Causes and remedies for porosity in composite manufacturing

G Fernlund, J Wells, L Fahrang, J Kay and A Poursartip

Department of Materials Engineering, The University of British Columbia, 309-6350 Stores Rd., Vancouver, BC, Canada, V6T 1Z4

E-mail: goran.fernlund@ubc.ca

Abstract. Porosity is a challenge in virtually all composite processes but in particular in low pressure processes such as out of autoclave processing of prepregs, where the maximum pressure is one atmosphere. This paper discusses the physics behind important transport phenomena that control porosity and how we can use our understanding of the underlying science to develop strategies to achieve low porosity for these materials and processes in an industrial setting. A three step approach is outlined that addresses and discusses: gas evacuation of trapped air, volatiles and off-gassing, and resin infiltration of evacuated void space.

1. Introduction

Our inability to foresee the technical challenges associated with producing large integrated composite structures within tight engineering tolerances, such as for the F 35, the Boeing 787 and many other recent development programs, has contributed to schedule delays and cost overruns [1]. One reason why we are poor at product and process scaling in composite manufacturing is that industrial composite manufacturing is largely based on heuristics and not on science. We have developed processes that work based on experience and trial-and-error, but we don’t fully understand how and why they work, which makes it challenging to scale them up in size and in production volume.

Most composite parts have multiple engineering requirements they must meet in order to be put into service. These often include a maximum porosity level, geometric dimensions, fibre alignment and other process outcomes. Requirements typically come in the form of engineering specifications that give the allowable range within which a component is deemed satisfactory. When making multiple nominally identical parts, the process outcome will be variable due to variability in incoming materials and in process conditions. Components that are outside engineering tolerances are deemed defective and have to be scrapped, or re-worked so that they meet requirements. Figure 1 illustrates this concept with two processes, process A and process B, where process A has a randomly variable outcome that is largely within engineering tolerances and produce acceptable parts, whereas process B has a variable outcome that does not meet engineering tolerances and produces defective parts.
Figure 1. Examples of variable process outcomes (e.g. % porosity) for two processes, A and B. In this case the engineering specifications require a porosity level below 2%.

Although Figure 1 is highly simplified it illustrates two important concepts. To get a process to produce parts that conform to engineering specifications (such as process A), two things needs to be addressed. First, the process needs to be designed or adjusted so that the mean value of the outcome is centered within engineering specifications. Second, the process needs to be controlled so that the variability in the outcome does not take it outside specifications. This means that to produce high quality components that are within tight engineering tolerances we need to understand the physics behind how process outcomes depend on process parameters, and in particular how we can design or adjust our processes so that both the mean outcome and the variability is acceptable.

1.1 Process-induced defects

There are three process outcomes that regularly cause composite fabricators problems and often lead to defective parts: porosity or voids within the composite material, wrinkling or misalignment of fibres in the components, and process induced shape distortions. The outcome of a process can be viewed from a system’s perspective, Figure 2, which illustrates a composite factory with equipment, tooling & consumables, a part to be made, and materials & processes [2]. All these objects will together determine the outcome of the process. In addition to ensuring that the manufacturing system is able to make parts within engineering tolerances, i.e. process A in Figure 1, we need to develop and design robust processes that can meet engineering tolerances with ease. Thus, we need to aim for high producibility and design processes that are insensitive to typical variations in process parameters.
2. Porosity

Porosity is defined as the volume fraction of (small) voids in a material. In a composite, a void is space that is not occupied with resin or fibre. When individual voids get large, they are no longer treated at a continuum level but as discrete objects with a size, shape and specific location within the material.

There are many causes for porosity in composite parts and it is very difficult to achieve zero porosity. A good approach to porosity management is to view it as a balance of void sources and void sinks, and strive to design processes where the sinks dominate the sources [3]. Void sources are features or mechanisms that increase porosity such as trapped air, volatiles and off-gassing, tool and bag leaks.

Void sinks are features or mechanisms that reduce porosity, such as vacuum evacuation, elevated resin pressure, and bubble mobility. The relative importance of different sources and sinks are dependent on the process and the materials used. The focus of this paper is on out of autoclave prepregs which are challenging to process with low porosity levels due to the low pressures applied.

