



Effects of Debulk Temperature on Air Evacuation during Vacuum Bag-only Prepreg Processing

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Abstract: Air removal prior to cure is critical for limiting porosity during vacuum bag-only (VBO) processing of prepregs. In this study, the effects of pre-cure dwell temperature (debulk) on air evacuation were investigated for both plain weave (PW) and unidirectional (UD) prepregs. *In situ* observations revealed that increasing dwell temperature promoted inter-ply air evacuation (by as much as 2x for UD prepregs). Through-thickness gas permeability increased with increasing temperature and decreased with increasing number of plies. The decrease in in-plane permeability during heated debulk was attributed to increased tow impregnation. The findings provide guidelines for cure cycle optimization. Heated debulk enhanced air evacuation in PW laminates, particularly as laminate width/thickness ratios exceed a threshold value. However, warm debulks were less effective, particularly for thicker laminates (>8 plies).

Key words: Vacuum Bag-Only (VBO) prepreg; heated debulk; permeability; air evacuation

1. INTRODUCTION

Vacuum bag-only (VBO) processing of prepreg offers advantages over conventional autoclave processing, including reduction of capital and operational costs, greater energy efficiency, increased throughput, and relaxation of size limits¹. However, the maximum pressure in VBO processing is limited to 0.1 MPa (1 atm), unlike autoclaves, where the pressure can be 0.5

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MPa – 0.6 MPa or greater. Consequently, resin pressure and vacuum can be insufficient to collapse/remove entrapped air bubbles, and these can remain after gelation, resulting in voids detrimental to mechanical properties ^{2,3}. Thus, air evacuation prior to gelation is critical to achieve low porosity in laminates produced by VBO processing of prepregs.

VBO prepregs are only partially impregnated by design to facilitate air evacuation, and typically feature dry fiber tows sandwiched between resin films. Because of this format, air is initially present within tows (intra-tow dry fiber regions), as well as between plies (inter-ply resin-rich regions) ⁴. Dry fiber regions provide high-permeability pathways for gas transport *within the plane of the plies*, promoting air evacuation via edge breathing ⁵. However, when air is trapped between plies during lay-up, air bubbles must migrate in the through-thickness direction (for a short distance) to reach in-plane evacuation pathways within the tows ⁶.

In practice, air removal is usually accomplished by a room temperature vacuum hold (debulk), typically hours, before initiating high-temperature cure. While edge-breathing is readily achieved for small and flat laminates, pathways are often occluded in large and/or complex geometries ⁷. For large and/or complex parts, prepreg manufacturers generally recommend debulks for 16 hours or more, which becomes the longest and thus rate-limiting step for VBO production of large parts ⁸. For some common geometric constraints, such as embedded ply drops, edge-breathing can be problematic and/or virtually impossible.

A recent study ⁹ reported that similar quality was achieved in laminates cured using a four-hour debulk at 50°C versus those cured with a 16-hour room temperature debulk prior to heated cures. They concluded that debulking at an intermediate temperature (50°C – 60°C), a so-called “super-ambient” dwell (SAD), reduced the cure cycle time without compromising laminate quality. However, the mechanisms operative in super-ambient dwell were not provided.



The increase in debulk temperature has a complex effect on air removal. On one hand, the decrease in resin viscosity increases resin flow, which generally enhances air removal. On the other hand, increased resin infiltration can also occlude pathways for air evacuation. The interplay between these factors introduces added complexity to the process. Thus, a clear understanding of the effects of pre-cure dwell temperature on air evacuation must be acquired to establish science-based guidelines for cure cycle optimization.

Permeability describes gas (and liquid) transport through a porous medium, and is thus an important process variable affecting air evacuation. The intrinsic permeability of a material is determined solely by solid matrix, and is independent of the fluid properties and flow mechanisms, while the effective gas permeability of composites is affected by both material and process parameters¹⁰. In-plane permeability of prepregs has been studied extensively^{11–14}, albeit mostly at room temperature. However, the initial in-plane permeability values for typical VBO prepregs are on the order of 10^{-14} m^2 ^{11,12}. In contrast, the through-thickness permeability is generally 3–4 orders of magnitude less than the in-plane permeability^{10,12}. Kratz, et al.¹⁰ and Tavares, et al.¹⁵ both investigated the through-thickness permeability during cure and reported an increase in through-thickness permeability at high temperature due to the decrease in resin viscosity. However, no observations have been reported on the effects of debulk temperature on air evacuation, and no comparison is available to identify which air evacuation pathway (in-plane or transverse) is more effective during this period.

In this study, the removal of inter-ply air during heated debulk was investigated using an *in situ* monitoring method (reported previously)¹⁶. The effective gas permeability of prepregs in both in-plane and through-thickness directions was investigated to understand the effects of temperature on gas transport. Tow impregnation during heated debulk was predicted using a model developed



by Centea et al ¹⁷. The relationships between gas permeability, resin properties, and tow impregnation as functions of time and temperature are established. Cure optimization guidelines are provided by a comparison of evacuation times at different debulk conditions.

2. EXPERIMENTAL DETAILS

2.1. Materials

The prepregs selected for this study featured a toughened epoxy resin (CYCOM 5320-1, Solvay) and two carbon fiber beds: IM7/12K unidirectional (UD) tape with fiber areal weight of 145 g/m² and a resin content of 33% by weight, and a T650-35 3K plain weave (PW) with areal weight 196 g/m² and a resin content of 36% by weight ^{5,6}. Neat resin film (CYCOM 5320-1) was also used, with areal weight ~ 92 g/m² and thickness ~50 μm.

2.2. *In Situ* Monitoring Method ^{6,16}

To observe inter-ply air evacuation and entrapment during debulk, a custom-built experimental setup afforded *in situ* visual observations of in-plane bubble motion. A perforated resin film with controlled pore size and distribution was prepared and laid up against the glass window of an oven, followed by four layers of prepreg plies and standard consumables, shown in Fig. 1. The resin film intentionally introduced air into the lay-up, replicating the condition of air bubbles that are inevitably trapped between prepreg plies during lay-up.

The perforated resin film was fabricated by punching holes 2 mm apart using a coring tool with diameter 0.25 mm. Prepreg plies were cut to 127 mm × 127 mm, while the perforated resin film was 38 × 38 mm. Each laminate consisted of 4 prepreg plies and was cured in a programmable air-circulating oven (Thermal Products Solution Blue M). A 4-hour debulk at room temperature and 60°C were performed for both PW and UD laminates. Temperature was measured



by two thermocouples on the glass plate side throughout the cure cycle. Time-lapse videos were recorded throughout the cure using a portable microscope (Dino-Lite Premier 2 Digital Microscope) with a magnification of 20.

Void content of the resin-rich prepreg surface as a function of time was measured *in situ* for each test panel. Six representative images were selected from the time-lapse video for subsequent analysis for each test. Regions where the prepreg was not in contact with the perforated resin film were considered as voids. Voids were manually selected and converted to binary, and void content and size were calculated using image analysis software (ImageJ). Void content was determined as the ratio of the area of voids to the total area.

