Defect Reduction Strategies for the Manufacture of Contoured Laminates Using Vacuum Bag-Only Prepregs

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Abstract

Complex structures manufactured using low-pressure vacuum bag-only (VBO) prepreg processing are more susceptible to defects than flat laminates due to complex compaction conditions present at sharp corners. Consequently, effective defect mitigation strategies are required to produce structural parts. In this study, we investigated the relationships between laminate properties, processing conditions`, mold designs and part quality in order to develop science-based guidelines for the manufacture of complex parts. Generic laminates consisting of a central corner and two flanges were fabricated in a multi-part study that considered variation in corner angle and local curvature radius, the applied pressure during layup and cure, and the prepreg material and laminate thickness. The manufactured parts were analyzed in terms of microstructural fiber bed and resin distribution, thickness variation, and void content. The results indicated that defects observed in corner laminates were influenced by both mold design and processing conditions, and that optimal combinations of these factors can mitigate defects and improve quality.

Keywords

Out-of-autoclave; Vacuum bag-only; Carbon fiber; Prepreg; Defects reduction

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1. Introduction

Out-of-autoclave (OoA) prepreg processing has been developed as an effective alternative to autoclave cure. While autoclaves use a pressurized environment to suppress voids and mitigate geometric variability [1], OoA processing consists of curing specially designed prepregs using vacuum bag-only (VBO) method, and can provide technical, economic and environmental benefits compared to conventional manufacturing. OoA processing can be used to produce flat laminates with autoclave-level microstructural and geometric quality without difficulty. However, the limited compaction pressure available during manufacturing and the distinctive characteristics of VBO prepregs render the production of parts with complex geometries challenging.

The two defects most commonly observed during composites manufacturing are microstructural voids and dimensional non-uniformity. Void content is a primary concern due to its effect on mechanical properties [2-4], and the mechanisms of void formation in prepreg laminates have been studied extensively [4]. It is now widely accepted that gas-induced voids can be caused by absorbed moisture, residual solvents within the resin, and air entrapped between and within prepreg plies [4,5]. Furthermore, flow-induced voids can arise if the resin matrix does not fully saturate the fiber bed during cure. However, in-situ monitoring of void formation within laminates remains difficult to perform, and the exact mechanisms that govern void nucleation, growth and migration are not entirely understood. Process-induced deformation such as thickness variation and laminate warpage are similarly complex, as they can be caused by microstructural features, process conditions, and phenomena such as cure shrinkage, anisotropic thermal expansion/contraction, and tool-part interactions.

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During autoclave cure, defects are typically suppressed by increasing the compaction pressure. Conversely, for low-pressure VBO prepreg cure, the compaction is primarily governed by a partially impregnated prepreg microstructure that features pervasive and highly permeable dry regions within the fiber tows [6]. These "evacuation channels" allow entrapped air or vaporized moisture to migrate towards the laminate boundaries and escape into the bag during the early stages of cure process. They are subsequently infiltrated by nearby resin to form a fully saturated microstructure. Despite these characteristics, higher void contents have been associated with elevated levels of dissolved moisture [5, 7], excessive out-time [8], and low-temperature cure cycles [4] that inhibit resin flow into the dry evacuation channels. Such defect sources are relevant to both flat and complex geometries. Fortunately, their effects may be minimized by rigorous process control during material handling, layup and cure. Due to their partial impregnation, VBO prepreg plies have a higher bulk factor (ratio of initial thickness to final thickness) than comparable autoclave prepregs [9]. Consequently, they must undergo greater compaction during cure, and may be more difficult to conform to non-flat geometries.

Investigators have identified several issues that arise specifically during the manufacturing of complex shape laminates. Ply layup over curved surfaces can pose difficulties due to the limited drapeability of the fiber bed. Furthermore, at corners, the pressure distribution between the mold-side and bag-side surfaces of thick laminates can be uneven, creating non-uniform compaction conditions [10]. This effect is particularly pronounced for prepreg product forms with high bulk factors. Prepreg and consumable materials can bridge over concave molds or wrinkle over convex tooling [11], introducing in-plane stresses and adversely reducing the compaction pressure over mold corners. Finally, large deformations can affect the initial prepreg microstructure, and hence alter its original permeability. While void content remains a major concern, commonly observed

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microstructural defects in complex shape laminates also include ply wrinkling, corner thickening or thinning for parts manufactured on concave or convex tools, respectively, and, in extreme cases, delamination [11]. Moreover, resin cure shrinkage and anisotropic thermal expansion can induce residual stresses in angle laminates during autoclave processing, leading to dimensional changes such as spring-in at corners and warpage in flat sections [12, 13].

Resin flow and fiber bed compaction are critical governing factors for defect formation in complex shape laminates. Percolation flow, during which the resin transport occurs relative to a compacting fiber bed, and shear flow, during which the fiber bed and resin are considered an inextensible viscous fluid, are the two major mechanisms of flow behavior during cure [14]. The compaction of angle laminates involves the interaction of both mechanisms [11, 15]. In addition to resin flow and fiber bed compaction, studies also show that during autoclave processing, the lay-up method has a significant effect on the thickness uniformity of cured laminates, while the corner curvature radius, flange length and laminate thickness have less effect on the thickness uniformity of the cured quasi-isotropic laminates than on the [90o]n laminates [16]. Within this context, the low compaction pressure available during VBO cure and the distinctive flow and compaction characteristics of VBO prepregs are likely to further complicate the fabrication of complex parts.