Out of autoclave prepregs are generally partially impregnated with resin in order to create an interconnected porous network for gas removal [4]. Figure 3 shows photos of a carbon/epoxy MTM 45-1 5HS (five harness satin fabric) OOA prepreg with a resin poor and a resin rich side. MTM45-1 is designed for high performance applications and flexible curing temperatures. It can be cured at temperatures as low as 80°C to allow use of inexpensive tooling with a 180°C post cure heat treatment to maximize mechanical properties [5]. The fibre mat consists of 6K IM7 carbon fibre tows measuring 2 mm in width woven in a 5-harness satin pattern (5 tows per crimp). When layers of partially impregnated prepreg are laid up on top of each other a complex porous gas network that facilitates gas transport is formed. Figure 4 shows a micrograph of an un-debulked and uncured MTM 45-1 5HS laminate that illustrates the nature of the complex porous network with interconnected voids [6].
Figure 3. Top view of uncured MTM45-1/CF2426A 5HS prepreg. Resin poor side (left) and resin rich side (right) [6].

Figure 4. Cross-section of an un-debulked and uncured MTM 45-1 5HS prepreg laminate showing different types of voids [7].

Figure 4 shows three distinct types of voids: voids within partially impregnated fibre tows (red), interlaminar voids between plies (green), and voids fully enclosed by resin (blue). The first two types of voids make up the interconnected porous network and image analysis has shown that the porosity of the interconnected porous network for this prepreg can be as high as 30% before vacuum is applied to debulk the material [7]. When vacuum is applied to the laid up laminate, the laminate compacts but the viscosity of the resin is high enough so that the porous network remains relatively intact during a room temperature debulk and thereby facilitating vacuum evacuation of trapped air. The amount of interconnected porosity in an uncured laminate of this material that has been under vacuum at room temperature for several hours was measured to be 15-20% [7]. For primary aerospace structures there is often a requirement that the porosity in finished parts is less than 2% and if we start with close to 30% porosity we need to ensure that the available void sinks are powerful enough to overcome this large initial porosity. A simple three step approach to achieve low porosity in OOA prepreg processing is as follows:

1. *Vacuum evacuation of trapped air.* Conduct a sufficiently long room temperature vacuum debulk to remove most of the trapped air (and perhaps some dissolved moisture).
2. *Keep volatiles in solution.* Heat the laminate up to cure it, but keep the resin pressure sufficiently high to keep any dissolved volatiles in solution until the resin gels.

3. *Resin infiltration.* Ensure that there is sufficient time (and resin pressure) for the resin to infiltrate any evacuated voids space between plies and within fibre tows.

The challenge is to turn these three qualitative steps into a robust scalable process recipe that reliably and repeatedly can produce low porosity parts with different sizes and characteristics. The following section will address the physics and timescales associated with advective removal of gas from a porous media by use of a vacuum system, which is the primary porosity sink for trapped air. The presented theory applies to partially impregnated prepregs, such as out of autoclave prepregs, as well as breathers and other porous materials in prepreg processing.

### 2.1 Vacuum evacuation of trapped air

Consider one-dimensional gas transport through a porous gas permeable medium, Figure 5. The medium can either be a partially impregnated prepreg, a breather, or any other medium that allows for gas transport in composite processing. We assume that there are gas channels, or an inter-connected “vascular network”, that allows gas to permeate though the medium and the permeability and volume of the network are constant during the evacuation process.

