EFFECT OF PROCESS PARAMETERS ON THE QUALITY OF LAMINATES MADE BY AUTOMATED FIBER PLACEMENT (AFP) USING OUT-OF-AUTOCLAVE (OOA) PREPREGS

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Keywords: Automated Fiber Placement (AFP), Out-of-Autoclave (OOA), Void Content, Prepreg, Manufacturing Parameters

Abstract

There are two aspects in this work, out-of-autoclave (OOA) prepregs and automated fiber placement (AFP). Compared to autoclave materials, OOA materials do not need the use of pressure thus removing the need for an autoclave. However a vacuum is still required. Since, pressure is no longer present the sensitivity to void presence is much greater in laminates made using OOA prepregs. Changing various parameters during the deposition and curing can help reduce the amount of void. To get desirable void reduction, high temperature debulking was utilized. The high temperature helps with the resin flow which is essential to reduce void content. The AFP parameters such as compaction force and nozzle temperature when increased lead to an increase in void presence in the laminate due to the increase in overlaps.

1. Introduction

Compared to autoclave materials, OOA materials do not need the use of pressure during the curing cycle, thus removing the need for an autoclave. However, a vacuum is still needed. Some of the advantages of OOA are lower capital investment, production size is not limited by autoclaves, and larger parts can be cured [1]. In the AFP process, a computer controlled machine forms components by applying multiple layers of thin prepregs strips. Thus, AFP can provide repeatable parts at a higher material deposition rate compared to traditional layup in addition to reducing waste material [2].

When manufacturing laminates using OOA prepregs, due to the lack of pressure, cured OOA laminates are more sensitive to the presence of voids in comparison to laminates made by prepregs cured using an autoclave. Many techniques have been developed to alleviate this problem, such as frequent and longer debulking periods and long vacuum hold periods during cure [3, 4]. With AFP, the application of force during material deposition helps with material compaction, which can affect the void content. On the other hand, the use of thin prepregs tapes in the AFP process causes a buildup of gaps and overlaps, which can lead to the formation of voids in the CFRP laminates [5]. The work in this paper aims to evaluate the effects of different manufacturing parameters on the void content CFRP laminates made using OOA prepregs and AFP.

Excerpt from ISBN 978-3-00-053387-7

2. Manufacturing of Specimens

The use of Cytec Advanced Materials CYCOM 5320-1 prepreg was used to prepare the laminates. This prepreg is a new generation of OOA prepregs tailored specifically for automated manufacturing (The material utilized for these tests has aged for a considerable amount of time). All samples were made using the CONCOM Fibre Placement System, which deposits bands of 4 prepreg tapes with a width of 6.35mm (.25inch) each for a band width of 25.4mm (1inch). The stacking sequences can be found in Table 1 for the 8 layer, 16 layer and 24 layer laminate samples. Each sample has dimensions of 152.4mm by 152.4mm (6 by 6 inches).

Table 1. Stacking sequences.

No.	Type of Laminate	Laying Sequence	Number of Layers
1	Unidirectional	$[0]_8$	8
2	Cross-ply	$[0/90]_{2S}$	8
3	Quasi-isotropic	$[0/+45/-45/90]_S$	8
4	Quasi-isotropic	$[0/+45/-45/90]_{2S}$	16
5	Quasi-isotropic	$[0/+45/-45/90]_{3S}$	24

To cure the laminates, two different bagging procedures were used which can be seen in Figure 1. With the use of a Baldor Industrial Motor vacuum compressor, a vacuum of -100kPa was produced. The bagged sample is then placed in a Heratherm OMH-S Series oven for curing and high temperature debulking.

