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ANALYSIS OF VBO GOVERNING SEQUENCE TO MINIMIZE POROSITY IN OUT-OF-AUTOCLAVE PREPREGS

The out-of-autoclave process is being used instead of the autoclave process due to its lower manufacturing costs to obtain products of the same quality. It is seen that in the out-of-autoclave, pre-cure processes like compaction in the vacuum bag, the bagging sequence, vacuum pressure as well as the application time of vacuum are the major factors to produce acceptable quality parts, especially aero structure parts. In this study we will discuss how the bagging sequence, along with a change in the consumable materials, affects the final porosity. The void content for different bagging sequence conditions was analyzed by means of C-scan and microsection analysis on OOA prepreg laminates. It was noted that the bagging sequence and consumable materials may cause the porosity to be as low as ≈ 0.23% to as high as ≈ 4.24%.

Keywords: out-of-autoclave, porosity, prepreg laminates, surface

INTRODUCTION

The out-of-autoclave process for the manufacturing of high-performance composite parts, especially aero structure parts, is becoming an increasingly suitable alternative to the traditional autoclave process due to its lower manufacturing costs. It is well understood that neither out-of-autoclave nor autoclave processes produce 100% defect-free parts. Despite the ability of autoclaves to manufacture better quality parts, they are very costly and require a substantial investment. Furthermore, large parts cannot be manufactured easily as they are dependent on the capacity of the autoclave. Therefore, prepregs were developed that could be cured in vacuum only, i.e. using a traditional oven. From this, the OOA manufacturing process was born, with carbon epoxy prepregs that could be cured at a lower temperature than autoclave prepregs. Thus, the advancement of OOA part manufacturing processes is necessary, with a focus on simplification, reduced financial costs, a reduced cycle time, reduced lead time and greater environmental sustainability [1]. This process achieves the same quality as that of an autoclave but through a different fabrication process. However, the mechanical properties are not as good as those of autoclave prepregs. New prepregs were then produced using a toughened epoxy resin, resulting in parts with improved mechanical properties and a higher glass transition temperature (Tg), which allowed a higher service temperature [2]. Aero structure parts require a less than 2% void content to attain good mechanical properties [3]. The mechanical properties of composite parts are greatly affected by the porosity level, e.g. if there is a 1% increase in the void content, the intralaminar shear strength will be reduced by 7% due to the propagation and promotion of crack initiation [4].

In the out-of-autoclave process, a vacuum bag only (VBO) technique is used to remove entrapped air from the porous network between the resin, fibers, and interlaminar spaces. Laminates fabricated using proper VBO techniques have shown properties equivalent to laminates fabricated in an autoclave. Many researchers have compared the mechanical properties of OOA processed laminates and autoclave processed ones. A Tencate TC-350 prepreg was cured using both autoclave and VBO methods, and their properties (mechanical) were examined by Villareal et al. [5]. The mechanical properties (tensile, compressive and flexural strength) were found to be equal for both sets of laminates. Courter et al. reported that the Toray T700G/2510 unidirectional VBO prepreg was cured using VBO and autoclave methods [6]. In this scenario, the oven-cured composite laminates had a greater void content and thickness than the autoclave cured composite ones as well as reduced mechanical properties. Cytec VBO prepregs (5215 and 754), which are first-generation ones, also exhibit mechanical properties equivalent to traditional autoclave materials. Both the woven fabric preform and unidirectional fibers exhibit equivalent glass transition temperatures in addition to other mechanical properties [7].

Later-generation prepregs (Cytec 5320 and 5320-1) also demonstrate equivalent properties [8].

The National Aeronautics and Space Administration (NASA) conducted a detailed study on comparison of the properties of OOA laminates and autoclave cured ones. Two autoclave carbon fiber epoxy composites (IM7/8552-1 and IM7/977-3) and two OOA carbon fiber epoxy composites (IM7/MTM45-1 and T40-800b/5320) were used for their study [9]. They were fabricated using both hand layup and fiber placement processes. Their out-time was also taken into account. Many properties were also taken under consideration such as the void content and mechanical properties. They also included short beam shear, fracture toughness, compression and open hole compression. Tack measurement was additionally performed on them. The out-time was more important in the VBO prepregs than the autoclave prepregs. They showed a decrease in the tack level, a higher void content and reduced mechanical properties in the cured laminates. When fresh VBO prepregs were used to cure laminates, it was found that they had a quality equivalent to that of autoclave processed parts in the tests that were performed. The parameters that affect the quality of VBO cured laminates were also studied.

The effects of the post-cure temperature on the compressive properties of the Cytec 5320 prepreg were investigated in [10]. Laminates were fabricated using a two-hour cure at 93°C and post-cure at 100-145°C. Combined loading compression (CLC) testing was used to analyze the performance of the laminate. The results showed there was a relation between the degree of cure, CLC strength and glass transition temperature. These properties increased with a high post-cure temperature and exhibited improved resin properties.

The above findings indicate the ability to fabricate autoclave quality parts using OOA process techniques. Nonetheless, they relate to small and flat laminates only. The manufacture of large and complex composite parts creates additional challenges.

