Effects of Vacuum Bagging Techniques on Mechanical Properties of Carbon-Epoxy Laminates

by

Arif Isyraf Bin Norafizal

22558

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Mechanical Engineering

With Honours

FYP II

January 2020

Universiti Teknologi PETRONAS

32610 Seri Iskandar

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Effects of Vacuum Bagging Techniques on Mechanical Properties of Carbon-Epoxy Laminates

by

Arif Isyraf Bin Norafizal

22558

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL)

Approved by,

Nabihah

Dr. Nabihah Sallih

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

ARIF

ARIF ISYRAF BIN NORAFIZAL

ABSTRACT

Conventionally, composite laminates were manufactured by applying vacuum bagging setup in an autoclave machine. However, the process needs a long production time and requires high-cost equipment. Alternatively, vacuum-bagging-only techniques are introduced as it does not require an autoclave vessel for the manufacturing procedure. However, this alternative suffers from manufacturing-induced defects such as void formation which will affect the mechanical properties of the produced laminates. This study investigates the effects of vacuum-bagging techniques and curing profiles on the void formation of carbon-epoxy laminates with complex shapes. Three vacuum bagging techniques are used namely single vacuum bagging (SVB), modified single vacuum bagging (MSVB) and double vacuum bagging (DVB) techniques are combined with three different cure profiles which consist of manufacturer's recommended cure cycle (MRCC), extended manufacturer's recommended cure cycle (EMRCC) and direct cure (DC). The combination of the two factors is accompanied by another factor which is the complexity of shape which consist of concave and convex with an angle of 45^o. The through-thickness void content was evaluated using images obtained using DSLR and microscopic in image processing application in MATLAB environment. Applying 3-way ANOVA analysis, it shows that only shape complexity makes a significant difference in the formation of void. The $\log_{10}$ standard deviation graph describes that the variation in the samples is not causing any significant changes in the consistency.

ACKNOWLEDGEMENT

First and foremost, I would like to express my endless gratitude to my supervisor, Dr. Nabihah Salih who has been teaching, advising and support me throughout my whole journey in completing this research. Without her determination and motivation, I would not be able to complete this research work and this dissertation. Dr. Nabihah helped me a lot in understanding and solving each problem I faced during the process.

Furhtermore, I would like to say thank you to Mr. Yasir, my colleague who is also part of this research team for helping me out especially in experimental and testing related knowledge. I am sincerely grateful to have Mr. Yasir alongside me in completing this research.

Next, I would like to thank other lecturers and the technician in UTP that has supervise me in conducting the experiment and testing for the research namely Dr Mazli who lend me their DSLR to carry out image processing procedures, Mr. Daniel from UTP Blok 17 lab technician who helped me in performing optical microscopy test and Mr. Kamarul who assisted me in fabricating the intensifier for the vacuum bagging method. I would also like to thank UTP for providing fund for me to fabricate my mould which is used for the experiment.

Table of Contents

List of Figures

List of Tables

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Composite materials are materials that are formed by the combination of two or more materials with different physical and chemical properties to produce a new material providing improvised properties. The use of advanced composite materials has increased especially in industries such as oil and gas, automobile and aeronautics industry [1]. The use of composite materials in these industries is due to their ability to provide light-weight and high stiffness in the application of the materials. The demand increases as it could also provide excellent advantages over other materials which traditionally used in industry such as it could cater high impact strength and high performance at a very high temperature. Besides that, composite materials are both corrosion and chemical resistance [2].

The easiest and low-cost manufacturing methods for composite material parts are by using hand layup technique. However, the quality of the laminates using this technique is poor because of the absence of compaction pressure on the laminate. Therefore, the vacuum bagging techniques are introduced and conventionally the laminates were manufactured with an autoclave.

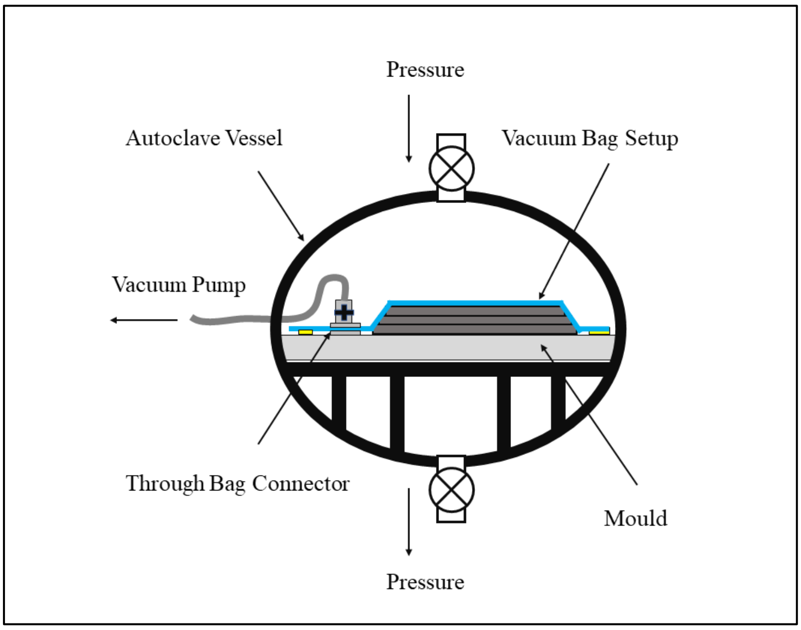


Figure 1.1: Setup for an autoclave manufacturing process [3]

This procedure could decrease the amount of excessive resin as well as extracting moisture, solvents and volatiles from the curing composite while the autoclave being a pressure vessel to provide pressure to the laminates as shown in Figures 1.1[3] and 1.2[4]. Despite producing very high-quality composite laminates with small void content, the procedure is provided with few cons which are high cost, long cure cycle and has limitation on the size and shapes of the composites [5].

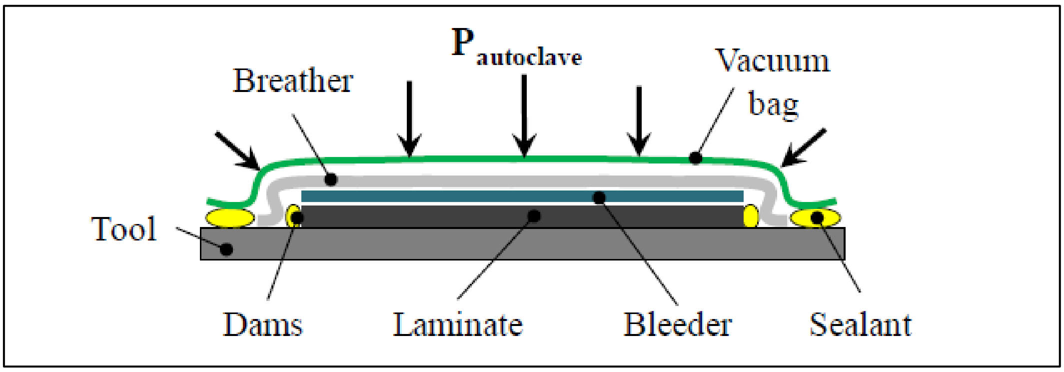


Figure 1.2: Illustration of bagging setup for autoclave manufacturing [4]

Vacuum Bagging only (VBO) is an alternative technique that is capable to manufacture high quality composite structures. VBO uses the atmospheric pressure to create concentrated force on the laminates to hold it together during the cycle. In comparison to the conventional autoclave procedures, this method has an upper hand as it provides an even clamping pressure, a high fiber volume and short installation time. Despite its advantages over the conventional autoclave method, VBO has a couple of manufacturing induced defects such as void formation and residual stress [6].

There are three types of vacuum bagging techniques which are applied in this study namely single vacuum bagging (SVB), double vacuum bagging (DVB) and modified single vacuum bagging (MSVB) techniques. For SVB and DVB, both the techniques involve the layers of the vacuum bagging component which are laid on laminates to consolidate it. An additional component of perforated tool is included in DVB to prevent the outer vacuum bag to collapse onto the first layer bag as the vacuum pressure is applied to the outer bag. MSVB is a modified version of SVB which requires intensifier on the laminates to provide an even pressure on the laminates.

In this study, another variable that is manipulated is the curing profile. In total, there are three curing profiles which consist of manufacturer's recommended cure cycle (MRCC), extended manufacturer's recommended cure cycle (EMRCC) and dissect cure cycle (DC). Both EMRCC and DC are the alteration of the MRCC profile.

Besides that, another factor is taken into consideration for this study which is the complexity of the shape. This factor is introduced because of the scenario in industry, most of the manufactured composites materials parts have a very unique and complex shape. Based on previous research it is proven that the vacuum bagging process is practical for both flat and complex shapes. Manufacturing of composites with complex shapes would give experience issue such as void formation and non-conformity of the shape. MSVB technique is found to be very practical when dealing with complex surface such as concave, convex and rounded corners. However, the combination of different types of VBO techniques, curing profiles and complexity of the shape is still yet to be discuss comprehensively. This study investigates the effects of the factors with various levels on void formation in the produced laminates.

1.2 Problem Statement

Application of OOA vacuum bagging technique on complex shape would induces manufacturing defects such as void formation and poor shape confirmation which would affect the mechanical properties of the laminates.

Void formation is one of the defects that could occur when applying vacuum bagging technique. The voids are formed after the volatiles, such as the air and the by-product of resin chemical process, were trapped during the high temperature curing period. The desirable percentages of void content would be lesser than 1% [7]. Failure such as inter-lamination would happen when the void content is high and thus reduces mechanical properties of the laminates produced. In order to minimize the void content, the cure cycle should be critically analysed and controlled.

1.3 Objectives and Scope of Study

The objective of this study is to investigate the effects of vacuum bagging techniques and curing profiles on the formation of voids formation of components with complex shapes. The study is limited to carbon prepreg 3K laminates with a total thickness of 2.05mm manufactured using single vacuum bagging (SVB), double vacuum bagging (DVB) and modified single vacuum bagging (MSVB) techniques. The curing profile is also limited to manufacturer's recommended curing cycle (MRCC), extended manufacturer's recommended curing cycle (EMRCC) and direct cure (DC) profile. The curvature of the surface is limited to two complexities which are concave and convex with an angle of 45^0.

CHAPTER 2
LITERATURE REVIEW

This chapter describes the previous works on vacuum bagging techniques, curing profiles and complex shapes. Findings of the research are assembled and analysed for every factor that each researcher focused on. The gaps in the literature are highlighted and demonstrated within the context of this study.

2.1 Vacuum Bagging Techniques

Vacuum bagging only technique also known as VBO is appealing in manufacturing process of composite materials product as it offers a sustainable manufacturing method which is able to produce similar quality results compared with those made by using autoclave process with a lower production cost. There are three setups for the vacuum bagging only techniques which are single vacuum bagging (SVB), modified single vacuum bagging (MSVB) and double vacuum bagging (DVB) as describe in the following subsection.