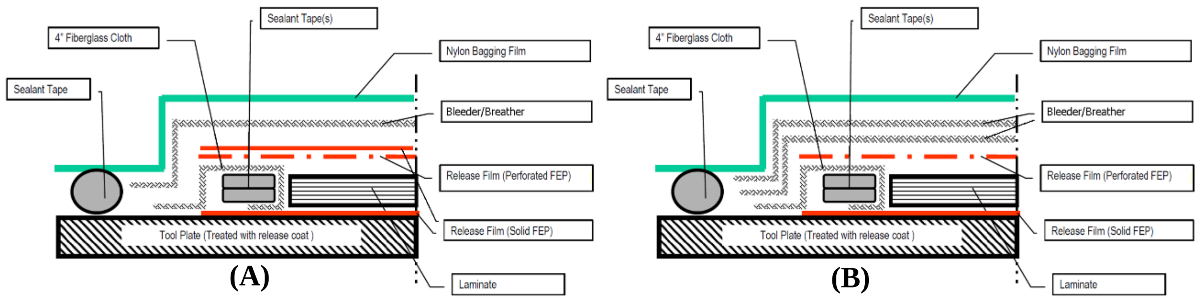

Figure 1: Bagging procedures (A) and (B)

In addition to two different bagging procedures, two cure cycles recommended by Cytec were investigated. Cure cycle A is as follows; ramp rate of 0.6°C/min, 12hrs at 93±6°C with a post cure at 177°C for 2hrs. The second cure cycle B is as follows; ramp rate of 0.6°C/min, 3hrs at 121±6°C with a post cure at 177°C for 2hrs [6].

2.1 Laminate Quality After AFP

With the use of AFP, there will be inherent defects associated with the manufacturing process. Gaps and overlaps are the main defects caused by AFP as the spacing between the adjacent tapes in the bands cannot be adjusted. In Figure 2 it can be seen how the accumulation of gaps and over laps deform the surface layer as well large void initiating at the edge of an overlapped tape.

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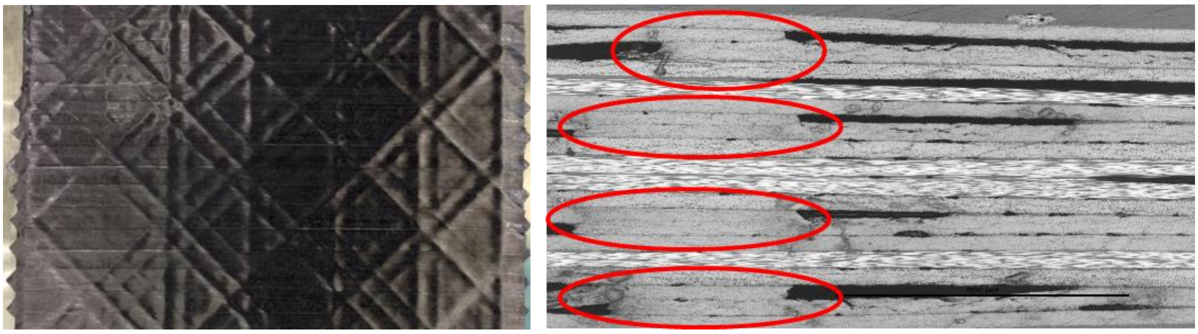

Figure 2: Visible ridges due to overlaps and gaps.

3. Void Calculation

To determine the void content, a sample is cut half way to produce approximately a 15mm by 152.4mm sample. This sample is further cut to approximately 15mm by 25mm samples. The resulting samples are placed in epoxy to make a puck. These pucks are then polished. The polished samples are examined under microscopes at X50 magnification. The resulting images are cropped to show only an image of the sample to remove the supporting epoxy from the image. The image is imported to ImageJ software, where the threshold of the histogram is set from 0 to 70. This converts the image to only show the voids. ImageJ, also allows to analyse the image with the measure tool and the results show the calculated void content in percent area [7, 8].

4. Experimental Outcomes

4.1 Debulking

Laminates were manufactured with the following constant AFP parameters: 30°C nozzle temperature, 18.14kg (40lbf) compaction force and deposition rate of 38.1mm/s (1.5inch/s). Three different stacking sequences were studied, which are unidirectional, cross-ply and quasi-isotropic with respective sequences 1, 2, 3 and 4 found in Table 1. Bagging procedure A was applied. After the hold period, samples were air cooled if needed and cut into samples. No curing was carried out.

