VARTM Variability and Substantiation

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Abstract:

Vacuum-assisted resin transfer molding (VARTM) has the potential advantages of relatively low cost processing with sufficiently high volume fractions of reinforcement and can be readily applied to large-scale structures. However, for many aircraft applications, VARTM does not currently provide sufficient repeatability or control of variability. Such variability is commonly observed when processing with the VARTM process. In order to routinely produce VARTM parts of aircraft quality, the sources of the process variability must be understood and minimized. This paper looks at the various processing steps and their influence on final product quality. Models have been developed to capture the process physics and have been validated via experiments.

Introduction:

Vacuum Assisted Resin Transfer Molding (VARTM) offers numerous cost advantages over traditional resin transfer molding (RTM) due to lower tooling costs, potential for room temperature processing and scalability for large structures. Historically, the wind energy and marine market has utilized this process to produce high-performance composite components. Low process repeatability and dimensional tolerances compared to autoclave processing, as well as lower materials performance of the resin versus prepreg limited its aerospace applications. Recently, improved understanding of the process physics [1-5] combined with advances in infusible toughened epoxies [6, 7] and automation equipment [3] enabled consideration of the process for structural aerospace components. Technology demonstrators such as the C-17 Main landing Gear Door and Forward Pylon of the Chinook met performance requirements for military components, while multiple primary structural components for civil air transportation such as the Airbus A380 flap tracks and Boeing 787 pressure bulk head are currently in production and manufactured by the VARTM process.

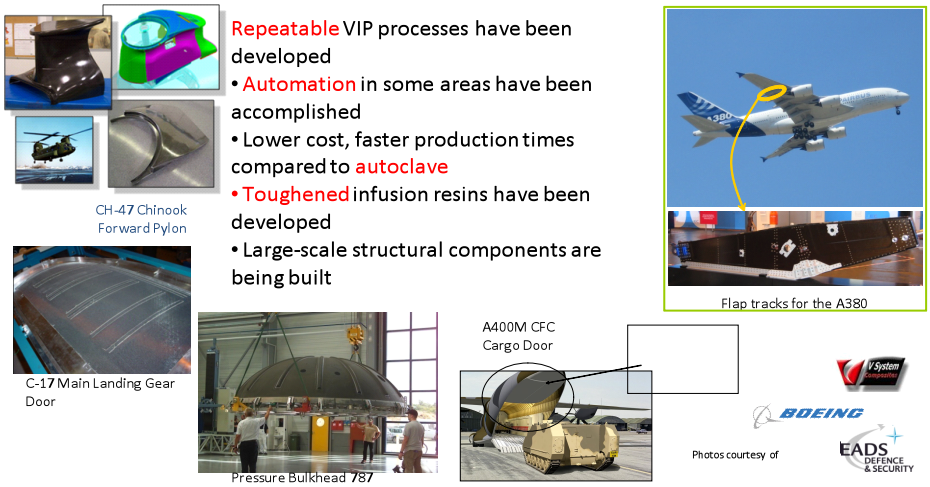


Figure 1: VARTM processing is used for production of aerospace components

Many patents have been granted with the same underlying principle of pulling liquid matrix material through the infusion ports into a sealed dry fiber preform under vacuum only. Compaction of the reinforcement and pressure gradient needed for resin flow is provided by applying a vacuum on the opposite side of the preform (vent). Three patented process commonly used in aerospace are described in detail:

SCRIMP

The Seeman Composites Resin Infusion Molding Process (SCRIMP [8]) is a patented VARTM variation with a highly permeable distribution medium incorporated as a surface layer on the preform. During infusion, the resin flows preferentially across the surface and simultaneously through the preform thickness enabling large parts to be fabricated. At the flow front, the surface leads the tool flow front while the lead length can be significant for thick preforms. Resin infusion times increase exponentially with injection length during VARTM processing. During sequential injection processing, several infusion tubes are located on the distribution media and the injection lines are sequentially opened to minimize cycle times. Sequential injection reduces the injection length to the distance between the resin gates, which effectively divides the part in multiple injection regions