2.1.1 Single Vacuum Bagging (SVB) Technique

Vacuum bagging only technique optimizing the atmospheric pressure to provide uniform pressure on the laminates. A typical SVB setup is made up of the mould, composite plies, peel ply, perforated film, breather material, vacuum bag, pressure gauge and vacuum pump together with fittings. A sample of setup is shown in Figure 2.1. Mould release is applied in the beginning as it is important to prevent the resin from sticking to the mould when laminating a part.

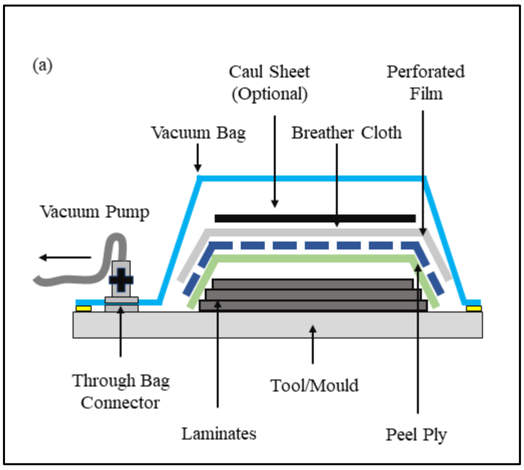


Figure 2.1: Setup for SVB technique [3]

Once the bag is sealed to the mould, pressure on both outside and inside of the envelope is equal to one atmospheric pressure. The vacuum pump will be activated and clear the air from the inside of the bag which then will reduce the pressure inside the bag meanwhile the air pressure outside of the bag still remains unchanged at 1 atm. The pressure from outside will provide an evenly distributed pressure to the surface of the laminates [8]. During B-stage, at elevated temperature, the resin softens and turn into molten state. By-products from the chemical reaction are released. Vacuum is applied in order to fully diminish the volatiles at lower temperature which would result the bag to lay tightly onto the caul plate and compress the laminates as shown in Figure 2.1. The increment of viscosity of resin matrix inside the prepreg plies creates a narrower space for the volatiles to escape. An elongation of B-stage duration is practised to achieve low residual volatile levels. [10]

Although single vacuum bagging has been proven to produce high-quality laminates with a low internal void, it results in poor shape conformation according to study conducted by Anderson and Altan [10]. This occurrence is because of the insufficient pressure which is applied onto the laminates which is only up to 1 atm (atmospheric pressure). Besides that, SVB also tends to result telegraphing sandwich structures when high pressure is applied [11]. This happens because in this technique, the bag would fall directly on the part with the applied pressure during B-stage of curing process. The pressure applied during the B-stage is sufficient to make the face sheet flag inside the hollow parts of the core.

2.1.2 Modified Single Vacuum Bagging (MSVB) Technique

Conventional single vacuum bagging technique is normally used for flat composite parts. However, in the case where complex shape is needed to be manufactured, SVB could not give the best shape confirmation to the mould which would result in manufacturing defects of the laminates. Modifications are made by researchers to get the maximum shape confirmation for complex shape part. The shape non conformity is a critical problem in complex shapes especially at the corner radius which mostly originated from the bagging arrangement itself. The corner thickening is reduced by the aid of pressure intensifier. Though, in a concave mould, the use of intensifier would invite local resin accumulation in the laminates, as the resin flow can be restricted. MSVB is applicable for complex shape composites consisting convex, concave and semi-spherical corners. Intensifiers or pressure strip are to enhance pressure distribution onto the laminates. However, the presence of an intensifier could block the passages for entrapped volatiles from escaping and consequently hinder them and thus result in porosity.

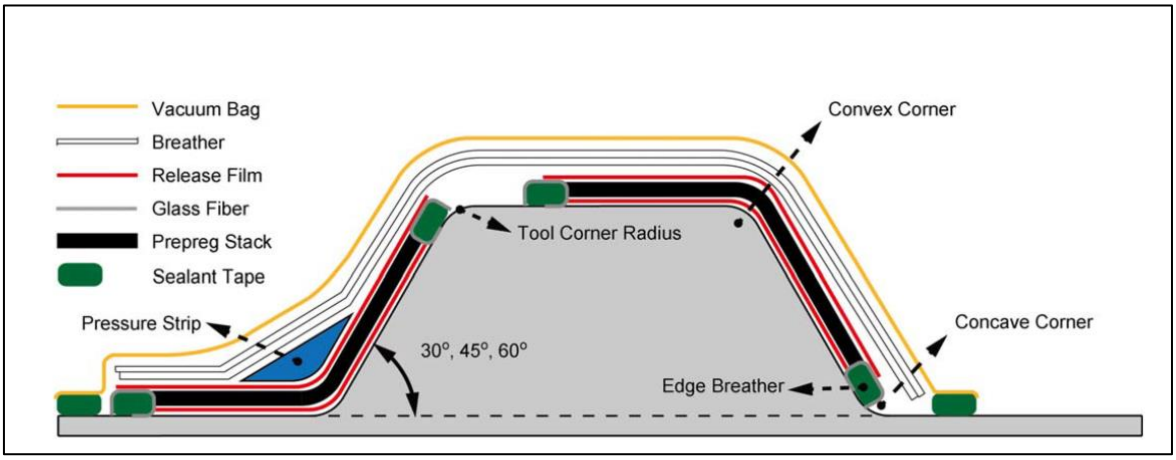


Figure 2.2: Setup for MSVB for concave and convex corner with angle of 30°,45° and 60° [12]

Based on previous research [12], Ma et al. focused on two type of prepreg which differ in the resin used for the prepreg. The first prepreg, named “prepreg A”, is made up of toughened epoxy resin (Cycom 5320) and a five-hames satin (5HS) carbon fibre fabric (T650-35 3K) whereas the second prepreg denoted as “prepreg B” was consist of a later-generation OoA resin (Cycom 5320-1) and an eight-harness stain (8HS) carbon fibre fabric (T650-35 3K). Both resins are cured at the same temperature profile which is MRCC. It is found that resin of prepreg B was less reactive compared to prepreg A which exhibits a longer out-life (30 days at surrounding conditions whereas 21 days for prepreg A) thus requires longer cure at a given temperature. Utilizing the MRCC cure profile, the results show that the both prepreg have a higher void formation on the concave corner which is likely because there is insufficient compaction force on the corner. Comparatively between prepreg A and prepreg B, prepreg B shows lower void contents which are <0.5% while prepreg A induced <2% void content. However, this study limited to only one type of vacuum bagging technique and one curing profile which leaves a gap for the combination of other vacuum bagging techniques alongside other curing profile which will be covered in this study [12].

2.1.3 Double Vacuum Bagging (DVB) Technique

Double vacuum bagging technique setup is an extended version of single vacuum bagging technique [13]. DVB consists of two vacuum bags covering the laminates instead of just one as in SVB arrangement. The inner vacuum bag seals around the edges onto the mould plate together with a vacuum port built into the tool plate inside the inner bag which connected to a vacuum pump to draw a vacuum within the inner bag as shown in Figure 2.3. Another layer of bag is designated as the outer bag is similarly set up to the inner bag with a perforated tool between the outer and inner bag. The presence of perforated tool is to prevent outer bag from collapses on the inner bag. The outer bag is connected with a second vacuum port which allows the creation of a second vacuum environment [9].

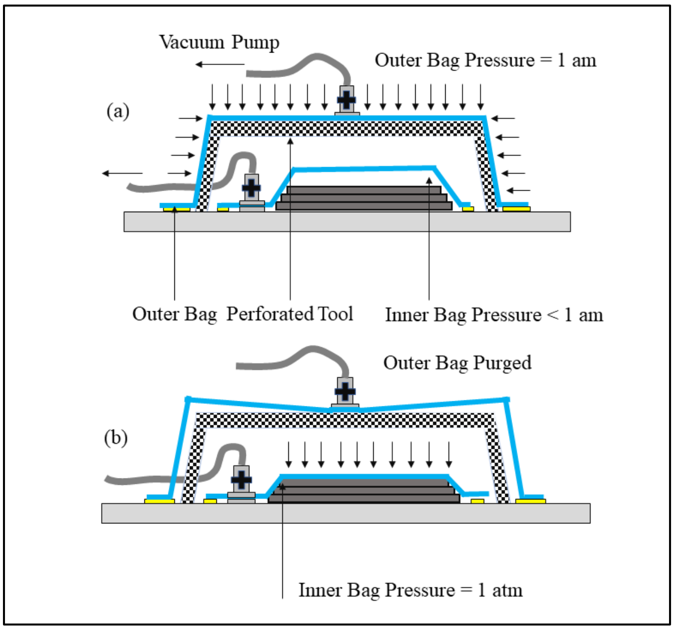


Figure 2.3: Setup for DVB technique [3]

The perforated tool is installed between the inner and outer bag which is build to withstand the atmospheric pressure of 101.3kPa created by vacuum. At B-stage, a full vacuum of 101.3kPa is applied to the outer bag while a lower vacuum level is applied for the inner bag. The outer bag layer will collapse onto the stiff perforated tool due to atmospheric pressure outside the bags. The inner bag inflates like a balloon and presses against the perforated tool leaving no compaction force on the composites due to the differential vacuum between the inner bag and outer bag. During this process, the composite which are layered up is not compressed by the atmospheric pressure through the inner bag and remain loose. Volatiles will escape due to the vacuum suction from the inner bag vacuum pump. At the C-stage, the outer bag is purged to the atmospheric pressure while the inner bag pressure is increased to 101.3kPa. This causes the outer bag expands from the tool while the inner bag layer onto the caul plate giving even pressure to the caul plate. This pressure helps to consolidate the laminates during the high temperature ramp as well as the next dwell of the cure cycle [9].

2.2 Curing Profile

A cure cycle to manufacture composite laminates with reactive resin matrices normally consists of two-step-ramp and dwell temperature profile. The temperature and dwelling time are different for each types of composite materials. The curing profile consists of a low-temperature ramp and dwell step which is called as the B-stage and a higher temperature dwell which is C-stage as shown in Figure 2.4.