4.1.1 Room Temperature Debulking

The laminates were subjected to debulking at room temperature for different periods to study the trend of void reduction. The experiments shows that unidirectional laminates would reduce to an average of 0.70% after 3hrs and a longer hold period did not show any significant improvements. However, with cross-ply laminates the reduction rate wasn’t as significant. After 3 hours the laminate still contained an average of 3.84% void content. To reduce the void content further longer hold times would be required. The trends can be seen in Figure 3.

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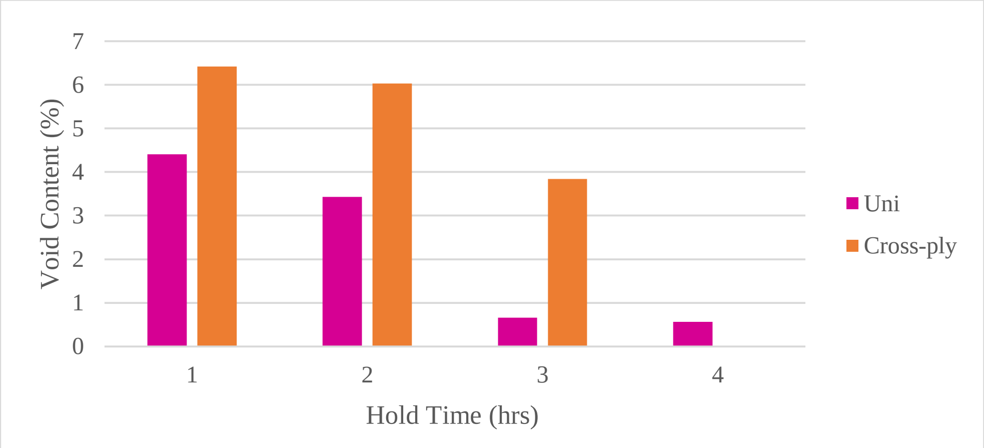

Figure 3: 8-layer RT debulking trend

4.1.2 High Temperature Debulking

For high temperature debulking the laminates were placed under vacuum at 50, 70 and 90°C. From the data obtained, a trend that the more complex the stacking sequence became the higher the final void contents. This can be associated to the increase in resistance to the flow of resin between plies. At 50°C the cross-ply samples with a 30min hold time, had a 3.91% void content average which reduced to 0.56% after 90mins. The results for 70°C were 0.93% and 0.49% for 30min and 2hr hold times respectively. Knowing this we did not expect decent results for quasi-isotropic at 50°C, thus we decided to only do the test for the quasi-isotropic samples at 70 and 90°C. At 70°C, 1.48% after 1hr and 0.18% after 2hrs was observed. With a 90°C hold temperature after 1hr the void content averaged 0.08% and reduced to 0.03% after 2hrs. From this we concluded that since, no curing to our samples was done any 8 layer laminate held under a vacuum at 90°C for one hour followed by post-cure at 177°C for 2hrs will result in high quality laminates. Micrograph of void content can be seen Figure 4.

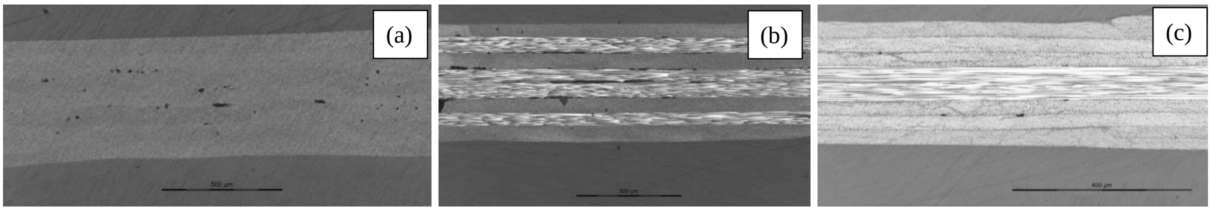

Figure 4: Micrograph of void content with high temperature debulking.
(a) Unidirectional, 70℃/2hrs, (b) Cross-ply, 70℃/ 2hrs, (c) Quasi-isotropic, 70℃/2hrs.