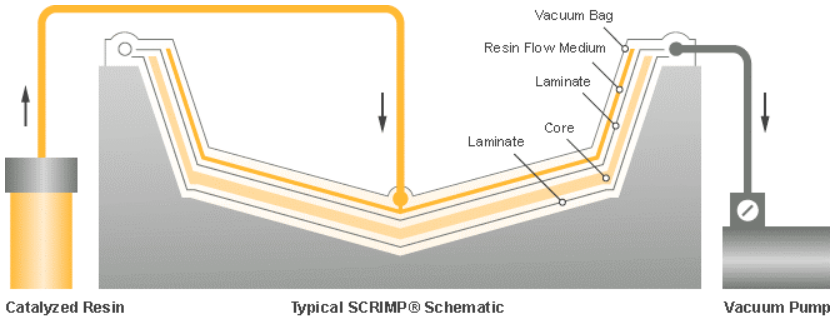


Figure 2. Schematic of the SCRIMP process [9]

VAP

The Vacuum-Assisted Process (VAP) developed and patented by EADS Deutschland [10] is using a gas-permeable membrane to allow for uniform vacuum distribution and continuing degassing of the infused resin. The VAP process results in a more robust VARTM process that minimizes the potential for dry spot formation as well as lower void content and improved dimensional tolerances [11].

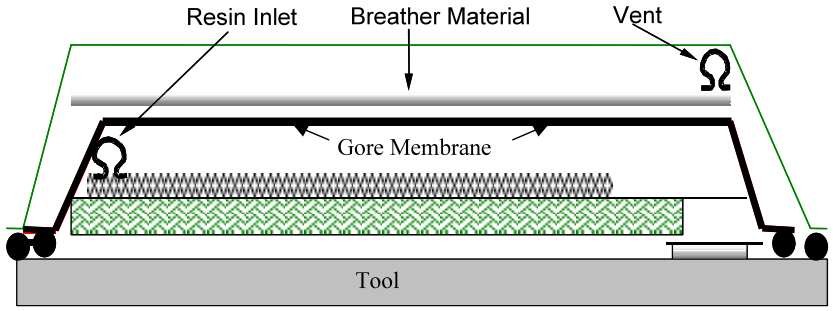


Figure 3: Schematic of the VAP setup

Several companies have developed the suitable membrane material. The membrane is designed to be impermeable to the resin system but permeable to gases. In general, these membranes have a nano-porous structure and rely on the capillary pressure to maintain its barrier characteristics for the fluids. These characteristics change with the resin material and pressures used in the VARTM method and thus have to be designed for a particular setup.

Figure 4: Low resin permeability creates a resin barrier while high air permeability enables continuous surface venting during VAP processing

CAPRI

The Controlled Atmospheric Pressure Resin Infusion (CAPRI [12]), patented by the Boeing Corporation, is a VARTM-variant that was developed to improve thickness/fiber volume variability in infused composites. Characteristic points are pre-infusion debulking (repeated compression-relaxation of preform) and application of partial vacuum to the resin reservoir during infusion, lowering the pressure gradient from inlet to vent location. This results in a smaller thickness gradient but can increase the infusion time significantly [13].