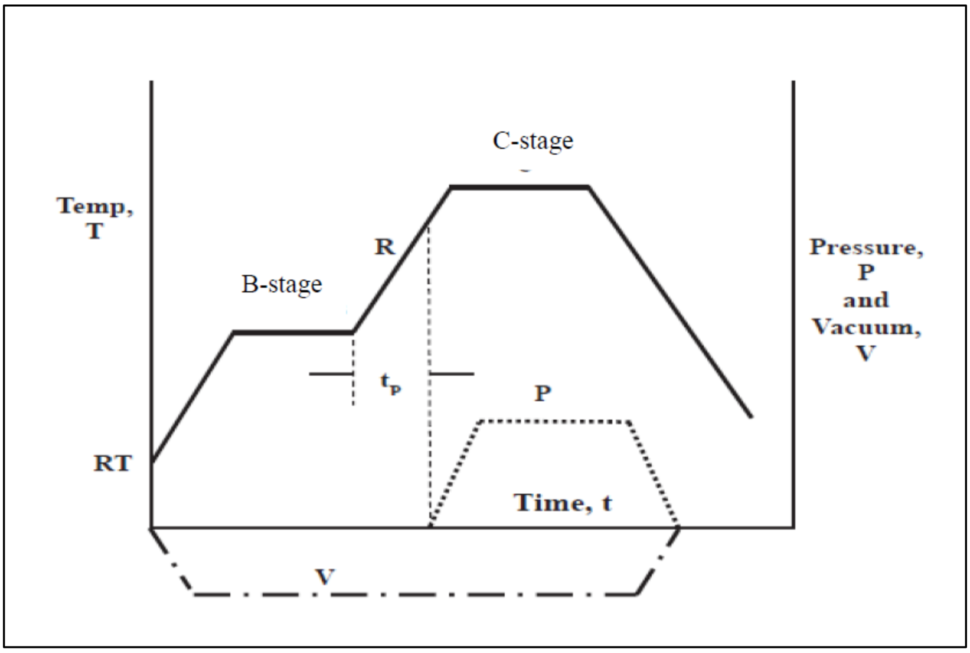


Figure 2.4:Schematics of standard two-step cure cycle profile [14].

During B-stage, the prepreg is heated at a low temperature. The composite transforms from a gel state to a liquid state due to the increased temperature of the samples [14]. In this stage, the viscosity of the resin will be low allowing it to flow and filled up the pores. Theoretically the volatiles such as solvent and by-product of the resin are able to escape due to the pressure difference. After the B-stage period, the second temperature ramp dwell is applied where the temperature is increased and pressure applied to fulfil the high temperature ramp and dwell period. During this period, the composites are able to strengthen and produce the desired final physical shape and mechanical properties [9].

When the volatiles are not drained out appropriately before the high temperature cure ramp, it would be trapped in the laminates which will be resulting in defects and affects the properties of the laminates. The cure cycle needs to allow sufficient percentage of volatiles to be drained out through B-stage period before final consolidation process while maintaining the resin fluidity after the stage for resin infiltration through fiber bundles through the composites during the pressure consolidation period. Four elements of resin and composite properties need to be deliberate when designing a workable cure cycle for a given resin which are the chemical cure kinetics, volatile management, evaluation of the resin morphology and residual processability after the B-stage period. The design procedures consist of measuring the volatile depletion mechanism by thermal gravimetric analysis (TGA) which measure the degree of thermally established reactions and the morphology of partially cured resin by different scanning calorimetry (DSC) [15]. However, the cure cycle cannot be studied solely to know the quality of the produced composites as it is also accompanied with several other factors such as composite structures and bagging techniques which will help in reducing the manufacturing defects.

2.2.1 Manufacturer's Recommended Cure Cycle

Manufacturer's Recommended Cure Cycle (MRCC) was obtained from the supplier and it consist of two-step ram profile which the first step is named B-stage while the other step is labelled C-stage. The expectation at B-stage is for the system to have a maximum volatile depletion and a minimum resin viscosity where resin could flow and fill up the voids. At C-stage, the viscosity of resin should increase and the laminate consolidates to become its final form.

2.2.2 Extended Manufacturer's Recommended Cure Cycle

Extended manufacturer recommended cure cycle (EMRCC) is an advancement made to MRCC with the presence of additional ramp stage before the post cure. EMRCC sums up to three-steps which includes the additional stage which is the B2-stage to the B-stage and C-stage in MRCC profile. B2-stage is between the B-stage and C-stage.

The post cure temperature is similar to the material glass temperature for MRCC. The vitrification temperature in EMRCC is set to be lower than the post cure temperature. The purpose of this stage is to reduce the thermal stress achieved after the transition temperature through the additional temperature ramp [14].

Kratz et al. [15] developed a formula to calculate the degree of cure by using the cure kinetics model which shown in Equation 2.1:

$$\frac{d\alpha}{dt} = K_1 a^{m_1}(1-\alpha)^{n_1} + \frac{K_2 a^{m_2}(1-\alpha)^{n_2}}{1+\exp\left[D\{\alpha-(\alpha_{co}+\alpha_{ct}T)\}\right]} \qquad (2.1)$$

K_1 and K_2 = Arrhenius temperature dependency

D = Diffusion constant

T = Temperature

α = Degree of cure

α_{co} = Critical DOC at absolute zero

α_{ct} = Increase rate in critical DOC with temperature m_1, m_2, n_1, n_2

2.2.3 Direct Cure Cycle

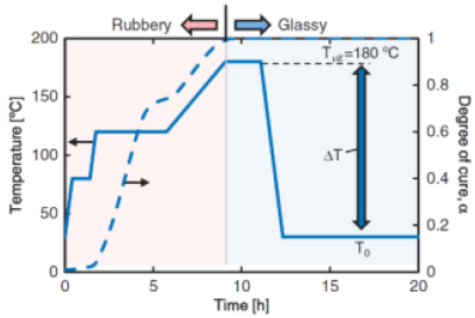
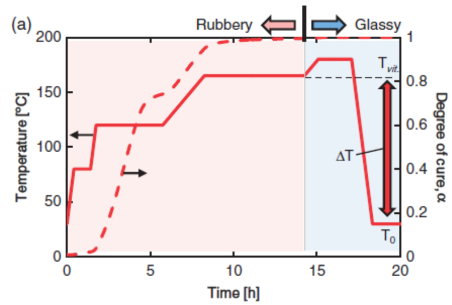
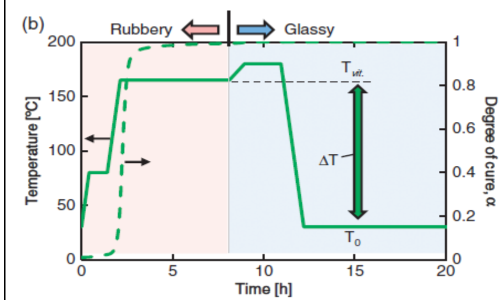
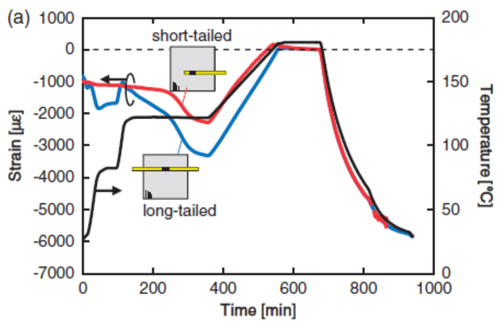
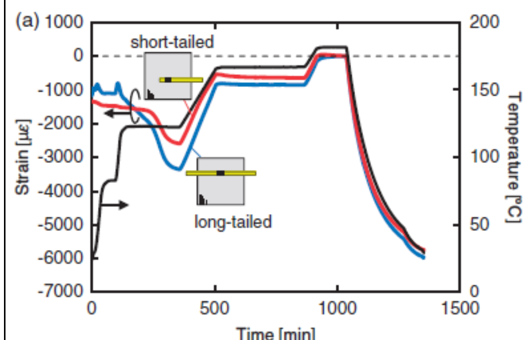
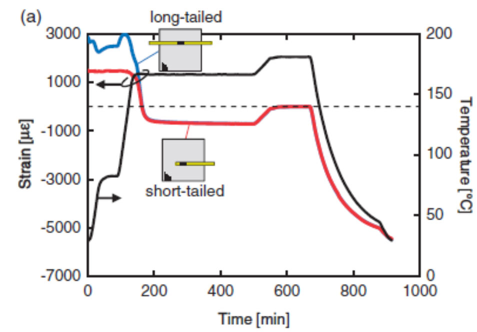
Direct Cure cycle (DC) profile has a two-step ramp profile which is similar to MRCC. In comparison to MRCC, the B-stage temperature is much higher and the stage is closer to the curing temperature, in which similar to EMRCC B-2 stage temperature. Tagaki introduced the temperature profile by eliminating the second dwell stage and increasing the ramp rate as shown in Table 2.1. The objective of this profile is to shorten the manufacturing time. The process time for EMRCC with the presence of additional dwell and ramp stage took more than 18 hours to complete meanwhile in direct cure cycle, temperature get to ramp up to vitrification temperature right after B-stage which shortens the manufacturing time to only 12 hours.

2.2.4 Comparison of MRCC, EMRCC and DC Profiles

Refer Table 2.1 in text to see the comparison between the three cure profiles. Tagaki et al. have found that the effects of the curing profiles on the induced residual stress and strain. They applied the manufacturer recommended cure cycle (MRCC) and showed that resin crystalized at C-stage of curing [15]. Additional cure cycles are proposed based on their research which are extended manufacturer recommended cycle (EMRCC) and direct cure cycle (DC). Each sample was experimented using tensile test and scanning electron microscopy (SEM) to analyse the material properties of the laminates. The findings showed that the residual strain was decreased by 12% by using EMRCC and reduction of 18% by using DC cure profile. The strength was increased by 26% in the case fot EMRCC while decrement of 8.5% in the case of DC. This is because of the difference in coefficient of thermal extension (CTE) which is likely caused by the variation in fiber volume fraction, V_f. The composites CTE increases as the V_f since resin expands more than the carbon fibers. V_f diversify depending on the prepreg condition, cure process cycle which might affect the residual strain [9].

The void content was not significantly change as the cure cycle change. This proves the importance of a proper design on curing profile to develop better mechanical properties and shape confirmation of the composite parts. However, the findings are based on laminates which are produced by only SVB technique which leaves question on effect of the curing profile when combined with other types of vacuum bagging techniques.

Table 2-1: Comparison of curing profile [3,15]

	MRCC	**EMRCC**	**DC**
Curing Profile			
Strain vs Time			
Curing Time	**12 Hours**	**18 Hours**	**12 Hours**
Void Content	**0.05%**	**0.14%**	**0.02%**

2.3 Void Content

Void formation is one of the most common defects induced during composites manufacturing process. Voids formation are a type of defect where small cavities presence in the composite part [4]. These voids differ in size and shape which also usually discovered between laminates plies, in the resin or in the fibre bundles. The void content for a composite part is normally used as one of the parameters to assess the composites quality and thus, to determine if it is acceptable for a specific application [10]. Figure 2.5 shows the illustration of the common location for voids to likely form.

