emerging new composite material systems, many variations from the basic VARTM process have been developed to help manufacture larger, thicker and sophisticated composite parts with improved capability, reliability and cost-effectiveness. Focused areas are (1) optimal design and fabrication of the fiber preform to achieve good permeability control and compaction control, (2) co-curable interlayer flow channel and interlayer distribution medium layer for successfully infusing a thick composite laminate part or a composite part with inserts, (3) new resin system with the viscosity and cure kinetics customized for VARTM, (4) improved reliability in detecting and fixing any leakage during VARTM process, (5) reusable bagging systems, (6) advanced flow and curing control of the VARTM process, and (7) an additional selective membrane (i.e., permeable to gas and impermeable to liquid) sandwiched between the vacuum bag and the flow distribution layer to prevent the dry spot formed on the surface of a VARTM part.[13]

3.3 *Resin Film Infusion (RFI)*

RFI is a manufacturing process wherein the resin and the fiber are laid together into the mold but are not initially combined. This process is reported in patent in late 80's.[53] The technology works on the same principle of VBO prepregs containing breathable paths for air removal during processing. Here, the reinforcement and the resin film are placed in the mold in separate steps and are combined by applying pressure and temperature. In some cases a resin film is placed on one or both sides of a sheet of dry fibers. These prepregs are commercially known as Sprint® (SP, Isle of Wight, UK), or Cycom™ (Cytec Engineered Materials, Tempe, AZ). In this technique majority

of the fiber stays dry, while most of the resin stays outside the cloth. A small region exists through the thickness of the prepreg where the resin and fibers mix.

Advantages of RFI process:

- They can be used in manufacturing processes in the same manner as dry reinforcement, but without a complex resin infusion process. This allows simple and efficient assembly practices to be maintained without the fear of having dry or resin rich areas after infusion of a complex part. Expensive resin distribution networks are not needed.
- The resin film exhibits a light tack at room temperature which allows adhesion to curved surfaces. Extra adhesives, which may introduce defects in a finished laminate, are not required for support before infusion.
- Repeated debulking operation for thick composite structures not required.
- High quality parts can be obtained using vacuum pressure only; external application of pressure is not required.
- Styrene emissions of processes involving styrenated resins are reduced, and handling of bulk resin is eliminated.
- In many cases, production costs can be brought down while product quality is maintained or improved.
- This process has special significance for large one-off structures: There is no possibility of an incomplete infusion.
- The elimination of dry spots in infusion processes may lessen the need for secondary bonding in complex parts, owing to the fact that larger and more complex sections can be fabricated in a single step versus multiple steps.
- Stored in refrigeration, the resin retains low-tack properties at room temperature. The resins typically maintain their handling properties for nearly a month of intermittent exposure to ambient temperatures (1 month out-life).

Research was intended in the direction to develop a cure and consolidation model for this technique. Of critical importance was the capability to predict resin flow and laminate compaction during cure. Such a model could be used to determine optimum cure cycles without a need for experimental trial and error. The overall model is composed of three main parts: a kinetics expression, a viscosity relation, and a flow model. The kinetics expression predicts how the resin will cure, the viscosity relation predicts what the viscosity of the resin will be during cure, and the flow model predicts how the resin will flow through the laminate and how the laminate will deform. These models are inter-related since the viscosity relation requires information from the kinetics expression, and the flow model requires information from the viscosity relation.

Loos and Springer's[54] work on the compaction of laminated composites formed a baseline for future efforts. They modeled the flow of Hercules 3501-6 resin through multiple layers of unidirectional carbon fiber, and experimentally and analytically investigated the mechanisms of consolidation. They combined Darcy's Law, the balance of linear momentum equation, and the conservation of mass to obtain equations governing the resin flow. However, they did not account for fiber deformation during consolidation, but considered laminate compaction resulting from resin loss.

A necessary ingredient for any model allowing deformation of the fibrous reinforcement is a relation between fiber deformation and permeability. The fiber volume fraction, porosity, and permeability of the reinforcement change as fibers deform. Relations between these properties and the applied pressure or deformation of a laminate are needed. A frequently employed expression to model permeability has used empirical relations with good results. Some researchers have developed dual scale analytical models that account for the variation in permeability between the fiber tows and the spaces between them in a reinforcement fabric.[55–58] Chen et al.[59] later proposed a simple relation for dry compressibility of woven fiber preforms. They define a bulk modulus as an analytical function of volume fraction and five parameters. The bulk modulus is called a bulk compressibility modulus in.[59]

The parameters for the bulk modulus can be determined in experiment. The modulus has been specified for limited material systems and shown to correlate well with experimental results. Its major limitation is its restriction to dry preforms.

To successfully produce laminates using resin film infusion in combination with a fast-curing process, the flow behavior of the selected resin material under changed processing conditions was investigated.[60] The effect of processing parameters, specifically heating rates and dwell times, on resin viscosity and laminate infiltration was evaluated through experimental work and supported by in situ process monitoring. A DC-resistance sensor system was applied to track the change in resin viscosity during cure. Results showed that cure cycles with a relatively short dwell time and higher heating rate compared to an autoclave cure led to enhanced flow properties of the toughened resin

system. High quality laminates, comparable to autoclave panels, were manufactured with vacuum pressure only by modifying the original vacuum bagging arrangement.

Recent advancements in this field are in the modification of resins with nano-materials. Resin film infusion being a local flow the issues related to filtration has been resolved and reported.[61–63] Rheological characterization of carbon nanofiber-filled epoxy revealed that viscosity, and in turn processing characteristics of the resin remain almost unaffected as compared to the pristine resin system at elevated temperature of composite processing. Glass transition temperature of epoxy showed a considerable improvement with carbon nanofibers. Local flow of the modified resin through the embedded fabric plies in the resin film infusion process made sure that a uniform distribution of nanoparticles is achieved throughout the composite. Compressive strength of hybrid composites showed over 40% increase while interlaminar shear strength improved by 33% with carbon nanofibers at a loading fraction as low as 0.5 wt%. These researchers also reported hybrid composite development using RFI process with carbon nanotubes modified using surfactants and nanosilica.

4 Conclusions

VBO prepregs and LCM processes using dry performs allow the manufacture of autoclave-quality parts under vacuum bag-only compaction, using conventional ovens or heated mould setups. This class of materials and processes feature a partially impregnated microstructure or dry fabric pathways that promote gas evacuation and suppress defect formation in the initial stages of processing before being fully saturated with surrounding resin during cure. The coupled air evacuation, fiber bed compaction, resin flow and void growth (or collapse) phenomenon that constitute consolidation/compaction depend on a combination of factors, including the properties of the constituent fibers and resin, cure parameters such as temperature, vacuum quality and consumable arrangement, and part characteristics such as geometric complexity and size. These relationships have been investigated in multiple studies, demonstrating that high quality parts can be successfully fabricated under appropriate conditions.

OoA processing reduces the costs and environmental impacts relative to traditional methods by decreasing energy consumption during the cure. However, additional research and development is required to improve process robustness and fully optimize the scale-up of VBO processing to industrial production levels.

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