Numerical Study of the Effect of Processing Parameters on Porosity

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ABSTRACT

Entrapped gas and incomplete resin infiltration are two major sources of porosity in composites processing. The underlying mechanisms, gas and resin transport, are simultaneously active during processing, which complicates an analytical approach to optimize the manufacturing process to reduce porosity. This motivated the current study to develop an explicitly-coupled gas/resin transport model. The model is used in a parametric study to demonstrate how to optimize the cure cycle and reduce porosity induced by entrapped air and incomplete resin infiltration.

KEYWORDS: *Porosity; Numerical analysis; Transport phenomena*

1 INTRODUCTION

Partially impregnated prepregs are commonly used in the composites industry to manufacture high-performance parts. In these prepregs, resin is placed on the top and bottom of the fiberbed, leaving an un-impregnated dry region in the middle of the prepreg. During processing, dry regions act as interconnected gas transport channels to extract entrapped gas and volatiles during cure. Manufacturing porosity-free parts is only possible if the gas phase inside these transport channels is completely extracted, and the remaining empty space is fully saturated with resin.

Based on the description above, gas transport and resin infiltration are two important mechanisms involved in prepreg-based manufacturing. Since these mechanisms are active simultaneously during processing, a representative transport model should include the interaction and coupling between them. The coupled transport models developed to date tend to be process specific (Helmus et al. 2016; Kourkoutsaki et al. 2015). For example, gas transport can only be predicted in previous work if a vacuum-induced pressure gradient exists. This means that the effect of resin infiltration on gas compression and gas transport through transport channels cannot be predicted with these models. This complicates porosity prediction in processes where vacuum pressure is substituted with increased ambient pressure, or in the case of resin infiltration into regions with entrapped gas.

To address these limitations, a generalized transport model is required that can capture the reciprocal interaction between gas and resin transport during processing. For this purpose, an explicitly-coupled model is developed in the present study. The model is based on volume sharing between resin and gas in the Representative Control Volume (RVE), Figure 1. Numerical test cases are presented to showcase the developed model's application in optimizing process parameters to minimize porosity. It is worth noting that porosity is defined as the volume fraction of the fiberbed that is not occupied by resin.

2 MODEL DEVELOPMENT

The RVE used in the present model development, Figure 1, includes in-plane gas transport and through-thickness resin transport. In-plane resin transport is neglected as it does not have a direct effect on resin interaction with the gas phase at the flow-front. Further, through-thickness gas transport is negligible due to the resin-rich layer on prepreg surface. The continuity equation for the gas phase is:

$$\begin{gathered}\frac{\partial}{\partial t}(\rho_g\varphi)+\nabla\cdot(\rho_g\varphi\boldsymbol{v_g})=\dot{m}\\ \boldsymbol{v_g}:(v_{g,x},v_{g,y})\end{gathered} \tag{1}$$

here, ρ_g is density and $\boldsymbol{v_g}$ is the velocity vector of the gas. φ represents fiberbed porosity. $\dot{m}$ is a source term for volatile release into the fiberbed. This term is set to zero in the present work, assuming a low-volatile resin system (Mohseni at al., 2018). Resin infiltration changes the pathways available for gas transport, i.e. fiberbed porosity. Therefore, the porosity term in Equation 1 is dependent on resin infiltration. Furthermore, assuming that a Darcy flow model explains both resin and gas transport in the fiberbed (Kay 2017), Equation 1 becomes:

$$\begin{cases}\varphi\dfrac{\partial P_g}{\partial t}=\dfrac{K_x}{\mu_g}\dfrac{\partial}{\partial x}\left(\left(1+\dfrac{b}{P_g}\right)P_g\dfrac{\partial P_g}{\partial x}\right)-P_g\dfrac{d\varphi}{dt}\\[2ex] \dfrac{d\varphi}{dt}=-\dfrac{K_z}{h^2\mu_r(1-V_f)}\dfrac{P_a-P_g}{(1-\varphi)}\end{cases} \tag{2}$$

In this equation, K_x is the in-plane permeability of the fiberbed for gas transport, and K_z the through-thickness fiberbed permeability for resin transport. μ_r and μ_g are resin and gas viscosity, respectively. b is the Klinkenberg parameter (Kay 2017), V_f fiber volume fraction, P_a ambient pressure, h uncured prepreg thickness, and P_g gas pressure. The boundary conditions for in-plane gas transport is set to $P_g=P_v$ at the edge of the laminate connected to vacuum, and $\partial P_g/\partial x=0$ at the far, closed edge.