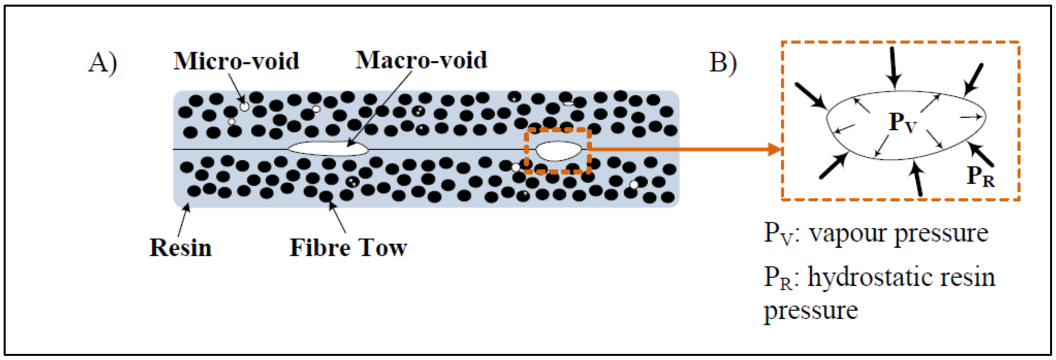


Figure 2.5: Voids from entrapped air between plies, in the resin and partially impregnated fibre bundles (A). Enlarged view of the pressure forces acting on the air or gas bubble surface (B) [4].

Void content is a crucial concern because it affects the mechanical properties of the laminates produced [12]. In addition, the mechanism of the void formation has been studied extensively [16]. Contemporarily, it is widely agreed that gas-induced voids can occurs because of absorbed moisture, residual solvents within the resin and air entrapped between prepreg plies [17]. In addition, flow-induced voids can happen if the resin matrix does not totally saturate the fiber bed during curing process.

Voids are harmful to the mechanical performance as they are cause of stress concentration regions and may induce defects to the composite by moisture infiltration and accumulation. The four mechanisms that could induce void deformation according to Malow and Kardos [18,19] are entrapped air during ply collation, volatiles released during curing process, dissolved gases or moisture in the resin and internal stress build up from the resin cure shrinkage [20]. According to research made by Strong and Brent [21], the moisture content may be minimized by allowing prepreg material to reach room temperature. Volatile gasses or entrapped air bubbles during the cure process may be removed before resin gelation if the hydrostatic resin pressure is higher than the local bubble pressure [4] as shown in Figure 2.5. The bubble pressure is controlled by the water vapor pressure which increase alongside with temperature. Therefore, low initial temperature is ideal in order to minimize the local bubble pressure. High hydrostatic resin pressure will reduce the void formation during processing because the resin could remove the air bubbles and prevent dissolved gas from creating void [4].

Hamill et al. [22] studied the interrelation of surface porosity with few factors which includes effects of prepreg out-time, effects of freezer time, effects of room temperature vacuum hold and effects of room temperature ageing method as show in Figure 2.6.

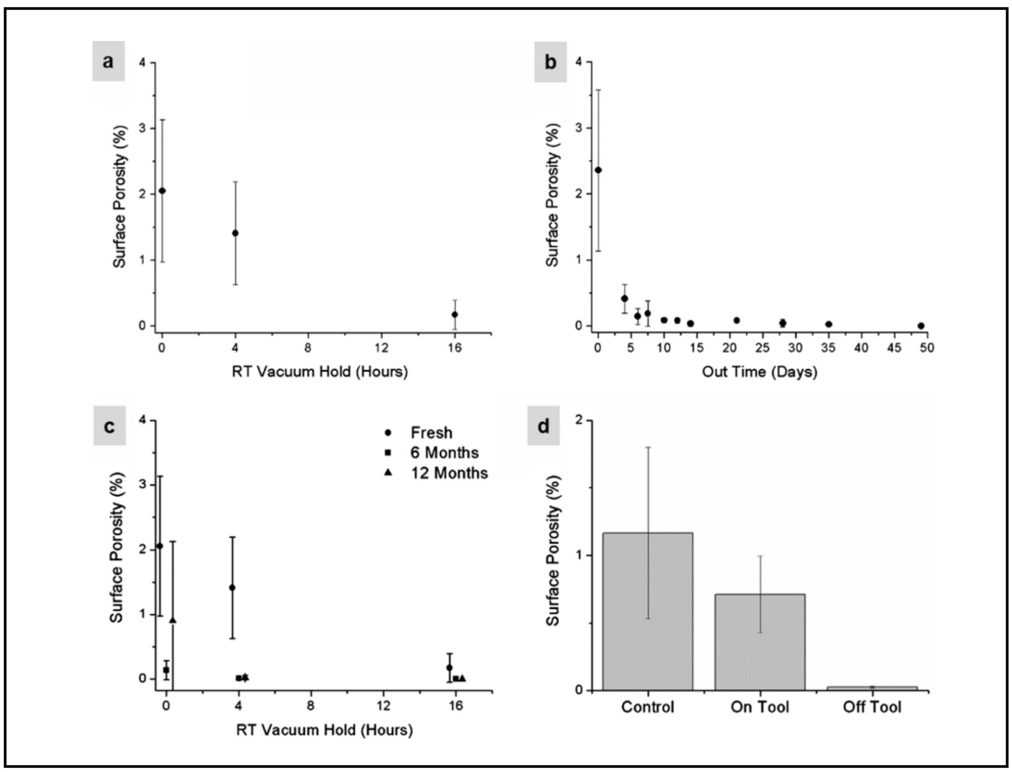


Figure 2.6: The effect of (a) room temperature (RT) vacuum hold time, (b) out-time at room temperature, and (c) freezer time on surface porosity. (d) The effect of the room temperature ageing method on surface porosity [22]

The amount of surface porosity decreased as the vacuum holding time risen as illustrated in Figure 2.6(a), which means that air expulsion is a time-dependant process and surface porosity is subjected to amount of entrapped air. Referring to Figure 2.6(b), increment in out-time of the prepreg improves the surface porosity by 83% after four days of out-time and by 99% after 14 days of out-time. This occurrence is because of the concurrent decrease in prepreg thickness and ply compliance. This will also cause the increment in ambient temperature resin viscosity associated with ageing of prepregs at room temperature. Surface porosity gradually decreased with freezer storage time as demonstrated in Figure 2.6(c). The results in Figure 2.6(d) shows that the laminate laid up on tool place at zero days which allowed to age on the tool display more surface porosity compared to laminate aged prior to layup procedure. No major changes found in surface porosity after 4 or more days out-time which means it is unnecessary to have more than 4-6 hours of out-time for the prepreg prior to layup. Fresh prepregs need more than 6-8 hours RT vacuum to retain their surface porosity less than 1%, and even less than 4 hours of RT vacuum holding time requires 6 or more months of older prepregs. An off-tool approach is more advantageous when ageing prepregs to acquire minimum porosity of the layer. Their research results provide crucial information to lessen porosity with the use of older prepregs (i.e. four to six months).

2.4 Complex Shapes

Composites materials are widely used in industries such as aeronautical and automotive because of their specifications which is light yet strong which is required for the industry. Most of the parts which were manufactured for the industries have complex shape.

Yija et al. [12] have conducted a study of defects for the manufacture of contoured laminates which includes 2 complex corner which is convex and concave shape. Total of 6 tools were used to manufacture the parts with specific corner angles (30^{o}, 45^{o}, 60^{o}) to evaluate the effect on increasing geometric complexity on laminates quality. The corner radius is diversified to (0 mm, 6.35mm, 9.53mm, 12.7mm) which is varied to analyse the effect of local geometric discontinuity. The results show that the void content produced is lesser in the convex corner compared to concave corner ash shown in Figure 2.7.

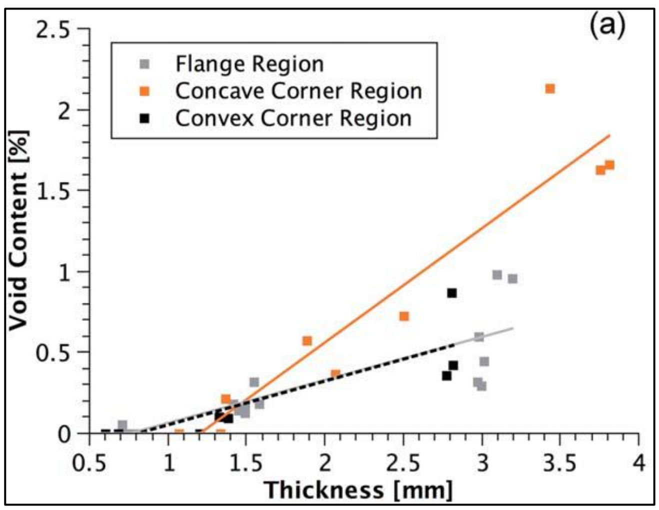


Figure 2.7: Void content in flange region, concave corner region and convex corner region [12].

In another research, Brillant [4] illustrated that there is significant difference in void formation which occurs in convex and concave shape. Convex shape has less than 0.1% void formation with the setup of SVB technique with accompanied with standard MRCC curing profile. However, for concave shape, the void content in the final laminates produced are ranged from 0.3% to 0.8%. A total of three setups for concave shape complexity which named Part E, Part F and Part G.

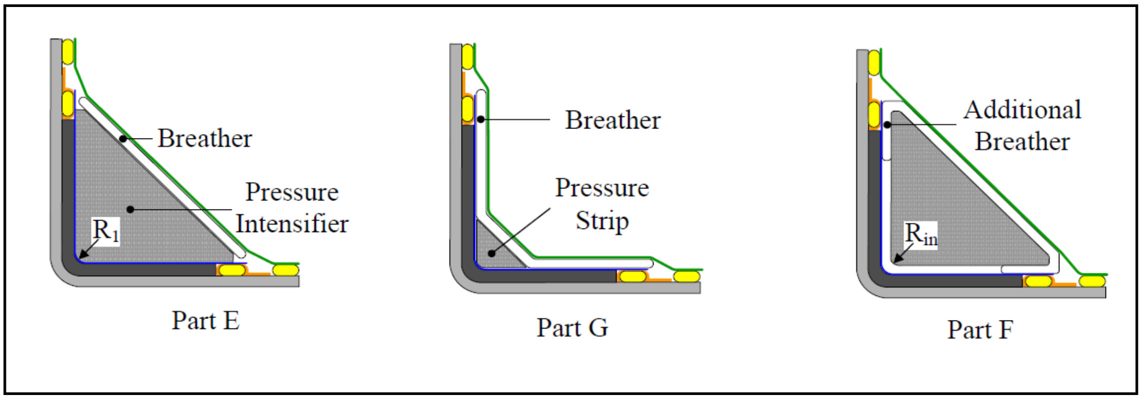


Figure 2.8: Schematic of Bagging Configuration for Part E,
Part F and Part G [4].

Part E includes the aid of pressure intensifiers and the void content formed are 0.8% which is the highest of all. The pressure intensifier limits the contact between the edge breathing setup and the breather material which suggests that the edges of the intensifiers might have deformed due to the applied pressure and pinched the laminates resulting in blocking the air evacuation flows. For Part F, the presence of additional breather material under the pressure intensifier drastically reduce the void content to 0.4%. As for Part G, the void content improved to 0.3% with the small pressure strips used which does not restrain the breathing system of the resin [4].

