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Mitigating void growth in out-of-autoclave prepreg processing using a semi-permeable membrane to maintain resin pressure

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ABSTRACT

In this work, we investigate the use of discontinuous resin films in prepregs (semipregs) combined with a semi-permeable (air-permeable, resin-impermeable) release film intended to allow through-thickness air evacuation while simultaneously restricting resin loss. In situ measurements of resin pressure were deployed to test the hypothesis that resin pressure was maintained during prepreg cure when using a semi-permeable release film. Concurrently, visualization of the tool-side surface during cure revealed efficient evacuation of entrapped air. Porosity in laminates formed at high temperatures when using resin-permeable consumables, but did not form when using resin-impermeable (semi-permeable) consumables. To confirm that the observed void growth behavior was due to a loss in resin pressure, experiments were conducted to measure resin pressure during cure with both resin-permeable and resin-impermeable (semi-permeable) consumables. In both cases, resin pressure peaked before decreasing, a finding attributed to resin flowing to fill dry regions in the fabric, present by design. The drop in resin pressure, however, was greater in magnitude and longer in duration when using resin-permeable edge and bag-side surface boundaries, indicating that the observed void growth at elevated temperature was caused by a loss in resin pressure. Use of a semi-permeable membrane was effective in retaining resin content and mitigating such porosity.

KEYWORDS

Prepreg; semipreg; out-ofautoclave; resin pressure measurement; in situ analysis; semi-permeable membrane

GRAPHICAL ABSTRACT



1. Introduction

Carbon fiber-reinforced composites are commonly cured in autoclaves, as the compaction pressure provided by the autoclave suppresses void growth and reliably yields low-porosity parts [1,2]. Autoclaves, however, represent a substantial capital and recurring expense, and restrict part size and throughput. To overcome these limitations, prepregs designed

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for oven cure (also called vacuum bag-only, or VBO prepregs) have been developed which rely on deliberate dry channels of fiber beds to evacuate air and thus limit/eliminate porosity (e.g. [3–7]). Dry regions in these out-of-autoclave (OoA) prepregs are achieved by sandwiching fiber beds between two layers of resin, and deliberately achieving partial impregnation. Thus, these materials rely on *in-plane* permeability and evacuation pathways to laminate edges to remove air. Studies have demonstrated that in-plane permeability in such OoA prepregs are generally orders of magnitude greater than through-thickness permeability, although the in-plane permeability approaches zero as resin flows to fill dry areas [8,9].

Because of the reliance on air evacuation at part edges, OoA prepregs are susceptible to air entrapment. For example, Arafath et al. characterized inplane permeability of an OoA unidirectional tape and modeled evacuation time, and predicted that a flow distance of 4 m would require 7 days to remove air [10]. Even in lab-scale studies, debulk times of up to 24 h were required to mitigate both internal and surface porosity due to entrapped air [11–13]. In related work, Kay and Fernlund also reported a gradient in porosity in laminates produced with OoA prepregs, with void content increasing as distance from the vacuum source increased [11].

To address issues with air entrapment in OoA prepreg laminates, studies have investigated methods to increase through-thickness air permeability in OoA prepregs. For example, prepregs can be perforated using a simple spike roller, promoting air evacuation in both laminate processing and honeycomb sandwich applications [14,15]. Grunenfelder et al. used discontinuous resin films to create through-thickness evacuation channels on a 2×2 twill fabric, demonstrating that such modified prepregs yielded laminates with negligible porosity, while commercial OoA prepregs generally yielded laminates with much greater porosity (e.g. with sealed edges and abbreviated room-temperature vacuum hold) [16]. Edwards et al. presented a method to produce unidirectional prepreg with through-thickness permeability, and similarly showed that such prepregs were less susceptible to porosity than conventional prepreg formats under challenging process conditions, such as humidity exposure and embedded ply drops [17].