![Figure 5](image.png)

**Figure 5.** Schematic of the 1D gas transport problem with flow through a porous media.

If we assume that the gas is an ideal gas and that the flow follows Darcy’s law, the governing differential equation in terms of gas pressure $p$ can be written

$$\phi \frac{\partial p}{\partial t} - \frac{K}{\mu} \frac{\partial}{\partial x} \left( p \cdot \frac{\partial p}{\partial x} \right) = 0$$

(1)

where $\phi =$ porosity, $p =$ pressure [Pa], $t =$ time [s], $x =$ distance [m], $K =$ gas permeability [m$^2$], $\mu =$ dynamic viscosity [Pa·s]. To solve eq. (1) for a specific case we can non-dimensionalize the equation with respect to distance, pressure and time as
where

\[ \frac{\partial p^*}{\partial \tau} - \frac{\partial}{\partial \xi} \left( p^* \frac{\partial p^*}{\partial \xi} \right) = 0; \]

\[ \xi = \frac{x}{L}; \quad p^* = \frac{p}{p_0}; \quad \tau = \frac{Kp_0}{\phi \mu L^2} \]

\( \xi \) is non-dimensional distance, \( p^* \) is non-dimensional pressure, and \( \tau \) is non-dimensional time. The non-dimensional factors in equation (2) give some interesting scaling laws for gas evacuation. For example, the time \( t \) it takes to reach a new pressure state is proportional to the viscosity of the gas, \( \mu \), the porosity \( \phi \), the length of the laminate squared, \( L^2 \), and is inversely proportional to the initial pressure \( p_0 \) and the permeability of the medium \( K \). Thus a laminate with twice the permeability will evacuate twice as fast, and a laminate with twice the distance to the vacuum system will take four times longer to evacuate.

We can now analyze one-dimensional gas evacuation of a laminate. The whole laminate is initially at pressure \( p_0 \) (ambient pressure), and vacuum pressure \( p_V \) is applied at \( x=L \) at time \( t=0 \) (Figure 5). The volume of gas in the porous laminate is assumed fixed and the vacuum applied at \( x=L \) evacuates the gas from the laminate via Darcy flow. In this case, eq. (2) needs to be solved for the following boundary condition

\[ \frac{\partial p^*}{\partial \xi} \bigg|_{\xi=0} = 0, \quad p^* (1,\tau) = p_V \]

Equation (2) with boundary conditions (3) has no known analytic solution and was solved numerically using the Mathematica software. The numerical solution was used to develop an approximate general expression for the amount of gas removed as a function of time during gas evacuation. By integrating the pressure distribution along the length of the laminate at different times, the mole fraction of gas remaining in the porous media as a function of time was calculated and the following simple relationship for the mole fraction of gas remaining \( n/n_0 \) as a function of dimensionless time \( \tau \) is obtained

\[ \frac{n}{n_0} \approx e^{-0.9 \tau^{0.6}} \]

Equation (4) is plotted in Figure 6 to illustrate the relationship between mole fraction of gas remaining and dimensionless time \( \tau \). The main reason for the strong exponential decay in eq. (4) is that the velocity of the gas is proportional to the pressure gradient in Darcy’s law and the more gas that is removed, the smaller that driving force becomes. Hence, it is not practical to strive to remove all the gas from the system but we need to determine what is sufficient to reach a specific porosity target.
By determining the dimensionless time \( t \) it takes to reach a specific remaining gas fraction \( n/n_0 \) from eq. (4), the actual time \( t \) can be calculated based on the length \( L \), permeability \( K \), initial pressure \( p_0 \), interconnected porosity \( \phi \) and gas viscosity \( \mu \) of the gas using the relationship between \( t \) and \( \tau \) in eq. (2).

\[
\frac{n}{n_0} \approx e^{-0.91 \tau^{0.6}}
\]

To determine how much gas we need to remove during a room temperature debulk of an out of autoclave prepreg to obtain a part with acceptable porosity we can make the following argument. During a room temperature debulk of an out of autoclave prepreg, the porosity level is approximately constant as the resin is designed not to flow at room temperature to keep the breathing network open [4]. Therefore, during debulk, the number of moles of gas in the porous network decreases but the volume is approximately constant. After the room temperature debulk, the prepreg is heated up and the resin flows into the partially evacuated porous network until pressure equilibrium between the resin and any remaining gas is established. Thus if we want a final porosity level \( \phi_F \) and begin with a porosity level \( \phi \) and assume that the resin pressure remains constant during the process, the ideal gas law gives the following condition of how much gas we need to remove

\[
\phi \frac{n}{n_o} = \phi_F
\]

By combining eqs. (5) and (6) we get the following approximate expression for the minimum required debulk time \( t^* \) to reach a specific porosity level \( \phi_F \) for a prepreg with an initial porosity \( \phi \)
Gas permeability testing has been performed on the MTM 45-1 5HS prepreg to determine the gas permeability during debulk [7]. The initial porosity during debulk has also been measured [7] and the other properties in eq. (7) are readily known. Table 1 show a summary of the values used to calculate the minimum required debulk time for the MTM 45-1 5HS prepreg.

