STUDY OF PROCESSING PARAMETERS IN MANUFACTURING OF FLAT GLASS-EPOXY COMPOSITE LAMINATES USING VACUUM BAGGING OVEN CURING

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by

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LIST OF ABBREVIATIONS

ANOVA	:	Analysis of variance
ASTM	:	American Society for Testing and Materials
CTE	:	Coefficient of Thermal Expansion
CFRP	:	Carbon fiber reinforced plastic
DMA	:	Dynamic Mechanical Analysis
DOE	:	Design of experiment
DSC	:	Differential Scanning Calorimetric
FEA	:	Finite Element Analysis
FRP	:	Fiber reinforced plastic
GFRP	:	Glass fiber reinforced plastic
ILSS	:	Inter-laminar shear strength
OoA	:	Out-of-Autoclave
PMC	:	Polymer-matrix composite
SEM	:	Scanning Electron Microscopy
TGA	:	Thermo-gravimetric analysis
UTM	:	Universal testing machine
VBO	:	Vacuum Bagging Only

KAJIAN TENTANG PARAMETER PEMPROSESAN DALAM PEMBUATAN GELAS-EPOKSI KOMPOSIT LAMINAT RATA MENGGUNAKAN VAKUM BEG PENGAWETAN KETUHAR

ABSTRAK

Proses pembuatan yang efektif bagi struktur pesawat yang diperbuat daripada komposit laminat melibatkan prepreg autoklaf dihasilkan menggunakan vakum beg dan autoklaf. Walau bagaimanapun, autoklaf melibatkan modal, kos pembuatan dan tegasan sisa yang terlalu tinggi. Pra-membentuk laminat menggunakan vakum beg dan pengawetan ketuhar adalah yang terdekat untuk beralih daripada autoklaf. Jadi, kajian ini menumpukan kepada kesan teknik pra-pembuatan menggunakan vakum beg di dalam pengawetan ketuhar daripada bahan prepreg autoklaf. Ia melibatkan teknik rekabentuk eksperimen yang sistematik. Kesan bagi parameter pemprosesan vakum beg yang merangkumi teknik pemamapatan vakum sebelum pengawetan dan konfigurasi vakum beg ia itu pengudaraan di pinggir laminat, pemberat dan jenis-jenis pelapik yang berbeza terhadap udara terperangkap dan kualiti mekanikal laminat yang dihasilkan telah disiasat menggunakan kaedah analisis varian. Analisis kualiti fizikal juga dilakukan untuk menilai variasi ketebalan dan keabnormalan bagi seluruh laminat. Peratusan keabnormalan laminat dikaji menggunakan algoritma pemprosesan imej ultrasonik C-imbasan. Untuk menilai hubungan antara ciri-ciri udara terperangkap dan kekuatan ricih antara laminat, analisis imbasan elektron mikrograf telah digunakan. Kesimpulan yang didapati adalah kekuatan ricih antara laminat dan kekuatan tegangan adalah berkait rapat dengan peratus kandungan dan saiz udara teperangkap di dalam komposit laminat yang juga sensitif kepada parameter pemprosesan.

STUDY OF PROCESSING PARAMETERS IN MANUFACTURING OF FLAT GLASS-EPOXY COMPOSITE LAMINATES USING VACUUM BAGGING OVEN CURING

ABSTRACT

The effective manufacturing process for aircraft structural parts made from composite laminate usually involved autoclave prepreg material manufactured via vacuum bagging pre-forming and autoclave. Though, autoclave involves high capital, running cost and extortionate residual stress. Vacuum bagging only (VBO) pre-forming process with oven curing is the closest out-of-autoclave (OoA) method shifts from autoclave. Thus, this study focuses on the vacuum bagging pre-forming process in oven cure using the autoclave. This work involved revising the design of experiment (DOE) to design the possible experiments to be conducted in a systematic approach. The effects of vacuum bagging process of layup technique (debulking) and vacuum bagging configurations (edge breather, intensifier and mould release type) towards void content and mechanical properties of laminate produced were investigated using analysis of variance (ANOVA). The physical quality analysis is also performed to evaluate the thickness variation and abnormalities throughout the laminate. The abnormalities percentage of the produced laminate was studied using the image processing algorithm of ultrasonic C-scan image. To assess the relationship between void and inter-laminar shear strength (ILSS), scanning electron micrograph analysis was employed. It was concluded that the ILSS and tensile strength were reflected directly to the void content and void dimension which were also sensitive to the processing parameters.

CHAPTER 1

INTRODUCTION

"He it is who shapes you in the wombs as He pleases. There is no god but Him, the Exalted in Might, the Wise." (Quran 3:6)

1.1 Research background

Laminated composite structures have recently gained enormous attention from aircraft industry as it has directly enhanced the capability of vehicle's structural performance as compared to existing traditional materials such as metal alloys, aluminium and polymers. It enables the engineers to successfully accomplish a structural design with better performance throughout its life cycle, whilst reducing the weight and maximizing the reliability, thus decreasing the capital cost, production cost, service cost, maintenance cost and manufacturing cost (Nandi et al., 2011). Consequently, the study and research on the manufacturing practice of these composite laminate is tremendously essential.