While the studies cited above demonstrated that increased through-thickness permeability reduces or eliminates porosity from air entrapment, voids also can arise when the pressure of gases dissolved in the resin exceeds the resin pressure. In autoclave processing, resin pressure is generally maintained by application of compaction pressure (typically \sim 700 kPa) [1]. VBO processes, however, are limited to the

compaction pressure applied by the vacuum bag, which is equal to the ambient pressure (~ 100 kPa). Grunenfelder et al. demonstrated that porosity in VBO-processed laminates increased when prepreg was humidity conditioned prior to layup, while the same material processed under autoclave conditions yielded void-free parts, regardless of humidity conditioning [18]. Similarly, Kay and Fernlund reported an increase in porosity with increasing moisture content [11]. Other studies have investigated the effect of reduced compaction pressure (either by reducing ambient pressure or increasing the absolute pressure within the vacuum bag), reporting that porosity increased as applied pressure decreased [11,13,19].

Resin pressure during cure of prepreg laminates is typically maintained by relying on a pressure gradient between atmosphere and vacuum. However, a loss of resin content in a laminate during cure can result in a drop in resin pressure that is generally accompanied by a transfer in load from the fluid resin to the fiber bed. Campbell et al. used a pressure sensor embedded in a tool plate to measure resin pressure during cure of a fully impregnated prepreg [1]. They reported that resin pressure remained near the applied autoclave pressure in a baseline case, but dropped below vacuum when resin bleed was deliberately increased [1]. In related work, Lynch et al. embedded sensors within laminates to measure through-thickness variations in resin pressure [20]. They reported an increase in pressure at the laminate-bleeder layer interface at the same time pressure dropped throughout the laminate, which they attributed to resin bleeding out of the laminate [20]. These studies were limited to autoclave prepregs. The evolution of resin pressure during cure of OoA prepregs has not been addressed in literature.

Investigations into scaling of OoA prepreg processing - both in terms of size and geometric complexity - have reported conflicting results. Ma et al. assessed the effect of corner geometry in OoA processing, reporting that reduced compaction pressure due to consumable bridging at concave corners led to increased porosity and laminate thickness [21]. Likewise, Levy et al. developed and validated a model capturing laminate thickening at concave corners, but did not discuss porosity. Hughes and Hubert reported porosity and laminate thickness variations in demonstration parts due to geometric complexities, including corners and ply drops [22]. Other studies claimed success in producing demonstration parts with acceptable quality (e.g. [23-25]). While OoA prepregs can often yield high-quality parts, the process is not robust, largely because of the absence of autoclave pressure.



Figure 1. Prepreg made with de-wetted resin film to create a discontinuous resin pattern, providing through-thickness evacuation channels to increase gas permeability. The resin appears as dark areas. The white squares are pinholes in the fabric weave.

The present work combines prior advancements in prepreg design to increase through-thickness air evacuation (e.g. [16,17]) with the use of a semi-permeable release film to maintain resin pressure and therefore retain resin content. Laminates were fabricated using prepregs with through-thickness permeability (semipregs) and resin-impermeable edge boundaries, then compared to similar laminates cured under conditions representative of conventional OoA prepreg processing. Real-time evolution of voids at the laminate-tool interface during cure was captured using in situ visualization, identifying porosity originating both from entrapped air and from volatile evolution. Results demonstrated that through-thickness gas transport combined with a semi-permeable release film could mitigate porosity from both sources.

A method to measure resin pressure during cure was employed, and results described trends in resin pressure evolution specific to OoA/VBO prepregs. In particular, a decrease in resin pressure was observed during cure, and was attributed to impregnation of dry fibers, a phenomenon that does not occur in fully impregnated autoclave prepregs. Measurements further confirmed that the use of a semi-permeable membrane maintained a higher resin pressure during cure than conventional OoA consumables, while resin format had no clear effect on resin pressure. In contrast, use of conventional consumables during cure resulted in a loss of resin pressure, which was consistent with volatile-induced porosity identified via in situ visualization. Overall, results of this work demonstrate additional measures



Figure 2. Experimental set-up for *in situ* void growth analysis. Top: Inside view of the frame inserted into the oven door. Bottom: Outside view showing the laminate surface visible through the oven window and glass tool plate.

that increase robustness of OoA processing by maintaining resin pressure during cure. The work also demonstrates that judicious selection of materials and consumables can mitigate porosity from both air entrapment and volatile evolution.