### Table 1. Properties and values used for calculation of the minimum required debulk time \( t^* \), eq. (7) for the MTM 45-1 5HS prepreg [7]

| Property          | Value          |
|-------------------|----------------|
| \( \mu \) (Pa*s)  | 1.82*10^{-5}   |
| \( p_0 \) (Pa)    | 101,000        |
| \( K \) (m^2)     | 6*10^{-14}     |
| \( \phi \) (-)    | 0.15           |

Figure 7 shows a plot of the calculated minimum debulk time \( t^* \) as a function of evacuation length \( L \). Note that the evacuation length \( L \) is typically half the total laminate length as we generally evacuate from all sides and the problem solved is one-sided.

Figure 7 shows that for long laminates the minimum debulk times get large, which is in accordance with the prepreg manufacturers recommendation of an approximately 20 hour debulk for large laminates. It also shows explicitly how the gas evacuation process scales with size and with other process parameters, which is very important when attempting to scale a process.
It is known empirically that a good (hard) vacuum is required to achieve low porosity and high laminate quality in OOA prepreg processing. The presented analysis clearly shows why. In the analysis above it was assumed that a perfect vacuum $p_V = 0$ was applied at the edge of the laminate during the debulk phase. If the vacuum level is not perfect, $p_V > 0$, we can reformulate eq. (4) as follows

$$\frac{n}{n_0} \approx e^{-0.99t_{as}} + \frac{p_V}{p_0}$$

(8)

If $p_V > 0$ then the mole fraction gas after infinite debulk time would equal that expected from the ideal gas law with a porous network at uniform pressure $p_V$. Using eq. (8) we can develop an expression for the minimum required debulk time $t^*$ in the case of imperfect vacuum, $p_V > 0$

$$t^* = \frac{\mu \phi}{p_0 K} \left[ -\frac{1}{0.9} \ln \left( \frac{\phi_F}{\phi} \frac{p_V}{p_0} \right) \right]^{0.6} L^2$$

(9)

From eq. (9) we see that there is a limit on the maximum absolute vacuum pressure $p_V$ allowed to achieve a fixed final porosity level $\phi_F$, even after infinite debulk time

$$p_V < p_0 \frac{\phi_F}{\phi}$$

(10)

From the data in Table 1, this gives that $p_V < 0.067$ atm to have a chance to achieve a final porosity of less than 1% for the current prepreg material. With $0 < p_V < 0.067$ atm, 1% final porosity is possible, but the increased absolute vacuum pressure will increase the required debulk time. Eq. (9) is plotted in Figure 8 for a few different vacuum levels $p_V$ to illustrate the effect imperfect vacuum has on the minimum required debulk time $t^*$. 
Figure 9. Effect of imperfect vacuum on the minimum required debulk time to achieve 1% porosity for a MTM 45-1 5HS prepreg laminate.

Figure 9 shows how sensitive effective vacuum evacuation is to imperfect vacuum and therefore producibility and the robustness of this process step. The presented analysis gave quantitative guidelines for the first step in the process to achieve low porosity, vacuum evacuation. The second step is to keep any dissolved volatiles in solution while heating the material to cure it as to not generate gases that may cause porosity.