Generally, manufacturing process for aircraft parts made from composite laminate material usually involved the prepreg material manufactured via vacuum bagging pre-forming and autoclave curing techniques. It was found that autoclave moulding provides the most effective curing method in producing low void content in laminated composites for critical engineering application especially the aircraft industry, which requires a maximum of 1% void content, due to the presence of extremely high compaction pressure (Thomas et al., 2008). Though, autoclave cure has raised a quantity

of issues and tribulations especially in terms of high capital and manufacturing cost along with extortionate residual stress due to the high pressure introduction during cure. Consequently, the evolution of out-of-autoclave (OoA) processes consists of oven cure, microwave cure, quickstep cure, ultraviolet radiation cure, infrared radiation cure and etc. were commenced to replace the traditional autoclave technology. In contrast to autoclave technology, the OoA curing offers an alternative solution of trimming down the overall cost with the absence of the enormous compaction pressure. The vacuum bagging only (VBO) pre-forming process with oven curing is the closest shifts from the autoclave curing technology of laminated composite for aircraft parts. In addition, by implementing these manufacturing techniques, lesser capital and running cost with lower residual stress can be achieved.

However, due to the absence of the elevated pressure during oven cure, the laminated composite laminates exhibit inferior qualities with respect to high void content and poorer mechanical performances. These qualities were most affected by the manufacturing process involved, during either the vacuum bagging pre-forming or curing process. The vacuum bagging construction recommended by prepreg manufacturer details in Figure 1.1 entails the mould, mould release, the prepreg plies, release film, breather, sealant, nylon vacuum bag and the vacuum port for the vacuum suction system during cure.

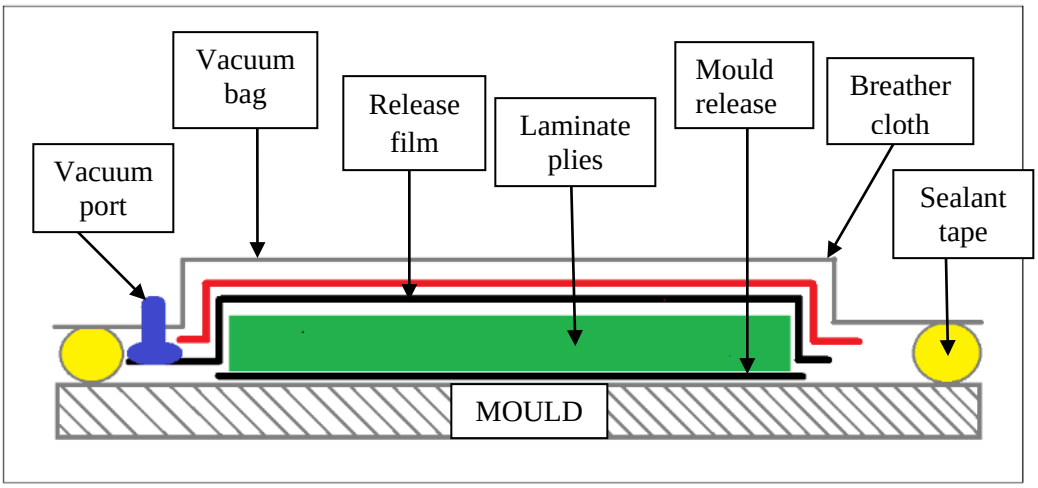

Figure 1.1: Schematic of a typical bagging construction for vacuum bagging pre-forming process.

Nonetheless, during the layup, prepreg plies tends to entrap voids and moisture, which are typically evacuated in a successful manner via immense compaction during conventional autoclave cure. It was found that layup (Yang & Lee, 2002) and bagging (Hubert & Poursartip, 2001) techniques in vacuum bagging pre-forming provide significant effects in improving the qualities of the cured panels. Therefore, without the high pressure in oven cure, numbers of techniques were presented during layup processing (e.g. debulking technique) and vacuum bagging (e.g. mould release agent type, intensifier weight, edge breather. etc) to relinquish the entrapped air and moisture, hence enhancing the void content and mechanical properties of composite panel.

Debulking is a technique employed by researches during the layup of laminate by applying vacuum pressure to compact the plies prior to the cure. Accordingly, the debulking technique was exploited in various different manners with respect to number of plies and period of debulking. Davies et al. (2006) recommended debulking for individual prepreg layup in 20 minutes, while Hubert & Poursartip (2001) stated that

debulking has to be executed for every stacked of four prepreg plies. On the other hand, Kim et al. (2004) claimed that debulking should be performed to the whole prepreg plies for two hours prior to the cure. Nevertheless, there are a lot of misconceptions where the debulking procedure was occasionally proved to have reduced the in-plane permeability due to the fact that the dimension of permeability is abridged (Louis, 2001, Xin et al., 2011) and thus increase the void content. However, Kratz & Hubert (2013) divulged a contradictory argument where debulking is essential in evacuating the entrapped air to further reduce the void content of the laminate especially when the laminate is cured in the oven.