Apart from entrapped air, there are other sources of voids that are also present like insufficient resin flow and evolved gases that can be handled during curing. Commercial prepregs used in the out-of-autoclave process do not demonstrate 100% impregnation (DI); instead, the prepregs are characterized by partial impregnation of the fibers by resin [11]. Moreover, some networks of these partially impregnated fibers, known as engineering vacuum channels, allow the migration of entrapped air towards the laminate boundaries [12]. If a fully impregnated prepreg is not used in OOA, individual voids remain in the prepreg because the atmospheric pressure is insufficient to collapse these voids, and also during curing the pressure gradient is not enough to allow sufficient resin flow to direct the voids towards the venting ports [13].

The publication of Thorfinnson and Biermann [14] showed that for the same resin and fiber material, a laminate which is has a DI (Degree of Impregnation) of 60% contains a very low void content compared to a laminate with a DI of 93%.

Notwithstanding, partially impregnated fibers also act as sources of voids that we intentionally introduce during the manufacturing of prepregs to allow the migration of entrapped air towards the venting port. In advanced out-of-autoclave prepregs, fully impregnated fibers with an addition of single dry fibers that act as a channel for evacuation are being used to prevent the difficulties that occur in partially impregnated fibers.

In this paper, the aim is to investigate whether the bagging sequence, along with a change in the consumable materials and curing profiles affects the final porosity. The bagging sequence in VBO also plays a vital role in the minimization of voids. The layup in VBO usually follows the sequential arrangement of peel ply, prepreg, bleeder fabric, vacuum bag, etc. This study will discuss the best sequence, along with the materials used in VBO, and will delineate how the sequence can impact the final porosity of the component. The goal is to examine and understand the effect of these processing parameters on laminated composites with complex shapes.

MATERIALS AND METHODS

Materials

High performance epoxy matrix out-of-autoclave carbon prepregs, HexPly® M56/40%/193PW/AS4-3K, were used to manufacture laminated composite samples. Figure 1 shows the HexPly® M56 prepreg, with yellow dry fibers that act as engineering evacuation channels for entrapped air. During the vacuum hold, these dry (yellow) fibers act as a path for entrapped air, which direct it towards the venting ports. The M56 resin is designed for oven cure at 180°C for 120 min with a 60 min dwell phase at 110°C respectively. The specified out life of the resin is 35 days, and the freezer life is 18 months from date of manufacture.

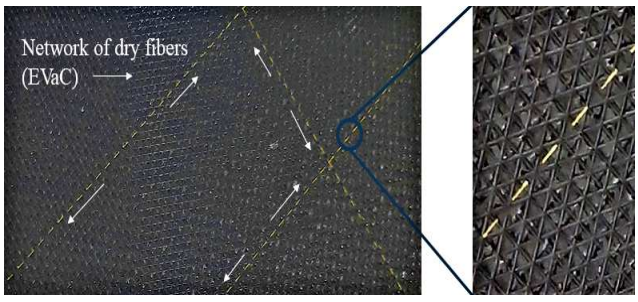

Fig. 1. Views of prepreg showing EVaC yellow dry fibers in HexPly® M56/40%/193PW/AS4-3K

All the laminates were fabricated on the same aluminium mold. Prior to use, the mold surface was prepared by orbital sanding with 80-grit sandpaper.

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Laminate manufacturing

The laminates were cured by VBO processing in an air-circulating oven. The hand layup technique was used to make the laminates. After the hand layup, vacuum debulking was performed to evacuate entrapped air through the vacuum port. The cure cycle was consistent with the manufacturer's recommendations; a schematic diagram of the cure cycle is shown in Figure 2. The cure cycle contained two dwell phases; in first dwell phase the soaking temperature was 110°C, and the holding time was 60 min. Similarly for the second dwell phase, the holding time was 120 min and the soaking temperature was 180°C. Here the heating rate was kept at 1°C/min for the first rise and 0.5°C/min (a lower rate for the second rise is to accommodate the heat release due to the exothermic reaction, which is usually observed in thicker laminates) for the second rise, whereas the cooling rate was 1.5°C/min. Also, a 0.85 bar vacuum was applied up to the end of the first dwell phase, and was reduced to a 0.5 bar vacuum till the end of the cycle. The vacuum bag assembly, shown in Figure 5, consists of a mold, the peel ply, the laminate, a perforated release film, a bag-side non-perforated fluorinated ethylene propylene (FEP) release film, edge breathing dams, dry glass fabric, a layer of breather and the vacuum bag. For liquid release, a commercial agent (Frekote 700NC) was applied on the mold three times in succession, allowing each coat to dry five minutes before applying the next layer. After the third coat, the mold was dried for thirty minutes before laying up the laminate.