Studies on the OoA/VBO manufacturing of laminates with corners or other sharp curvatures have been reported. Laminates manufactured over concave (female) tools exhibited resin accumulation and corner thickening, whereas corner thinning was observed for convex (male) tooling, in agreement with their autoclave counterparts [17]. Lightfoot et al. [18] suggested a mechanism of wrinkling formation in L-shape laminates governed by the shear force generated by mismatches of coefficient of thermal expansion between tool and laminate, as well as ply slippage during compaction, and experiments based on this mechanism were able to minimize wrinkles and

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severe in-plane misalignments. Brillant and Hubert [10,19] studied the effect of different bagging configurations on thickness uniformity and void content in L-shaped concave and convex laminates with various laminate thicknesses and corner radii. Their results showed that void content and thickness variation could be greatly influenced by lay-up strategies. Levy et al. [20] proposed an analytical corner compaction model for L-shaped laminates that accounted for local pressure difference and interplay friction, and data from the model agreed with experiments. Cauberghs and Hubert [21] focused on the effect of Z-shaped tight corner geometry with one convex corner between two concave corners and the levels of connectivity required between ply drop-offs and the vacuum source. They showed that resin accumulation in concave corner regions was associated with consumable bridging, and low void content could be achieved by connecting the dropped plies to the vacuum source.

More complex OoA/VBO composite structures were also evaluated in previous studies. For example, Grunenfelder et al. [22] studied the void content in embedded doublers that consisted of a local build-up of additional plies in regions of laminates and hat-stiffeners. Results showed that voids within the embedded plies could be reduced by fostering air evacuation through prepreg plies impregnated on only one side and longer vacuum hold times prior to cure. Finally, Hughes and Hubert [23] investigated how quality changes with part size and complexity scale-up. They observed that while the microstructural quality of small-scale samples was indicative of what were observed in samples extracted from a large-scale part, the physical and manufacturing parameters governing part quality could interact to increase void content and render industrial-scale manufacturing challenging.

The literature cited above clarified several phenomena governing the manufacturing of complex shapes, and confirmed that deviations from a flat geometry introduce additional defect

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sources during VBO processing. However, the fundamental aspects of VBO prepreg compaction, which are affected by local regions with complex geometry, remain unclear. Moreover, most studies have focused on L-shaped or C-shaped laminates with 90° angles, and have not analyzed the effects of other geometries, or of increasing geometric complexity. Finally, effective strategies to limit defect levels and ensure part quality remain elusive, but highly sought after.

1.1 Objectives and Structure

Several factors are typically considered during studies that seek to optimize processing. Some, including the prepreg format and ply stacking sequence, are "intrinsic" to the part and cannot be easily adjusted due to material availability, design constraints, and desired mechanical properties. Others, such as processing conditions and tool design, are "extrinsic" and can be altered to maximize quality if the relevant scientific relationships are understood. In this work, we seek to identify the effect of key processing conditions and tool characteristics (extrinsic factors) on part quality for several prepreg and laminate combinations (intrinsic factors). We focused on a generic part geometry consisting of a corner located between two flanges. First, we studied the effect of increasing geometry complexity by varying tool corner angles for two prepreg materials and various thicknesses. Then, we investigated three feasible process modifications: variation to local corner radii, the use of intermediate vacuum hold prior to oven cure, and the application of pressure intensifiers at corners. This study aims to expand the existing knowledge of OoA processing by clarifying the compaction mechanisms that lead to defects in complex shape laminates, and form the basis for practical guidelines for the selection of mold designs and processing parameters that mitigate defects and improve part quality.

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2. Methods

Corner laminates were manufactured using VBO prepreg processing. Two extrinsic factors, mold design and pressure application methodology, were considered in detail. These factors are specifically relevant to non-flat geometries, and can be adjusted feasibly within a production environment. In addition, several intrinsic factors, including prepreg product and laminate thickness, were also varied.

Mold Design. The typical tooling used in this study is shown schematically in Figure 1. A total of six tools were used to manufacture parts. Each corner angle was associated with two tools, which featured sharp corners or corners with finite radii of curvature. Each tool included both concave and convex corner regions, allowing concave and corner laminates to be manufactured simultaneously. Specific corner angles (30o, 45o, 60o) were chosen to evaluate the effect of increasing geometric complexity on laminate quality, while various corner radii (0 mm, 6.35 mm, 9.53 mm, 12.7 mm) were selected to verify the effect of local geometric discontinuity. The tools were machined from a single billet of aluminum to avoid leaks, and surfaces were fine-polished.