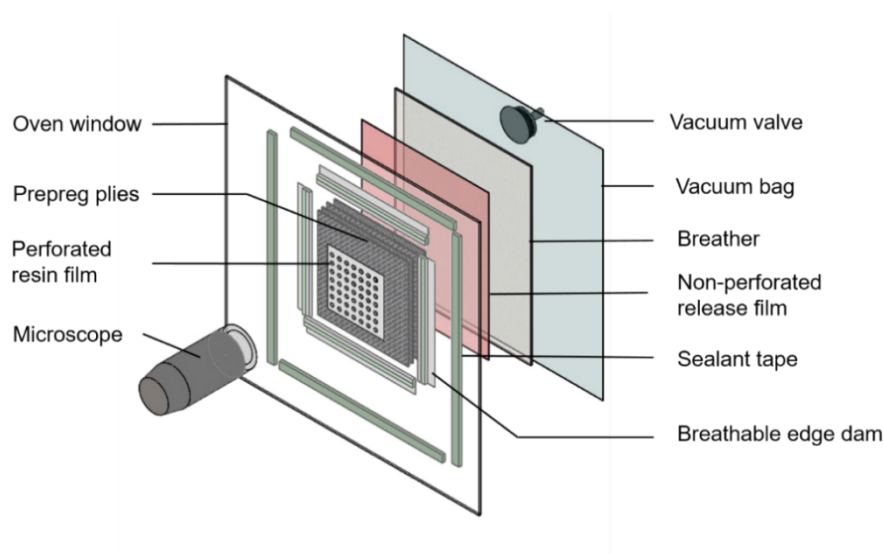


Fig. 1 Schematic of in situ monitoring method set-up

2.3. Permeability Measurements

Gas flow can be used to characterize permeability of a porous medium. For laminar flow, the relationship between the flow rate and permeability is commonly expressed by 1-D Darcy's law^{10,12}:

$$Q = -\frac{KA}{\mu} \frac{dP}{dx} \quad (1)$$

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where K is the permeability scalar in the flow direction, A is the cross-sectional area of the sample, P is pressure, x is distance, and μ is gas viscosity.

2.3.1 In-Plane Permeability Test

In-plane permeability was measured using a steady-state air flow test. According to Eq. (1), gas permeability can be measured by applying a constant flow rate of fluid through a porous medium and measuring the pressure drop across the length of the sample. For compressible gas, assuming the gas follows the ideal gas law, the flow rate at constant temperature can be described as ¹⁸:

$$Q = - \frac{KA}{2L\mu} \frac{P_2^2 - P_1^2}{P_1} \quad (2)$$

where P_1 is the pressure at the vent side, P_2 is the pressure at the vacuum side, and L is the sample length.

The experimental set-up is shown in Fig. 2 based on the work by Arafath et al. ^{11,12}. The laminate was bagged with three isolated compartments. The right compartment (vacuum side) was used to apply vacuum to the laminate, while the left compartment (vent side) was connected to a mass flow rate controller (MC-10SCCM, Alicat Scientific) to allow air flow into the laminate. The center compartment contained the laminate, which was sealed on all sides with sealant tape, allowing flow only in the in-plane direction. In this way, by imposing a known volumetric flow rate using the flow rate controller and measuring the pressure on both sides, permeability was calculated using Eq. (2).

During the pre-cure heated dwell, resin viscosity drops, and resin gradually infiltrates the dry fiber tows. Consequently, a steady state flow cannot be achieved, hampering measurement of permeability. Thus, rather than attempting to measure the in-plane permeability during dwell,

laminates were first partially processed to different degrees of impregnation according to the tow impregnation model developed by Centea et al.¹⁷, then cooled to room temperature at each point of interest to avoid further resin flow. Permeability measurements were then conducted on such laminates at room temperature. The length and width of samples were $L = 50.8$ mm and $W = 101.6$ mm, while the thickness of each sample was measured before each permeability test using a micrometer. For UD preregs, each sample consisted of 12 plies of prepreg stacked $[0]_{12}$, while for PW preregs, each sample consisted of 8 plies stacked $[0/90]_{4s}$. To obtain an average effective permeability value, three samples (replicates) were measured for each degree of impregnation with a minimum of three flow rate trials per sample.

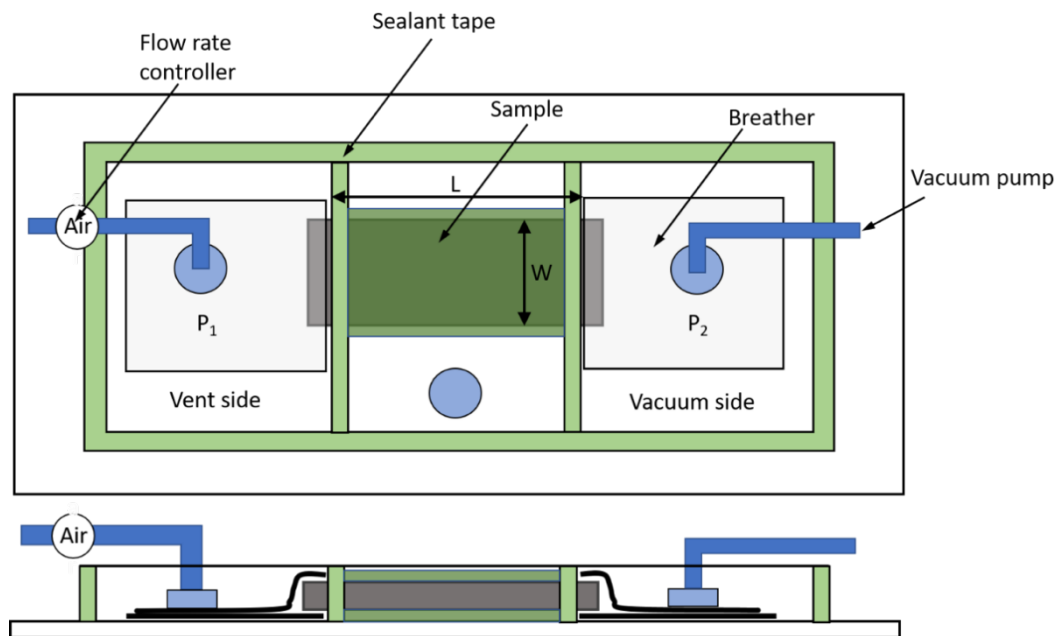


Fig. 2 Schematic of in-plane permeability test set-up

2.3.2 Through-thickness Permeability Test

Through-thickness permeability was measured using a “falling pressure” method, which is frequently used in cases of low gas permeability where the steady-state flow test cannot be applied.