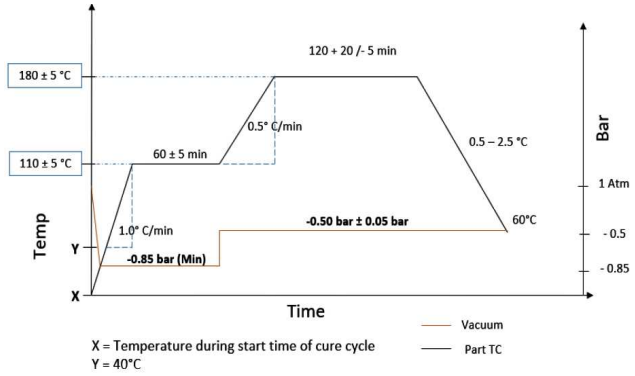

Fig. 2. Schematic diagram of hexcel recommended M56 cure cycle

TABLE 1. **Experimental details of laminates**

Laminate	Dimensions [inches]	Variant	Peel ply material
1	20×20	48 layers with caul plate and without hot debulking	Cytec polyester (85 GSM)
2	20×20	48 layers without caul plate and without hot debulking	Cytec polyester (85 GSM)
3	20×20	48 layers without caul plate and without hot debulking	Cytec polyester (85 GSM)
4	20×20	48 layers without caul plate, with hot debulking, change of peel ply material, and three dwell phases	Airtech nylon (62 GSM)

The size of each laminate was 20" x 20" x 0.4" with a $[90°/45°/–45°/0°]_{12S}$ woven fiber orientation. In total, 4 laminates of 48 layers with different sequential arrangements were produced for this study, as listed in Table 1. The materials used in the VBO bagging sequence are listed in Table 2.

TABLE 2. **Consumable materials used in VBO**

Consumable	Consumable material
Peel ply	Cytec 60001 NAT or Airtech nylon (62GSM)
Breather	N10 Airtech
Release film	FEP1 Mil thick A4000
Bagging film	Wrightlon 8400 3 Mil
Edge breather	7781 Style Glass
Sealant tape	Airtech GS43 or equivalent

Curing profiles

Once the laminates completed their curing cycles in the oven, the mold was allowed to cool down. The laminates were removed from the mold and underwent C-scan examination, followed by microstructure evaluation to calculate the percentage of porosity in each cured laminate. The C-scan was performed on an Olympus OmniScan MX series machine using the through transmission method with a frequency of 2.5 MHz. To perform the C-scan of the actual laminates, a standard reference laminate was manufactured and provided with some voids for evaluation and comparison of the results.

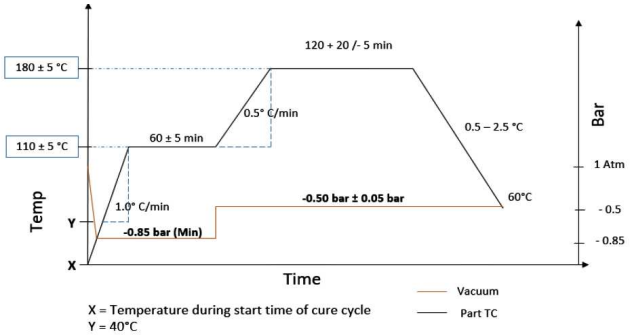

Fig. 3. Cure cycle for Laminates 1, 2 and 3 (hot debulking for 60 min at 60°C)

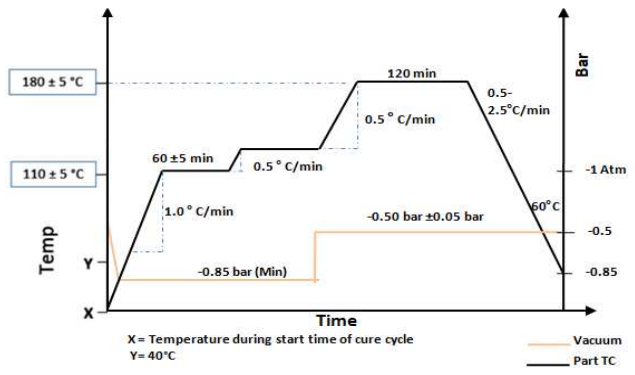

Fig. 4. Cure cycle for Laminate 4

Porosity measurement

For the microstructure evaluation, micrographs of each laminate surface were recorded at 20x magnification using an Olympus MX-50 microscope and analyzed with Olympus image analysis software dedicated to porosity analysis. Two samples were analyzed from each laminate; one sample for the lower dB value and another sample for the higher dB value obtained from the C-scan examination.

RESULTS AND DISCUSSION

The publications of Repecka et al., Ridgard, and Naresh et al. discussed several features usually encountered in VBO prepregs and highlighted the importance of the layup and bagging sequences [7, 15, 16]. The bagging sequences with the consumables are shown below in Figure 5. The bagging sequence is as follows: release agent, peel ply, prepregs, bleeder fabric, caul plate, breather fabric, vacuum bag, etc.

Before starting the layup, we ensured that the dust level in the clean room was less than 3,520,000 per m^3 and the dust particle size 0.5 µm according to ISO class 8. The room temperature and relative humidity were maintained at 22 ± 3°C and 40 to 60%, respectively. The positive pressure inside the clean room must be a minimum of 5 Pa greater than the surroundings so that dust particles may not enter the clean room.