2. Experimental methods

2.1. Materials

The resin used in this study was a non-commercial epoxy intended for out-of-autoclave processing (Hexcel HCR140-15). Prepreg was produced by pressing resin films (55.5 g/m^2) to either side of a plain-weave carbon fabric (Toray TORAYCA T300, 3k tows, 194 g/m^2). Two types of prepregs were fabricated – one with continuous resin (CR) film, similar to commercial out-of-autoclave prepregs, and one with discontinuous resin (DR) film, intended to increase through-thickness gas permeability.

To produce prepreg, resin films and fabric were cut to $305 \text{ mm} \times 305 \text{ mm}$ (12 in \times 12 in). A resin film was placed on either side of the fabric (two layers of resin film per ply, yielding a total areal

Table 1. Testing conditions for lab-scale laminate fabrication.

	-		
Test	Resin Format	Edge Condition	Bag-side Surface Layer
C:B/B	Continuous	Bleed (breathing dams)	Bleed (perforated film)
C:B/S	Continuous	Bleed (breathing dams)	Sealed (semi-permeable membrane)
C:S/B	Continuous	Sealed (tacky tape)	Bleed (perforated film)
C:S/S	Continuous	Sealed (tacky tape)	Sealed (semi-permeable membrane)
D:B/B	Discontinuous	Bleed (breathing dams)	Bleed (perforated film)
D:B/S	Discontinuous	Bleed (breathing dams)	Sealed (semi-permeable membrane)
D:S/B	Discontinuous	Sealed (tacky tape)	Bleed (perforated film)
D:S/S	Discontinuous	Sealed (tacky tape)	Sealed (semi-permeable membrane)

Two laminates were produced for each condition. All laminates were produced using the non-commercial resin.

density of 305 g/m^2 and a resin weight fraction of $\sim 31\%$) and pressed onto the fabric under 2 tons of force for 5 min at room temperature (Wabash Genesis). DR film was produced through a de-wetting process in which films were subjected to a mild thermal cycle (10 min at 70° C, which advanced the degree of cure 6.5%) that reduced viscosity and allowed resin to de-wet on the backing paper, yielding islands of resin separated by dry spots. After de-wetting, prepreg was produced using the same process as with the continuous film. Figure 1 shows the surface morphology of a prepreg ply with discontinuous resin.

A second (commercial) prepreg was used to compare resin pressure measurements obtained with the experimental prepreg and discontinuous resin to a commercial prepreg with conventional continuous resin format. This prepreg also featured an epoxy resin and was designed for VBO processing (Solvay Cycom 5320-1/T650-35, 3k tows, 8HS, 367 g/m^2); it required no further processing before testing.

2.2. Lab-scale sample fabrication

To assess the effect of processing parameters on void behavior – both the time-dependent evolution of porosity and void content in the cured part – a set-up enabling *in situ* visualization of the tool-surface interface was employed (Figure 2). The framed glass tool plate, which was inserted in the door of a windowed oven during testing, enabled visualization while allowing for air flow on both sides of the tool plate to minimize temperature gradients.

Two values each for three different processing variables were tested, as listed in Table 1. The prepreg format (resin distribution) affects gas transport pathways, enabling both in-plane and through-thickness transport (in the case of discontinuous resin) or restricting transport to in-plane only (continuous resin). The edge conditions and the bag-side surface conditions also affect resin bleed, in one case sealing the respective interfaces (sealed edges, semi-permeable membrane), while in the other, allowing resin bleed at edges and through a perforated release film.

Prepreg laminates (102 mm \times 102 mm, [0°/90°/ 0°]_{3s}) were placed on a glass tool plate after application of a liquid mold release agent. Edges were either

sealed using vacuum sealant tape, or configured to be permeable to gas and resin by constructing breathing dams (fiberglass cloth wrapped around sealant tape). The bag-side release film – either a semi-permeable membrane for the sealed condition (Airtech Dahltexx SP-2) or perforated film for the bleed condition (Airtech A4000) – was then laid over the laminate. The bagging assembly was completed with a breather cloth and vacuum bag.