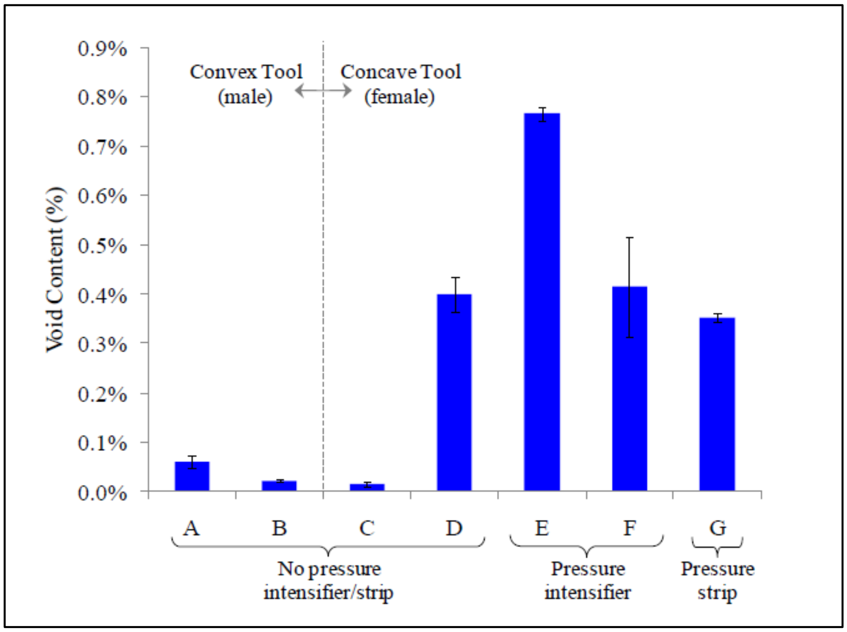


Figure 2.9: Void content (%) measurements [4].

However, studies done related to complexity of shapes does not focus on finding the void formation produced when varying the variables. In addition, the curing cycle used is the only one which is MRCC and only two vacuum bagging techniques are used which leaves a question to the application of DVB to produce the laminates.

2.5 Summary of Literature Review

In conclusion, one of the main defects that could occur in manufacturing laminates is void formation. Many types of research have been carried out to reduce those defects. One of the common methods which are studied is the vacuum bagging technique such as single vacuum bagging (SVB) technique and double vacuum bagging (DVB) technique as well as curing profile. According to T.H. Hou et al [8], it is analysed that the application of DVB is more effective in reducing laminates voids compared to SVB which is because of more volatiles depletion and consolidation in DVB. However, the comparison is valid only for flat surface parts and not proven for parts with complex shape and corner. In the case of complex shape which deals with the convex and concave corner, it is shown in [12] that void formation is produced more in the concave corner compared to convex corner. In addition, a similar result is shown by Brillant [4] where concave corner induces more void content when compared to convex corner. However, for this research only SVB and MSVB bagging techniques are used accompanied by the MRCC curing profile, which leaves a gap for other vacuum bagging techniques as well as other curing profiles.

For this study, a combination of three vacuum bagging techniques and three types of curing profile was conducted to investigate their effects on through-thickness void content on carbon-epoxy laminates with complex shapes.

CHAPTER 3
METHODOLOGY

This chapter explains briefly on the steps and procedures conducted to achieve the objective of this study. Data gathered from literature has shown that several factors contribute towards the formation of manufacturing induced defects. The effects of both bagging techniques, curing profiles and shape complexity were quantified by analysing the through-thickness voids formation by using image processing method via MATLAB software.

3.1 Mould Fabrication

The mould would be the reflection of the desired outcome of the layered laminates onto it. It gives the shape and design for the product that was intended to be made by using composite materials. Aluminium is chosen to be the material for the because heat transfer easily and it is easy to manufacture. The focus in this study is to study the effect of the factors on the complex shapes which consist of concave corner and convex corner. An angle of 45^o is implemented to analyse the effect of increasing geometric complexity on the laminate quality, whereas the corner radii are varied to 6.35mm to determine the influence of the local geometric discontinuity [12].

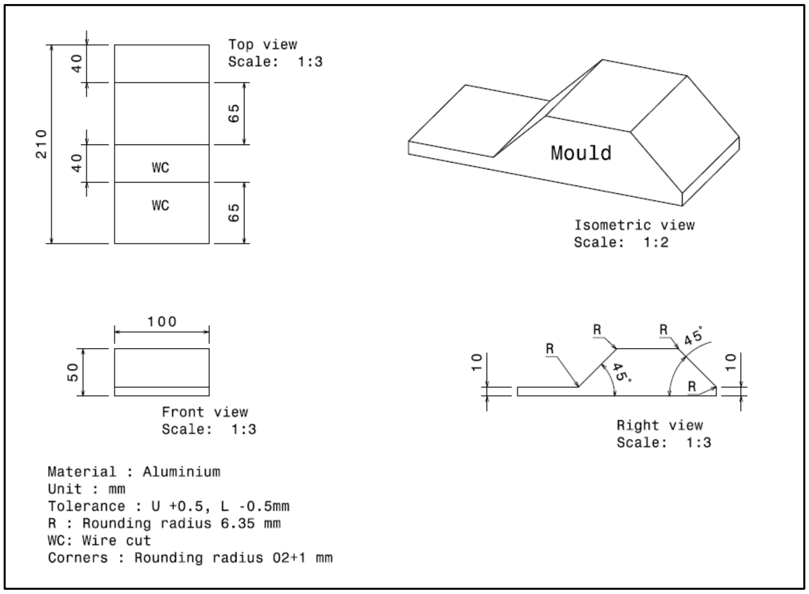


Figure 3.1: Drawing for the mould.

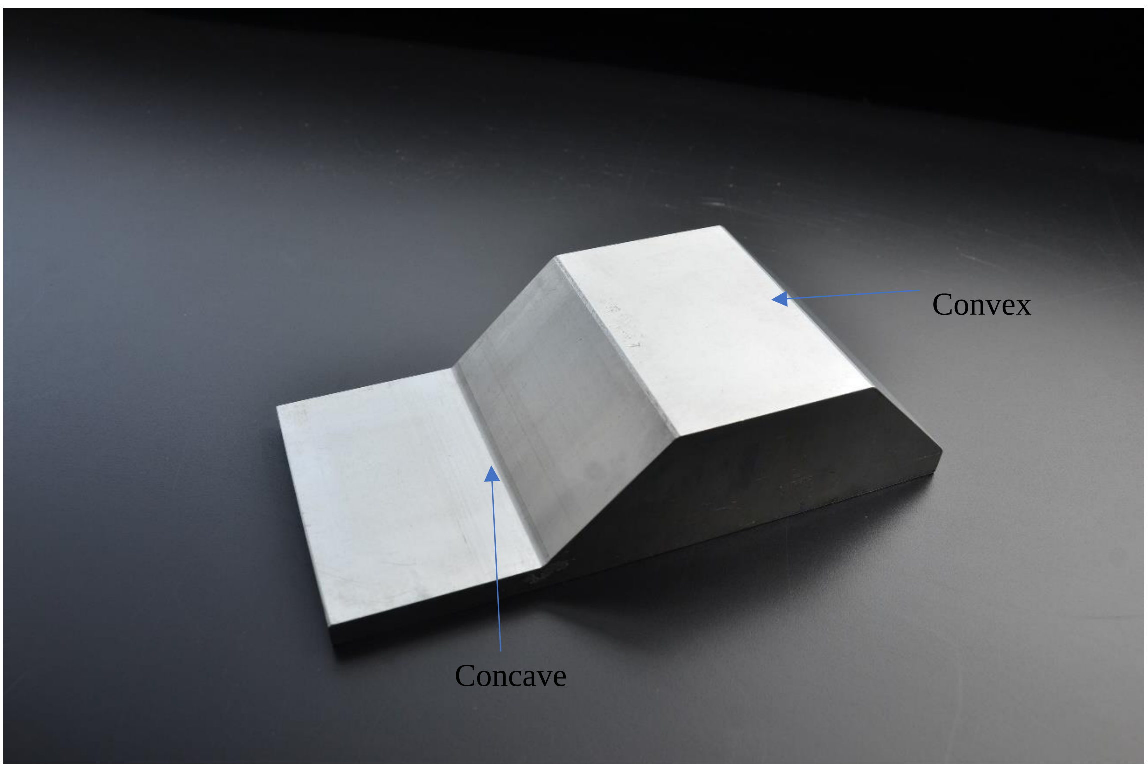


Figure 3.2: Image of the mould

3.2 Materials

The materials for composite laminates which is selected for this study is the XC110 prepreg carbon 3K, 210g, 2/2 Twill, purchased from Easy Composite Ltd, United Kingdom. (See Figure 3.2) XC110 prepreg is chosen as it is designed for out-of-autoclave process.

Figure 3.3: XC110 prepreg carbon 3K, 210g, 2/2 Twill [23]

3.2.1 Stacking Sequence

In this study, six layers of prepreg are layered on top of each other to form the laminates. Each lamina is layered in the same direction and angle as shown in Figure 3.3. The dimension of the laminate is 100mm x 50mm. The dimension is chosen to accommodate the samples in the perforated tool. The sequence of the layer-up from the top to bottom is vacuum bag, breather cloth, perforated film, release film, sample layer and mould.

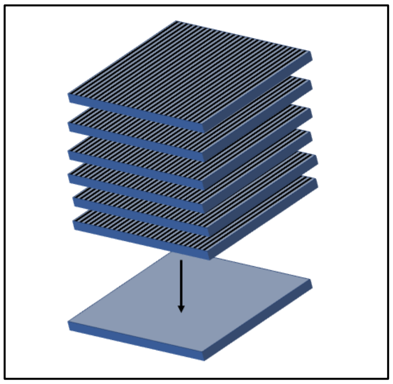


Figure 3.4: All laminas are stacked in the same direction.

Figure 3.5: Sequence of layer for MSVB technique

3.3 Manufacturing Method

Laminates and the layered composites will be manufactured using the three vacuum bagging techniques alongside with the three different curing profiles. A total of 18 set of samples will be manufactured as stated in Table 3.1. Each set of samples represents the combination of 1 vacuum bagging techniques with the curing profile. Since three vacuum bagging techniques and three curing profile will be used, 18 combination of samples will be analysed. The laminates which were produced will then be evaluated based on its surface porosity and through-thickness void percentage. The table indicates the combination of the variation made throughout the study which varies both bagging techniques and curing profiles.