Results for Laminate 1– 48 layers with caul plate and without hot debulking

To achieve the best monolithic laminate quality, Hexcel recommends the bagging sequence for HexPly® M56 shown in Figure 5a and 5b. For Laminate 1, we employed the Hexcel recommended cure cycle and bagging sequence. In addition to the Hexcel recommended bagging sequence, we added a cured silicon rubber caul plate after the non-perforated release film A rubber caul plate is used to transmit uniform normal pressure and provides a uniform smooth surface.

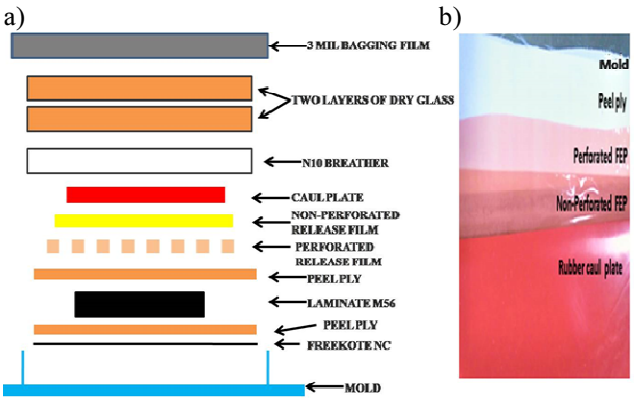

Fig. 5. Diagram of bagging sequence with caul plate (a), Photograph of layup consumables (b)

Vacuum debulking was applied to the first ply, followed by sequential arrangement of the consumables. After every third layer of prepreg layup, three suction ports were applied for 10 min to evacuate the entrapped air between the plies. The vacuum pressure through each port was 28 Hg. The laminate was then cured as per the cure cycle shown in Figure 3. During post curing, the laminate underwent C-scan examination, followed by microstructure evaluation to calculate the porosity level or percentage of porosity.

In the reference laminate as shown in Figure 6a, some voids were introduced intentionally for reference purposes. It was observed that in the reference laminate, the values corresponding to the voids lie at less than 45 dB, which is treated as a bad area and greater than 45 dB treated as a good area. For the actual laminate, two samples of the low dB value ~10 to 45 dB, Area 1 shown in Figure 6c, and the ~20 to 30 dB value, Area 2 shown in Figure 6d, were considered for porosity analysis. It is clear from Figure 6 that the acceptable area only corresponds to a high dB, i.e. > 45 dB.

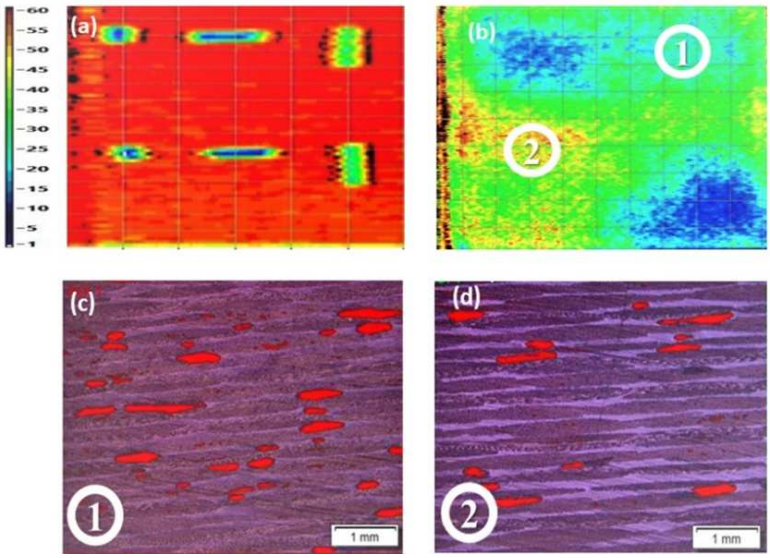

Fig. 6. C-scan attenuation plot for reference laminate (a), C-scan attenuation plot for Laminate 1 (b), Microsection image of Area 1 (~15 to 25 dB) (c), Microsection image of Area 2 (~20 to 35 dB) (d)

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The results of the microsection analysis of both the samples are shown in Table 3. The observed porosity values for the dB values in the range of ~15 to 25 was 4.24% and for ~20 to 35 it was 2.19%, which are unacceptable for aero structure components.

TABLE 3. **Results of microstructure analysis of samples from Laminate 1**

Sample S	Porosity [%]	Pore count	Planer pore density [mm^{-2}]	Max pore size [µm]
S1 at ~15 to 25 dB	4.24	1308	53.84	1165.37
S2 at ~20 to 35 dB	2.19	1081	44.63	1235.06

The thickness of the caul plate will play a major role during curing. The greater thickness of the caul plate, the less the application of uniform pressure to the part is since the OOA material will be cured only with vacuum. This may create resin-rich areas wherever uniform pressure was not applied and may also create porosity resulting in dB loss. Moreover, the caul plate used should be a little smaller in dimension than the actual part because there is a chance that it may block the edges of the air path.