A custom test fixture, shown schematically in Fig. 3, was used for the experiments based on the



work of Tavares et al.^{10,15}. A reservoir with a known volume was added to the set-up. When vacuum is applied, the reservoir pressure will decrease if flow occurs through the porous media, provided no leaks are present within the fixture. Using Eq. (1), the 1-D laminar flow of compressible air through a porous medium at isothermal conditions is described by

$$-\frac{KAP_{Bag}}{L\mu V_{Core}}t = \ln \left[\frac{(P_{Core}(0)+P_{Bag})(P_{Core}(t)-P_{Bag})}{(P_{Core}(0)-P_{Bag})(P_{Core}(t)+P_{Bag})} \right] \quad (3)$$

where P_{Bag} is the pressure at the bag side, P_{Core} is the pressure at the honeycomb core side, t is time, and V_{Core} is the volume of the core ($6.37 \times 10^{-4} \text{ m}^3$), L is the thickness of the laminate, which was measured after each permeability test using a micrometer. The air viscosity μ is a function of temperature, which can be updated using the following equation:

$$\mu = \mu_0 \left(\frac{T_0+C}{T+C} \right) \left(\frac{T}{T_0} \right)^{3/2} \quad (4)$$

where $\mu_0 = 1.83 \times 10^{-5} \text{ Pa s}$ at $T_0 = 293 \text{ K}$, and C is the Sutherland Constant, 117 K. Plotting the right-hand side versus time yields a straight-line plot, the slope of which can be used to determine the effective transverse permeability of the prepreg.

Prepregs were cut to 127 mm \times 127 mm and were placed over the reservoir, supported by aluminum honeycomb core. All four edges of the samples were sealed with sealant tape to prevent in-plane gas flow, and a perforated release film was placed on top of the sample to allow air evacuation only in the through-thickness direction, followed by breather cloth and vacuum bag. Vacuum was drawn in the bag to compact the laminates and create a pressure difference between core and bag. The evolution of pressure in the cavity was monitored over time using a pressure transducer (Omegadyne, Inc) and data acquisition software (LabView, National Instruments). Measurements were recorded for 4-, 8-, 16-, and 24-ply PW laminates and 1-, 2-, 4-, and 8-ply UD



laminates at isothermal temperatures (20°C, 40°C, 50°C, 60°C, and 70°C) for four hours, and temperature was monitored throughout the tests using thermocouples.

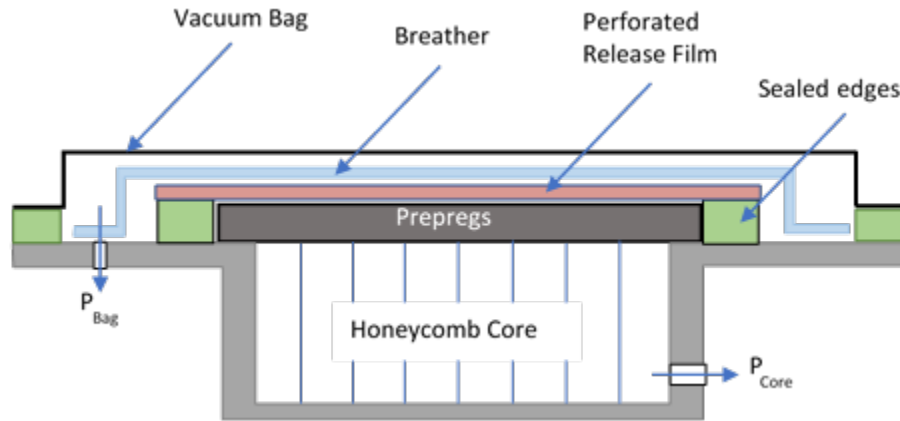


Fig. 3 Schematic of through-thickness permeability test set-up.

2.3.2 Degree of Impregnation

To determine the degree of impregnation for the in-plane permeability samples, a coupon was processed alongside each sample. The coupons were removed from the oven with the samples and quenched to room temperature to prevent further resin flow. The partially cured laminates were then cold-cured in an ammonia environment at room temperature for a week (following the protocol described by Howard¹⁹). Ammonia vapor reacts with epoxy at a low temperature as a curing agent to achieve a hard and stiff structure while preserving the morphology of the laminates at each point of interest⁶. Samples were sectioned at the center, polished, and inspected using a stereo microscope (Keyence VH-Z100R).

3. RESULTS AND DISCUSSION

3.1. Inter-ply Air Evacuation

The effects of debulk temperature on inter-ply air evacuation are shown in Fig. 4. Initially, air was trapped both in the artificial pores and between the perforated resin film and the first



prepreg ply (Fig. 4a white regions). These bubbles were situated primarily in the gaps between the resin film and depressed regions of fabric due to the natural fiber crimp of PW prepreg. Once vacuum was applied, bubbles disappeared rapidly through the pinholes at the intersections of warp and weft tows. After a 4-hour debulk, the inter-ply air was completely evacuated, both at 20°C and at 60°C (Figs. b-c).

In UD prepregs (Fig. 4d), the air naturally trapped between resin film and the first prepreg ply (the white regions) was randomly distributed, but was much less prevalent than in PW laminates. After debulk for 4 hours at room temperature (RT), the white regions decreased slightly in size, while the larger artificial pores did not change in both size and position (Fig. 4e). However, after a 4-hour debulk at 60°C, most naturally trapped air bubbles had disappeared, and some of the artificial air bubbles decreased in size, indicating that debulk at 60°C was more effective in reducing inter-ply porosity in UD prepregs.

Fig. 5a shows void content as a function of time in PW prepreg. The initial void content was ~ 35 % due to the naturally trapped air. Though the air evacuation rate was slightly lower during the RT vacuum hold, in both cases, void content decreased sharply to ~ 0.3% within the first hour. UD prepregs exhibited a lower initial void content of ~ 13%. However, the evacuation of inter-ply air was much slower in UD prepregs. The void content decreased to ~ 6% and ~ 3% after a 4-hour debulk at 20°C and 60°C, respectively.

As mentioned before, inter-ply air bubbles must migrate a short distance to the dry fiber tows to reach evacuation pathways. PW prepregs exhibit large open pores at the intersections of the tow bundles (Fig. 4b circled in red), affording a grid of pathways for efficient evacuation of inter-ply air. In contrast, UD prepregs feature resin film that is more uniformly distributed on the surface, and air can be evacuated only via some resin-starved regions⁶. As debulk temperature



increases, resin viscosity decreases, facilitating resin flow, which promotes air evacuation through those resin-starved regions. However, the larger, artificial air bubbles require further resin flow to allow air bubbles to migrate towards evacuation pathways ⁶.