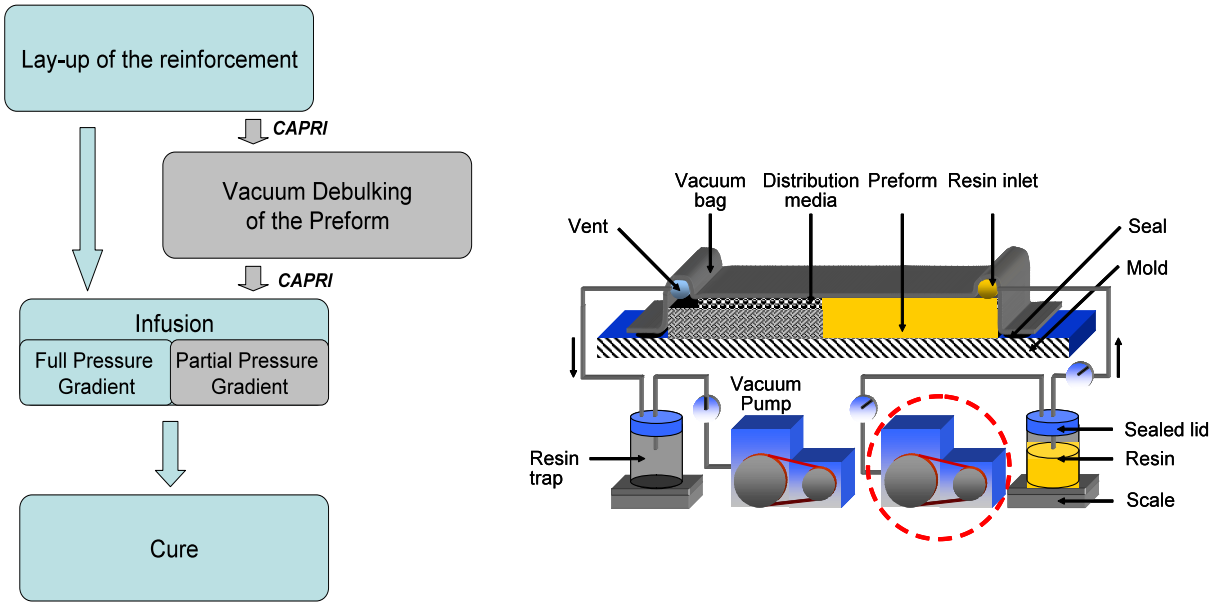


Figure 5: Schematic of the CAPRI setup and processing steps

In general, all VARTM processes can be divided into three processing steps including material and tooling preparation, the infusion step and the post-infusion step. Each process step will influence final material quality in particular the fiber volume fraction and void content distribution. This paper provides a brief overview of the various mechanisms influencing final

part quality and for some processing steps includes more detailed information on the more important mechanisms.

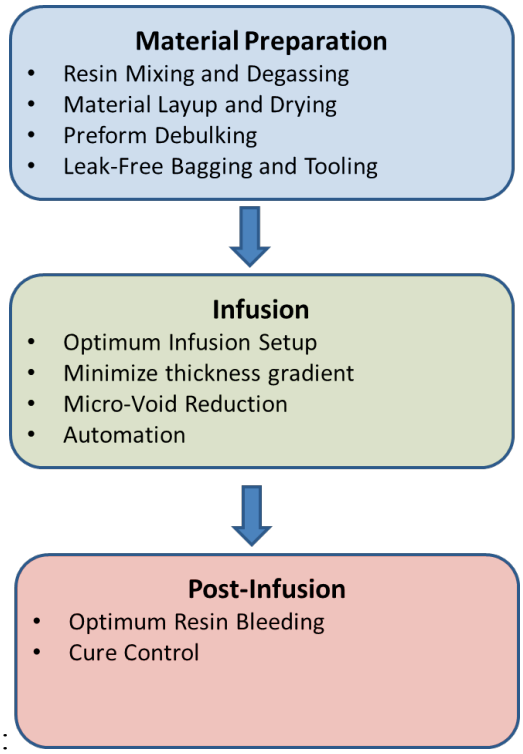


Figure 6: VARTM Processing Steps

MATERIAL PREPARATION

During Material Preparation, fibers, preforms and other reinforcing materials are placed into the mold. Often, these materials have taken up moisture and depending on the resin selection and final part quality requirements, the material has to be dried under vacuum prior to infusion. This is in particular important for resins reacting with water during cure and resins which are infused at room-temperature (or below the water boiling temperature) and cured at above 100C where the entrapped moisture vaporizes resulting in a significant increase in void content. Resin mixing and degassing prior to infusion ensures blending of the various components and low content of entrapped gases. Often, mixing has to be done under elevated temperature where resin viscosity is low as well as under continuous vacuum application to ensure minimum entrapped air in the mixture. Another important aspect is the leak rate of the bagged component on the tool. Typical leak rate in aerospace and high-performance marine application have been reported to be approximately 3-5mBar per minute. These rates can only achieved with tooling designed for VARTM applications and properly installed bags. It is recommended to use digital leak rate equipment which enables continuous monitoring of the leak rate when the installed bag is checked for leaks.

Debulking of the fabric prior to infusion is of particular interest as it increases the nesting of the fibers and thus increases overall fiber volume fraction. Here, the compaction behavior of the preform [14, 15] influences both the infusion process as well as the final part thickness. The CAPRI process as outlined before changes the compaction and permeability behavior during the debulking process prior to infusion [13]. An out-of-plane permeability cell [16] has been used to

characterize the permeability and compaction changes during dry debulking.. The system is placed under a mechanical loading machine allowing controlled cycling of the pressure enabling simulation of a typical vacuum debulking step. As an example, the permeability changes during debulking of a 15 layer fabric stack (24oz plain weave E-Glass 324-2407 supplied by Mahogany) was characterized. Figure 7 shows the reduction in permeability for each debulking cycle under maximum load (100kPa). It can be seen that the greatest reduction occurs during the initial debulking cycles. After 200 cycles the permeability reduced to approximately 20% of the un-debulked baseline material potentially increasing the infusion time and lead length during part impregnation.