Results for Laminate 2 – 48 layers without caul plate and without hot debulking

For Laminate 2, all the production parameters conditions were the same as for Laminate 1 except omission of the caul plate from the VBO sequence as shown in Figure 7a and 7b. During post curing, the laminate underwent C-scan examination, followed by microstructure evaluation to calculate the porosity level or percentage of porosity.

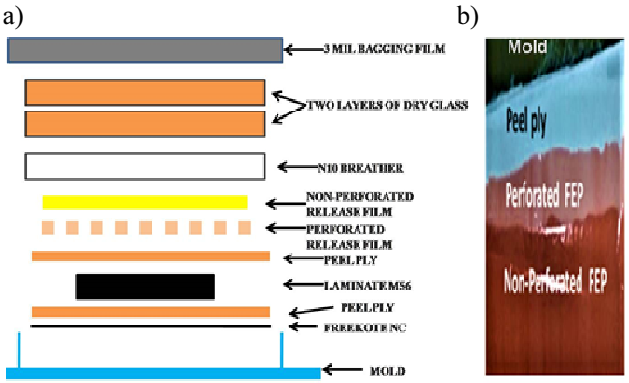

Fig. 7. Diagram of bagging sequence (a), photograph of layup consumables (b)

The observed dB values are a minimum of 8 dB and a maximum of 55 dB. Two samples of the dB value ~35 to 40, Area 1 shown in Figure 8c, and the ~20 to 30 dB value, Area 2 shown in Figure 8d, were considered for porosity analysis. The results of the microsection analysis of both the samples are shown in Table 4. For dB values in the range of ~20 to 30, the observed porosity was 4.24%, whereas for ~35 to 40 dB, the observed porosity was 2.19%, which are unacceptable for aero structure components.

It is clear from Table 4 that Laminate 2 exhibits better results as compared to Laminate 1. The removal of the caul plate created a major difference as vacuum is applied to the layers directly. Reason being is that the use of the caul plate blocks the path of entrapped air, which will remain in the final component as porosity. Also, the breather plies are in direct contact with the fibers through the peel ply, which was difficult in the case of Laminate 1. This helped to control the voids or porosity compared to Laminate 1. Still, the thickness of the laminate is greater, and the desired result could not be achieved, leading to more dB loss.

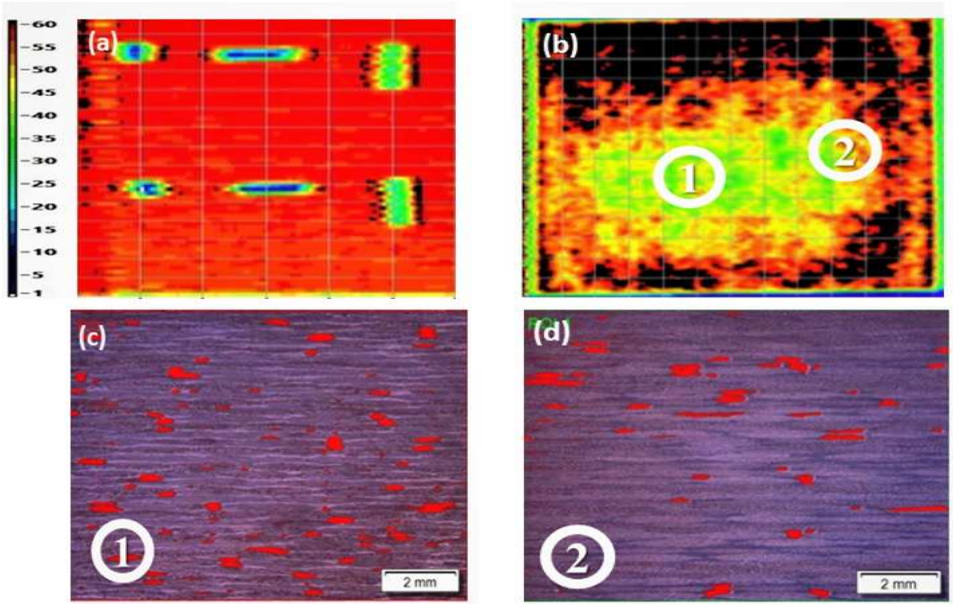

Fig. 8. C-scan attenuation plot for reference laminate (a), C-scan attenuation plot for Laminate 2 (b), Microsection image for bad area corresponding to ~20 to 30 dB value (c), Microsection image for bad area corresponding to ~35 to 40 dB value (d)

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TABLE 4. **Results of microstructure analysis of samples from Laminate 2**

Sample S	Porosity	Pore count	Planer pore density [mm^{-2}]	Max pore size [µm]
S1 at ~20 to 30 dB	3.79%	2494	25.88	1785.43
S2 at ~35 to 40 dB	1.95%	1127	20.37	1241.45

Results for Laminate 3 – 48 layers without caul plate, with hot debulking

For Laminate 3, all the production parameters were the same as Laminate 2 except the fact that it underwent hot debulking for 60 min at 60°C, as shown in Figure 9, which is less than the minimum required temperature for the initiation of polymerization of the resin. During post curing, the laminate underwent C-scan examination, followed by microstructure evaluation to calculate the porosity level or percentage of porosity.