Table 3-1: Experiment Design Matrix

Trial	Bagging Techniques (A)			Curing Profiles (B)			Complex Surface (C)		
Samples	A_1	A_2	A_3	B_1	B_2	B_3	C1	C2	Flat [3]
1	/			/			/		
2	/				/		/		
3	/					/	/		
4	/			/				/	
5	/				/			/	
6	/					/		/	
7	/			/					/
8	/				/				/
9	/					/			/
10		/		/			/		
11		/			/		/		
12		/				/	/		
13		/		/				/	
14		/			/			/	
15		/				/		/	
16		/		/					/
17		/			/				/
18		/				/			/
19			/	/			/		
20			/		/		/		
21			/			/	/		
22			/	/				/	
23			/		/			/	
24			/			/		/	
25			/	/					/
26			/		/				/
27			/			/			/

3.4 Selection of Factors

Variable 1: Vacuum Bagging techniques

The void formation and shape confirmation are directly related to the selection of these vacuum bagging techniques. The following are the bagging techniques which have been selected for this study.

A_1: Single Vacuum Bagging Technique (SVB)

SVB will be done to analyse its limitation since it is proven to produce high quality laminates with less internal voids but with poor shape confirmation according to previous studies [10]. Applying SVB to manufacture a complex shape parts such as L-shape, convex, concave and round shape corners is found to be difficult as the pressure distribution by the vacuum bag would not be uniform. The uneven pressure would cause resin accumulation and corner thickening in the concave corners, corner thinning problem in convex shape and spring back in round shaped composites. The purpose for including SVB is to see the maximum void content could formed by using this technique.

A_2: Modified Single Vacuum Bagging Technique (MSVB)

This technique is introduced to counter few of the problems faced in conventional SVB setup which in this case for complex-shaped composites. The modification is done by adding the use of intensifiers and pressure strips [24]. The modifications have been proven to minimize the difficulties faced by using SVB. Caul-sheets [25] are used for flat laminates with higher thickness (approximately 10 or more layers) to spread a uniform pressure throughout the parts. Complex-shaped parts need the aid of intensifiers and pressure strips to assure the laminates are following the shape of the moulds. The presence of intensifiers and pressure strips can avoid the phenomenon of corner bends, resin accumulation, corner thickening, corner thinning and bridging. This technique is widely used in manufacturing laminates for complex shapes. However, the purpose of choosing this technique is to analyse the void content produced when combined with different cure cycle and to evaluate if it will produce the least void content provided with the cure cycle chosen compared to DVB technique.

A$_3$: Double Vacuum Bagging Technique

DVB is also a favourable vacuum bagging technique besides MSVB [26]. Double vacuum bagging technique prevents inner bag to totally compress the composite during the first stage, rather the outer bag makes inner bag to inflate due to the vacuum in the outer bag. This occurrence allows the resin bi-products, volatiles and entrapped air to vacate during the B-stage without full compaction pressure of inner bag. Entering C-stage, the composites are then fully compressed by the inner bag and the outer bag is purged to the atmosphere. This process will strengthen the composites and the shape confirmation is achieved. This technique is proposed to evaluate the void content of the produced laminates which could be compared with the MSVB technique.

<u>Variable 2: Curing Profiles</u>

Cure cycle is expected to affect formation of mechanical properties and residual strain of the composites. Previous studies only show the combination of these three curing profiles with SVB technique. Therefore, this research focus on the combination of these curing profiles with other VBT on complex shapes to evaluate the void content for each combination of the manufacturing methods.

B$_1$: Manufacturer's Recommended Cure Cycle (MRCC)

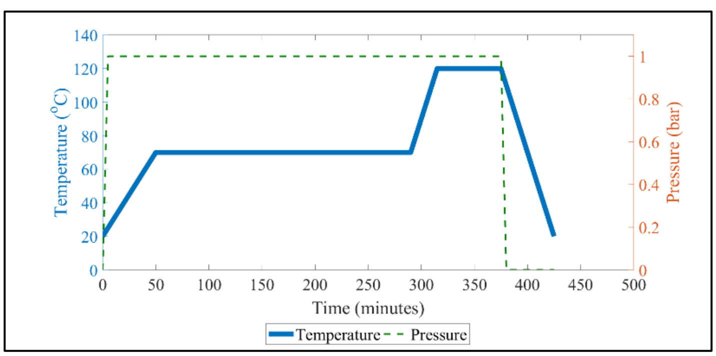


Figure 3.6: MRCC curing profile.

B_2: Extended Manufacturer's Recommended Cure Cycle (EMRCC)

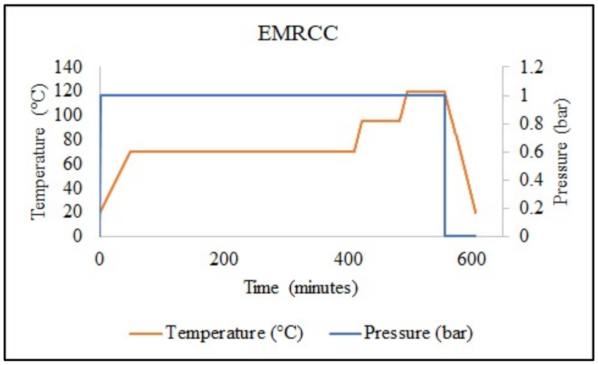


Figure 3.7: EMRCC curing profile.

B_3: Direct Cure Cycle (DC)

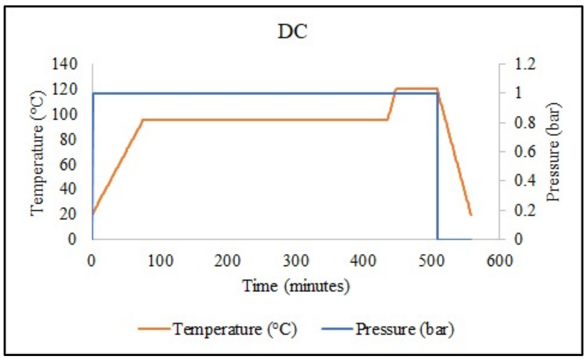


Figure 3.8: DC curing profile.

<u>Variable 3: Complex Shapes</u>

C_1: Convex

C_2: Concave

C_3: Flat [3]

The angle selected for both convex and concave is 45^{o} with a corner radius 6.35mm. The selection of the angle and corner radii are based on the previous study [12] that has covered the complex shapes consisting concave and convex shape. The results of the void formation on complex shape laminates will be compared to a published result on flat laminates [26].

3.5 Characterization of Void Content

After the manufacturing process is completed, the samples were cut using a diamond cutter and the surface of the cross sectioned area were analysed by using image processing tools to observe the void formation of the samples. The void in the laminates is characterized by using an optical microscopy and a digital single-lens reflex (DSLR). DSLR images are snapped in a studio to ensure a proper lighting source and distribution. Two image orientations were taken which are the surface image and the through-thickness image. Through thickness voids are detected as a dark spot while the surface porosity was recognized as a white spot. The void contents for the both surfaces were calculated by using Equation (3.1). The evaluation of the surface porosity was evaluated by using an image processing code in MATLAB environment. The code as shown in Figure 3.5 will convert the image taken into a black and white to analyse the voids by mapping them according to their coordinates.

$$Void\ content(\%) = \frac{total\ area\ of\ void\ detected}{total\ surface\ area} \times 100\% \tag{3.1}$$

3.5.1 MATLAB Image Processing Code

The following is the MATLAB image processing code constructed to analyse voids percentage in the laminates:

```
>> %% setup new environment%%
clc;
clear all;
close all;
%% Define initial value %%
Avg=0; TotalWT=0; Total=0;
%% Read image%%
I=imread('photo.jpg');
C=imsharpen(I);
BW = im2bw(C,0.45); % convert to black and white
%% Calculated void percentage %%
TotalWT=nnz(BW)+TotalWT; % find number of white elements
Total=numel(BW)+Total; % find number of total elements
VoidPercentage=(TotalWT/Total)*100 % find the percentage of black area
%% Display before and after image side-by-side %%
subplot(1,2,1);
imshow(I);
subplot(1,2,2);
imshow(BW);
%% End %%
```

Figure 3.9: MATLAB code for image processing.

3.6 Three Way ANOVA Analysis

Analysis of variances (ANOVA) is a statistical measure to identify the difference between the mean of all the independent factors in the experiment. The significance of a factor compared to other factors in this experiment in contributing to the void formation is discovered by performing ANOVA analysis. The significance of the particular factor was determined by calculating the f-stat and comparing the value of F-stat at 90% confidence with respect to the degree of freedom of the sum between groups (SSB) and sum within groups (SSW). The $\log_{10}$ standard deviation of the void content graph is plotted to see the variability of the values of each sample, which would reflect the accuracy of the results. The F-stat values are calculated by using the formula shown in Equation (3.2).

$$F - stat = \frac{\frac{SSB}{DOF\ 1}}{\frac{SSW}{DOF\ 2}} \tag{3.2}$$

SSB: Sum of Squares Between Groups

SSW: Sum of Squares Within Groups

DOF 1: Degree of Freedom for SSB

DOF 2: Degree of Freedom for SSW

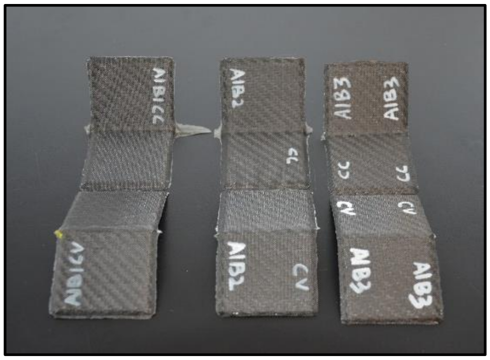
CHAPTER 4
RESULTS AND DISCUSSION

This chapter includes all the results and discussion throughout the experiment. Starting with the brief description of the procedures for the sample experiment process and the problems faced throughout the experiment. Next, it consists of void formation findings which includes images taken using a digital single-lens reflex (DSLR). The images were evaluated using an image processing tools via MATLAB for surface porosity. The images from DSLR are compared with optical microscopy images for validation purposes.

4.1 Sample Laminates

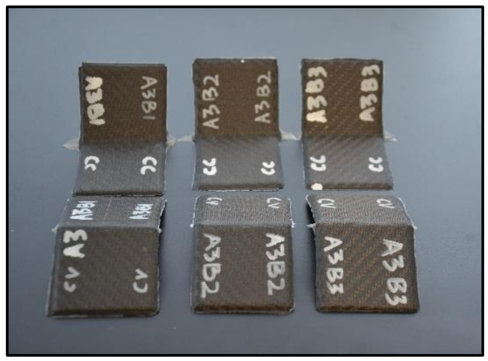
18 sets of samples were manufactured with different combination between the vacuum bagging techniques, curing profile as well as the complexity of the shape, as tabulated in Table 3.1. The sample's dimension is 120mm x 50mm.

The samples are labelled accordingly to the vacuum bagging process, curing profile and the complexity of the shapes to ease the analysing procedures. Figure 4.1 shows the images of the completed samples. The laminates were successfully produced according to the mould for both convex and concave shape. Total of 18 sample laminates that were manufactured are in good quality.



A_1

A_2



A_3

Figure 4.1: Manufactured Laminates for samples for SVB (A_1), MSVB (A_2) and DVB (A_3).