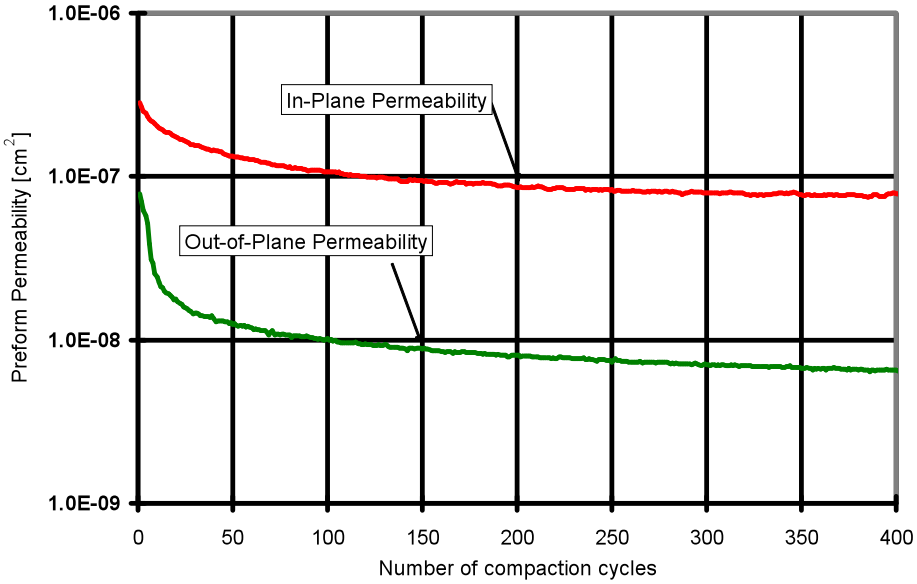
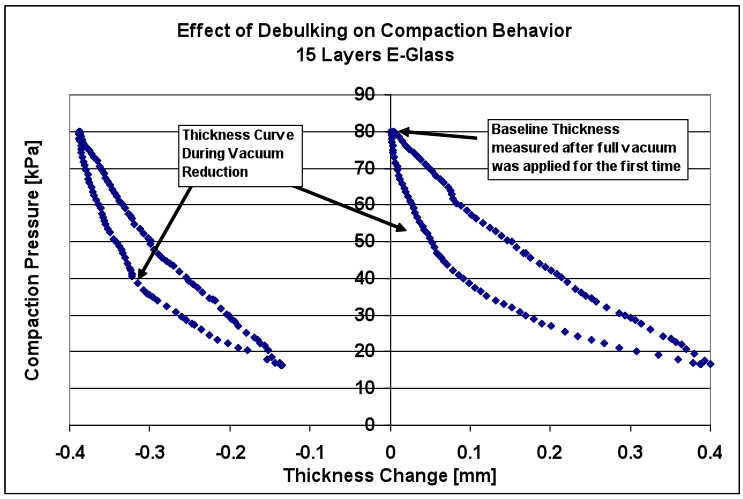


Figure 7: Permeability as a function of debulking cycle

Figure 8a compares the dry compaction behavior before and after 400 debulking cycles and Figure 8b shows the thickness reduction during the first 400 debulking cycles. Here, during each debulking cycle the compaction pressure was increased for 30 seconds to 90kPa and decreased for 30 seconds to approximately 15kPa. The result of the nesting effect on thickness can be clearly observed. A thickness reduction of approximately 0.4mm for the same compaction pressure before and after 400 debulking cycles is seen corresponding to an approximately 5% decrease in total thickness or 5% increase in fiber volume fraction. The maximum thickness difference from the un-compacted (15kPa) to the compacted (80kPa) preform changes from 0.4mm for the un-debulked case to 0.25mm for the debulked case indicating a reduced spring-back effect of the preform. The thickness is primarily reduced during the initial debulking cycles as seen in Figure 8b. The first 100 cycles reduce the fiber preform thickness by 0.3mm versus an additional 0.1mm reduction for the remaining 300 cycles. The overall thickness reduction will increase the average fiber volume fraction in a VARTM part and the reduced spring-back effect of the un-compacted versus compacted preform could potentially reduce the thickness gradient of the preform during infusion improving dimensional tolerances.