The results of the C-scan for Laminate 3 with microstructural analysis are shown in Figure 10. The observed dB values were a minimum of 40 dB and a maximum of 60 dB, which demonstrate good agreement with the porosity level. Two samples at ~55 to 60 dB (Sample 1), shown in Figure 10c, and ~50 to 55 dB (Sample 2), shown in Figure 10d, were considered for microstructural analysis. The observed value was 0.36% for Sample 1 and 0.93% for Sample 2. Other details of the porosity analysis are shown in Table 5.

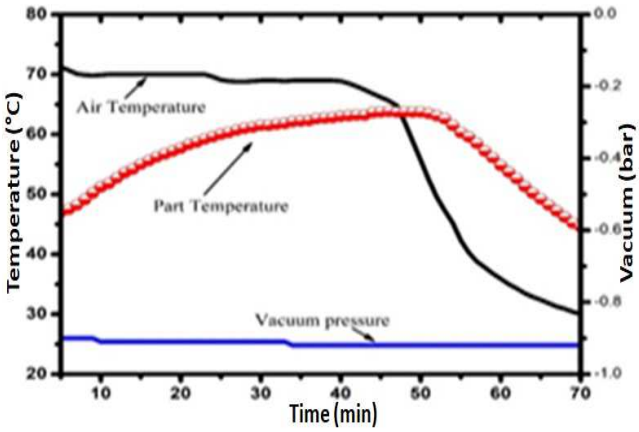

Fig. 9. Experimental hot debulking cycle

TABLE 5. **Results of microstructure analysis of samples from Laminate 3**

Sample S	Porosity	Pore count	Planer pore density [mm^{-2}]	Max pore size [µm]
S1 at ~50 to 55 dB	0.93%	144	1.53	1906.34
S2 at ~55 to 60 dB	0.36%	150	1.59	613.18

The reason for attaining better results is that during hot debulking extra heat is imparted to the setup, which allows the laminate of prepregs to compress easily, and ensures a stronger and reliable cure by limiting the number of voids in the layup.

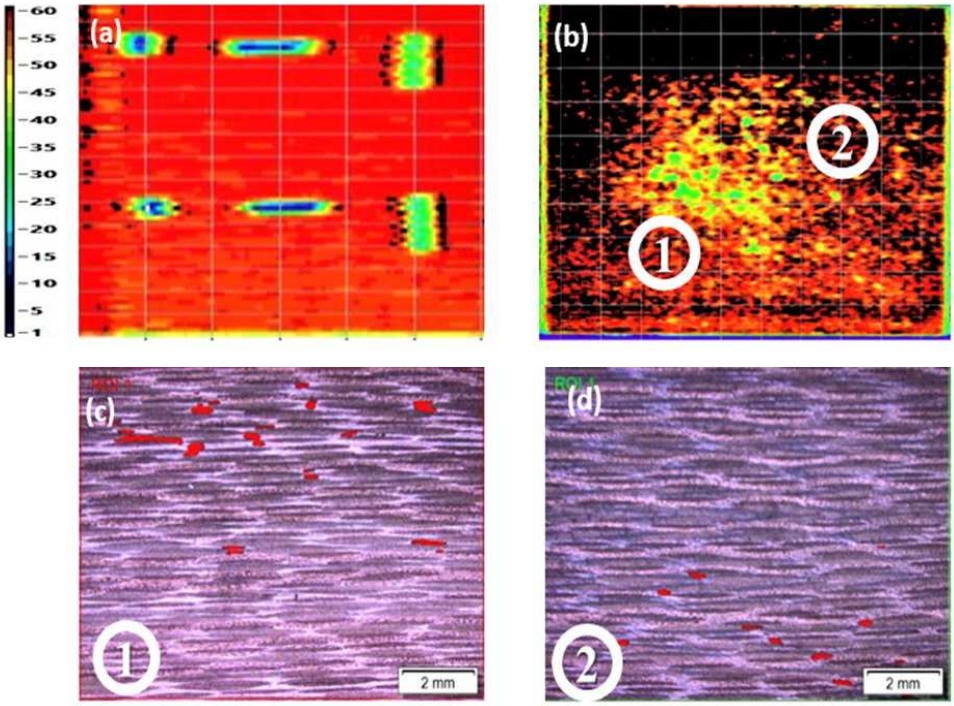

Fig. 10. C-scan attenuation plot for reference laminate (a), C-scan attenuation plot for Laminate 3 (b), Microsection image for good area corresponding to ~50 to 55 dB value (c), Microsection image for good area corresponding to ~55 to 60 dB value (d)

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Results for Laminate 4 – 48 layers without caul plate, with hot debulking, changed peel ply material from Cytec polyester (85 GSM) to Airtech nylon (62 GSM), and with three dwell phases

For Laminate 4, all the production parameters were the same as for Laminate 3 except for the fact that it underwent an additional dwell at phase at 125°C for 60 min, as shown in Figure 11. It is common for an exothermic reaction to occur during the transition phase from solid to gelation of the resin due to the formation of secondary and tertiary amines. During this period, the temperature rises owing to exothermic heat, resulting in localized polymerization of the matrix phase of the composite, which leads to non-uniform curing. During post curing, the laminate underwent C-scan examination, followed by microstructure evaluation to calculate the porosity level or percentage of porosity.