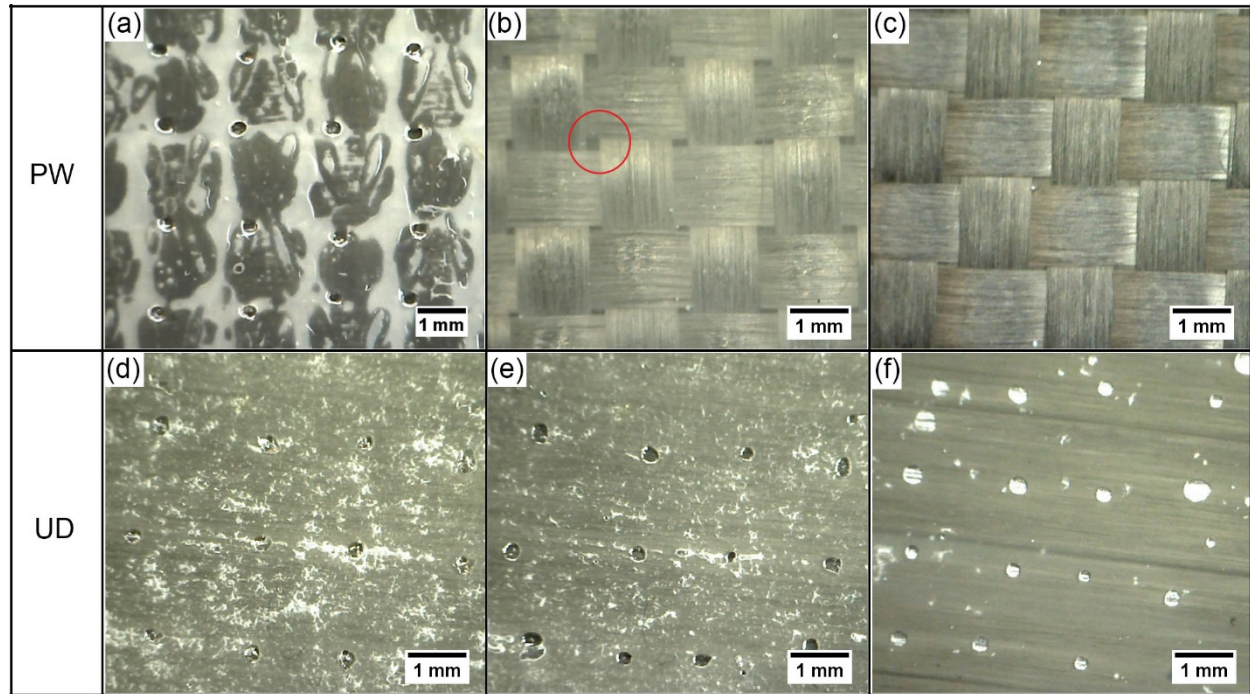


Fig. 4 Void evolution during pre-cure dwell of PW prepregs: (a) initial state, (b) after 4-h RT vacuum hold, (c) after 4-h 60°C vacuum hold; and for pre-cure dwell of UD prepregs: (d) initial state, (e) after 4-h RT vacuum hold, (f) after 4-h 60°C.

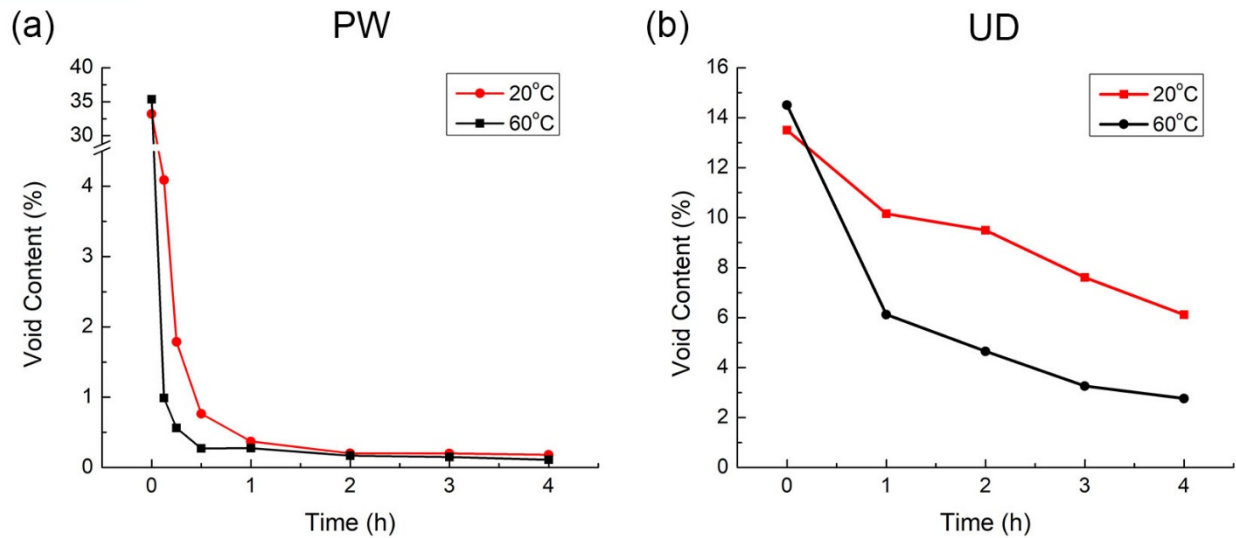


Fig. 5 Void content as a function of time during debulk for (a) PW and (b) UD laminates

3.2. Through-thickness Permeability during Heated Debulk

The effects of debulk temperature and number of plies on the through-thickness permeability of PW and unidirectional laminates are shown in Figs. 6(a-e). These plots show transverse permeability of PW laminates as a function of time at different debulk temperatures. Initially, permeability decreases with increasing ply number. For a 4-ply laminate, the permeability was $\sim 1 \times 10^{-14} \text{ m}^2$, while for a 24-ply laminate, the permeability decreased by ~ 50 times to $\sim 2 \times 10^{-16} \text{ m}^2$. The decrease arises because through-thickness gas flow occurs predominately via open pores at tow bundle intersections (Fig.4b). As ply number increase, these open channels in the laminate do not align, resulting in decreased permeability.

After the 4-hour RT debulk, the transverse permeability decreased by ~ 2 -3 orders of magnitude in all cases (Fig. 6a). The reduction in permeability was attributed to fiber bed compaction, ply nesting, and the redistribution of resin and air pathways¹⁵. When the debulk temperature increased to 40°C, resin viscosity decreased ten-fold (from $6.5 \times 10^4 \text{ Pa}\cdot\text{s}$ to $4.7 \times 10^3 \text{ Pa}\cdot\text{s}$), while the transverse permeability decreased by an order of magnitude in the first hour, then



increased slightly for 4-ply and 8-ply laminates, while for 16-ply and 24-ply laminates, the permeability fluctuated during the remainder of the debulk (Fig. 6b).

As resin viscosity decreases and resin mobility increases, new air pathways can form, provided the gas pressure gradient overcomes the resin resistance. As ply number increases, creating continuous flow channels becomes more difficult, decreasing permeability. Delay time is another indication of this process. Delay time refers to the time between the start of vacuum hold and the onset of the pressure decrease in the honeycomb core ¹⁰. A delay in pressure drop in PW permeability tests was observed only at 40°C. For an 8-ply laminate, the average delay time was ~ 6 minutes, while for a 24-ply laminates, the delay time increased to ~32 minutes.