After layup and bagging, the entire frame was placed in the oven with the bag-side inward, and a digital microscope (Dino-Lite Edge AM7815MZTL) outside the oven was used to record time-lapse videos of the tool-side laminate surface during cure. Images were collected every 30 s. Thermocouples were also used to record temperature during cure. The applied thermal cycle consisted of 120 min at 121 °C and 120 min at 177 °C, with a 2 °C/min heating rate. The time-lapse videos captured during cure provided real-time data on void evolution at the tool-side surface. A representative viscosity profile for the prescribed thermal cycle is shown in Figure 3. Note that the data only runs through the intermediate hold, as the resin had gelled by this point.

Resin film samples were also analyzed to evaluate the behavior of the resin alone. Samples consisted of a layer of de-wetted resin and were processed with compaction (using a vacuum bag and impermeable surface ply to provide approximately 1 atm or 101 kPa of compaction pressure) and without compaction (using a rigid frame inside the vacuum bag to prevent sample compaction by the bag, which provided > 5 kPa). Samples were heated at 2 °C/min with no intermediate hold.

In addition, cured laminates were assessed for void content through polished sections. After cure, sections of laminates (25 mm in length) were cut, polished, and imaged using a digital stereo microscope (Keyence VHX-5000) to assess internal porosity. Void content was measured and quantified (as percent of total area) using image processing software (Adobe Photoshop CC).

2.3. Resin pressure measurement

Resin pressure was measured *in situ* using a probe inserted between plies during cure, a method that



Figure 3. Measured viscosity for the non-commercial resin subjected to the prescribed temperature cycle. The resin gels by the end of the 120 min hold at 121 °C.



Figure 4. Example of an in-progress layup using pressure probe assembly incorporated into the laminate for resin pressure measurements. The needle is inserted between plies, and a ball of excess resin is placed at the tip of the needle to seal the interface upon initial application of vacuum. The needle of the pressure probe is passed through the bag sealant tape to avoid introducing bag leaks.

was previously deployed to measure resin pressure [20,26]. The resin pressure measurement assembly used is shown in Figure 4 and contains three main components: 1) a probe inserted into the sample, 2) a reservoir situated outside the vacuum bagging assembly, containing a transfer fluid, and 3) a pressure transducer. The probe was a 19-gauge stainless steel needle with a 90° tip, which limited the influence of fibers on the pressure measurement [20]. The pressure transducer (Honeywell Model S) had a pressure range of 689 kPa (100 psi) and maximum operating temperature of 149 °C, with temperature compensation range of 20–160 °C. A synthetic oil intended for hydraulic applications up to 204 °C (400 °F) was used as the transfer fluid.

The layup for resin pressure measurements followed procedures for the lab-scale *in situ* tests, albeit with a few key differences. Laminates were $102 \text{ mm} \times 102 \text{ mm}$ and consisted of either 9 plies (commercial prepreg, $[0^{\circ}/90^{\circ}/0^{\circ}]_{3s}$) or 18 plies (non-commercial prepregs, $[0^{\circ}/90^{\circ}/0^{\circ}]_{6s}$) to ensure sufficient thickness compared to the needle (final laminate thickness for both materials was ~4.5 mm, and the outer diameter of the needle was 1.07 mm). The laminate was placed close to the vacuum bagging tape so that the probe could be placed through the bag and edge dams and into the laminate. To keep the probe parallel to the tool plate and laminate, the needle was placed between the first and second plies for tests with the commercial prepreg, and between the second and third plies for tests with the non-commercial prepregs. Before placing the probe, a small ball of excess resin was placed at the tip to ensure the tip remained sealed at room temperature. This was especially a concern for prepreg with discontinuous resin films, as the probe tip would be exposed to vacuum if placed in a resinfree region.