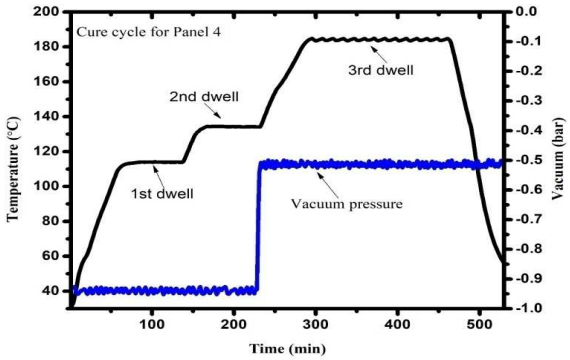

Fig. 11. Cure cycle with three dwell phases for laminate

In Laminate 4, another major change was the fact that the material of the peel ply was changed from Cytec polyester (85 GSM) to Airtech nylon (62 GSM). Both nylon- and polyester-based woven fabric are used in the advanced composite industry. The primary function of using peel ply is to obtain the desired surface finish on the cured laminate. It is usually the impression of the woven fabric left on the surface that ensures the desired surface roughness. This roughness is a key factor during the adhesive joining of two composites. Moreover, the peel ply has a permeable and woven structure which absorbs the excess resin during curing. More resin bleeding was found through the polyester peel ply, resulting in a greater dB loss, whereas there was a little less in the nylon peel ply. In our study, it was observed that after the curing, the weight of the peel ply increased ~35% for the Cytec polyester peel ply (85 GSM). Initially, the weight of the dry peel ply before curing was 18.7 g and after curing it increased to 29g; this extra weight is due to resin bleeding into the peel ply that can be utilized for filling the voids. For the Airtech nylon (62 GSM) peel ply, the observed increase in weight was ~21%. Before curing the weight was 13.64 g and after curing it was 21.8 g.

By changing the peel ply material and introducing an intermediate dwell phase, we observed an appreciable reduction in the void content. Figure 12 shows the C-scan attenuation plot for Laminate 4 having a maximum dB value of ~60 and a uniform attenuation plot. Two samples with dB values ~55 to 57 (Sample 1), and ~55 to 60 dB (Sample 2), were considered for microstructure analysis, as shown in Figure 12c and 12d. The observed value of porosity was 0.23% for Sample 1 and 0.63% for Sample 2. Other details of the porosity evaluation are shown in Table 6.

TABLE 6. **Results of microstructure analysis of samples from Laminate 4**

Sample [S]	Porosity	Pore count	Planer pore density [mm^{-2}]	Max pore size [µm]
S 1 at ~ 55 to 57 dB	0.23%	689	7.14	729.63
S2 at ~ 55 to 60 dB	0.63%	454	4.67	1307.10

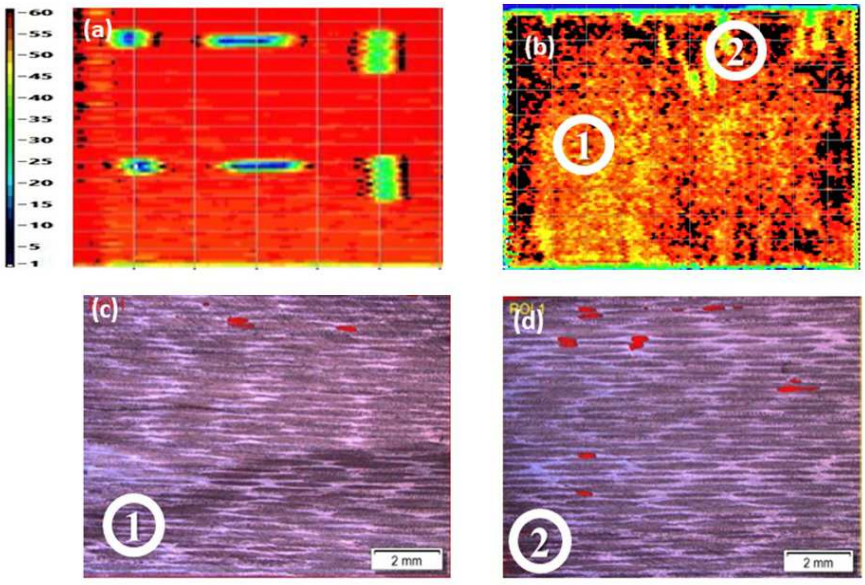

Fig. 12. C-scan attenuation plot for reference laminate (a), C-scan attenuation plot for Laminate 4 (b), Microsection image for good area corresponds to ~55 to 57 dB value (c), Microsection image for good area corresponds to ~55 to 60 dB value (d)