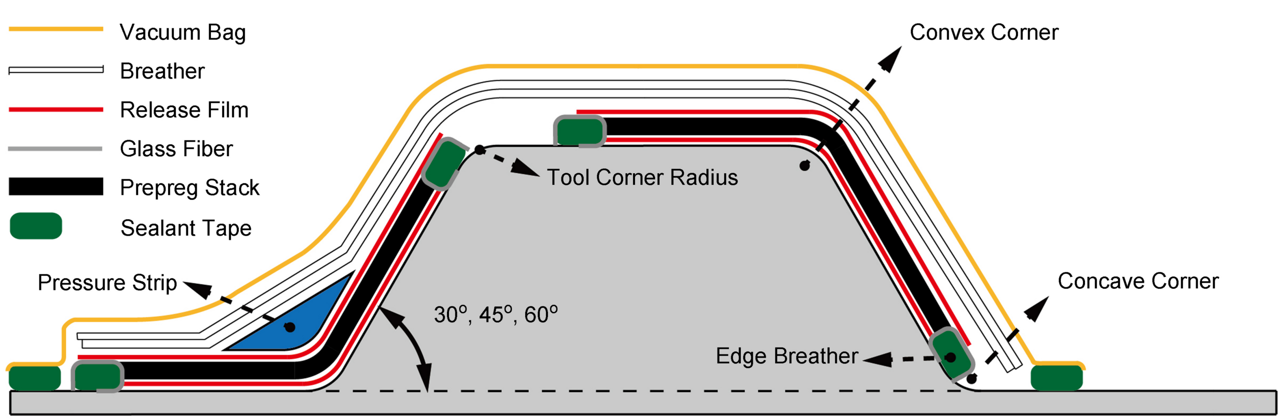

Figure 1: *Schematic illustration of mold design and bagging configuration*

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Materials. Experiments were carried out using two kinds of prepregs designed for OoA processing. The first, denoted “prepreg A,” consisted of a toughened epoxy resin (Cycom 5320) and a five-harness satin (5HS) carbon fiber fabric (T650-35 3K). The second, “prepreg B,” was comprised of a later-generation OoA resin (Cycom 5320-1) and an eight-harness satin (8HS) carbon fiber fabric (T650-35 3K). Both fabrics possessed the same areal weight (375 g/m2). The two resins can, and were, cured at the same temperature. However, the resin of prepreg B was less reactive, exhibiting a longer out-life (30 days at ambient conditions, versus 21 days for prepreg A), thus requiring a longer cure at a given temperature. Note that the freezer storage time of prepreg A exceeded the 12 months freezer storage time stated by the manufacturer, resulting in reduced tack and potentially other resin degradation phenomena, whereas prepreg B underwent negligible storage time, and was therefore comparatively pristine. Both materials were used within the study because, as described below, prepreg A was more prone to voids and consequently highlighted several trends.

Cure. The laminates were manufactured using traditional OoA/VBO prepreg processing protocols. Figure 1 shows details of the layup configuration. Prepreg plies measuring 76.2 mm (width) by 63.5 mm (flange) by 63.5 mm (flange) were laid up on non-perforated release film in the 0o direction (along the laminate length). Edge-breathing dams, which provided paths for air evacuation while preventing resin bleed, were placed along the laminate perimeter. A second non-perforated release film was placed on top of the laminate. Two layers of breather were applied evenly on the top of the parts within the bag. In some cases, pressure strips were used to intensify the compaction pressure locally, at the corners. The vacuum bag was finally set, with excess bag material located at the corner region to prevent bridging. After a vacuum bag was assembled and vacuum was drawn with a stand-alone vacuum pump (Busch R5), a leak test was performed by

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measuring the pressure inside the vacuum bag using a pressure gauge to ensure that sufficient vacuum was drawn in the bag and no leak was present. First, the vacuum pump was disconnected from the bag. Then, the gauge was used to ensure that the vacuum level within the bag did not decrease by more than 1” Hg (3.3 kPa) in five minutes, as recommended by the manufacturer. The laminates were cured in a convection oven (Thermal Product Solutions Blue M). Manufacturer recommended cure cycles were used in all laminates, consisting of a four-hour room temperature vacuum hold prior to cure, a 1.5°C/min ramp rate, and a 121°C dwell of two hours for prepreg A or three hours for prepreg B.

Test Matrix. The five sets of manufactured parts are summarized in Table 1. First, Sets I and II studied the effect of laminate thickness (four and eight plies), geometric complexity (corner angles of 30°, 45° and 60°) and corner type (concave and convex). These laminates comprised a baseline

Set	Material	Debulk	Pressure Strip	Tool Shape	Corner Radius/mm	Corner Angle	No. of Plies
I	Prepreg A	None	None	Concave	0	30°, 45°, 60°	4, 8
		None	None	Convex	0	30°, 45°, 60°	4, 8
II	Prepreg B	None	None	Concave	0	30°, 45°, 60°	4, 8
		None	None	Convex	0	30°, 45°, 60°	4, 8
III	Prepreg B	Yes	None	Concave	0	30°, 45°, 60°	8
		Yes	None	Convex	0	30°, 45°, 60°	8
IV	Prepreg B	None	None	Concave	9.53, 12.7	30°, 45°, 60°	8
		None	None	Convex	6.35, 9.53	30°, 45°, 60°	8
V	Prepreg B	None	Yes	Concave	0, 9.53, 12.7	30°, 45°, 60°	8

Table 1. Test matrix

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dataset that was used to evaluate the effect of further process modifications. In Set III, the influence of intermediate debulking was assessed by applying a five-minute vacuum hold after laying down every 2 plies. In Set IV, the effect of mold corner curvature was analyzed, using corner radii of 9.53 mm and 12.7 mm for concave corners and 6.35 mm and 9.53 mm for convex corners. Finally, in Set V, the local pressures at the concave corners were intensified by the application of pressure strips. One laminate was manufactured for each test point.

Quality Analysis. Two samples were cut along the laminate length from each laminate for analysis. To avoid edge effects, samples were taken no closer than 10 mm from the end. The two inward-facing cross-sectional areas were polished to 2400 grit abrasive using a metallographic grinder/polisher (Buehler MetaServ). A digital stereo microscope (Keyence VHX-600) was used to capture micrographs over the entire cross-sectional area at a 100 × magnification. These individual micrographs were stitched into a complete image of the cross-section. For convenience, the complete image was divided into a corner region and two flange regions.