2.2 Keep volatiles in solution

Once sufficient amount of trapped gas has been removed before cure commences we want to avoid that more gas in produced by volatiles and off-gassing before the resin gels and the void morphology is locked in. Up to the point of gelation, when the resin transforms from a liquid to a solid material, voids can be generated, expanded or shrunk because of the fluidity of the resin. After gelation, the void geometry is essentially fixed. Previous generations of prepreg were often solvent impregnated and contained dissolved volatiles in the resin. Modern OOA prepregs are manufactured using either the hot melt or resin filming process, which do not require the use of solvents and therefore the amount of dissolved volatile species in the resin is significantly reduced [8]. However, epoxy resin is hygroscopic and will absorb moisture from the environment and volatiles may be generated during the cure process. Moisture can vapourize from the resin causing existing voids to grow resulting in porosity in the final part. Prepreg exposed to relative humidity (RH) above ~70% RH has been shown to develop porosity in OOA processing but not in autoclave processing [9] due to the higher applied pressure.

Kardos developed a criterion for moisture driven bubble growth which is based on the premise that moisture concentration gradients drive evaporation and bubble growth [10]. Resin that has equilibrated with surrounding moist air has shown to have a concentration of dissolved moisture in the resin $C$ (g/cm³) that is proportional to the square of the relative humidity $RH$ [11]
\[ C = \rho_{\text{resin}} k_1 (RH)^2 = \rho_{\text{resin}} k_1 \left( \frac{p_{\text{H}_2\text{O}}}{p_{\text{H}_2\text{O}}^*} \right)^2 \]  

\( \rho_{\text{resin}} \) is the resin density (g/cm\(^3\)), \( k_1 \) is an experimentally determined fitting parameter = 0.00558 (at room temperature), \( p_{\text{H}_2\text{O}} \) is the partial pressure of moisture vapour in the surrounding humid air (atm) and \( p_{\text{H}_2\text{O}}^* \) is the equilibrium partial pressure of moisture vapour (atm). The relative humidity \( RH \) is defined as the ratio of the partial pressure of moisture in the surrounding air divided by the equilibrium partial pressure. This relationship was found to agree very well with the measured concentration of moisture in the MTM 45-1 resin used in the current study [6]. At equilibrium, the resin at any resin/air interface will have the same moisture concentration \( C \) as in the bulk resin. However, if the relative humidity \( RH \) of the air decreases by increasing the temperature, there will be a higher concentration of moisture in the bulk of the resin than at the resin/air interface which will promote diffusion, void growth and evaporation of moisture at the resin/air interface. This is shown schematically in Figure 10.

**Figure 10.** Schematic of moisture driven bubble growth.

Growth of the resin void will occur if bulk moisture diffuses to the resin void interface, requiring \( C_{\text{H}_2\text{O},B} < C_{\text{H}_2\text{O},\infty} \), which using eq. (11) can be expressed

\[ p_{\text{H}_2\text{O}} < p_{\text{H}_2\text{O}}^*(RH_0) \]  

where \( RH_0 \) is the relative humidity of the moist air that the resin was equilibrated with. Ignoring surface tension effects, assuming that \( P_{\text{Resin}} \approx P_{\text{H}_2\text{O}} \) at equilibrium, and that the equilibrium vapour pressure is described by the Clausius-Clapeyron relation we get the following criterion for moisture driven bubble growth

\[ P_{\text{Resin}} < P_0 \exp \left( \frac{\Delta H_{\text{Vap}}}{RT_0} \right) \exp \left( \frac{\Delta H_{\text{Vap}}}{RT} \right) (RH_0) \]

\( \Delta H_{\text{Vap}} \) is the enthalpy of vapourization, \( P_0 \) and \( T_0 \) are the Clausius-Clapeyron reference pressure and temperature respectively. Inserting moisture values for the constants (Table 2) and equating the sides yields the critical resin pressure below which moisture can cause resin voids to grow by diffusion and vapourization [10].

\[ P_{R,\text{Critical}} = 4962 \exp \left( -4892 \frac{\Delta H_{\text{Vap}}}{T} \right) (RH_0) \]  

---

37th Risø International Symposium on Materials Science IOP Publishing
IOP Conf. Series: Materials Science and Engineering 139 (2016) 012002 doi:10.1088/1757-899X/139/1/012002
Table 2. Values used in the Clausius-Clapeyron relation for calculating the equilibrium vapour pressure of water, eq. (13).

| Variable   | Value     |
|------------|-----------|
| $\Delta H_{\text{vap}}/R$ | 4892 K |
| $P_0$      | 1 atm     |
| $T_0$      | 373 K     |

In out of autoclave processing, the maximum possible resin pressure is 1 atm but the resin pressure is often slightly lower than that because some of the applied pressure is carried by the fibre bed [12]. If we set $P_{R, \text{critical}}$ to 1 atm in eq. (14) and solve for the temperature for different relative humidity levels $RH_0$, we can calculate the maximum temperature we can expose the resin to, prior to gelation, before we run into problems with moisture driven bubble growth, see Figure 11.