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The publications of Di Landro et al. and Lee et al. [17, 18] discussed the effect of an exothermic temperature rise when curing in an oven, which is undesirable. In the case of epoxy, the matrix and amines act as hardeners during the exothermic chemical reaction. The epoxy bond splits into a hydroxyl group and secondary amines; these secondary amines further react with the epoxy and form tertiary amines along with a hydroxyl group. This chain reaction process occurs till the end of curing. The exothermic temperature rise is due to the additional reaction of the primary amines. Due to this chemical reaction, a difference in enthalpy occurs between the start and end of the reaction. It is well understood that the thermal conductivity of epoxy resin is much less and heat remains entrapped locally within the matrix. Owing to this localized heating non-uniform polymerization of the resin takes place, which is undesirable.

Consequently, we can conclude that different laminates produced employing different process parameters with varying consumable materials may greatly impact the porosity of the final cured component. Figure 13 shows a porosity graph for all the produced laminates. The average porosity values for Laminates 1, 2, 3, and 4 are 3.215, 2.87, 0.645 and 0.43%, respectively.

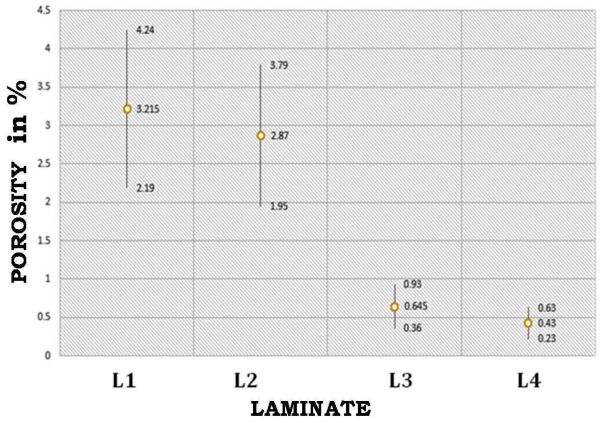

Fig. 13. Graph of porosity for all laminates

CONCLUSIONS

HexPly® M56 with a $[90°/45°/–45°/0°]_{12S}$ woven fiber orientation was manufactured in OOA. In our study we used 4 variants as follows:

- Laminate 1 – 48 layers with caul plate and without hot debulking
- Laminate 2 – 48 layers without caul plate and without hot debulking
- Laminate 3 – 48 layers without caul plate and with hot debulking
- Laminate 4 – 48 layers without caul plate, with hot debulking, three dwell phases and exchanged peel ply material Cytec polyester (85 GSM) for Airtech nylon (62 GSM)

This study investigated the effects of variable processing parameters including vacuum bagging techniques (bagging sequence), a change in the consumable materials (caul plate, peel ply), curing profiles (manufacturer's recommended curing cycle and extended manufacturer's recommended curing cycle). The results presented in this study could also be extended to other OOA processes with various complex part geometries. In this study, we demonstrated the roles of several material and processing parameters in void formation and mitigation. The air trapped during the layup process and curing was identified as the source of porosity of the cured composite laminates. On the basis of our study following points can be concluded:

- Removal of the caul plate in the vacuum bagging sequence can reduce the porosity by freeing the path for entrapped air, which was blocked in Laminate 1. The recorded values of porosity with removal of the caul plate for Samples 1 and 2 of Laminate 2 are 1.95% corresponding to the dB value ~35 to 40 and 3.79% corresponding to the dB value ~20 to 30.
- It is seen that for a thick laminate, hot debulking gives better results. In hot debulking extra heat is imparted to the VBO setup to allow the laminate of prepregs to compress easily. After hot debulking Laminate 3 exhibited a reduced porosity level of 0.63% compared to Laminate 2, which had a porosity level of 2.87%.
- The impact of the change in the peel ply material recorded in this study was that the polyester peel ply (85 GSM) absorbed 10.3 g of the bled resin, whereas the nylon peel ply (62 GSM) absorbed only 8.16 g of the bled resin during curing.

A change in the VBO governing sequence was not the primary focus of this particular study, and further investigation is required to draw conclusions about the formation and mitigation of porosity that arises from non autoclave curing. For voids that arise from entrapped air, the results confirm that a change in the vacuum bagging technique, consumables and curing cycle are the primary drivers of effective mitigation. As aero structure parts require a less than 2% void content to attain good mechanical properties, porosity levels will continue to play a major role in consumer acceptance**.** Non-autoclave cured parts will only be successful if the defects usually restrained by autoclave pressure are eliminated, and the performance is comparable to parts processed in an autoclave. Due to the lack of high pressures to limit the various sources of deformities, imperfections and variability, OOA prepregs in particular are susceptible to the entrapment of air and gas-induced voids. Nevertheless, all sources of porosity can be managed by fabricating prepregs with increased air evacuation. These defect reduction strategies can enhance fabrication efficiency and sustainability by minimizing the steps required to manufacture a part, a common objective within the composites industry.

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