Testing conditions are listed in Table 2. The conditions selected matched the extremes of the labscale tests, in which both boundary conditions were either permeable to resin (breathing edge dams, perforated release film) or sealed to resin flow (tacky tape edge dams, semi-permeable release film). Tests were conducted using both CR and DR prepreg, as well as the commercial prepreg (Cycom 5320-1). Because of the temperature range of the pressure transducer, tests were conducted only through the 120 min dwell at 121 °C, and not through the rest of the thermal cycle. However, rheology tests showed that resin gelation occurred during the intermediate dwell, so measuring resin pressure after this point would not have yielded meaningful data.

The commercial prepreg was selected to provide a benchmark for results obtained with experimental prepreg. The degree of impregnation (DoI) was expected to influence the development of resin pressure in OoA prepregs, and a model describing the evolution of DoI for the commercial prepreg was reported elsewhere [27]. Campbell et al. described the development of resin pressure in a fully impregnated prepreg, noting that resin pressure was approximately equal to applied compaction pressure until resin bleed out of the laminate caused a decrease in resin pressure [1]. Because OoA prepregs are not fully impregnated, resin pressure is expected to be always less than compaction pressure due to dry fibers carrying a portion of the applied load. Additionally, resin can flow to fill dry tows

Table 2. Testing conditions for resin pressure measurements.

Test	Resin Format	Plies	Edge Condition	Bag-side Surface Layer
Commercial Bleed	Continuous	9	Bleed	Bleed
Commercial Sealed	Continuous	9	Sealed	Sealed
CR Prepreg Bleed	Continuous	18	Bleed	Bleed
CR Prepreg Sealed	Continuous	18	Sealed	Sealed
DR Prepreg Bleed	Discontinuous	18	Bleed	Bleed
DR Prepreg Sealed	Discontinuous	18	Sealed	Sealed

Each test was repeated twice.

regardless of boundary conditions, which is expected to yield a reduction in pressure, with further development of resin pressure dependent on resin format and consumables used.

Impregnation of PW and 8HS fabrics was modeled (for the commercial resin), and results showed that impregnation occurred more slowly in 8HS than in PW, a finding attributed to the lower permeability of the 8HS fabric [27]. The cure cycle included a temperature ramp and hold at 90 °C. The model predicted that DoI for 8HS fabrics would reach 100% at the start of the temperature hold. Consequently, increasing the hold temperature from 90 to 121 °C was expected to have negligible effect on resin pressure development.

3. Results and discussion

3.1. Lab-scale samples

Frames from resin-only samples are shown in Figure 5. In the initial state, areas of resin (dark) and air (light) appear, as a result of film de-wetting prior to testing. When processed under compaction, resin regions remained void-free. However, impermeable boundaries were used to ensure compaction, preventing air egress *via* edge breathing, and the initial dry regions remained throughout cure. When no compaction was applied, voids within the resin grew, providing evidence of volatile-based void growth due to low resin pressure.

Time-lapse videos showed the evolution of porosity at the tool-side surface for each testing condition (provided as supplement material), and frames for select tests are shown in Figure 6. For brevity of videos, the final dwell was omitted, as the resin gels prior to this stage, and no change in surface morphology was observed. Test C:B/B (continuous film resin, edge breathing dams, perforated release film) is representative of conventional OoA prepreg cure. At t_1 (30 min, mid-way through the initial heating stage), porosity due to entrapped air that could not be evacuated was observable. By t_2 (75 min, beginning of the intermediate dwell), these voids had migrated to pinholes in the fabric and increased in radius. Porosity remained trapped at the surface after gelation at t_3 (150 min, end of the intermediate dwell).

In Test D:B/B the same consumables were used as with conventional OoA prepreg processing (edge breathing dams, perforated release film). However, the prepregs in this test featured increased throughthickness gas permeability because of the different format (discontinuous resin). The increased permeability increased air evacuation to the surface, and no porosity was observed at t_1 , after resin flowed to fill dry spots. However, new voids formed at t_2 , which were attributed to evolution of volatiles as resin pressure dropped. These voids grew throughout the intermediate dwell and remained trapped at the surface after gelation (t_3).