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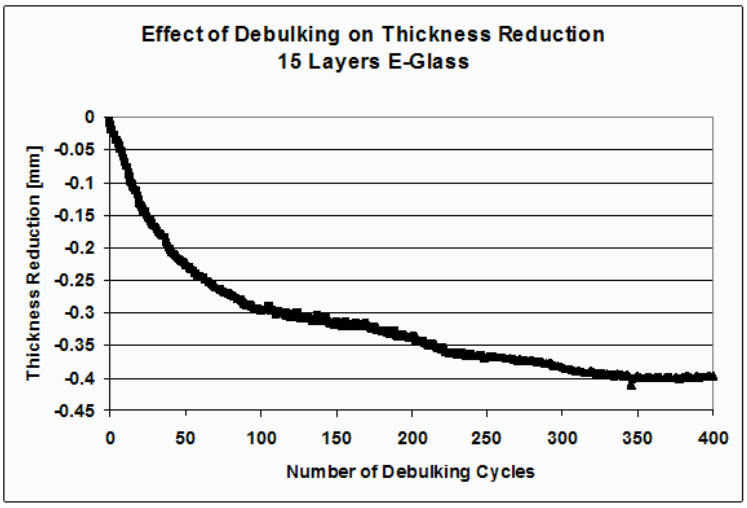


b)

Figure 8: Compaction behavior: a) before and after 400 debulking cycles; b) thickness change at each debulking cycle measured during peak vacuum

Resin preparation, fiber drying and bag integrity can directly impact the final void content in the part while the debulking step can maximize the fiber volume.

INFUSION STEP

The infusion step has been investigated by various researchers. Typically, the flow behavior has been modeled using flow through porous media and Darcy's Law. The flow behavior has significant complexity compared to Resin Transfer Molding (RTM) processing where is infused in a fixed cavity mold. In VARTM, the vacuum pressure compacts the preform but also is driving force of the resin goes through the reinforcement. The addition of the distribution media creates a fairly complex 3-D flow where there is a significant flow gradient through-the-thickness of the reinforcement (Figure 9).

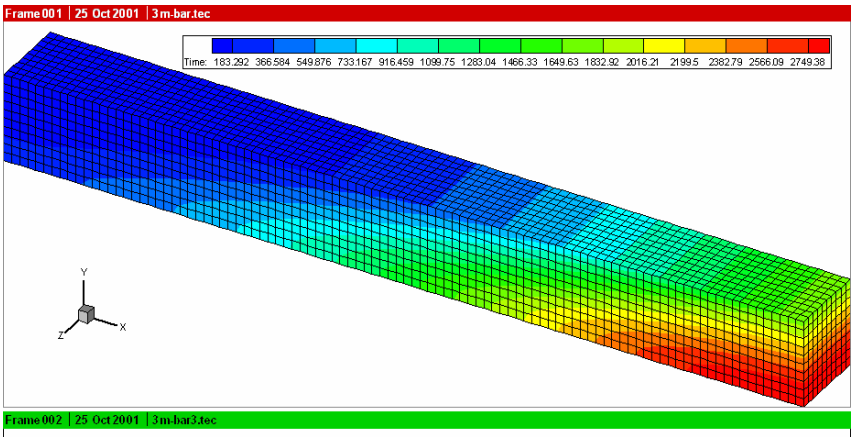
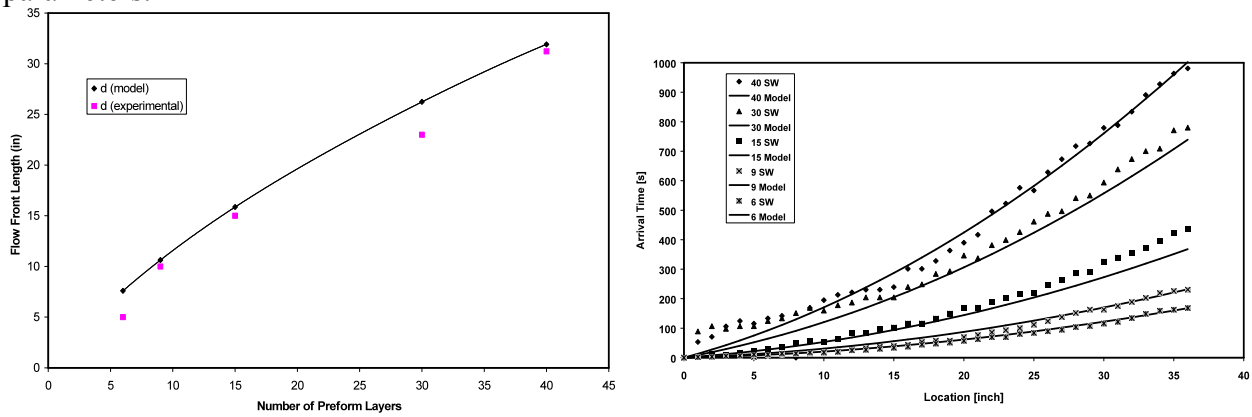