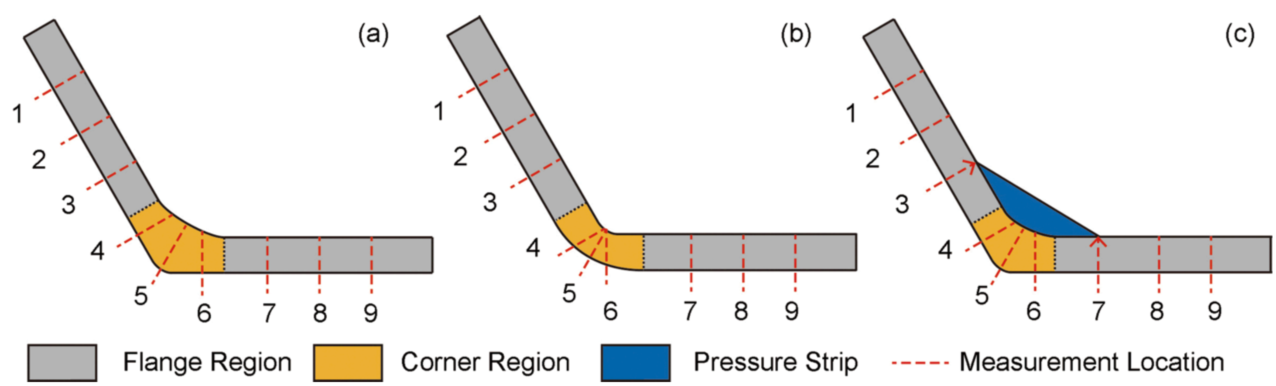

Figure 2: *Thickness measurement locations for: (a) concave corner laminate, (b) convex corner laminate, (c) concave corner laminate manufactured with a pressure strip*

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Laminate quality was analyzed on the basis of void content and thickness variation, two frequently used defect metrics that can be accurately quantified via light microscopy. The void content was measured using image analysis software (ImageJ) by converting the stitched color image to 8-bit binary image, selecting the void regions, applying a binary threshold, and calculating the ratio of void area to total cross-sectional area within the region of interest. The void contents within the flange and corner regions were calculated individually for comparison. To quantify the thickness variability, nine measurement locations were selected, with three located in the left flange, three in the corner, and three in the right flange (Figure 2). The thickness at each individual location (xi) was then measured from the micrographs. The coefficient of variation (CoV) of the thickness, shown in equation (2), was used to compute a single numerical metric for the thickness non-uniformity of the entire laminate (n is the number of measurement locations). Other microstructural features, such as resin accumulation, were analyzed individually as described in the following section.

$$\bar{x} = (x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9)/9 \tag{1}$$

$$Coefficient\ of\ Variation = \frac{1}{\bar{x}}\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}} \tag{2}$$

3. Results and Discussion

3.1 Sets I and II- General Defects in Sharp Corner Laminates

The two main defects observed in laminates were thickness variation and void content, both of which were concentrated in corner regions. Figure 3 (a) shows void contents in laminates made of prepreg A as a function of laminate thickness in flange regions, concave corner regions and convex

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corner regions, respectively. The average void contents over the entire cross-sections were < 2% in all prepreg A laminates. However, void contents were < 0.5% in laminates made of prepreg B, which was much less than those in the corresponding prepreg A samples. The relatively high void content in prepreg A laminate was attributed to the prepreg age, which resulted in reduced tack and potentially compromised the ability for resin to flow and eliminate entrapped air. For prepreg A, the void content increased with laminate thickness in a quasi-linear manner in all three regions, but the defect level increased more markedly in the concave corner regions than in the convex corner regions, where behavior was similar to that of the flange areas. In contrast, the void content in prepreg B was negligible, and no clear trend was observed.

Figure 3 (b) shows the coefficient of variation (CoV) for thickness of concave and convex laminates made of prepreg A. The thickness variation in concave parts was generally greater than those in convex parts. Furthermore, in the concave laminates, for a given number of plies, the CoV

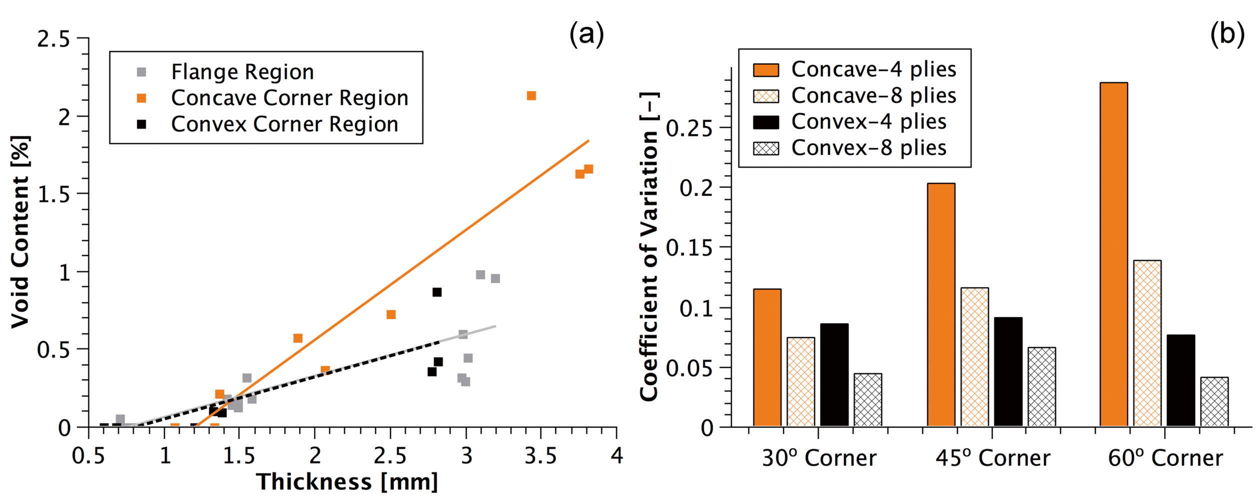

Figure 3: *Laminates made of prepreg A: (a) void content in flange region, concave corner region and convex corner region; (b) thickness variation*

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increased linearly with corner angle. However, this trend was not consistent in convex corner parts. For a given corner angle, the CoV decreased as the laminate thickness increases in both mold types. Similar thickness variation behavior was observed in prepreg B laminates, as shown in Figure 4, indicating that prepreg age affected the amount of voids but not the variation in laminate thickness, and that mechanisms governing laminate dimensional uniformity were therefore generally applicable. Laminates with a wider flange on one side (127 mm (flange 1) versus 63.5 mm (flange 2)) were also manufactured to evaluate the effect of flange width, and results showed that flange width had no significant effect on thickness variation of laminate or on fiber distribution.