Test D:S/S combined discontinuous resin with sealed boundary conditions (sealed edges, semi-permeable membrane) and showed initial behavior similar to Test D:B/B, yielding a void-free surface at t_1 as resin flowed and air was evacuated. Because boundaries were resin-impermeable, resin pressure did not drop, and no further void growth occurred through the remaining cure. The surface of the cured laminate exhibited negligible porosity.

Cross-sections for each testing condition are shown in Figure 7, and porosity measurements (average of two samples for each condition) are presented in Figure 8. Figure 7a (Test C:B/B) followed conventional OoA processing and exhibited relatively minimal porosity presenting as small (\sim 0.2 mm), oblong inter-ply voids. Changing any of the consumables (Figure 7b-d) yielded an observable increase in porosity relative to Test C:B/B, as sealing laminate boundaries limited both air and volatile removal. Voids were larger (up to \sim 1 mm in length) and more numerous but retained the oblong shape. In the most extreme case, sealing all boundaries led to pores that spanned multiple plies (Figure 7d). As DR prepreg was demonstrated to effectively remove initially entrapped air, porosity in Test D:B/ B (Figure 7e) was attributed to volatile evolution and presented as oval or spherical voids (~0.1 to 0.5 mm in diameter). Sealing either boundary independently (Figure 7f and g) yielded fewer and smaller voids (< 0.1 mm to \sim 0.3 mm in diameter) by reducing resin bleed, and porosity in Test D:S/S contained small (< 0.1 mm in diameter) interply voids.

For laminates fabricated with continuous resin, void content was lowest when using conventional



Figure 5. Frames from *in situ* tests for de-wetted resin film processed under compaction (left) and without compaction (right). In the initial state, resin (dark) and dry regions (light) were visible, due to the film being de-wetted. At 65 °C, voids had formed and grown in the sample without compaction, while the sample with compaction did not have porosity form in the resin.

VBO consumables (Test C:B/B, 0.99%). This result was not unexpected, as prepregs with continuous resin layers rely solely on edge breathing to evacuate air. Thus, sealing the edges (C:S/B) resulted in an increase in void content (4.35%). However, replacing the bag-side surface boundary from the perforated release film to the semi-permeable membrane (C:B/ S) also increased porosity (3.47%). This finding was unexpected, since in-plane air evacuation was still enabled by edge breathing dams. The finding indicates that a degree of air removal can occur through perforated release films even without through-thickness gas permeability. The air removal occurs via resin bleed that removes air bubbles and/or dissolved volatiles along with the resin itself. Porosity was greatest when all boundaries were resin-impermeable (C:S/S), as no pathway for gas removal existed.

Void content for laminates produced with DR prepreg was equal to or less than the respective CR laminates for each set of boundary conditions (Figure 8). Porosity was lowest (0.23%) when all boundaries were resin-impermeable (D:S/S), a finding that was consistent with *in situ* visualization tests. Through-thickness permeability enabled air

evacuation through the semi-permeable membrane, and resin pressure was maintained by restricting resin flow out of the laminate. Varying boundary conditions demonstrated robustness imparted by discontinuous resin patterns, as porosity remained low (< 2%) regardless of consumables used. Because the discontinuous resin enabled air evacuation through both bag-side surface layers used (perforated or semi-permeable) regardless of edge conditions, any porosity in these laminates was attributed to evolution of volatiles as resin presdropped. Relative porosity differences sure between tests would indicate which boundary accounted for more resin loss. However, except for the low-porosity fully sealed case (D:S/S), there was no statistically significant difference in void content between discontinuous resin laminates, and no conclusion could be drawn.