The non-dimensional form of Equation 2 is implemented using the finite volume method and the open source DevC++ 5.11 compiler. The material properties used in this paper, Table 1, are related to a partially-impregnated woven prepreg, MTM45-1/5HS CF2426A by Cytec Solvay (ACG 2012). Resin viscosity variation with time and temperature is calculated by the RAVEN software (RAVEN V3.7.4 n.d.), while other properties remain constant throughout simulation.

3 RESULTS AND DISCUSSION

For the case studies in the present work, A 2-meter long laminate is used. A typical cure cycle is shown in Figure 2(a) that includes a 4-hour room-temperature debulk before cure, a temperature ramp from 25˚C to 120˚C at 1.5 C/min, and a 4-hour hold at 120˚C before cool-down. Figure 2(b) shows the corresponding porosity evolution throughout the length of the laminate as a function of time, with vacuum pressure (P_v) set to 0 atm, and ambient pressure (P_a) equal to 1 atm. This graph shows that a gradient in porosity level exists with higher porosity at regions close to the edge connected to vacuum. This is caused by the internal gas pressure gradient through length of the laminate that results in a resin infiltration gradient (Kay 2017). Considering the porosity gradient, results reported in the rest of the paper represent the average porosity through length of the laminate. The final porosity in the case reported in Figure 2 is about 7%. Furthermore, results show that the vacuum edge of the laminate closes during processing, as demonstrated by zero porosity level, which means further gas transport from this region is not possible. However, resin

Table 1 Material properties and parameters used in numerical test cases of coupled gas/resin transport model.

Parameter	Nomenclature	Value
Uncured prepreg thickness	h	0.1 mm
Initial prepreg porosity	φ_0	19.7%
Through-thickness permeability	K_z	1.0E-16 m^2
In-plane permeability	K_x	3.2E-15 m^2
Fiber volume fraction	V_f	54%
Klinkenberg parameter	b	13 KPa
Gas (air) viscosity	μ_g	1.8E-05 PaS

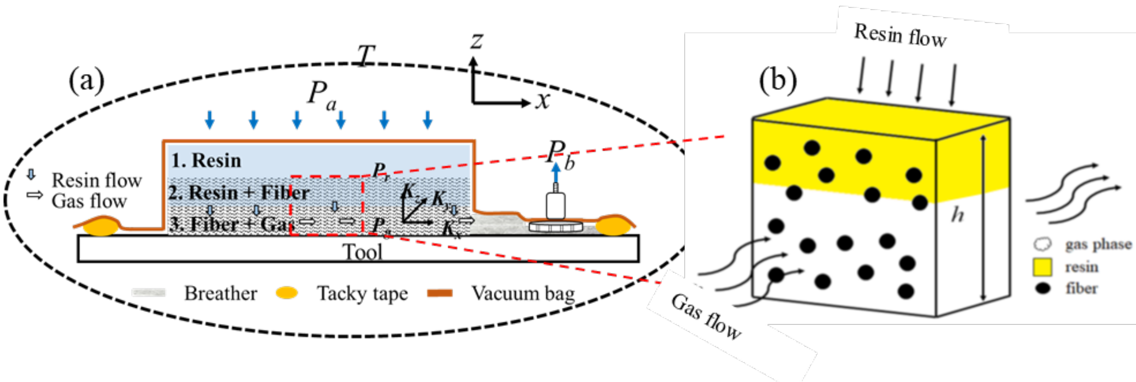

Figure 1: (a) schematic of the partially-impregnated prepreg processing parameters, and (b) the corresponding RVE considered for coupled gas/resin transport modeling.

infiltration and porosity reduction continue until either the entrapped gas inside is compressed to reach equilibrium with the ambient pressure, or the resin gels. In the present case, the latter situation stops further porosity reduction.