When resin viscosity decreased to ~ 1500 Pa·s during the 50°C debulk, the permeability of PW prepreg increased slightly for all cases, but continued to decrease with increasing ply number (thickness), as shown in Fig. 6c. However, during 60°C and 70°C dwells, the permeability of 4-, 8-, and 16-ply laminates increased and stabilized at a similar value ($\sim 2 \times 10^{-14} \text{ m}^2$) throughout the dwell. In contrast, the 24-ply laminates exhibited a permeability value one order of magnitude lower. This finding, while somewhat unexpected, can be understood because when resin viscosity is sufficiently low ($< 1000 \text{ Pa}\cdot\text{s}$), the resistance of resin to air flow decreases to a minimum, and when a pressure gradient is present, air evacuation pathways can be easily created. Air permeability is independent of number of plies within a thickness range ($< \sim 4 \text{ mm}$). However, as ply number increases, the driving force for air evacuation (pressure change per thickness) decreases, and air evacuation pathways become more tortuous, causing air permeability eventually to decrease.

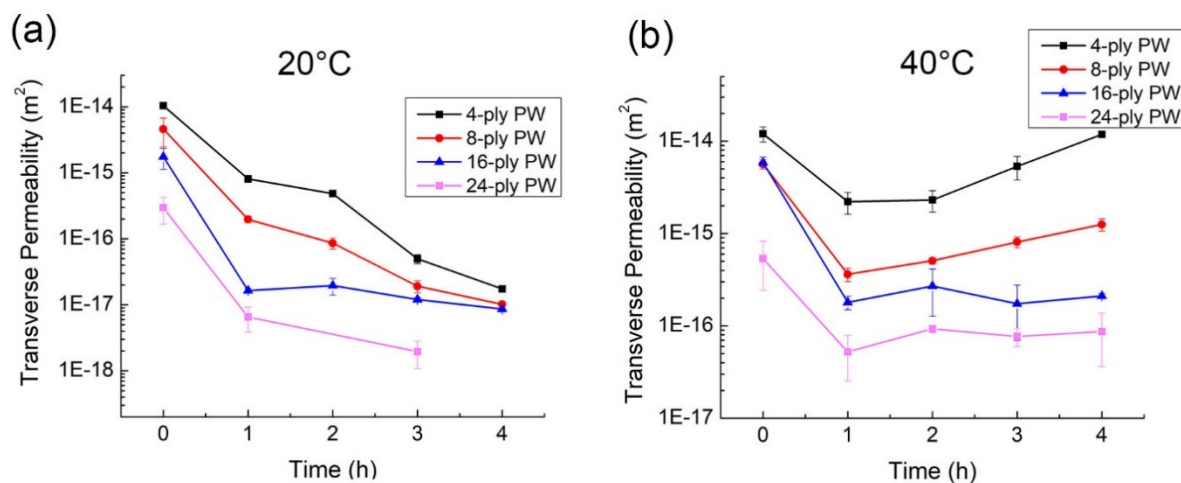
The effects of debulk temperature on transverse permeability of UD prepegs exhibited clear differences from PW prepegs. First, because each pressure decay test required 30 minutes to



several hours for UD laminates due to low permeability, the transverse permeability was plotted as a function of temperature rather than time (Fig. 7). UD laminates exhibited much lower permeability than PW laminates. For a 1-ply laminate, the average permeability at room temperature was $1.1 \times 10^{-17} \text{ m}^2$, ~ 3 orders of magnitude less than that of a 4-ply PW laminate.

As the number of UD plies increased, transverse permeability decreased sharply. For a 2-ply and 4-ply laminate, the initial permeability at room temperature decreased to $4.8\text{E-}19 \text{ m}^2$ and $1.0\text{E-}19 \text{ m}^2$, respectively, two orders of magnitude lower than that of the 1-ply laminate. For an 8-ply laminate, permeability was effectively zero (undetectable). The sharp decrease in gas permeability with increasing number of plies occurred because gas flow was dominated by a few resin-starved areas, and as ply number increased, these air pathways were occluded.

Permeability increased with increasing temperature in all cases. However, as ply number increased, higher debulk temperature was required to achieve an increase in permeability. The air permeability began to increase when the debulk temperature reached 60°C for a 4-ply laminate, while for an 8-ply laminate, no pressure drop was observed until the temperature reached 70°C . The increase in transverse permeability facilitated through-thickness gas evacuation, and contributed to the more efficient inter-ply air evacuation described in Section 3.1.