Figure 5 shows representative micrographs of laminates manufactured over concave and convex molds. Microstructural defects were observed, including voids, corner thickening and corner thinning, and resin accumulation. Generally, more defects were observed in the concave molded laminates than in their convex counterparts. In the concave corner, resin was accumulated beyond the fiber bed, resulting in greater thickness changes in corner regions, while curvature radii

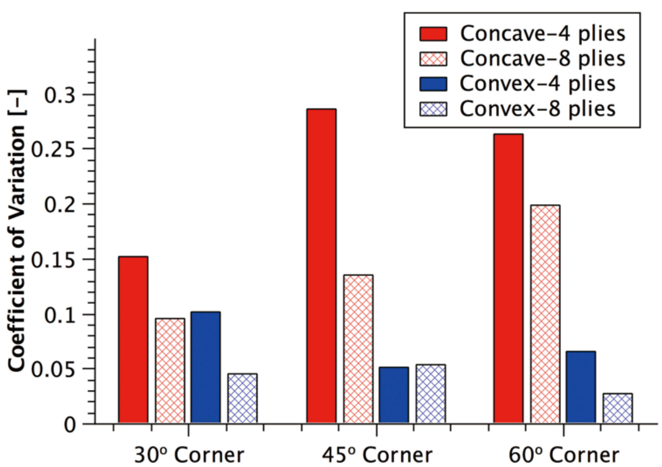

Figure 4: *Thickness variation of laminates made of prepreg B*

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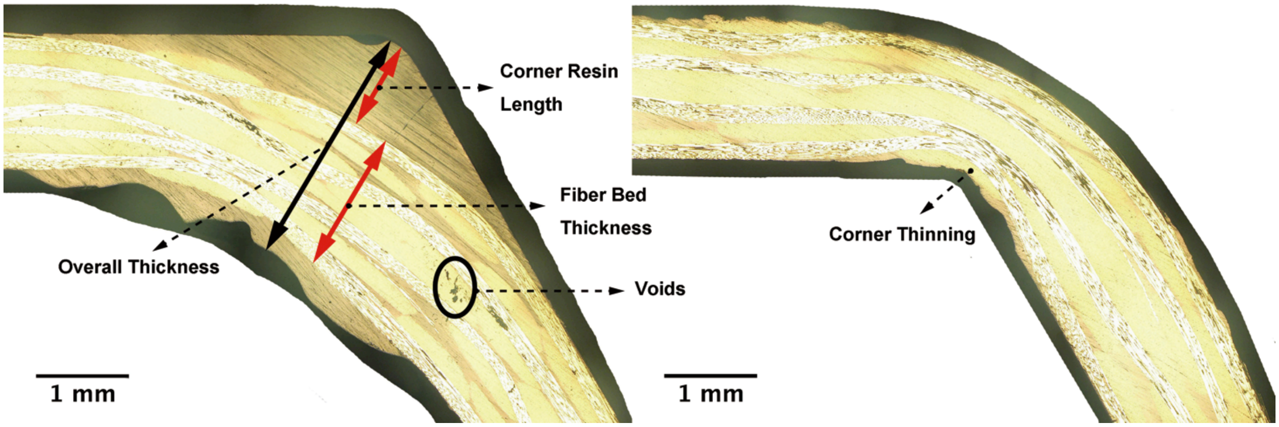

Figure 5: *Defects in corner laminates: (a) concave corner, (b) convex corner*

of the fiber bed were consistent through the thickness. In the convex corner, no resin accumulation was observed, although the radius of curvature of the fiber on the mold side was significantly less than others on the bag side, leading to convex corner thinning and increased thickness variation.

To identify the fundamental causes of thickness non-uniformity, microscopic inspection was used to measure the CoV of the fiber bed thickness, independent of the overall laminate thickness. Figure 5 (a) shows how the measurement of both thickness values was performed at a given location. Figure 6 compares the overall thickness variation measured from such micrographs to that of the fiber bed thickness in prepreg B laminates. Figures 6 (a) and (b) display graphs of four-ply and eight-ply data, respectively. In concave corner laminates, the CoV of the fiber bed was significantly less than that of the laminate thickness, but remained greater than that of the flanges. This difference, along with observations of consistent fiber curvature radius through the thickness, suggested that thickness variation in concave laminates was caused mainly by resin accumulation at the concave corner. The stiffness of the fiber bed and its inability to conform to the sharp mold radius during low pressure processing was a contributing but minor cause. Conversely, in convex