3.1 Ambient pressure (P_a) effect

In an out-of-autoclave process, the ambient pressure is equal to the atmospheric pressure, i.e. 1 atm, similar to the case in Figure 2. With the use of an autoclave, this ambient pressure can be increased to enhance resin infiltration and gas compression that consequently results in reduced porosity. Figure 3 shows the predicted porosity variation with ambient pressure. Results show that to reach a porosity level of 2%, the ambient pressure should be increased to 4 atm. A 2-meter laminate used in this test case is equivalent to a 4-meter laminate processed using the typical manufacturer recommended bagging system (Advanced Composites Group (ACG) 2012). Increased ambient pressure inside an autoclave is expected for low-porosity processing of such a large laminate. This may change with the application of a different cure cycle as discussed in the following sections. It is worth noting that the rate of porosity reduction with increasing ambient pressure, decreases at low-porosity regions.

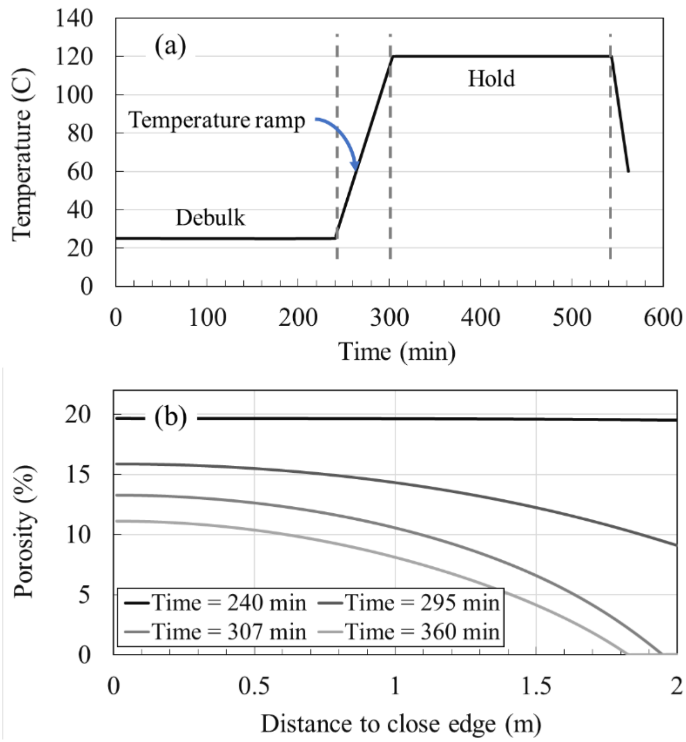

Figure 2: (a) A typical cure cycle and (b) the corresponding porosity contour through length of the laminate at different processing times; P_a = 1.0 atm, and P_v = 0.0 atm.

3.2 Debulk time effect

Results for porosity variation with room-temperature debulk time, Figure 4, show that debulk step has significant effect on final porosity. An extended debulk time further reduces the internal gas pressure prior to cure. Therefore, when temperature ramp starts (Figure 2), the pressure gradient for resin infiltration is higher. This leads to more resin infiltration throughout the laminate and lower porosity. In the case that the debulk step is omitted from the processing cycle, i.e. debulk time = 0 hour, the final porosity is about 13.0%. Porosity reduces to 1.5% with the application of a long, 24-hour debulk, which means that manufacturing a 2-meter laminate with acceptable porosity using out-of-autoclave process (P_a = 1.0 atm, P_v = 0.0 atm) is possible given adequate debulk time.

3.3 Heating rate

During debulk, the resin viscosity is high, therefore resin infiltration, hence porosity reduction is negligible, Figure 2(b). However, when the temperature ramp starts, resin viscosity drops and facilitates infiltration into the fiberbed. Viscosity evolution and resin infiltration rate can be controlled by cure cycle variation, for example changing the heating rate. This is investigated with the results shown in Figure 5 for porosity variation with heating rate at different ambient pressures. It is shown that when P_a = 1.0 atm, i.e. out-of-autoclave processing, increasing the heating rate causes a porosity increase. However, from the results at higher ambient pressures, i.e. autoclave processing with P_a = 2.0 and 3.0 atm, it is shown that porosity variation is less sensitive to heating rate in these cases. A takeaway from the present numerical case study is that debulk time and ambient pressure are more influential than heating rate, with regards to porosity induced by entrapped air/incomplete resin infiltration.