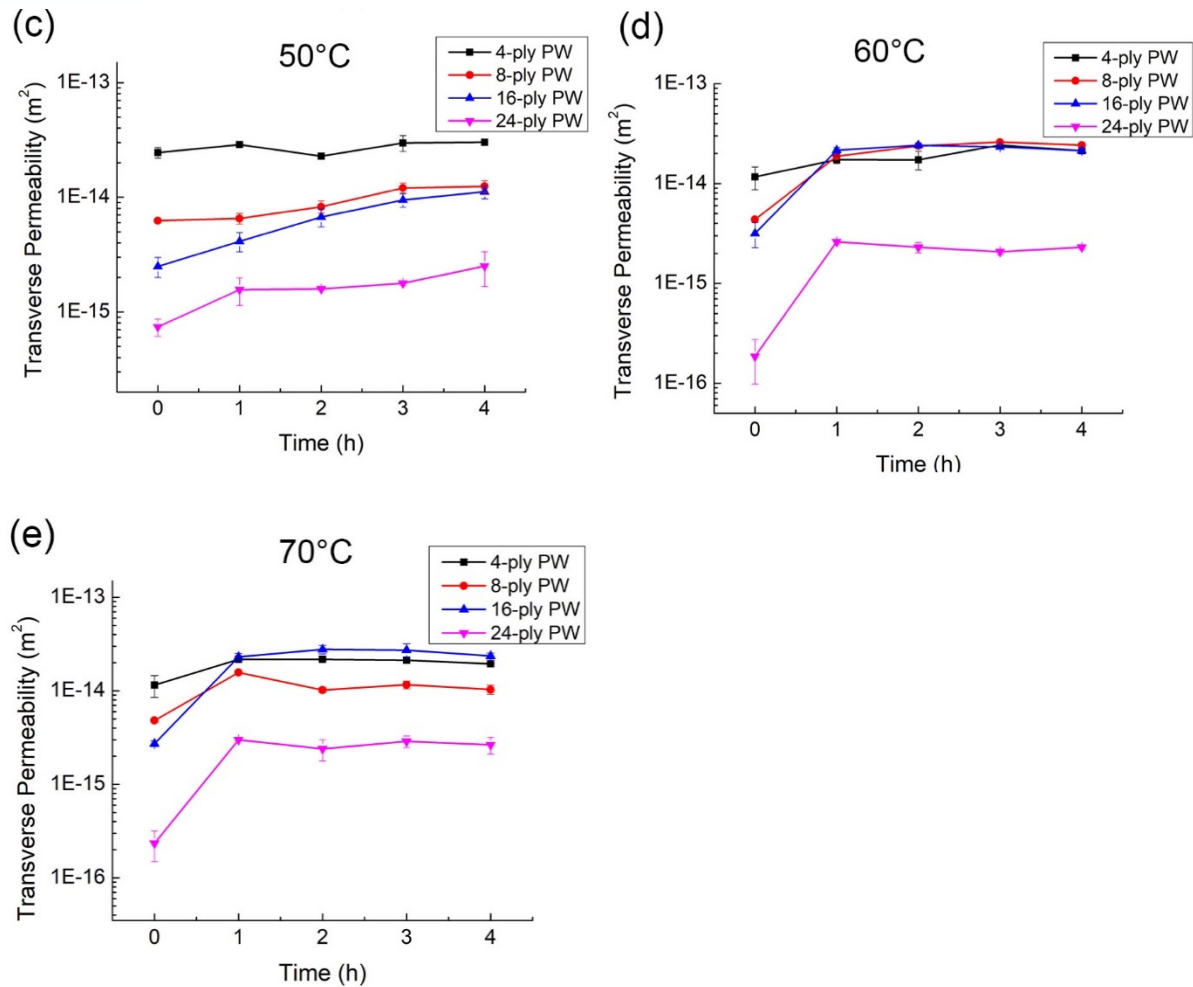


Fig. 6 Transverse permeability as a function of time at (a) room temperature; (b) 40°C; (c) 50°C; (d) 60°C; (e) 70°C for PW laminates;

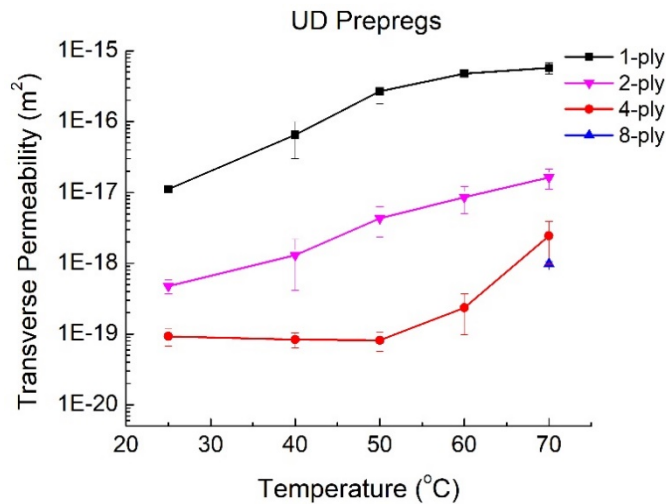


Fig. 7 Transverse permeability as a function of temperature for UD laminates.

3.3. In-plane Permeability during Pre-cure Dwell

Fig. 8a shows the *in-plane* permeability as a function of degree of impregnation (DOI). The initial in-plane permeability of PW laminates ($\sim 6 \times 10^{-14} \text{ m}^2$ with DOI = 0.25) was slightly greater than that of UD laminates ($\sim 2 \times 10^{-14} \text{ m}^2$ with a DOI = 0.3). However, for both PW and UD laminates, in-plane permeability decreased continuously with increasing degree of impregnation, as resin infiltrated and occluded gas evacuation pathways. When the degree of impregnation reached ~ 0.8 , the in-plane permeability decreased to 2.3×10^{-15} and $3.7 \times 10^{-16} \text{ m}^2$, for PW and UD, respectively, ~ 1 -2 orders of magnitude less than the initial state. The permeability of fully impregnated laminates was also measured, although a steady state was not achieved with the lowest flow rate, indicating a permeability less than $1 \times 10^{-18} \text{ m}^2$.

The permeability data were then correlated to predictions of a tow impregnation model developed by Centea et al.^{17,20}. The model was used to generate in-plane permeability during dwell for both PW and UD prepregs (Figs. 8b-c). During the RT vacuum hold, the laminate exhibited the greatest in-plane permeability, which remained constant throughout the debulk.



However, when the debulk temperature increased, permeability decreased with time, as resin gradually infiltrated the dry fiber pathways. The dashed vertical lines mark when the laminate was “impermeable” in the in-plane direction (out of measurement range). When the debulk temperature was $>60^{\circ}\text{C}$, both PW and UD laminates became impermeable within ~ 1 hour.

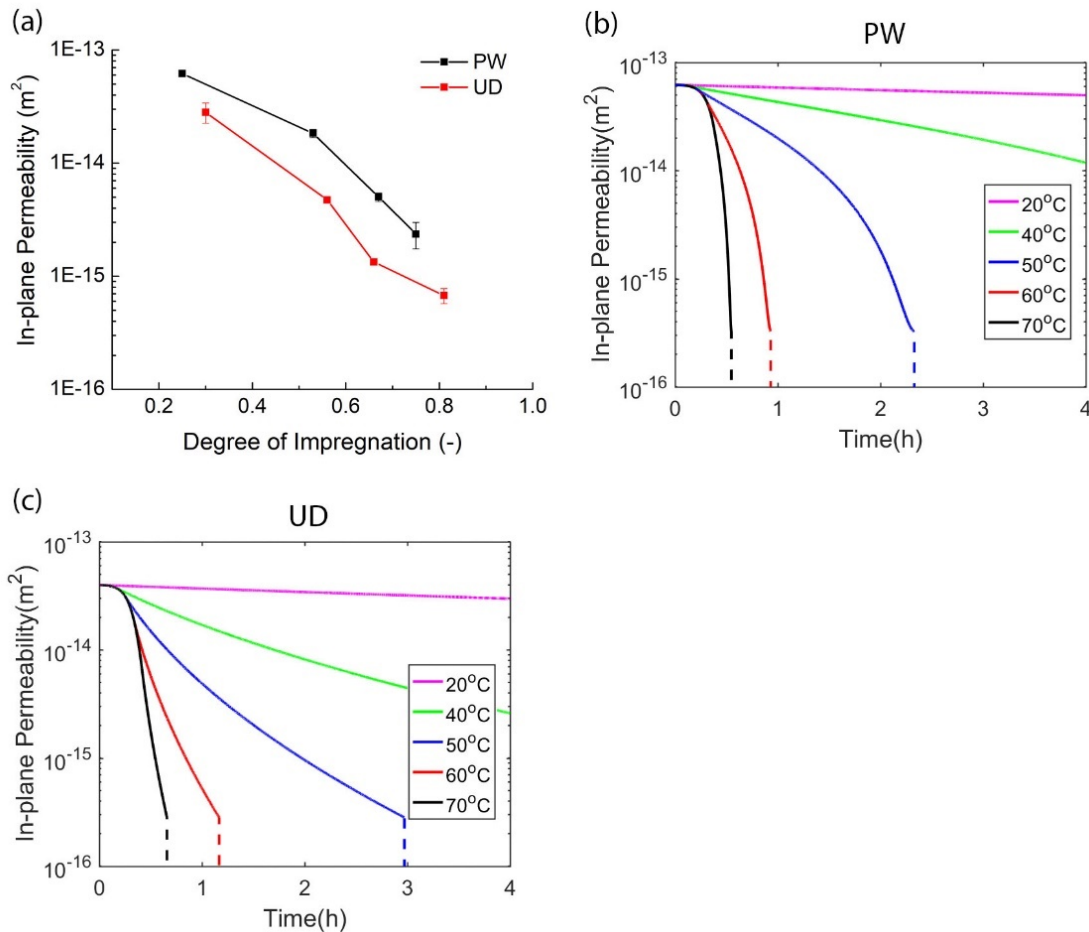


Fig. 8 (a) Measured in-plane permeability as a function of degree of impregnation. In-plane permeability versus time during debulk for (b) PW and (c) UD laminates. The cure cycle used in the model was $2^{\circ}\text{C}/\text{min}$ to designated temperatures and hold for four hours.