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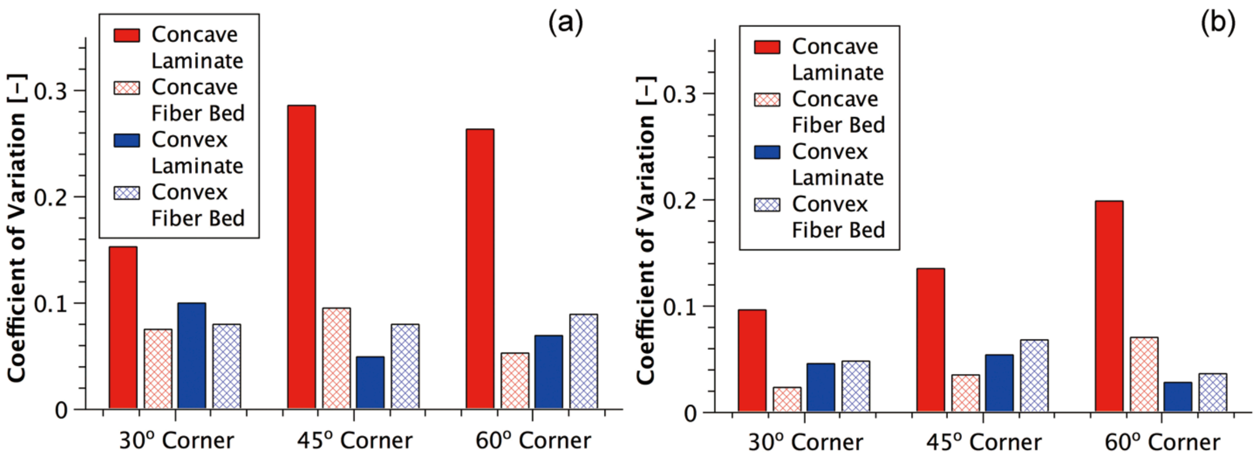

Figure 6: *Overall thickness variation and fiber bed thickness variation in prepreg B laminates: (a) four-ply laminates, (b) eight-ply laminates*

corner laminates, the two thickness data sets were generally comparable. Locally, the fiber bundles nearest the mold had a curvature radius of 0.8 mm, which was much less than that of the far-field plies (4 mm). This specific difference implied that in convex laminates, corner thinning arose due to increased compaction pressure at the sharp corner region but was limited by the average stiffness of the fiber bed during low-pressure processing.

To support this assertion, the length of the accumulated resin region in concave corners was measured directly from micrographs (as shown previously in Figure 5 (a)). Figure 7 shows the concave corner resin length as a function of corner angle in prepreg B laminates. The resin length generally increased with corner angle, just as the CoV of the overall thickness increased, confirming that thickness variation in concave laminates was generated primarily by resin accumulation.

From the results described above, we concluded that defect formation mechanisms in concave corner laminates were more prone than their convex counterparts to parameters such as corner

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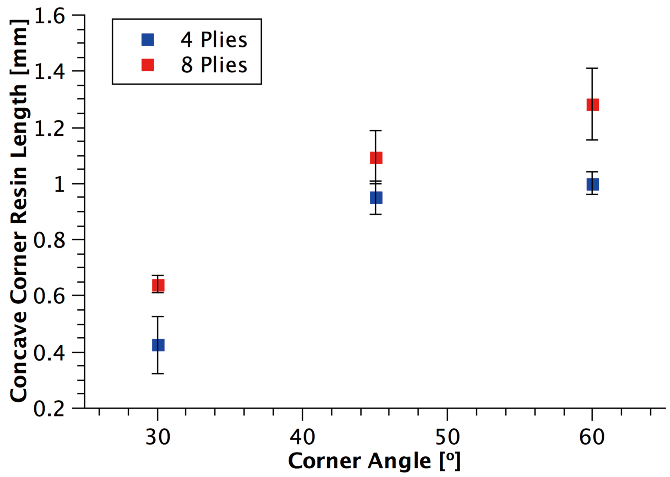

Figure 7: *Concave corner resin length in laminates made of prepreg B*

angle and laminate thickness. In concave parts, both the inability of the fiber bed to conform to the tool under low compaction pressure, and the consequent resin accumulation, adversely influenced the laminate dimensional uniformity. Furthermore, low compaction force also increased the likelihood of void formation. Conversely, the stiffness of fiber beds in convex corners prevented corner thinning during low-pressure processing, thus reducing thickness variation. The dataset presented above forms a benchmark against which further process modifications were evaluated.

3.2 Set III - Effect of Intermediate Debulk Method

Intermediate debulking can improve compaction and reduce void content in laminates by ensuring that individual prepreg plies conform to substrate layers during layup, and by allowing entrapped air pockets to escape more readily. Laminates consisting of eight plies of prepreg B were cured on both concave and convex tools, with vacuum compaction applied every two plies for 5 minutes during layup. Microscopic inspection of polished sections revealed that most of these laminates were void-free. This represented a marked improvement from laminates manufactured without intermediate debulking, which exhibited voids.

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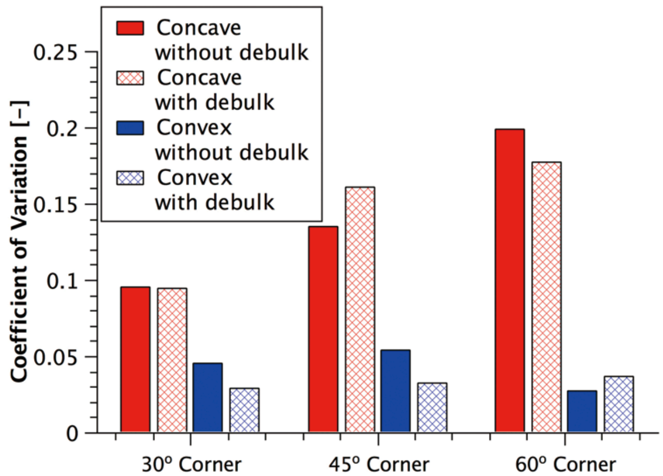

Figure 8: *Thickness variation of laminates manufactured with and without debulking*

Figure 8 shows a comparison of thickness variation in laminates with select corner angles processed with and without debulking. The CoV was not strongly affected by debulking, and no clear trend was observed across all corner angles. The inconsistent and negligible nature of the effect was confirmed by comparing the corner resin length in concave laminate, which was also insensitive to debulking. These results indicated that the debulking steps used in this study contributed to the removal of entrapped air and reduced the void content, but did not affect the conformation of the prepreg laminate to the tool.