Figure 9: LIMS [17] flow time prediction for a simple plate with surface distribution media showing the through-thickness flow gradient

Analytical and finite element tools have been developed to capture the resin flow process physics. One analytical tool is described in [4]. It takes the material properties of the DM and fabric (permeability, fiber volume fraction, and geometry), process pressure and resin viscosity to and calculates the flow times through the thickness of a constant cross-sectional part. It can be used for a optimize gate spacing and for sensitivity analysis of critical material and process parameters.



a) b)

Figure 10: Arrival time of resin at the bottom layer (a) and length of flow region (b)

Another important flow issue is the typical dual-scale behavior of the fabric [18, 19]. Flow around the tows (macroscopic flow) is typical much faster than the flow into the tows (microscopic flow) (Figure 11). Often capillary pressure has to be considered. The issue with dual-scale flow is the opportunity of void formation within the fiber bundle. As the macro-flow impregnates faster the outside of the tow, the inside of the tow will be disconnected from the vacuum source. Capillary pressure can either help to further infuse the tow in case of a wetting fluid but can restrict flow for a non-wetting fluid. Ultimately each tow cell could result in a micro-void.

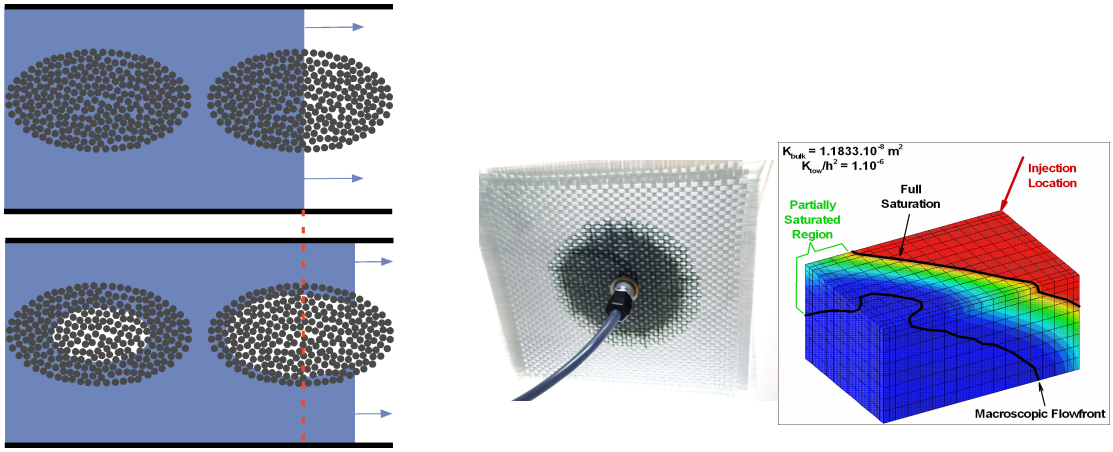
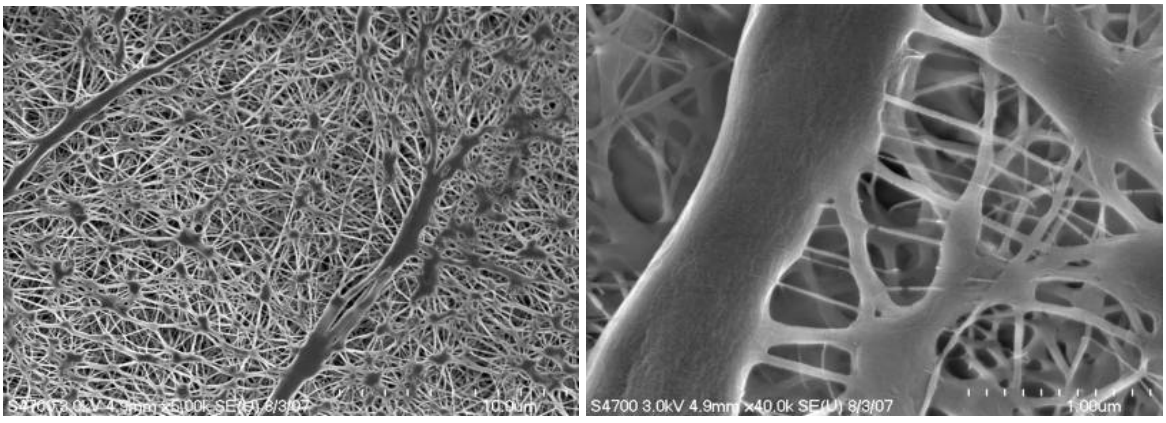