3.4. Cure Optimization Guidelines



The permeability data in the previous sections showed that transverse permeability did not increase significantly until the debulk temperature reached 60°C in UD preregs. The transverse permeability at 60°C was ~ 3-4 orders of magnitude less than the in-plane permeability. To compare the gas removal efficiency of RT and 60°C vacuum holds, models can be used to estimate the time required for air evacuation in both cases. Multiple models have been developed to predict the evacuation of entrapped air in preregs, and most of them relying on Darcy's Law ^{13,14,21}. Combining Darcy's law and the continuity equation, flow in the porous medium can be expressed:

$$\nabla \cdot \left(P \frac{K}{\mu} \nabla P \right) = \emptyset \frac{\partial P}{\partial t} \quad (5)$$

where P is pressure, K is the permeability, μ is gas viscosity and \emptyset is the initial porosity of the laminate. Considering a two-dimensional problem with K in the X and Z direction, Eq. (5) becomes ¹⁴:

$$\frac{K_x}{\mu} \frac{\partial \left(P \frac{\partial P}{\partial x} \right)}{\partial x} + \frac{K_z}{\mu} \frac{\partial \left(P \frac{\partial P}{\partial z} \right)}{\partial z} = \emptyset \frac{\partial P}{\partial t} \quad (6)$$

As the permeability, K_x and K_z , changes during heated or RT debulk, solving the two-dimensional equation requires extensive calculation. The problem was therefore simplified to one-dimensional by assuming that in-plane air evacuation is the sole pathway during RT debulk, while air evacuation occurs exclusively via through-thickness pathways during heated (60°C) debulk. These assumptions are used for estimation because during RT debulk, the transverse permeability of 2- and 4-ply UD laminates were 5-6 orders of magnitude less than the in-plane permeability, and decreased with increasing time. Besides, during a 60°C debulk, tow impregnation reaches full saturation in about an hour. The solution for one-dimensional gas transport can be expressed as ²¹:

$$t = \frac{\mu}{P_0} \frac{\emptyset L^2}{K} \left[-\frac{1}{0.9} \ln \left(\frac{\emptyset_F}{\emptyset} \right) \right]^{0.6} \quad (7)$$



In this equation, permeability K can be in-plane, K_x , or through-thickness, K_z , and L can be the length to breathing edge (half the laminate length) or the thickness of the laminate, accordingly. Initial porosity \emptyset was calculated from the cross-section micrographs of uncured UD laminates, while \emptyset_F , the final porosity, was assumed to be 1%. With all the constants determined, the vacuum hold times required for RT and for 60°C were estimated for different part sizes (L) using Eq. (7).

Fig. 9 shows the vacuum hold times required for room temperature and 60°C air evacuation. Transverse permeability data for 2- and 4-ply laminates were used to estimate the air evacuation time required for 4- and 8-ply laminates, assuming that perforated release film was applied to both sides of the laminates. The solid black line shows air evacuation time during RT debulk as a function of laminate length. The solid blue and red lines show the time required for air evacuation at 60°C for 4- and 8-ply laminates. The figure shows that if the laminate length exceeds 48 mm for a 4-ply laminate, or 460 mm for an 8-ply laminate, debulking at 60°C is more efficient than at room temperature. The delay time should also be considered to estimate air evacuation time, as pressure drop (i.e. air evacuation) does not occur instantaneously upon application of vacuum (discussed in Section 3.2), and as number of plies increases, the delay time increases. The dashed lines showed that the laminate critical length increases to 184 mm and 910 mm for a 4- and 8-ply laminate, respectively, when taking delay time into account. The plot also indicates that for thin UD laminates, a vacuum hold at 60°C prior to cure can be more effective when the laminate length exceeds a threshold value. However, note that as the number of plies increases, the through-thickness permeability decreases sharply and can eventually go to zero (no gas flow in the through-thickness direction), even at elevated temperature.

For PW prepreg debulking at 60°C, the *transverse* permeability of a 4-, 8-, and 16-ply laminates consistently reached $\sim 2 \times 10^{-14} \text{ m}^2$, a level comparable to the initial *in-plane* permeability



($\sim 6 \times 10^{-14} \text{ m}^2$), while the transverse permeability for a 24-ply laminate exhibited slightly lower permeability ($\sim 2 \times 10^{-15} \text{ m}^2$). The evacuation efficiency for in-plane and transverse gas removal can be compared using the following equation, derived from Eq. (7):

$$\frac{t_x}{t_z} = \left(\frac{L_x}{H_z} \right)^2 \cdot \frac{K_z}{K_x} \quad (8)$$

Eq. 9 indicates that provided $L_x/H_z > 5.5$, a heated debulk at 60°C is more effective than a RT debulk. In practice, laminate length is almost always 2-3 orders of magnitude greater than laminate thickness, so a 60°C debulk will greatly increase the efficiency of air evacuation in PW laminates.

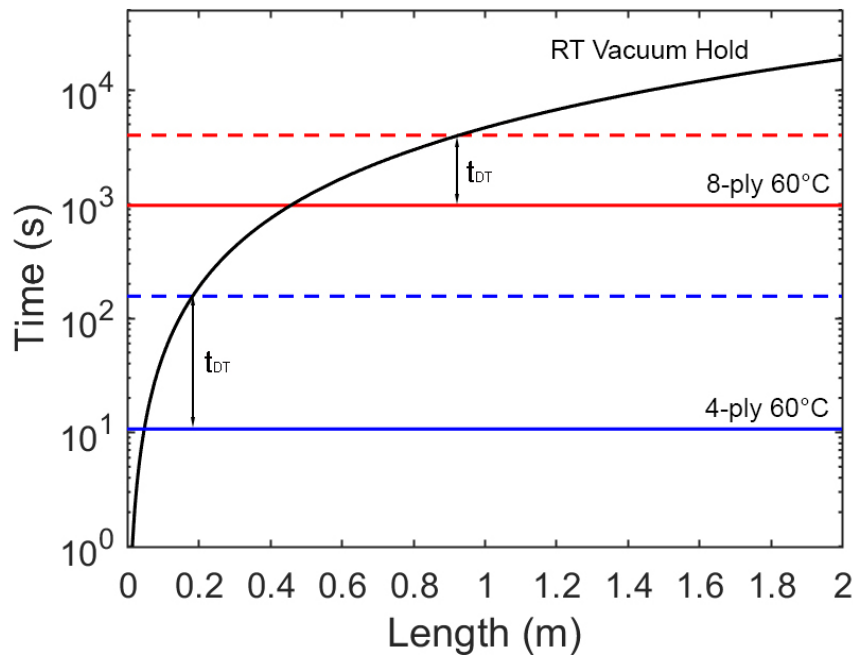


Fig. 9 Air evacuation time vs laminate length. Comparison of air evacuation time between room temperature vacuum hold and 60°C vacuum hold.