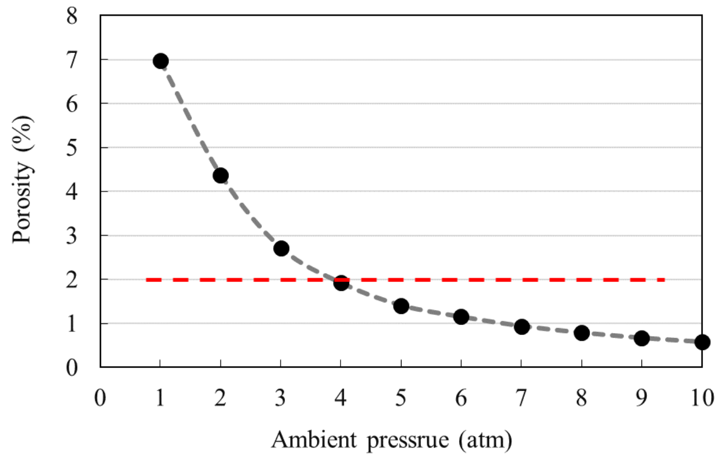

Figure 3: Porosity variation with ambient pressure (P_a); the red line highlights an acceptable porosity level of 2%; P_a = variable, and P_v = 0.0 atm.

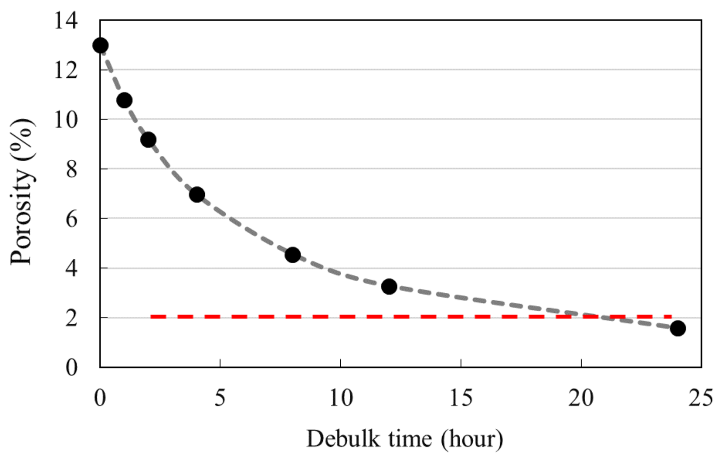

Figure 4: Porosity variation with debulk time; the red line highlights an acceptable porosity level of 2%; P_a = 1.0 atm, and P_v = 0.0 atm.

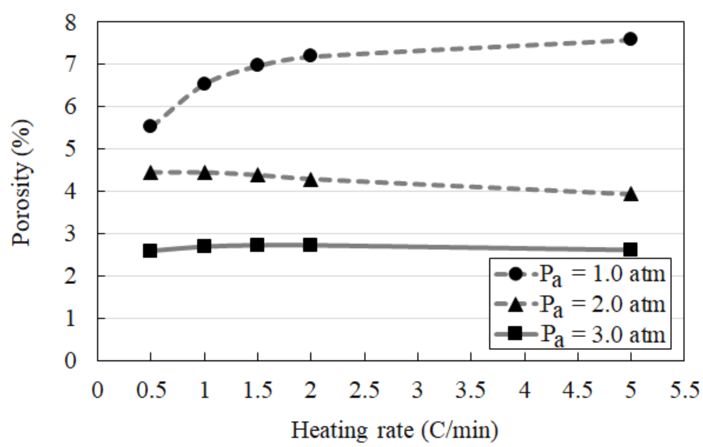

Figure 5: Porosity variation with heating rate and ambient pressure (P_a).

4 CONCLUSION

In this paper, a fully-coupled gas/resin transport model is introduced that enables porosity estimation as a function of processing parameters for prepreg-based manufacturing. The model is built on the concept of volume-sharing between gas and resin in a representative control volume. Different tests are discussed to showcase the developed model's applicability in determining optimal processing parameters.

It is shown that manufacturing a large four meter part using the MTM45-1 prepreg, requires special attentions to reduce porosity below an acceptable 2% level. For this purpose, the variation of ambient pressure and debulk time turn out to be more effective than heating rate. Furthermore, it can be concluded that the effect of processing parameters should be investigated simultaneously and the developed coupled transport model provides a practical mean to this end.

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