3.2. Resin pressure measurements

The commercial prepreg was used to assess and confirm the effectiveness of the resin pressure measurement procedure. Results are shown in Figure 9,



Figure 6. Frames from *in situ* tests for Test C:B/B (left; continuous resin, breathing edge dams, perforated film), Test D:B/B (center, discontinuous resin, breathing edge dams, perforated release), and Test D:S/S (discontinuous resin, sealed edges, semi-permeable membrane). Times correspond to those marked on the thermal cycle (bottom).

which shows plots of temperature and resin pressure versus time. Times indicated in the plots correspond to modeled onset of dry fiber impregnation (t_1 , ~45 °C), measured drop in pressure under bleeding conditions (t_2 , ~60 °C), and approaching full impregnation (t_3 , ~90 °C) [27]. Pressure development manifested three stages:

1. Initially (up to t_1), no pressure change was detected as vacuum was applied, as resin viscosity was high at room temperature. The

measurement also confirmed that the excess resin placed at the needle tip effectively sealed the probe. As temperature increased and resin viscosity decreased, resin pressure increased.

2. Between t_1 and t_2 , resin pressure peaked at ~ 115 kPa abs and subsequently decreased. As discussed in Section 2, resin pressure for fully impregnated prepregs typically peaks at a value equal to the applied compaction pressure [1]. However, for semi-impregnated OoA prepregs, the resin pressure was expected to peak at a



Figure 7. Internal images of cured *in situ* testing samples. The left column was produced with continuous resin film, and the right with discontinuous film. Boundary conditions were: a and e) breathing edge dams, perforated film; b and f) breathing edge dams, semi-permeable membrane; c and g) sealed edges, perforated film; and d and h) sealed edges, semi-permeable membrane.



Figure 8. Comparison of internal void area content (%) for continuous and discontinuous resin formats for each set of boundary conditions. Test labels correspond to those in Table 1: either bleed (B) or sealed (S) conditions for the edges and for the bag-side surface, respectively.

value less than the compaction pressure, because dry fibers share some of the applied load. The decrease in pressure following the peak occurred regardless of boundary conditions used and was attributed to resin flow to dry spots in the prepreg.

3. After t_2 and through the remainder of the temperature cycle, resin pressure either equilibrated at ~ 100 kPa abs (under sealed conditions) or continued to decrease (t_2) before equilibrating below ambient pressure (under high-bleed conditions).



Figure 9. Resin pressure measurements for commercial OoA prepreg under bleed (edge breathing dams, perforated release film) and sealed (sealed edges, semi-permeable membrane) conditions. Times t_1 and t_3 are the predicted onset and full impregnation of the material, respectively [27]. At time t_2 , measured pressure deviates between boundary conditions: the bleed test continues losing resin pressure, while pressure equilibrates under sealed conditions.

Results from these experiments were compared to those from a model for impregnation [27]. The peak in measured resin pressure occurred at \sim 45 °C, while the model predicted resin flow into the fiber bed to begin at this temperature. The model also predicted that full impregnation would be achieved at \sim 90 °C, and at this temperature, resin pressure had equilibrated.



Figure 10. Resin pressure measurements for the non-commercial resin under bleed (edge breathing dams, perforated release film) and sealed (sealed edges, semi-permeable release membrane) conditions for both continuous and discontinuous resin formats. Time t_1 is the peak in resin pressure, independent of boundary condition. At time t_2 , a second drop in resin pressure was observed under bleed conditions but not sealed conditions. Time t_3 is the end of the first temperature ramp, during which void growth at the tool surface was observed in *in situ* tests.

Resin pressure measurements for the non-commercial prepregs are presented in Figure 10. Times denoted represent key behaviors observed: t_1 corresponds to the initial peak in pressure, t_2 corresponds to a second drop in pressure that occurred only under bleed conditions, and t_3 corresponds to observed void growth from in situ visualization tests. Trends in resin pressure evolution were consistent with tests conducted with commercial prepreg, indicating that the initial decrease in resin was due to impregnation of dry tows, while further pressure reduction occurred if/when resin bled out of the laminate. Resin pressure depended strongly on boundary conditions (i.e. whether resin content was retained), while no conclusive effect of resin distribution pattern on pressure evolution was observed.