Figure 11: LIMS can be used to estimate the dual-scale flow behavior

Pressure gradients exist and are complex and dynamic. The preform is initially uniformly compacted under the applied pressure. Once resin is infused, a pressure gradient develops in the wetted region leading to changes in the compaction pressure, fiber volume fraction and ultimately changes in the permeability. The permeability influences the flow behavior which also affects the pressure gradient. In order to fully capture the process physics a coupled model has to be developed. Nevertheless, often simplifications are made allowing the use of a constant effective permeability of the preform.

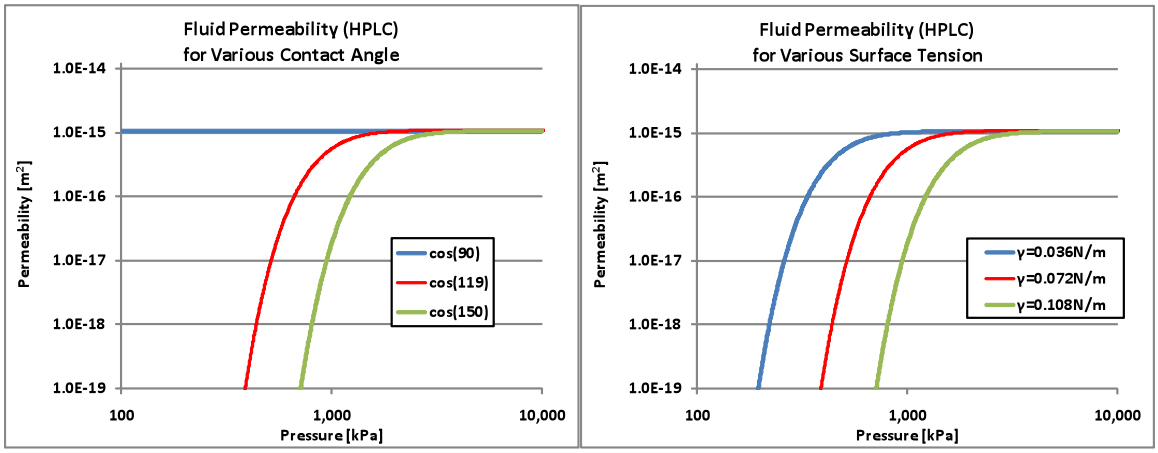
Recently, membranes have also been used in Liquid Composite Molding (LCM) processing as a surface layer enabling continuous venting of gases and volatiles on the complete part exterior [11] or in the layup to improve mechanical. The surface layer membrane ideally functions as a total barrier layer for non-wetting resin or more realistically to limit flow rates to an acceptable level of resin penetration for a desired process pressure and time. In general, these membranes have a nano-porous structure (Figure 12) and rely on the capillary pressure to maintain its barrier characteristics for non-wetting fluids.



a) b)

Figure 12: SEM images of a typical membrane surface used in composite processing ("Albatros" by W. L. Gore and Associates); (a) 5,000x magnification and (b) 40,000x magnification

The pore size distribution of the membrane is one of the critical parameters used to evaluate the performance of the membrane by its characteristic permeability [20, 21]. It is shown that the membrane permeability is variable and depends on the applied external pressure, fluid/membrane interactions and pore size distribution. Figure 13a shows the influence of a changing contact angle. If a wetting fluid is considered ($\theta \leq 90^{o}$), then the capillary pressure is positive and all pores are filled immediately. Thus, permeability of the membrane for a wetting fluid is constant and equivalent to the permeability of a non-wetting resin system at high pressure (steady-state permeability). Increasing the contact angle, increases the capillary pressure requirement and the permeability curve shifts to higher pressures without changing the steady-state permeability or the general permeability trend. Similar behavior can be seen for varying surface tension where the capillary pressure is either reduced (decrease in surface tension) or elevated (increasing surface tension). Nevertheless, in comparison the maximum contact angle factor is limited and peaks at $\theta = 180^{o}$ while surface tension can vary significantly more.



a) b)

Figure 13: Permeability behavior for various contact angle (a) and surface tension (b)

The VAP process adds a membrane to the VARTM process allowing uniform vacuum pressure on the complete preform surface. Resin wet-out of the preform is typically identical compared to standard VARTM processes as long as the dry reinforcement is connected to the vacuum port. In setups where dry-spots develop, the membrane allows venting through the surface and continuous flow into the fabric reducing/eliminating large void areas. In addition, overall void content is reduced as the membrane allows a short path through-the-thickness to vent any remaining volatiles in the part.