1.2 Problem statements

The studies pertaining to the qualities of composite laminates manufactured via vacuum bagging with oven cure techniques are still in its nascent stage. The scope for future studies in this domain is tremendous. The existing work in laminate curing is mostly majoring in optimizing the traditional autoclave by temperature and pressure cycle along with ex-situ and in-situ monitoring which entails the laminate products feature. Moreover, the overall performance measurement (i.e. void content and mechanical performances) of the VBO-oven cured laminates using the traditional autoclave prepreg have not been conducted exclusively since the development of the OoA prepreg materials which exhibit remarkable qualities with any OoA cure technology. Provided that new OoA prepreg is more expensive than the customary autoclave prepreg, much attraction is expected if the development of laminate manufacturing techniques via low cost oven cure can bestow comparable qualities with those of the autoclave, using the common cheaper autoclave prepreg.

Thus, the effects of VBO-oven curing of common autoclave prepreg material need to be further investigated. The influence of each processing parameters including the layup technique and bagging configuration are required to provide detailed contributions of these imperative factors to the void content and mechanical performances of oven-cured laminates. As the oven curing resembles the closest alternative on shifting from the conventional autoclave cure for aircraft structural composite laminate, this is proved to be highly critical. Besides, with the absence of high compaction pressure during cure, the processing parameters may provide significant effects on the quality requirement of the composites.

Moreover, the debulking procedure were claimed to have reduce the void content by several researches (Lin et al., 2010, Kim et al., 2004), while others opposed (Louis, 2001). The debulking technique by previous works was performed in different means with respect to ply frequency and period of debulking. Thus, the investigations on the effect of debulking process and the accurate consequence of debulking could be comprehensively considered. Moreover, the analysis on the quality effects (physical quality, void content and mechanical properties) of combining the methods in bagging configuration (different type of mould release, intensifier and edge breather) and layup parameters (debulking) during the vacuum bagging only pre-forming of oven cured laminate could be thoroughly deliberated. Additionally, since void were claimed to reduce the physical and mechanical properties of laminate (Bowles & Frimpong, 1992, Guo et al., 2005), the mechanical property investigations should be considered to find the relationships between voids and physical along with mechanical performance of laminate.

1.3 Objectives

The overall objective of the present study is to investigate the contribution of vacuum bagging pre-forming techniques on the quality characteristic of oven-cured flat laminate composite using the common autoclave prepreg with respect to physical quality, void content and mechanical performances. The study includes the following objectives:

- To determine the effects of intensifier, mould release type and edge breather on the physical quality, void content, inter-laminar shear strength (ILSS) and tensile strength of VBO-oven cured laminates.
- To investigate the effects of debulking on the physical quality, void content, ILSS and tensile strength of VBO-oven cured laminates.
- To investigate the relationship of void content with physical quality, ILSS and tensile strength of VBO-oven cured laminates.
- To analyze the effects of void distribution and size towards the ILSS of VBO-oven cured laminates with respect to the crack of ILSS.

1.4 Scope of study

In this thesis report, the work is focused on determining the effects and contributions of vacuum bagging only pre-forming processing parameters towards the quality of flat composite laminate cured in oven. The composite laminates were made using 9 plies of 308 mm by 308 mm (1 ft by 1 ft) dimension of Cycom 7668/7881-1 plain weave common autoclave glass-epoxy prepreg. A constant stacking sequence of 0 degree was employed in producing all the laminate panels in this research work.

During the vacuum bagging only pre-forming process, the prepreg were treated according to the designated techniques by 2 factorial design of experiment (DOE) method, which were debulking, edge breather, different mould release type and intensifier. The curing cycle was performed with heating and cooling rates of 2 ^{o}C/min, and one dwell section for 120 minutes at 180 ± 12 ^{o}C.

The flat laminate panels produced were then examined by non-destructive ultrasonic C-scan attenuation and image processing algorithm to analyze the level of abnormalities within the laminate. The destructive tests was carried out based on of ASTM D3171-99, ASTM D2344/D2344M-00 and ASTM D 3039 in determining the void content, inter-laminar shear strength (ILSS) and tensile properties of the produced laminate, respectively. A further investigation of the combined effects of those processing parameters was elucidated using ANOVA (Analysis of Variance) method. To assess the relationship between void and ILSS, post-test was done to the failed ILSS specimen using scanning electron micrograph analysis.

1.5 Organization of the thesis

There are 5 chapters in this thesis and each chapter gives information related to the research interest.

- Chapter 1 encloses introduction of the study. It covers brief introduction on the research background, problem statements, aims and objectives, and the organization of the thesis.
- Chapter 2 contains the literature review which involves briefing explanations regarding the material, manufacturing process and quality of flat laminated composite structure for general aircraft applications.
- Chapter 3 contains the information about the methodology utilized with the material, and the design of experiment entails in the study.
- Chapter 4 contains results and discussion. It covers the quality characteristic of the laminate produce in terms of void content and mechanical performances with the analysis of variance (ANOVA) evaluation.
- Chapter 5 concludes the findings in chapter 4 with suggestion for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This review chapter initiates with an overview of composite material and composite laminate. The material used in producing composite laminate parts is presented. The topic on the composite laminate manufacturing system which entails pre-forming and curing processes would be explained in more detail. A brief discussion on the processing parameters that are affecting the composite laminate quality is described, which then followed with a review of previous studies on the performance and quality of laminated composite structure with respect to the manufacturing process involved. This section also explains on the quality inspection methods that are usually employed to evaluate the performance measurement process for composite laminate produced. Finally, the findings of the literature are proposed at the end of the chapter.