4.1.3 Debulking During Layup Procedure

Another form of debulking was performed to verify if any improvements in void content can be perceived. This involves debulking the laminate after every forth ply for 10min. The samples with stacking sequence 5 (Table 1), were manufactured using bagging procedure A and cure cycle A. The resulting void content for the debulked laminate was of 1.706% and 1.320% for two different samples. Other laminate that did not undergo the debulking resulted in similar void content which was 1.319% and 1.641%. This shows that debulking after every fourth ply results in no improvement in the void content.

4.2 Effects of Nozzle Temperatures

To study the effects of how the temperature of the AFP nozzle impacts the quality of the laminate, 24 layer samples (laminate type 5) were made using a compaction force of 18.14kg (40lbf). Bagging procedure B and cure cycle A were used for all samples. Temperatures of 30°C and 60°C were investigated. From the data obtained, it was determined that the increased temperature had negative effect on the void content. When the samples were made using 30°C an average void content of 0.05% was present, however at the higher temperature a content of 0.56% was present.

With the increase in nozzle temperature the prepreg tapes soften when being laid down. With softening the compaction force is able to compress the tapes to a greater extent. Doing so the width of the tape increases. Without being able to compensate for the added width of the tapes, as the band guides are fixed, overlaps of greater prominence were present in the laminates.

4.3 Effects of Compaction Force

To study the effects of how the compaction force applied by the AFP robotic arm during the material deposition procedure, a constant nozzle temperature of 60°C was held followed by bagging procedure B and cure cycle A. The laminates made for this study were 24 layer quasi-isotropic laminates, with the following compactions forces; 18.14kgf (40lbf), 27.22kg (60lbf) and 36.29kg (80lbf). Similarly to the increase in nozzle temperature, the increase in compaction force, also led to an increase in void content. The results can be seen in Figure 5 and Figure 6. The cause for the increased void content is the same as the increased compaction force. The increased compaction caused for more prominent overlaps.