4.2 Through-thickness Void Content of Laminates Composites

4.2.1 Image Processing Procedure

Two types of image processing procedures were conducted namely using DSLR and optical microscopy. Optical microscopy images were processed to validate the results achieved by using the image taken using DSLR. However, only the samples with the highest void content and the lowest void content were chosen for the optical microscopy procedures with regards to time constraint to complete the study. The difference in the through thickness void content between microscopy images and images from DSLR is within 10% variation, therefore, the results is valid. Given the consistency of the results, DSLR techniques were chosen for the rest of the analysis because it is not time-consuming. The results of void content for the composite laminates produced are as shown in Appendix 1. Figure 4.2 shows the processed image using optical microscopy for the through-thickness void formation.

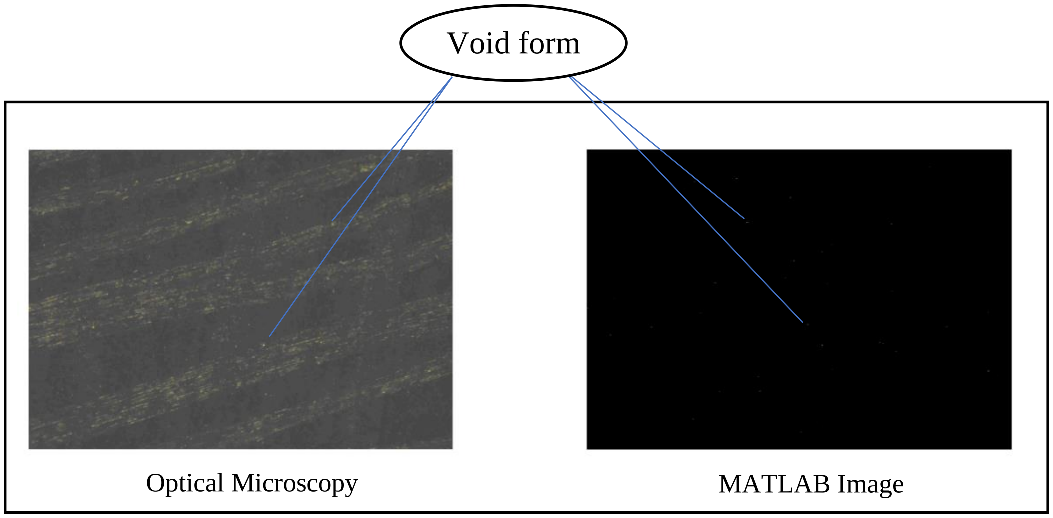


Figure 4.2: Optical Microscopy Image vs MATLAB Image for $A_2B_2C_1$

Optical microscopy shows that the void formation is 0.0821% while for the DSLR processed image shows that the void formed is 0.076%. The white spots in image shows the void formed in the sample.

4.2.2 Statistical Analysis

In this study, three factors are taken into account which results into 18 different samples made with different void percentage. The three independent factors are studied by using 3-way ANOVA analysis. The results of the ANOVA analysis are as shown in Figure 4.3. The grand mean value is 0.183 for the three factors contributing to the void content. This indicates that regardless which vacuum bagging techniques, curing profiles and shape complexity, the amount of void content would be around the grand mean value. The zoom-in image for the graph of Figure 4.3 is illustrated in Figure 4.4. The lower the values in the graph, the better it is as we are considering less void formation is desirable.

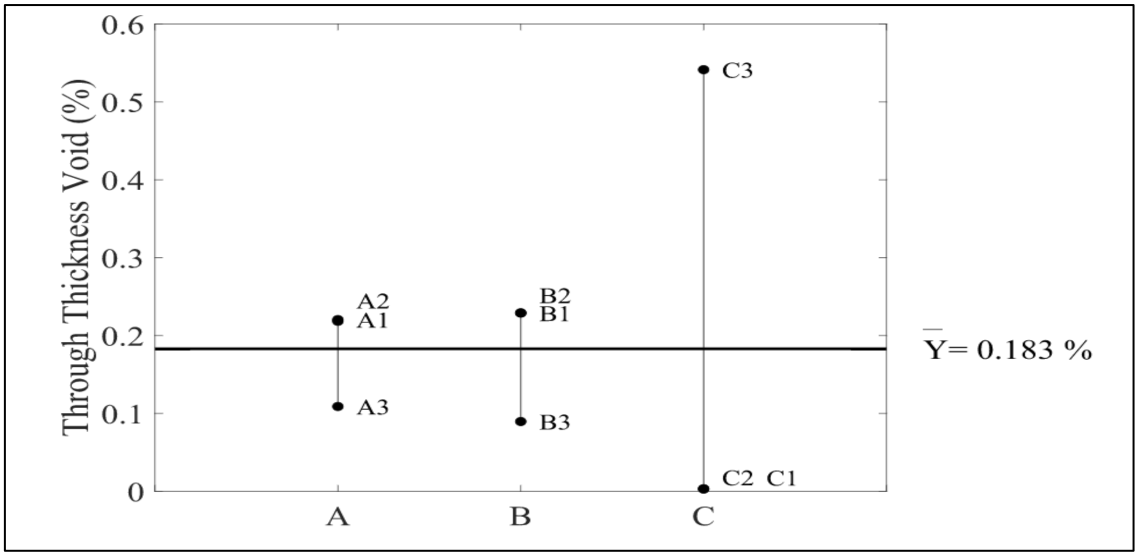


Figure 4.3: Graph of through-thickness void content with additional flat surface void formation from [3].

Table 4-1:Values for F-stat calculated

	A	B	C
F-stat	0.3194	0.5613	19.1295

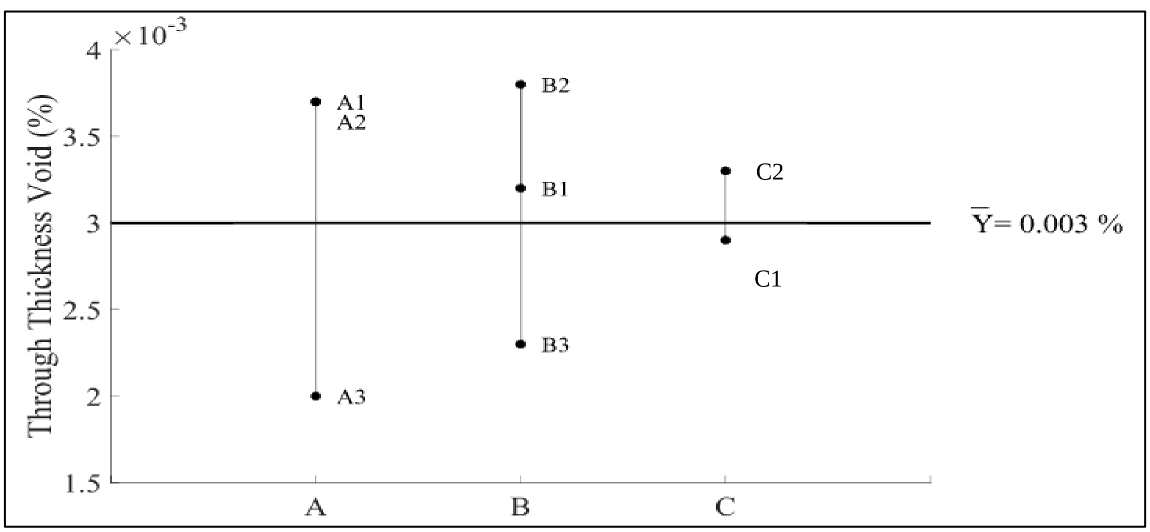


Figure 4.4: Through-thickness void content

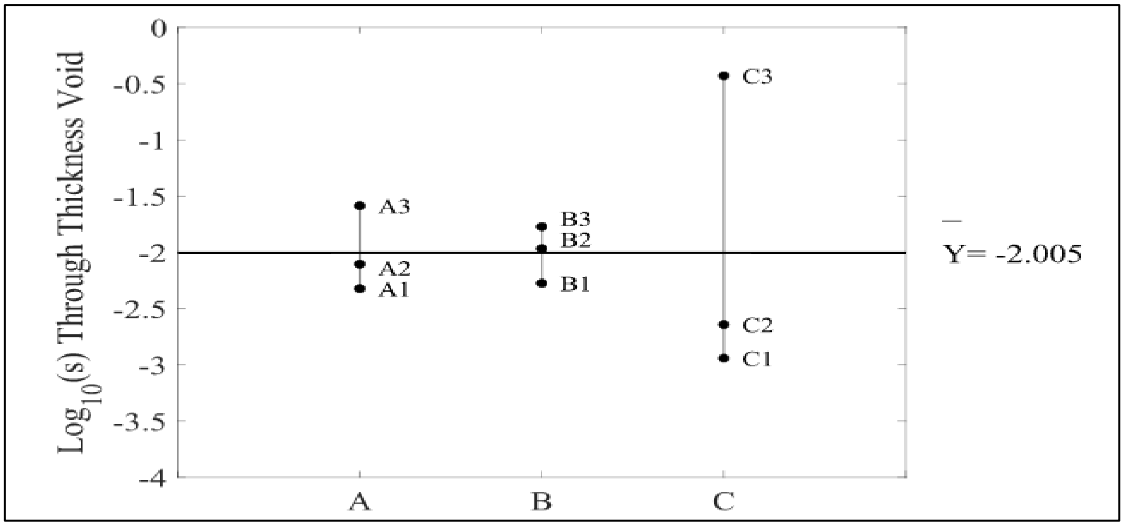


Figure 4.5: Log_{10} (s) Through Thickness Void

This analysis indicates which factor(s) that would affect the formation of voids in the carbon laminates. According to the F-stat table, with 90% confidence, the F-stat value is 9.45. Table 4.1 shows that the F-stat for factors A and B, both of the values are lower than 9.45 which indicates both factors are not significant in void formation in the composite laminates. Figure 4.3 and 4.4 both show that A_3, Double Vacuum Bagging technique and B_3, Direct Cure cycle would produce minimal void for flat and complex shaped laminates. This is because for DVB there is balloon effect on the first bag which gives a sufficient amount of time for the resin to spread across the area of laminates resulting in less void formation.

Next, F-stat value for shape complexity is higher than 9.45 which indicates the factor significantly affect the formation of voids in the manufactured composite laminates. Therefore, by changing the complexity of shape would have a huge impact on the void formed in the laminates. Figure 4.4 shows that factor C_2 produces higher void formation compared to C_1 which means concave complexity tend to produce more void compared to convex shape. This is proven by the study made by Yija et al. [12]. However, the additional flat surface in the results is to extend the study made by Yasir Mujahid [3] might affect the results of F-stat value for the complexity of the shapes. Theoretically, the complex shape would produce more void content when compared to flat surfaces as the complexity of the shape would be one of the factors that contributes to the void formation. This is because complex shapes have the presence of certain angles which tend to accumulate the resin not allowing it to spread thoroughly through the surface area. However, in this comparison shows flat laminates have more void content when compared to concave and convex shape laminates. All the parameters are kept the same between the experiments except for the size of laminates which flat surface has a higher surface area which causes the resin could not flow through the entire area with the same time and temperature provided for complex shape laminates. Due to time and resource limitation, the complex shape laminates are fabricated in a small-scale sample.