![Figure 11](image)

Figure 11. Temperature at which the critical resin pressure for moisture driven bubble growth equals 1 atmosphere for the MTM 45-1 resin system.

Based on Figure 11, we see that for resins equilibrated with air at a $RH_0$ of less than about 10% we can heat up and gel the material directly to 180°C without causing moisture driven bubble growth. For resins equilibrated at higher relative humidity levels, the figure suggests that we need to put an intermediate hold in the cure cycle, at which the material gels before it is heated up to 180°C for final cure. Using the cure kinetics for the MTM 45-1 resin we can calculate how long these holds have to be [13]. Figures 12-14 present cure cycles for different relative humidity levels that were been designed using the RAVEN composite process simulation software [14] to ensure that moisture driven bubble
growth does not occur until the resin gels. Gelation for this resin is assumed to occur at a degree of cure of 50% in the presented analysis.

Figure 12. Default cure cycle for $R_{H0} = 10\%$ or less. The critical temperature from Figure 11 is 180°C and there is no need for an intermediate hold.

Figure 13. Cure cycle for $R_{H0} = 25\%$. The critical temperature from Figure 11 is 144°C and an intermediate hold for 40 mins at 144°C has been added to gel the resin before further heating is performed.
Figure 14. Cure cycle for $RH_0 = 50\%$. The critical temperature from Figure 11 is 121°C and an intermediate at 120°C hold for 140 mins has been added to gel the resin before further heating is performed.

Figures 12-14 show cure cycles that are designed to suppress moisture driven bubble growth for the MTM 45-1 based on the Kardos criterion and the assumption that the resin pressure can be maintained at 1 atmosphere during cure. In all three cases the temperature of the intermediate hold is based on the Kardos criterion, Figure 11. The length of the hold is based on the cure kinetics of the resin [13] so that the resin gels and transforms from a liquid to a solid at the hold temperature. The length of the final hold at 180°C was designed using the RAVEN software to ensure that the resin is fully cured before cool-down. The final degrees of cure for the three cure cycles are 0.96, 0.95 and 0.95, which ensures fully developed physical and mechanical properties of the resin.

2.3 Resin infiltration

Once sufficient amount of trapped gas has been removed according to the principles outlined in section 2.1 and moisture driven bubble growth has been prevented using the methods shown in section 2.2 we need to ensure that the resin pressure, resin viscosity and time are sufficient to fill any evacuated void space within fibre tows or between plies. This is typically not difficult to achieve but approximate analysis for this has been presented elsewhere [15] and will not be discussed in detail here.

3. Discussion

The proposed three step approach to achieve low porosity in OOA prepreg processing: 1. Vacuum evacuation of trapped air; 2. Keep volatiles in solution; 3. Resin infiltration of evacuated void space does not account for all void sources and sinks. It assumes that there are no additional void sources such as bag or tool leaks. It also ignores void sinks such as drying of the resin: diffusion, evaporation and moisture removal through the engineered vacuum channels during room temperature debulk and heat up; and bubble mobility: movement of bubbles through the resin and removal through the vacuum channels [16]. However, provided that there are no bag and tool leaks, the presented approach should be conservative as the ignored voids sinks will only further reduce the porosity.
Individual mechanisms for porosity formation have been addressed in the past but it is important to view this as a systems problem with multiple sources and sinks, establish the physics for the individual mechanisms and link them together so that comprehensive porosity predictions on real structures and processes can be performed. By taking a comprehensive science based approach, we can improve the design of our processes and achieve better producibility.