2.2 Composite overview

Composite is defined as a combination of two or more distinct materials having a distinct feature interface between them in order to achieve an exclusive set of properties. The exclusive set of properties was obtained from the optimization of individual properties from those constituent materials. This definition is commonly used for materials containing reinforcing material (fiber) bonded together with a matrix (binder) material (Campbell, 2004). Generally, fiber materials can be classified into glass, carbon, aramid, organic fibers, boron, continuous silicon carbide and aluminium oxide.

Whereas, the matrix are classified into four major types which are polymers, metal, ceramic and carbon (Akovali & Kaynak, 2001). The matrix served to bind the fibers together by virtue of its cohesive and adhesive quality that enabled the transfer of the loads between fibers and protect them from the environments and handlings. In comparison with matrix, the reinforcement is responsible for carrying the load, due to its higher stiffness and strength (Gay et al., 2003). Therefore, most composite material have been developed to improve combinations of mechanical, physical, and other characteristics such as stiffness, toughness, impact and etc.

Composite material is further divided into major classes according to morphology of the binder (matrix) and the reinforcement, which is listed in Figure 2.1. Figure 2.1 represents a various classification scheme for composite structure types (Callister, 1997). The most conventional structural form of matrix and reinforced fiber combination that results in those material variations after consolidation is called laminate (Mallick, 1993), which will be further discussed.

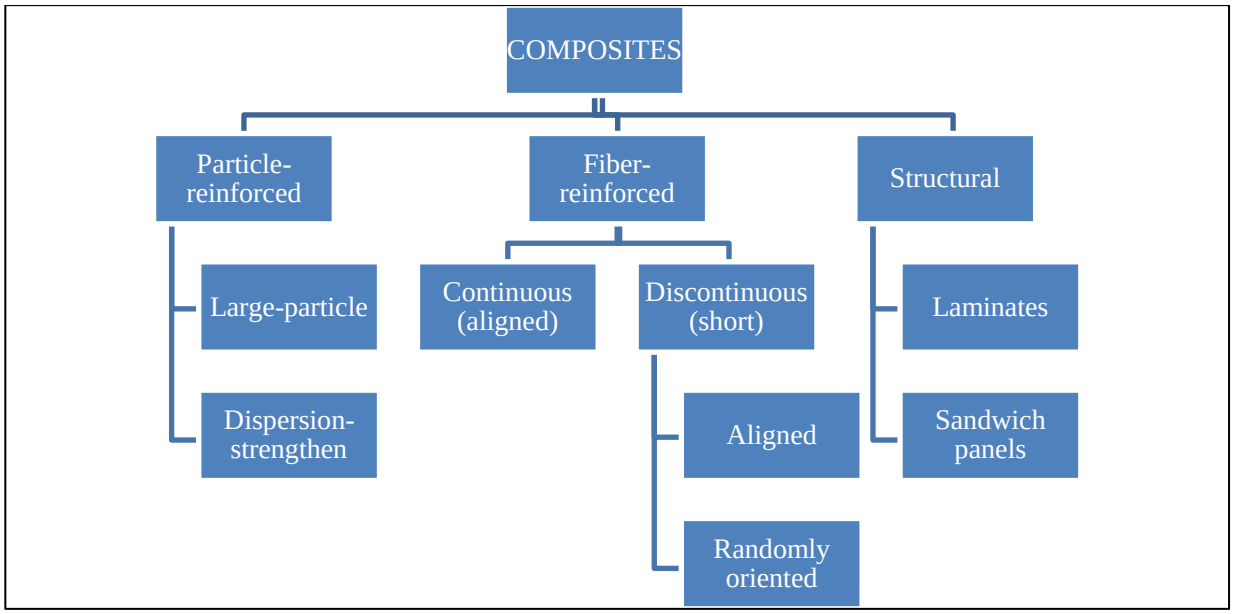

Figure 2.1: A classification scheme for various types of composites structure (Callister, 1997)

2.2.1 Composite laminate

According to Walker and Smith (2003), composite laminates are stack of laminas includes of dry fiber reinforcement layers injected with resin or prepreg ply. A familiar technique of composite structure construction is to employ these materials and assemble them up as laminate structures. Lamination itself is a technique of manufacturing a material in multiple layers to enhance the strength and mechanical performance of products.

During the recent years, laminated composite are found to have an increasing number of applications in the scale from simple households to heavy industrial purposes. The principal reason for this intensifying attention is related with the fact that laminated composites product offer selection flexibility upon designing for the manufacturers due to their extensive bounds of features (Walker & Smith, 2003). The potential

improvement in properties of the composites have led the researches to manipulate and improvise the qualities of these laminate to successfully accomplish better performances throughout its life cycle, whilst reducing the weight and maximizing the reliability, decreasing the capital cost, production cost, service cost, maintenance cost and etc. (Nandi et al., 2011). Guo et al. (2005) claimed that the composite laminates have recently gained multitudinous attention from the aircraft industry where components of high strength to weight ratio and minimum environmental impact were desired to directly enhance the vehicle's performance capability. The composite parts were introduced with the attention to yield lighter structure compared to existing traditional metallic components, thus reducing the fuel and increasing the payload. There are numerous types of composite materials used in the aircraft industry such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced plastic and etc. Table 2.1 shows the example of composite laminate material in aerospace applications.