3.3 Set IV - Effect of Mold Corner Radius

Eight-ply laminates of prepreg were manufactured on molds with varying corner radii. Because concave corner laminates were shown to be more prone to defects than convex corner laminates, larger corner radii (9.53 mm and 12.7 mm) were selected for the concave tooling than for the convex tooling (6.35 mm and 9.53 mm). No debulking was carried out.

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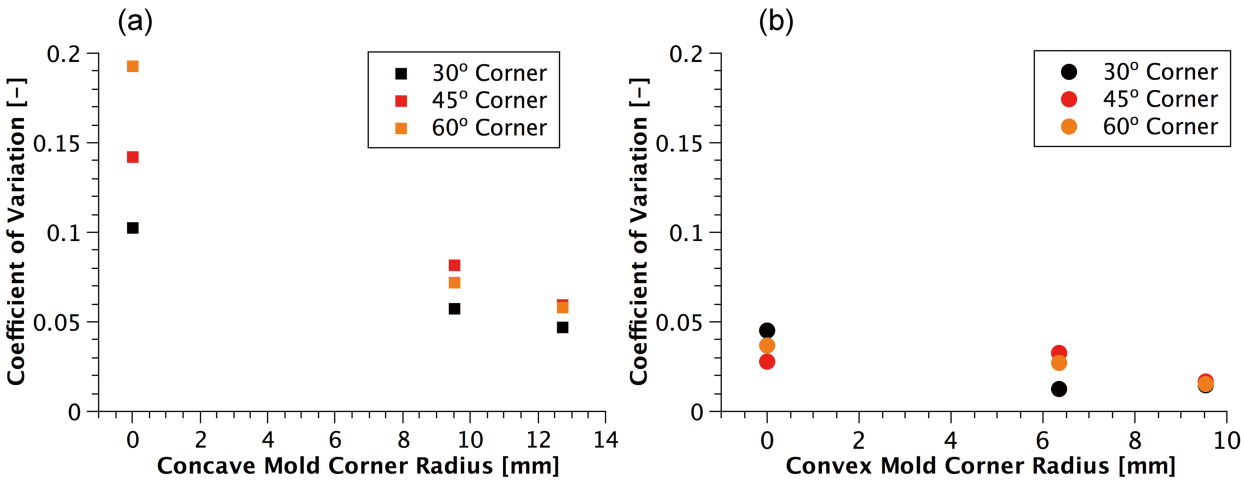

Figure 9: *Thickness variation of laminates manufactured with various tool corner curvatures: (a) concave corner laminates, (b) convex corner laminates*

Inspection of polished sections revealed that resin accumulation within the corner regions was almost eliminated in all cases. Figure 9 (a) and (b) show the CoVs in concave and convex laminates versus mold radius. In concave laminates, the CoV decreased with increasing corner radius. Moreover, the difference in thickness uniformity between corner angles was also greatly reduced. Molds with large corner radii required the fiber bed to deform less, and therefore prevented resin accumulation. In concave laminates fabricated on molds with radii of 12.7 mm, the CoV decreased close to that of the flanges (about 0.02). In convex laminates, larger corner radii also decreased the thickness variation, but the effect was less pronounced than in concave corner parts, since only the prepreg plies closest to the tool were affected.

These observations indicated that increasing the radius of curvature of the mold was an effective and practical approach to reduce (or control) thickness variation at corners in low-pressure VBO processing, especially when concave tooling was used. In addition, increasing the corner curvature could also counteract the detrimental effects of increasing geometric complexity,

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allowing parts with large corner angles to attain the same dimensional consistency as those with smaller angles.

3.4Set V - Pressure Strip Application

The pressure distribution conditions at a concave corner can be improved by using a pressure strip (a silicone insert) placed between the bag-side release film and the breather. The strip concentrates the pressure at the corner region, while potentially mitigating the effects of consumable bridging. Laminates comprised of eight plies of prepreg B prepreg were fabricated using pressure strips over molds with sharp corner radii (as in Sets I and II) and corner radii of 9.53 mm and 12.7 mm (as in Set IV). During layup, the pressure strip material was carefully shaped into the form of the concave mold. Debulking was not performed.

Figure 10 presents the thickness variation of laminates produced with and without pressure strips. For molds with corner radii of 0 mm and 9.53 mm, thickness variation was greatly reduced by deployment of pressures strips, indicating that the insert redistributed pressure and concentrated compaction force at corner regions, increasing the extent of conformation of the fiber bed to the

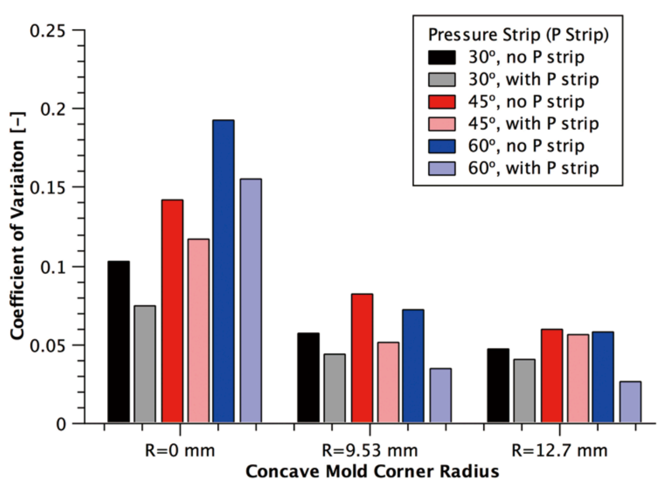

Figure 10: *Thickness variation of laminates manufactured without and with a pressure strip*

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tool surface. However, the pressure strip did not affect laminates produced using the mold with a corner radius of 12.7 mm, since the tool geometry already reduced the CoV close to flange levels.