In the introduction, the notion of a variable outcome for industrial processes, such as the level of porosity, was introduced (Fig 1). The science base presented here is deterministic, for example eq. (9) describing vacuum evacuation of trapped air and eq. (14) describing the resin pressure required to keep moisture in solution as a function of temperature and relative humidity. With appropriate material constants, these equations can guide us in determining appropriate nominal process conditions to achieve acceptable mean porosity levels. By measuring or estimating the variability in material constants and process variables we can also get a sense of the expected variability in the process outcome which is essential to achieve low re-work and scrap rates.

Figure 2 presented a system’s view of a composite factory consisting of equipment, tooling & consumables, part, materials & processes. We can now relate the developed science base back to these objects so that we better understand how they affect the process outcome. For example, the parameters that govern the minimum required debulk time in eq. (9) can be related to the different factory objects. Equipment: vacuum pressure $p_V$; Tooling & consumables: presence of vacuum leaks; Part: length $L$; Materials & Processes: initial porosity $\phi$, permeability $K$, initial pressure $p_0$, air viscosity $\mu$. By establishing these relationships, we can make better decisions regarding the best corrective actions for a process that produces parts outside engineering specifications (e.g. process B in Fig. 1). For example, we can quantify the return on investment of a high performing vacuum system (lower $p_V$) on the required minimum debulk time and expected porosity level.

Acknowledgments
We would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for their financial support of this research. We would also like to acknowledge current and past colleagues at The University of British Columbia as well as our industrial collaborators, particularly Michael Thompson at Boeing Research and Technology for sharing his vast knowledge in this area.

References
[1] National Defense Industrial Association 2011 21st Century Manufacturing Modeling & Simulation Research and Investment Needs.
[2] Fabris J, Fernlund G, Poursartip A 2016. Introducing a knowledge framework to integrate composites manufacturing science and industrial practice. In preparation.
[3] Mobuchon C, Keulen C, Hsiao K, Fernlund G, Poursartip A 2014. Development of a structured approach to porosity management in composites manufacturing. SAMPE Technical Conference, Seattle, US.
[4] Ridgard C 2009. Out of Autoclave Composite Technology for Aerospace, Defense and Space Structures. SAMPE Technical Conference, Baltimore, US.
[5] MTM45-1 Matrix Resin Product Data Sheet, Advanced Composites Group (ACG Inc.), Vol. PDS1104/09.06/4.
[6] Wells J 2016. Behaviour of resin voids in out-of-autoclave prepreg processing. MASc Thesis The University of British Columbia, Canada.
[7] Farhang L 2014. Void Evolution during Processing of Out-of-Autoclave Prepreg Laminates. Ph.D. Thesis The University of British Columbia, Canada.
[8] Campbell FC. 2004. Manufacturing Processes for Advanced Composites. Elsevier, New York.
[9] Grunenfelder LK, Nut SR 2010. Void Formation in Composite Prepregs – Effect of Dissolved Moisture. Composites Science and Technology, 70, 2304-2309.
[10] Kardos JL 2000. Void Growth and Dissolution, in Processing of Composites, Edited by R.S. Dave and A.C. Loos, Hanser Publishers, Munich, 182-206.
[11] Brand RA, Brown GG, McKague EL 1984. Processing Science of Epoxy Resin Composites. Materials Laboratory, Air Force Wright Aeronautical Laboratories.
[12] Roy M, Kay J, Fernlund G, Poursartip A 2015. Porosity in Configured Structures. SAMPE Technical Conference, Baltimore, US.
[13] Shahkarami A. VanEee D, Poursartip A 2009. Material Characterization for Processing: ACG MTM45-1 Material Model Development. NCAMP Final Project Wrap-Up.
[14] Convergent Manufacturing Technologies. www.convergent.ca
[15] Centea T, Hubert P 2012. Modelling the effect of material properties and process parameters on tow impregnation in out-of-autoclave prepregs. Composites Part A 43 9 1505–1513
[16] Gangloff Jr, JJ, Hwang WR, Advani SG 2014. Characterization of Bubble Mobility in Channel Flow with Fibrous Porous Media Walls. International Journal of Multiphase Flow 60 76-86.