Thus, the engineers have indicated that the composite laminates offer the best design consideration for the aircraft's performance requirements owing to its outstanding peculiarity. Nevertheless, the appropriate selection of material manufacturing process for producing aircraft laminated structure is also very crucial since ones have to consider especially on the parts quality as well as the manufacturing cost (Silcock et al., 2007).

Table 2.1: Example of composite laminate material in aerospace applications

Authors	Aerospace applications	Advantages
Ye et al. (2005)	-Fuselage skin of Vultee BT-15 trainer aircraft in 1944 by Dehavilland Aircraft Co.	High damage tolerance, high strength, high modulus and high fatigue life at a relatively low weight.
Ye et al. (2005)	Boeing and Airbus have also used the prepreg material of carbon-fiber reinforced epoxy laminated composite from prepreg material in the manufacturing of fuselage and wing structure for Dreamliner B-787 and centre wing box, flap track panels and upper deck floor beams for jumbo commercial A380 aircraft, respectively	Low fuel to low consumption due to lighter power to weight ratio and better mechanical performance during applications
Soutis (2005)	-Fuselage crown of Europe Airbus A380 used hybrid aluminium/glass reinforced plastic composite (GLARE) laminated composite material. -The aircrafts' wing trailing edge panels are made of glass combined with CFRP laminate.	Higher damage tolerance and fatigue life with lighter structure
Kim et al. (2004)	-Nozzle for combustion chamber of solid rocket used carbon-phenolic thick composite material.	Heat resistance, ablative and tremendous strength qualities. Thick laminate of above one inch thickness was utilized in the nozzle to tolerate high pressure and temperature of the combustion gas to insulate the other components from heat
Wang et al. (2002) and Mallick (1993)	-Inboard aileron in Lockheed L-1011 aircraft was made from T-300 carbon fiber reinforced epoxy composite laminate which includes front spar, main ribs and other ribs	Laminated structure is 23.2% lighter than the traditional metallic aileron and demonstrates equal to or better performance.
Bellenger et al. (2005)	-Structural components in future European Supersonic Civil Transport (ESCT) aircraft has also employed the unidirectional carbon-fiber reinforced epoxy laminated composite	Low fuel to low consumtion due to lighter power to weight ratio

2.3 Composite Laminate Design and Formulation System

2.3.1 Material classification

Fundamentally, pre-impregnated fiber preforms (prepregs) or dry fiber performs with injected resin are used extensively as the principal materials for producing composite laminate for aircraft applications due to its modest bleeding condition during cure (Chandrakala et al., 2008, Shimokawa et al., 2007). The following sections discuss details of the composite laminate material classification with regards to the benefit offered through the architectural designs and mechanisms.

Dry preforms with resin

Dry preforms injected with resin served as an alternative for composite laminate material which is typically implemented in Quickstep (Kafi et al., 2011), microwave (Papargyris et al., 2008), oven (Cao and Cameron, 2007), and electrical curing processes (Zhu and Pitchumani, 2000, Ramakrishnan et al., 2000). The advantage of using this material is the bleeding process facilitates the emigration of voids from the laminate without of the high autoclave compaction. This void evacuation process was done by controlling the amount of resin to be injected into the laminate and bleeds out from the laminate. However, this injection method is critical as the quantity of resin content need to be correctly determined to attain the accurate quality required for the composite part application (Hattabi, 2005). Plus, the fiber wet out mechanism depends largely on the fiber architecture of woven, stitched, or braided (Zhou et al., 2008) as well as on the fiber morphology, including filament count, fiber bundle length and superficial density (Endruweit et al., 2008).

Prepreg material

Prepreg is flat sheet containing reinforcing fibers pre-impregnated with matrix resin, usually supplied in a roll form. In a prepreg, the resin is advanced to a B-stage condition in which it is in gel condition at room temperature, which melted and cured during the cure cycle (Chandrakala, 2008). Prepregs are preferred for the use in high performance applications. One of the example of aircraft component that use prepreg is the structural window frame on Boeing 787 that employd Hexcel HexMC prepreg for its low density and tremendous damage tolerance than conventional aluminium material (Feraboli et al., 2010).

The prepregs are commercially classified based on the fiber bedding and morphology; the three common types are unidirectional prepreg tapes, woven prepreg and prepreg tows (Akovali & Kaynak, 2001). Nevertheless, Kratz and Hubert (2011) claimed that during the past several years, manufacturers have developed two categories of prepreg materials according to the processing technology: prepregs for autoclave moulding process; and prepreg for out-of-autoclave (OOA) technology. Meanwhile, the autoclave prepreg material typically contents much higher resin exceptionally for the unique bleeding condition. The particular prepreg system effortlessly exhibited a high quality of void-free composite by utilizing high compaction pressure and bleeding condition that evacuated the excess resin and entrapped air out from the laminate. This type of prepreg is commercially and conventionally used by most of the aircraft manufacturers (Shimokawa, 2007).