Figure 4.5 shows that $\log_{10}$ of the standard deviation of the void content values which indicates the variability of the results. The lower the value in the graph, the lesser variation between the values for each factor. A_1 is the least which means the value for each sample does not vary much which indicates the results for A_1 is the most accurate. The F-stat values for all factors in the $\log_{10}$ standard deviation graph is lower than 9.45 which indicates the variation in the samples is not causing any significant changes in the consistency of the results. This means the values that are retrieved are consistent and can be considered accurate.

Flat surfaces composites show the least void formation by using DVB technique accompanied by EMRCC cure cycle. In the context of concave shape, the lowest void content formed is 0.0003% which by using MSVB technique and DC cure cycle while for convex shape the lowest void formed is 0.0009% by using MSVB technique as well but accompanied with EMRCC curing profile. However, DVB vacuum bagging technique and DC cure cycle produce the least average value of void formation. As mentioned previously, the balloon effect on the inner bag for DVB gives time for the resin to flow through the carbon fibre ply even though with the presence of complex angle which in this case is 45^{o}. DC cure cycle produces less void content because the glass transition temperature has the longest dwell when compared to MRCC and EMRCC which ensures maximum resin impregnation into the dry region resulting lower values of void content.

CHAPTER 5

CONCLUSION AND RECOMENDATIONS

5.1 Conclusion

In conclusion, an out-of-autoclave procedure was introduced to improvise the disadvantages of conventional technique such as time consuming and complexity of shape and size. However, this technique would induce manufacturing defects such as formation of void in the composites which affects the mechanical properties of the laminates. This study proposes three factors which would contribute to the void formation in the manufactured composite laminates which are vacuum bagging techniques, curing profiles and complexity of the shape. By utilising the 3-way ANOVA analysis, it shows that only the complexity of the shapes would give significant changes to the void formation in the laminates. Therefore, in the production line, the manufacturer should change the shape complexity to reduce the void content in the product. However, if the shape is fixed, DVB technique and DC cure cycle are recommended as both factors were proven to produce the least average void formation. The variability of the results is analysed by plotting the $\log_{10}$ standard deviation of the values and the variation between the results are not causing any significant changes in the consistency of the results in which describes the result as an accurate result.

5.2 Recommendation

For future development of vacuum bagging only procedures, a more emphasize and detailed study should be conducted. In this study, the comparison between the complex shape with flat surface would be better if the size of the flat laminates is similar to the samples used in the study as the other variables such as factors such as vacuum bagging technique, curing profile. thickness and type of laminates are kept constant. Therefore, the first recommendation is to increase the size of laminates which used to be studied for complex shape. Besides that, another alternative is modification of DVB setup to suit the industrial application scale. There are still a few limitations for composite production with the current setup. The composites are limited to the size of oven and perforated tool. Replacement of curing oven with an external heating element for curing and replacement for perforated tool steel and other measure which can prevent outer bag to collapse on the inner bag during the B-stage. In addition, if given sufficient time, instead of using DSLR image, optical microscopy image is preferable as it is more accurate compared to DSLR image.

REFERENCES

[1] Sumanta Bhandary, Biplab Sanyal, Mingchao Wang et al., “Composites and Their Properties”, InTech, 2012.

[2] F.C. Campbell, “Structural Composite Materials”, Chapter 1, pp 1, 2010. [Online]. Available:https://www.asminternational.org/documents/10192/1849770/05287G_Sample_Chapter.pdf .

[3] Y. Mujahid, “Effects of Vacuum Bagging Processing Parameters for Vacuum-Bagging-Only Method on Formation of Manufacturing-Induced Defects and Mechanical Properties of Sandwich and Laminates Composites”, Universiti Teknologi Petronas, 2019. (Unpublished Data)

[4] M. Brillant, “Out-of-Autoclave Manufacturing of Complex Shape Composite Laminates”, McGill University, Canada, 2010

[5] F. C. Campbell, “Engineering 360,” IEEE GlobalSpec, 2006. [Online]. Available: https://www.globalspec.com/reference/37444/203279/7-9-curing .

[6] G. Francucci, S. Palmer and W. Hall, “External compaction pressure over vacuum-bagged composite parts: Effect on the quality of flax fiber/epoxy laminates”, Journal of Composite Materials, vol 0, no 0, pp 1-13, 2017.

[7] J. Sloan, “Out-of-autoclave processing: <1% void content?” CompositesWorld, 6 January 2015. [Online]. Available: https://www.compositesworld.com/articles/out-of-autoclave-processing-1-void-content. [Accessed September 2018].

[8] W. S. Epoxy, "Vacuum Bagging Techniques," 002-150, April, 2010, Available: https://www.westsystem.com/wp-content/uploads/VacuumBag-7th-Ed.pdf.

[9] T. H. Hou and B. J.Jensen, “Evaluation of Double-Vacuum-Bag Process For Composite Fabrication,” 2014.

[10] J. Anderson and M. Altan, "Formation of voids in composite laminates: coupled effect of moisture content and processing pressure," Polymer Composites, vol. 36, no. 2, pp. 376-384, 2015.

[11] G. T. Franck, Bartolome, Alvin S, Jarvis-Shean, Patrick G, "Honeycomb sandwich panel paint ready surface," ed: Google Patents, 2018.

[12] Y. Ma, Centea, Timotei, Nutt, Steven R, "Defect reduction strategies for the manufacture of contoured laminates using vacuum Bag-only prepregs," Polymer Composites, vol. 38, no. 9, pp. 2016-2025, 2017.

[13] T.H. Hou and B.J. Jensen, “Double-Vacuum-Bag Process for Making Resin-Matrix Composites”, NASA Tech Brief, Langley Research Center, Hampton, 2007. Available: https://www.techbriefs.com/component/content/article/tb/techbriefs/manufacturing-prototyping/1118?start=1

[14] T.-H. Hou, "Cure cycle design methodology for fabricating reactive resin matrix fiber reinforced composites: A protocol for producing void-free quality laminates," NASA Tech Brief, Langley Research Center, Hampton 2014.

[15] Takagaki,K , Hisada,S , Minakuchi,S and Nobuo,S, “Process improvement for out-of-autoclave prepreg curing supported by in-situ strain monitoring,” *Journal of composite materials,* vol. 0, no. 0, pp. 1-13, 2016.

[16] T. Centea, L.K. Grunenfelder, and S.R. Nutt,” A review of out-of-autoclave prepregs - Material properties, process phenoma, and manufacturing considerations.” Composites Part A: Applied Science, 70, 132 (2015).

[17] J.P. Anderson and M.C. Altan,” Formation of voids in composite laminates: Coupled effect of moisture content and processing pressure.” Polym. Compos., 36, 376, (2015).

[18] Mallow, Andrew R. & Campbell, Flake C. "Autoclave Processing." *Processing of Composites*. Ed. Raju S. Davé and Alfred C. Loos. Vol.1. Munich: Hanser, (2000): 295-316

[19] Kardos, J. L. "Void Growth and Dissolution." *Processing of Composites*. Ed. Raju S. Davé and Alfred C. Loos. Vol.1. Munich: Hanser, (2000): 182-207.

[20] Eom, Y., Boogh, L., Michaud, V. & Manson, J.-A. "A Structure and Property Based Process Window for Void Free Thermoset Composites." *Polymer Composites* 22 (2001): 22-31.

[21] Strong, Brent A. "Manufacturing Methods." *Fundamentals of Composites Manufacturing: materials, methods, and applications*. 1st edition. Dearborn, Mich: Society of Manufacturing Engineers, Publications Development Dept., Reference Publications Division, (1989): 107-159.

[22] L. Hamill, Centea, Timotei, Nutt, Steven, "Surface porosity during vacuum bag-only prepreg processing: Causes and mitigation strategies," Composites Part A: Applied Science and Manufacturing, vol. 75, pp. 1-10, 2015.

[23] “XPREG XC110 Prepreg Carbon 3K, 210g, 2/2 Twill, (1250mm) 1m Roll,” easycomposites, [Online]. Available: http://www.easycomposites.co.uk/#!/prepreg/component-prepregs/xpreg-xc110-prepreg-carbon-fibre-22-twill-210g.html

[24] L. A. Khan, Mahmood, A. H., Ahmed, S., Day, R. J., "Effect of double vacuum bagging (DVB) in quickstep processing on the properties of 977-2A carbon/epoxy composites," Polymer Composites, vol. 34, no. 6, pp. 942-952, 2013.

[25] G. Fernlund, Griffith, J, Courdji, R, Poursartip, A, "Experimental and numerical study of the effect of caul-sheets on corner thinning of composite laminates," Composites Part A: Applied Science and Manufacturing, vol. 33, no. 3, pp. 411-426, 2002.

[26] C.A. Wern, “Effects of Vacuum Bagging Processing Parameters on Mechanical Properties of Carbon-Epoxy Laminates: Experimental and Numerical Studies”, Universiti Teknologi Petronas, 2019.

APPENDIX

Table A1 are the results of void content in the 18 samples manufacture.

Table A1: Taguchi Table for Void Formation

Trials	Bagging Techniques (A)			Curing Profiles (B)			Complex Shape (C)		
Samples	A_1	A_2	A_3	B_1	B_2	B_3	C1	C2	Flat [3]
1	0.0029			0.0029			0.0029		
2	0.0043				0.0043		0.0043		
3	0.0025					0.0025	0.0025		
4	0.0018			0.0018				0.0018	
5	0.0063				0.0063			0.0063	
6	0.0045					0.0045		0.0045	
7	0.7542			0.7542					0.7542
8	1.0494				1.0494				1.0494
9	0.1587					0.1587			0.1587
10		0.0054		0.0054			0.0054		
11		0.0009			0.0009		0.0009		
12		0.0045				0.0045	0.0045		
13		0.0035		0.0035				0.0035	
14		0.0076			0.0076			0.0076	
15		0.0003				0.0003		0.0003	
16		0.8241		0.8241					0.8241
17		0.9465			0.9465				0.9465
18		0.1718				0.1718			0.1718
19			0.0018	0.0018			0.0018		
20			0.0030		0.0030		0.0030		
21			0.0009			0.0009	0.0009		
22			0.0039	0.0039				0.0039	
23			0.0011		0.0011			0.0011	
24			0.0011			0.0011		0.0011	
25			0.4619	0.4619					0.4619
26			0.0441		0.0441				0.0441
27			0.4619			0.4619			0.4619
Average	0.2205	0.2183	0.1089	0.2288	0.2292	0.0896	0.0029	0.0033	0.5414