POST-INFUSION STEP

After infusion, the resin has still low viscosity and often the setup is designed to allow bleeding into the vacuum trap. The resin bleeding takes out some of the excess resin from the area of low vacuum pressure and moves it toward the vent. The volume loss reduces the thickness of the part and improves fiber volume fraction. Thus it is an important step in the overall process. An analytical model has been developed to capture the process physics [22] and has been validated experimentally. Boundary and initial conditions and their influence on the final results were explored. The numerical model was implemented and solved for a fairly simple geometry and well-characterized materials. The resulting solution was applied to several post-

filling scenarios applied or considered in VAP processing. The solution can predict the time needed to achieve resin equilibrium within the part as well as the final part thickness.

The material permeability and compliance may have significant effect on the time to reach steady state as well as the final thickness. Decrease of permeability leads to extending the necessary time for pressure and thickness to reach equilibrium, while decrease of compliance reduces this time period. As less compliant preforms tend to be less permeable, these effect would tend to counter balance each other, making the predicted time less sensitive to change in preform material.

Figure 14 shows the injection pressure during VAP processing after full infusion of the preform (t=100s). The injection has been switched to a vacuum port allowing resin bleeding. The pressure gradient is significant; full vacuum at both the vent and previous injection side while partial atmospheric pressure in the part center. Pressure and thickness gradient are getting smaller over time as resin bleeds out. Time scales depend on the resin viscosity and permeability of the preform. The model predicts the time to achieve acceptable uniform thickness and thus uniform fiber volume fraction.

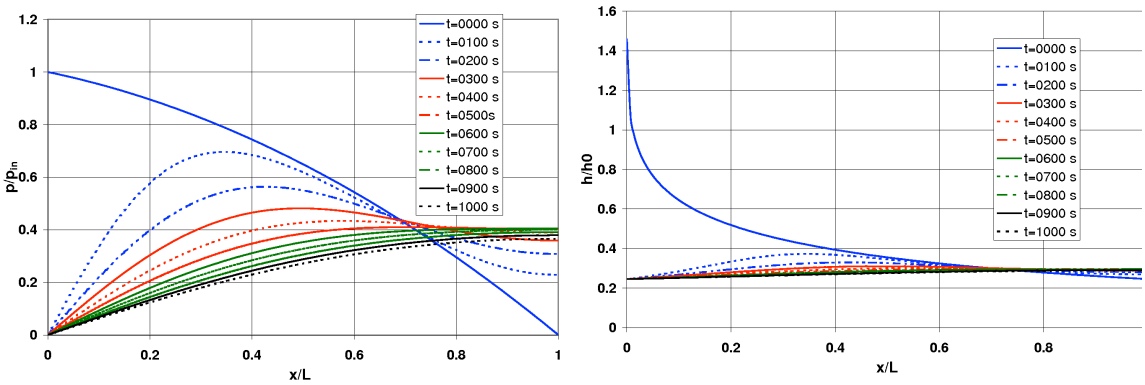


Figure 14. Pressure and thickness development for the scenario in which the injection line is switched to a vacuum line after the mold is filled.

This shows the important aspect of the post-infusion process. Fast curing resins will gel prior to reach uniform thickness while excessive resin bleeding can lead to dry spots and high void content.

SUMMARY

The FAA program has evaluated the VARTM process and the influence of the various processing steps on final product quality. Models have been developed to capture the process physics and have been validated via experiments. This paper provides an overview of some of the most important VARTM processes and highlights the most important processing challenges. The processing steps include pre-infusion, infusion and post-infusion and all steps can influence final part quality. Material characterization is important and provides the inputs necessary for the physics-based models. Together, they can be used to ensure uniform part quality and to understand processing issues during scale-up.

ACKNOWLEDGMENTS

This research is gratefully supported by the Federal Aviation Administration. Although the FAA has sponsored this project, it neither endorses nor rejects the findings of this research.

The presentation of this information is in the interest of invoking technical community comment on the results and conclusions of the research.

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