Based on the widely used of composite laminate, Kaufman et al. (2010) reported that the common composite used for aircraft parts is the conventional carbon-fiber reinforced polymer (CFRP) prepreg that has been utilized for the primary structures since the last 20 years due to its high strength-to-weight property. Utilization of this type of composite material offers an alternative for a better performance, improves dexterity, higher quality and lower fuel-consumption for their optimum design. Nevertheless, production of CFRP laminated composite is expensive owing to high labor and material costs. Since carbon/graphite fiber is the most expensive fiber reinforcement in comparison with other reinforcements such as glass, the CFRP composite outlays much higher cost than the other laminated composite materials (Enamul Hossain, 2011). Though, the utilization of glass fiber composite in the aircraft industry is insignificant due to lacking number of research on the use of such reinforcement for aircraft structural purposes (Soutis, 2005).

On the other hand, the out-of-autoclave (OoA) prepreg exhibits significant difference from the traditional autoclave prepreg in that the resin system is created for cure optimization at lower pressures and/or lower temperatures with similar product's quality especially in inter-laminar shear strength, compression strength, void content percentage, resin distribution and free from dry spots (Xin et al., 2011, Bowles & Frimpong, 1992). The fiber is semi impregnated with enhanced formulated resin in order to increase the in-plane permeability through the presence of dry-fiber pathway for entrapped air and gasses transport evacuation. Since the advanced OoA prepreg is only partly impregnated and behaves without the tackiness property, it is proficient in removing the entrapped air during kitting and layup as well as via vacuum only

mechanism during cure. Because of that, the consolidation pressure to suspend the entrapped air resembling the autoclave cure becomes surplus to requirements (Centea and Hubert, 2011, Thomas et al., 2008). Consequently, current development on the OoA prepreg explicitly for OoA manufacturing practice such as oven, Quickstep, hot press, microwave and etc. has trounced this problem (Kratz & Hubert, 2011, Dang et al., 2011, Walczyk et al., 2011).

Several experimental procedures attested that humidity and temperature environment during kitting and layup would not increase the void content in the OoA prepreg lamina. Thus, the development provides an excellent preference of shifting from autoclave to OoA cure process as the composite laminate can be fabricated straightforwardly without the demanding environment controlled and size limitation of production (Grunenfelder and Nutt, 2010). Nonetheless, the majority of research on OoA cure was anchored in attaining an outstanding quality of the prepreg materials, which is attributable to the high price tag of OOA prepreg material in contrast to long-established autoclave prepreg (Kafi et al., 2011).

In the present study, glass-fiber reinforced epoxy (GRP) prepreg was used. Despite the fact that the epoxy polymer resin system that conventionally implemented on aircraft parts was claimed to be brittle and has lower damage tolerance than thermoplastic resin, the mechanical properties of the resin can yet be optimized and improvised with glass fiber reinforcement and reliable processing parameters (Soutis, 2005). Even though the utilization and research of GRP laminate in aircraft industry is still diminutive, the European Airbus A380 has adopted the glass reinforcement which results in better aerodynamic performances (Soutis, 2005). Moreover, according to Oh

and Lee (2002) the potential properties enhancement of thicker GRP laminates is recognized to have tremendous quality and meet the requirements for producing primary aircraft structure and has led to increased applications in the airline industry. In addition, Murray et al. (2002) has also verified that the glass fiber possesses out-of-plane stiffness and low in-plane axial and high strain capability and highly recommended to be used in aircraft wing structure.

2.3.2 Material design

Laminated composite could be designed into two, based on their thickness range; thick and thin composite laminates (Dufour et al., 2004). Thick laminate is identified to have thickness equal and more than one inch (25mm) while the counterpart should possess thickness less than that (Oh and Lee, 2002). Due to the difference in the out-of-plane geometry, the curing of these laminates is proved critical with the intention of acquiring and maintaining the uniform temperature distribution especially in the thickness plane. Thus, the optimization of the composite manufacturing process is critical as non-uniform curing might take placed thus plummeting the high strength characteristic needed for such applications (Kim et al., 2004), which will be discussed further in the next section.

2.4 Composite Laminate Manufacturing Technology

According to Malick (1993), the composite manufacturing can be mainly categorized into phases of pre-forming and curing process. In the former, the reinforcement (fibers) and/or the matrix are placed into a structural form, while in the curing process, heat and/or pressure application is utilized to fortify the structure. Generally, resin transfer moulding (RTM), filament winding, liquid moulding, vacuum bagging only (VBO), compression moulding and etc. are implemented as the pre-forming processing techniques whereas the curing was further ensued in autoclave and Out-of-Autoclave (OOA) cure, consisting of oven, room temperature, microwave and etc. (Mallick, 1993, Kaynak, 2001, Campbell, 2004).

2.4.1 Preforming process

There are a wide variety of preforming processing techniques available for the composite productions, including liquid moulding, filament winding, vacuum bagging and etc. The liquid moulding process incorporates filling of wet resin into the mould where the layup of dry performs are in presence. Via this process, a sufficient fiber wetting is critical as incomplete filling leads to faulty parts with dry spots, resin rich area, high void content, non-uniform thickness and non-uniform void distributions (Babu et al., 2008). Optimizing the injection rate time is vital to minimize fill-time and fluid pressure buildup during the filling by controlling the amount of resin bleeds and the compaction during layup to ensure lower cost consumption (Pillai, 2004). However, slower injection profile however improved the quality of the component but the production cost is expensive (Dong, 2008). Resin transfer moulding (RTM), vacuum

assisted resin transfer moulding (VARTM) and resin infusion are considered as cost-effective liquid moulding preforming processes where short cycle periods, small employment requisite, and are capable in producing large parts economically (Park et al., 2004). Figure 2.2 entails a typical RTM preforming in which the fibrous reinforcement or prepreg material is placed at the bottom half of two-part closed mould, sealed with a controlled velocity and finally clamped with force to desired thickness before wet resin is injected and curing begun.