These results indicated that the application of pressure strips was an effective method for reducing thickness variation in laminates produced over concave molds with relatively low corner curvatures (0 mm and 9.53 mm). They are therefore well-suited to situations in which the part geometry is tightly prescribed and cannot be locally adjusted by changing the mold geometry.

While the use of pressure strips effectively reduced CoVs in concave laminates, poorly compacted areas (or laminate fillets) were sometimes observed at the boundary of the region of application, as shown in Figure 11 (a). These defects were sensitive to the manner in which the pressure strip was placed, and could be eliminated by carefully designed layup. However, they reduced the robustness of the process. In addition, the use of pressure strips was also associated with concentrated void distributions along the pressure strip, as shown in Figure 11 (b). These

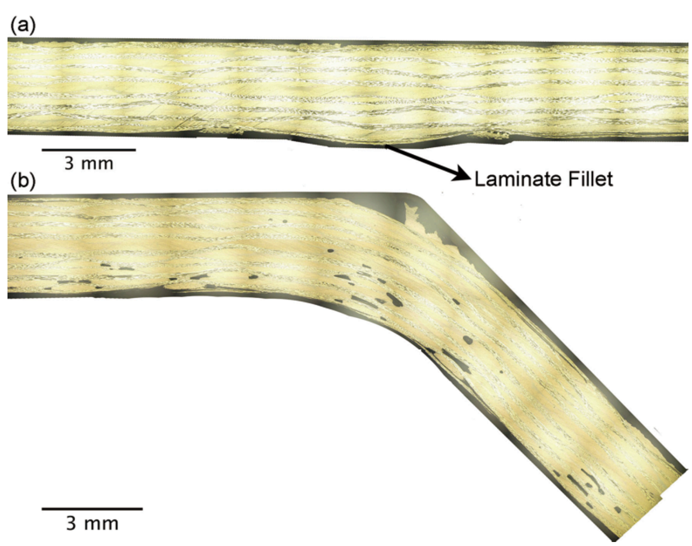

Figure 11: *Typical microscopic images of laminates manufactured with a pressure strip: (a) laminate fillet at the end of the pressure strip, (b) void distribution*

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voids were larger than those observed in previous laminates, and exhibited elongated ellipsoidal shapes. Increasing the room-temperature vacuum hold time from four hours to eight hours eliminated the voids. These defects can be attributed to the modified pressure distribution caused by the pressure strip. The fillets corresponded to the edge of the strip, which experienced a local and steep reduction in compaction pressure. The concentrated pressure caused by the strip could also possibly decrease the air permeability of the prepreg, reducing the rate of air evacuation and, for an equivalent ambient evacuation time, causing higher void contents. The longer room temperature vacuum hold allowed more time for the evacuation of entrapped air, and consequently decreased the void content.

4. Conclusions

We investigated several aspects of the OoA manufacture of VBO prepreg laminates with corner geometries. First, concave and convex corner parts were manufactured for various corner angles and laminate thickness levels and from two prepreg materials. Polished sections revealed that for both concave and convex parts, defects were concentrated in corner regions, and increasing geometric complexity led to a reduction in quality. However, defects levels were always greater in concave laminates than in convex laminates. Microstructural data indicated that two different mechanisms caused the dimensional non-uniformities. For concave laminates, corner thickening was primarily associated with resin accumulation due to reduced compaction pressure and the inability of the fiber bed to conform to the geometry of the tooling. Conversely, in convex laminates, corner thinning was caused by uneven pressure distribution but counteracted by the stiffness of the fiber bed. The void content was primarily affected by the prepreg age, with the

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aged material exhibiting greater void content. However, void content was also associated with the compaction quality, with greater laminate thicknesses leading to higher voids levels.

Based on these observations, three defect reduction strategies were considered: intermediate debulking, variation in the mold corner radius, and the use of a pressure strip intensifier. Debulking was an effective means of reducing void content in laminates, providing evidence that air entrapped between plies during layup was a key source of voids. Increasing the mold corner radius improved quality by allowing the fiber bed to conform to the tool and reducing the potential for resin accumulation. The pressure strip effectively concentrated pressure in concave corners, and improved the quality of laminates fabricated on molds with tight corner radii, although air evacuation was partially impeded.

The results presented here can be used as guidelines for reducing defects and optimizing a manufacturing cycle. For example, for a given laminate layup and geometry (corner angle), a concave molding set-up may be converted to a convex one to reduce defect levels. The results further indicated that this conversion is particularly important when transitioning from an autoclave to an OoA environment (e.g., vacuum bag). If concave tooling is specifically required, the local mold geometry can be modified to increase the corner radius and reduce resin accumulation. Moreover, a pressure strip can be used to further control local defects. Interestingly, the effects of increasing geometric complexity can be counteracted by relatively simple modifications to the mold corner radius or by using a pressure strip, enabling the fabrication of more aggressive geometries. Finally, for a generic set of prepreg, laminate, and molding conditions, these results provide approximate predictions for laminate quality.

The shift from autoclave to non-autoclave manufacturing methods necessarily eliminates the safeguards associated with elevated pressure. As a result, the successful expansion of OoA

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manufacturing requires the development of optimized and robust processes, as well as more careful attention to protocols. The present study reveals some of the fundamental phenomena associated with low-pressure processing of corner laminates, and provides a basis for developing effective manufacturing guidelines. The existing literature suggests that size and complexity scale-up may also complicate other phenomena that govern quality, including air evacuation. Furthermore, such scale-up may also lead to non-ideal temperature and pressure distributions within the vacuum-bagged part. As a result, the insights developed here must be combined with further research on factors affecting prepreg compaction, and with the development of more accurate predictive simulations for compaction, cure, and microstructural quality.

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