4. CONCLUSIONS



The effects of debulk temperature on inter-ply air removal and gas permeability of VBO prepregs were investigated. Results showed that debulk temperature (resin viscosity) and fiber bed architecture are critical factors for through-thickness air transport. Reducing resin viscosity promotes inter-ply air removal via through-thickness gas transport while concurrently impeding the in-plane gas transport due to increasing tow impregnation. *In situ* monitoring observations confirmed that inter-ply air evacuation during 60°C debulk was more effective than room temperature debulk. This method can be applied more widely to assess mechanisms of void formation and migration, as well as revealing bubble behavior under different cure conditions and with different prepreg formats.

The permeability data was used to guide the development of more effective cure cycles for prepregs under VBO conditions. For this PW laminate, results showed that, if laminate length/thickness ratio > 5.5 , a debulk at 60°C can be applied to reduce total processing time. However, in UD prepregs, transverse air evacuation relies on random resin-starved regions, which are easily occluded. Thus, while increasing vacuum hold temperature can benefit for thin UD laminates (< 8 plies ~ 1 mm), the transverse permeability of UD prepregs will eventually decrease to zero when the number of plies increases (> 8 plies, in this case).

This study also provides new insights into air transport in prepregs at intermediate temperatures in general. Woven prepregs have large openings in the fiber bed, and thus increased debulk temperature greatly enhances through-thickness gas transport. However, for most laminates comprised of UD prepregs, heated debulk is not an effective means to achieve air evacuation prior to cure. To increase transverse air evacuation efficiency in UD prepregs, prepreg formats with discontinuous resin distributions can be a more effective approach^{22,23}.



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References:

1. Centea T, Grunenfelder LK, Nutt SR. A review of out-of-autoclave prepregs - Material properties, process phenomena, and manufacturing considerations. *Compos Part A Appl Sci Manuf* 2015; 70: 132–154.
2. Grunenfelder LK, Nutt SR. Void formation in composite prepregs - Effect of dissolved moisture. *Compos Sci Technol* 2010; 70: 2304–2309.
3. Bowles KJ, Frimpong S. Void Effects on the Interlaminar Shear Strength of Unidirectional Graphite-Fiber-Reinforced Composites. *J Compos Mater* 1992; 26: 1487–1509.
4. Farhang L, Fernlund G. Void and porosity characterization of uncured and partially cured prepregs. *J Compos Mater* 2016; 50: 937–948.
5. Centea T, Hubert P. Measuring the impregnation of an out-of-autoclave prepreg by micro-CT. *Compos Sci Technol* 2011; 71: 593–599.
6. Hu W, Grunenfelder LK, Centea T, et al. In-situ monitoring of void evolution in unidirectional prepreg. *J Compos Mater* 2018; 52: 2847–2858.
7. Ma Y, Centea T, Nutt SR. Defect Reduction Strategies for the Manufacture of Contoured Laminates Using Vacuum BAG-Only Prepregs. Epub ahead of print 2017. DOI: 10.1002/pc.
8. Schlimbach J, Ogale A. *Out-of-autoclave curing process in polymer matrix composites*. Woodhead Publishing Limited. Epub ahead of print 2012. DOI: 10.1533/9780857096258.3.435.
9. Rigard C. Process Selection and Optimization for Out of Autoclave Prepreg Structures. In: *Proceedings of the CAMX*. Dallas, TX, 2015.
10. Kratz J, Hubert P. Anisotropic air permeability in out-of-autoclave prepregs: Effect on honeycomb panel evacuation prior to cure. *Compos Part A Appl Sci Manuf* 2013; 49: 179–191.
11. Louis B, Hsiao K, Fernlund G. Gas permeability measurements of out of autoclave prepreg MTM45-1/CF2426A. *SAMPE Conf 2010 May 17–20, Seattle, WA; 2010*<http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:GAS+PERMEABILITY+MEASUREMENTS+OF+OUT+OF+AUTOCLAVE+PREPREG+MTM45-1+/+CF2426A#0> (2010).
12. Arafath ARA, Fernlund G, Poursartip A. Gas transport in prepregs: model and permeability experiments. In: *Proceedings of the 17th International Conference on Composite Materials, July 27-31, pp. 1–9*.
13. Cender TA, Simacek P, Advani SG. In-plane gas evacuation of partially impregnated pre-preg laminates in out of autoclave processing. In: *International SAMPE Technical Conference*. Baltimore, MD, 2015.
14. Levy A, Kratz J, Hubert P. Air evacuation during vacuum bag only prepreg processing of honeycomb sandwich structures : In-plane air extraction prior to cure. *Compos Part A Appl Sci Manuf* 2015; 68: 365–376.



15. Tavares SS, Michaud V, Manson JAE. Through thickness air permeability of prepregs during cure. *Compos Part A Appl Sci Manuf* 2009; 40: 1587–1596.
16. Hu W, Centea T, Nutt S. Effects of material and process parameters on void evolution in unidirectional prepreg during vacuum bag-only cure. Epub ahead of print 2019. DOI: 10.1177/0021998319864420.
17. Centea T, Hubert P. Modelling the effect of material properties and process parameters on tow impregnation in out-of-autoclave prepregs. *Compos Part A Appl Sci Manuf* 2012; 43: 1505–1513.
18. AE S. THE PHYSICS OF FLOW THROUGH POROUS MEDIA.
19. Howard S. Evaluating Consolidation Dynamics - Study of Key Consolidation Parameters in a Vacuum Bag Only (VBO) Cure. In: *Proceedings of the SAMPE 2016 Technical Conference*. Long Beach, CA, 2016.
20. Centea T, Peters G, Hendrie K, et al. Effects of thermal gradients on defect formation during the consolidation of partially impregnated prepregs. *J Compos Mater* 2017; 51: 3987–4003.
21. Fernlund G, Wells J, Fahrang L, et al. Causes and remedies for porosity in composite manufacturing. *IOP Conf Ser Mater Sci Eng*; 139. Epub ahead of print 2016. DOI: 10.1088/1757-899X/139/1/012002.
22. Grunenfelder LK, Dills A, Centea T, et al. Effect of prepreg format on defect control in out-of-autoclave processing. *Compos Part A Appl Sci Manuf* 2017; 93: 88–99.
23. Schechter SGK, Centea T, Nutt SR. Polymer film dewetting for fabrication of out-of-autoclave prepreg with high through-thickness permeability. *Compos Part A Appl Sci Manuf* 2018; 114: 86–96.