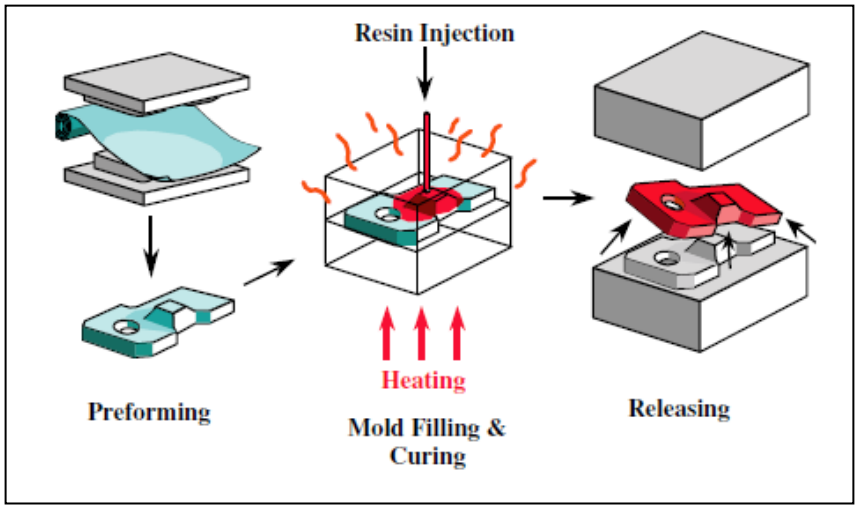

Figure 2.2: Schematic representation of the resin transfer moulding process (Park et al., 2004).

Further enhancements on RTM technique where VARTM is introduced entails a similar process to typical RTM, but with the utilization of vacuum pressure and resin bleeding system where the void content can be reduced dramatically to an extent of less than 1% with more uniform void distribution (Kuentzer et al., 2007). However, liquid moulding process has not been widely utilized in the aircraft application since the mould is required for each different types and size of panels. The design optimization of the mould configuration is as well strenuous and complicated as the imprecise arrangement

of the vents for excess resin bleeding and voids evacuation pathways resulted in inhomogeneous resin distribution throughout the fiber perform and high void content (Chern et al., 2002).

In aerospace applications, filament winding is one of the widely used pre-forming technologies to fabricate spherical and cylindrical aerospace components such as high pressure vessels, rocket motor casings and etc. (Morozov, 2006). As illustrated in Figure 2.3, the conventional filament winding process engaged tapes or continuous fiber reinforcement wetted by resin, which then wrapped around a rotating mandrel and subsequently cured typically to produce cylindrical hollow components.

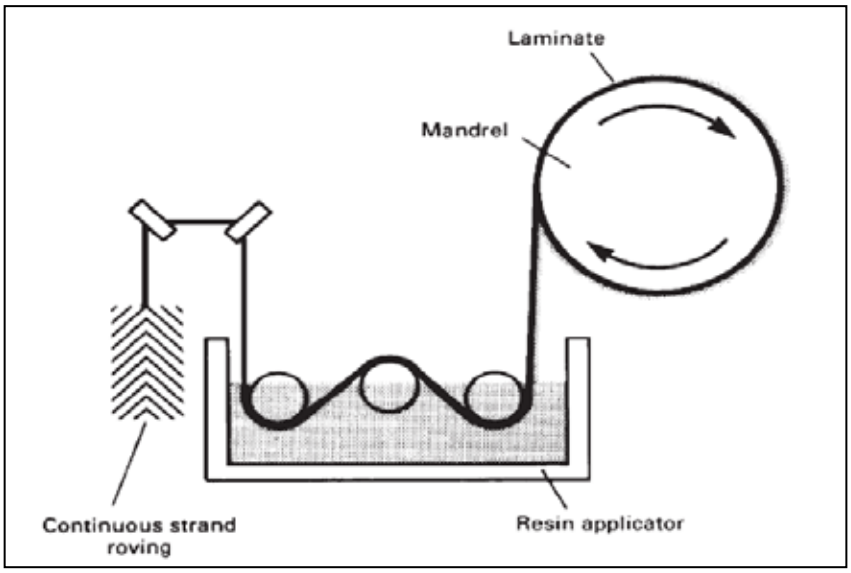

Figure 2.3: A typical filament winding system (Greene, 1999).

According to Hassan et al. (2005), the filament winding system is considered to have a low capital and running cost for constructing the composite components. However, the design optimization on the processing parameter and techniques are highly critical and perplexing due to the development of uncontrolled residual stresses which

may promotes warpage or redundant alteration in the curvature radius, thus leads to matrix cracking, interply delaminations and failure especially in larger design.