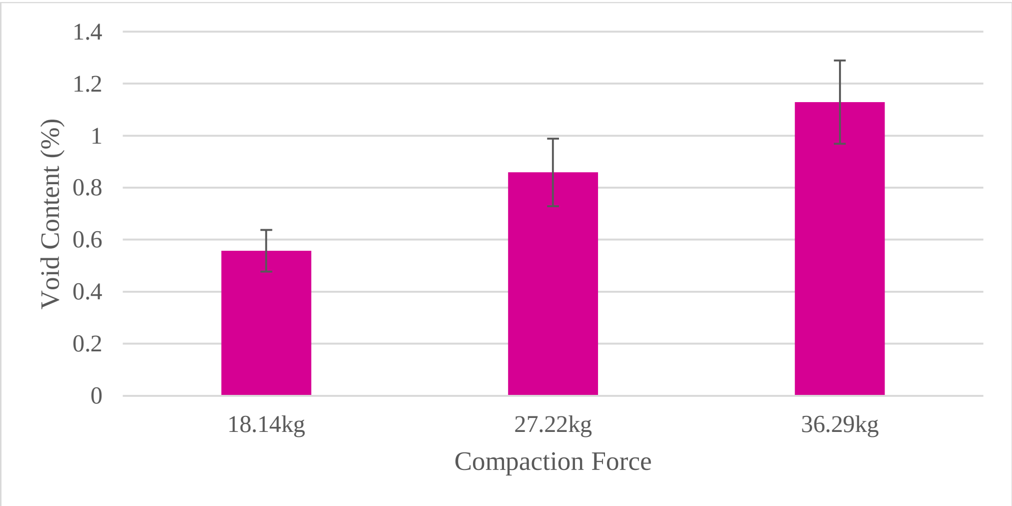

Figure 5: Void content vs compaction force

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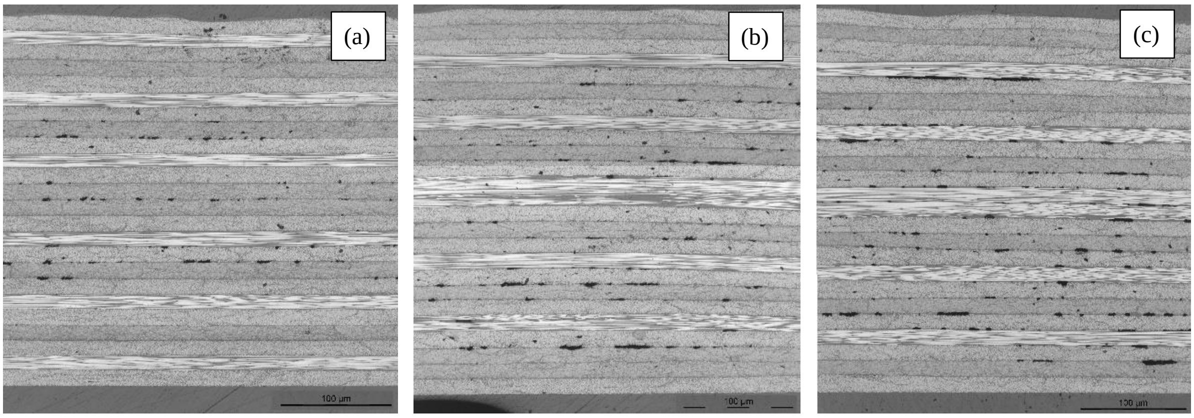

Figure 6: Macrograph of void content with different compaction force.
(a) with force 18.14kg, (b) with force 27.22kg, (c) with force 36.29kg.

4.4 AFP Repassing

AFP repassing consists of doing a second compression pass using the AFP arm without material deposition. 24 layer quasi-isotropic laminates, undergoing bagging procedure B and cure cycle A with AFP settings at 18.14kg (40lbf) compaction, a nozzle temperature of 30°C and rate of 38.1mm/s (1.5inch/s) were manufactured. Some laminates was made using repassing and the others were not. There was a difference of ±5% on 0.5% void content depending on the sample. This is not sufficient to say that the repassing procedure provides any gains as the manufacturing time doubles since 2 passes are required to deposit a single ply.

5. Conclusion

When using OOA materials with AFP manufacturing various parameters have different effects on the quality of the laminates. Therefore, when manufacturing 8-layer laminates with any stacking sequences, a vacuum hold at 90°C for 1hr will eliminate voids to less than 0.1%. To make high quality 16-layer and 24-layer laminates, the following AFP parameters need to be used; compaction force of 18.14kg (40lb) and nozzle temperature of 30°C. For the cure, bagging procedure B seen in Figure 1 needs to be employed, and the cycle is as follows; ramp rate of 0.6°C/min, 12hrs at 93±6°C with a post cure at 177°C for 2hrs [6].

Various debulking techniques were investigated and it was concluded that 10min of debulking every forth layer during the layup sequence did not improve the final void content in the laminates. Room temperature debulking only showed effective for unidirectional 8-layer laminates. As soon as the complexity of the stacking sequence increased as well as the thickness, high temperature debulking at 90°C was required to effectively reduce void content.

During AFP manufacturing, an increase in the nozzle temperature and compaction force lead to a rise in the amount of voids in the laminates. The increase in temperature and compaction force resulted in an increase in overlaps between the adjacent tapes within the same ply. These overlaps are one of the main contributors to presence of voids in OOA laminates made by AFP. The larges voids tend to stem from the edge of a tapes that have overlapped others. The use of repassing did not provide any improvement in the void content in the laminates. This procured doubles the deposition time with no significant gains in laminate quality.

Concerning the outcomes due to the AFP parameters, the results are only valid for CYCOM 5320-1 that have a high cure rate before manufacturing. The flow of resin is hindered due to the high cure rate, as

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the bonds between molecular chains solidify as the cure rate increases [9]. This prevents the progression of the resin to areas void of resin. When the material is new, it could behave differently when subjected to higher nozzle temperatures and compaction forces. This is to be studied further to determine if these trends are present in both aged and new material.

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