Porosity increase in laminates was caused by a drop in resin pressure during cure, which began near the start of the intermediate dwell, at \sim 75 min. Under bleed conditions, resin pressure equilibrated prior to the intermediate dwell, indicating that prior to this point, the reduced pressure was not sufficient to trigger volatile evolution. However, after the intermediate dwell temperature was reached (121 °C), volatile evolution caused porosity. Note that in situ tests afforded insights to the tool-side surface only. Related studies have reported that resin pressure decreases nearer to the site of resin bleed [1,20]. Therefore, pressure was expected to be lower near the bag-side surface of the laminate, a location that was not observed directly.

4. Conclusions

A method was demonstrated to increase robustness of OoA prepreg processing by (a) modifying the resin format and (b) using appropriate consumables to mitigate/eliminate porosity. Prepregs featuring discontinuous resin provided through-thickness pathways for air and volatile removal, reducing/ eliminating laminate porosity. In situ visualization was used to assess porosity evolution at the toolside laminate surface during cure, identifying void formation during the intermediate temperature dwell that was attributed to volatile evolution. To retain resin content and therefore maintain resin pressure and suppress void growth, resin-impermeable boundary conditions were used. Specifically, use of a semi-permeable membrane effectively mitigated void growth by allowing for through-thickness evacuation of gas while maintaining resin content. A method to measure resin pressure during cure was employed to test the hypothesis that resin-impermeable boundaries (semi-permeable membrane, sealed edges) maintained higher resin pressure than conventional OoA consumables. Results showed that regardless of whether boundaries enabled resin flow out of the system, resin pressure in OoA prepregs decreased as resin flowed to fill dry fiber tows. A subsequent observed decrease in resin pressure was unique to conventional OoA consumables and attributed to resin flow out of the laminate, while resin pressure equilibrated to a higher value when resinimpermeable consumables were used. The reduced resin pressure with conventional consumables was correlated to observed void growth during in situ visualization tests. Semi-permeable membranes maintained a higher resin pressure, thus mitigating this porosity.

Resin pressure measurements elucidated general behavior for OoA prepregs and highlighted challenges faced in limited-compaction scenarios like VBO processing. While fully impregnated prepregs used in autoclave processing can maintain resin pressure close to the applied compaction pressure if resin content can be maintained, OoA prepregs experience a reduction in the peak resin pressure from dry fibers carrying part of the applied load and resin flowing to fill tows. Maintaining resin content in OoA prepreg processing is especially important, as the maximum possible pressure can be only a fraction of the applied compaction pressure (already limited to ambient pressure) and any further drop in pressure can lead to void growth.

This study investigated the utility of combining a semi-permeable release film with OoA prepregs featuring discontinuous resin patterns to restore process robustness to an OoA process. There was no attempt to optimize material or process parameters, yet despite this, and using prepregs produced by hand in a lab setting, the process consistently yielded laminates with negligible porosity (0.23%), without autoclave pressure. Insights into cure cycle optimization can be extracted from in situ visualization of void growth combined with resin pressure measurements, and thus guide process modifications. For example, for the non-commercial resin, the decrease in resin pressure under bleed conditions occurred while temperature was increasing, prior to observed void growth attributed to reduced resin pressure. Therefore, reducing the intermediate dwell temperature so that the decrease in resin pressure occurs at a constant temperature could avoid reaching conditions for void growth, even if resin bleed out of the laminate occurs. While there is room for materials optimization, prior studies have investigated effectiveness of different resin patterns to reduce air entrapment and minimize flow distances for discontinuous resin formats (e.g. [28-30]).

This study represents an important step in the broader effort to impart process robustness to OoA prepregs. VBO processing of prepregs is susceptible to voids both from entrapped air and from the limited compaction pressure. The use of a semi-permeable membrane in conjunction with discontinuous resin film effectively mitigates porosity from both sources, and resin pressure measurements confirm that reduced resin pressure and subsequent void growth were caused by resin bleed from the laminate. By restricting resin flow out of the laminate, semi-permeable membranes and sealed edges were able to maintain higher resin pressure during cure than traditional OoA consumables. The insights gained here can inform processing decisions intended to reduce porosity in OoA processing, and the insights can be combined with material and process optimization to further increase robustness of VBO processes.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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