2.4.1.1 Vacuum bagging only (VBO)

Meanwhile, the vacuum-bagging-only (VBO) process is the simplest and preferred method of pre-forming the laminated composite particularly in aircraft composite parts (Crump et al., 2009). VBO is a cost-efficient, high-speed and straightforward technique in comparison with other pre-forming process by which the laminate is firstly layup, bagged and then cured in any curing process (Davies et al., 2006). Crump et al. (2009) reported that there was a significant saving of approximately 30% of manufacturing cost and time with the utilization of VBO in an oven cure to produce a 1.5 mm thick laminate (layup of 12 plies of prepreg) face sheet for a single skin trailing edge access panel of a secondary wing structure for a passenger aircraft, in comparable to that of VBO in autoclave process. In VBO, the composite laminate is sealed within an airtight envelope and a vacuum pump is utilized to relinquish air entrapped from the inside of the envelope and form the composite laminate into desired shape based on the mould design. Figure 2.4 shows detail description of typical VBO layout with the consumables, namely; nonporous Teflon release films, breather fabric, sealant tapes, bagging films, vacuum valves, vacuum hose, and vacuum pumps (Xin et al., 2011).

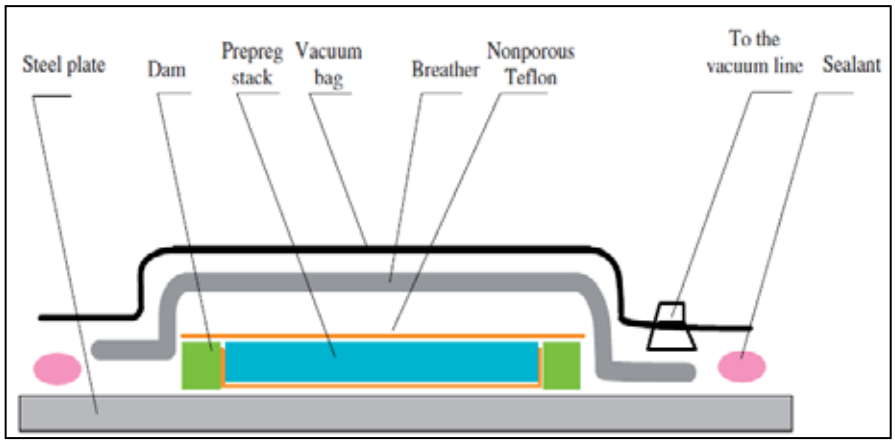

Figure 2.4: Composite laminate in VBO system (Xin et al., 2011).

The laminated composite parts for aircraft structure are required to have an extremely high quality to withstand numerous acting loads during the service. Accordingly, during the design phase, the investigation on the determinants that affects parts quality is enormously vital for the engineers and researches alike. With reference to the established aircraft-standard manufacturing process of VBO- autoclave cure, several factors were found to contribute to the laminate quality during the preforming and curing conditions, which were conversed in this chapter.

The typical pre-forming process of the aircraft composite engages VBO system, where the bagging configuration and layup technique are involved. These techniques may be altered and design efficiently in order to produce a different quality of laminate especially when the compaction pressure is absence during cure practice (Cao and Cameron, 2007). Table 2.2 demonstrates the setup of bagging configuration and layup techniques used in previous researches which may alter the quality especially on the void content.

Table 2.2: Specific bagging and layup optimization techniques in autoclave and oven cure.

Authors	Material used	Specific bagging and layup optimization techniques
Joshi et al. (1999)	-Thick stack of AS4/3501-6 graphite/epoxy prepreg (140 plies)	-1 ply release film on mould -2 layers of breathers
Guo et al. (2005)	-Thick stack of T300/HD03 carbon/epoxy prepreg (15mm thickness)	-1 ply release film on mould -Caul plate as intensifier (5 mm thickness) -Dams (25 mm thickness) covered by release film on top and 4 edges of laminate
Hubert & Poursartip (2001)	-Thin stack of AS4/3501-6 carbon/epoxy prepreg (32 plies) -Thin stack of AS4/8552 carbon/epoxy prepreg (24 plies)	-Room temperature debulk for every stack of 4 prepreg plies -Mould coated with release agent -A layer of breather cloth -Dams (side: silicone rubber, edge: sealant tape) -In no bleed condition, teflon impermeable film on top of laminate -In bleed condition, bleeder cloth on top of laminate
Lystrup & Andersen (1998)	-Thin stack of APC-2 ICI carbon/PEEK prepreg - Thin stack of Quadrax 5 Harness Satin carbon/PEEK prepreg - Thin stack of Filmix UD carbon/PEEK postpreg - Thin stack of Filmix 8 Harness Satin postpreg - Thin stack of Filmix 5 Harness Satin carbon/PEEK postpreg	-Addition of thin matrix films between prepreg. - Stainless steel press frame to ensure contact between vacuum bag and sealant tape. - Adhesive tape seals bagging film to mould and protects sealant tape during cure. -Aluminium cover plate placed after mould to avoid vacuum bag being squeezed between top mould and edge mould of laminate. -Stainless steel edge mould of laminate with same thickness as laminate.
Kim et al. (2004)	-Thin stack of CF3336 8 Harness Satin carbon/phenolic prepreg (9 plies)	-Debulk at room temperature for 2 hours with predetermined compression by jig pressure. -Laminate was placed in sandwiched plate of jig, and fixed by nuts and cured under vacuum and low pressure autoclave. -Dams at the edges of laminate stack.