EFFECT OF THE BAGGING CONFIGURATION ON THE PROPERTIES OF VACUUM-BAGGING-ONLY (VBO) - OVEN CURED IN COMPLEX-SHAPED COMPOSITES

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by

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LIST OF ABBREVIATIONS

ANOVA	:	Analysis of variance
ASTM	:	American Society for Testing and Materials
CBS	:	Curve beam strength
DOE	:	Design of experiment
DOU	:	Degree of uniformity
DT	:	Destructive test
GRP	:	Glass Reinforced Plastic
ILSS	:	Inter-laminar shear strength
ILTS	:	Inter-laminar tensile strength
MIS	:	Maximum inter-laminar stress
NDT	:	Non destructive test
OOA	:	Out of Autoclave
PTFE	:	Polytetrafluoroethylene
RML	:	Resin mass loss
RTM	:	Resin Transfer Moulding
SEM	:	Scanning electron microscopy
UTM	:	Universal testing machine
VBO	:	Vacuum Bagging Only

Kesan daripada Konfigurasi Beg ke atas sifat-sifat Vakum Beg Sahaja- Pengawetan Ketuhar dalam Komposit Berbentuk Kompleks

ABSTRAK

Dengan keperluan dalam industri aeroangkasa yang semakin meningkat untuk mengeluarkan komponen komposit yang lebih besar dalam masa yang sama, kos dapat dikurangkan, teknologi pembuatan di luar-penggunaan-autoklaf mungkin memberi jawapan untuk permasalahan tersebut. Walau bagaimanapun, kerja-kerja pembangunan ke atas proses tersebut yang menggunakan bahan-bahan pra-pembentukan laminat untuk mencapai kandungan udara terperangkap yang minimum tanpa dikenakan tekanan luar yang tinggi dari autoklaf telah terbukti ia adalah cabaran utama. Kajian penyelidikan ini memberi tumpuan khusus kepada proses vakum beg. Dalam kajian awal, lapan konfigurasi vakum beg yang terdiri daripada tiga parameter utama pemprosesan, iaitu penggunaan pelapik filem (PTFE), pengudaraan di pinggir laminat dan penggunaan pemberat telah dicadangkan untuk meningkatkan kualiti komposit laminat berbentuk L. Spesimen seterusnya dinilai berdasarkan tahap keseragaman dan tahap kandungan udara terperangkap. Keputusan kemudiannya dinilai menggunakan kaedah analisis varians untuk menentukan peratusan pengaruh bagi setiap proses parameter dalam peningkatan kualiti stuktur laminat. Keputusan eksperimen menunjukkan bahawa penggunaan PTFE telah menyumbang 37.84 % kepada pembentukan udara terperangkap yang ketara di bahagian lengkuk laminat. Sebaliknya, penggunaan pengudaraan di pinggir laminat dan pemberat berjaya mengurangkan tahap kandungan udara terperangkap sebanyak masing-masing 19.64% dan 29.41%. Untuk respon tahap keseragaman, penggunaan pengudaraan

di pinggir laminat dan pemberat hampir mencapai nilai sasaran (1) masing-masing dengan nilai sebanyak 4.4% dan 6.9%. Walau bagaimanapun, penggunaan PTFE telah menunjukkan hasil yang paling buruk dengan mengurangkan nilai tahap keseragaman dari nilai sasaran sebanyak 17.8 %. Di samping itu, untuk bahan ini, kandungan udara terperangkap yang meningkat daripada 3.85 % kepada 6.64%, penurunan sebanyak 60% untuk nilai kekuatan rusuk lengkuk dan kekuantan maksimum antara laminat diperhatikan. Kemudian , penyiasatan yang berterusan telah dijalankan untuk kajian yang selanjutnya ke atas kesan jenis pemberat (aluminium dan getah asli) dan luas ketumpatan pengudaraan di pinggir laminat (109 g/m^2 dan 244 g/m^2). Hasil kajian mendapati bahawa, apabila kekakuan pemberat dan luas ketumpatan pengudaraan di pinggir laminat meningkat, kandungan udara terperangkap di kawasan lengkuk stuktur laminat juga meningkat sebanyak masing-masing 13.48 dan 4.36%. Sebaliknya, peningkatan dalam kekakuan pemberat telah mencapai hampir kepada nilai sasaran (1) dengan nilai sisihan daripada 1.44 %. Peningkatan luas ketumpatan pengudaraan di pinggir laminat menunjukkan hasil yang paling teruk dengan pengurangan nilai tahap keseragaman oleh 2.92 %.

Effect of the Bagging Configuration on the Properties of Vacuum Bagging Only (VBO)-Oven Cured in Complex-Shaped Composites

ABSTRACT

With the growing needs of the aerospace industry to produce larger composite components at reduced costs, Out-of-Autoclave (OOA) manufacturing technology is perhaps the answer for the problem. However, the development work of the OOA process using prepreg materials to achieve minimum void content without high external pressure from the autoclave proved to be a major challenge. The research study focused specifically on the vacuum bagging process. In the initial study, eight bagging configurations which consist of three main processing parameters, including the use of release film (PTFE) , edge breather and the intensifier were proposed to improve the quality of the L-shaped laminate composites. The specimens were assessed based on degree of uniformity (DOU) and void contents levels. The results were subsequently evaluated using the analysis of variance (ANOVA) to determine the percentage of influence of the processing parameters to the quality improvement. The experimental results indicated that the use of PTFE has contributed 37.45% to the significant void formation at the corner section. In contrast, the edge breather (VBO) and intensifier successfully reduced the void content level by 19.64% and 29.41%, respectively. For DOU response, the use of VBO and intensifier almost achieved the target value (1) with the value of 4.4% and 6.9% respectively. Nevertheless, the PTFE application has shown a worst result by reducing the DOU away from the target value by 17.8%. In addition , as the void content increased from 3.85% to 6.64% for this material, a decrease of 60% in

the CBS and MIS value is observed. Subsequently, an extended investigation has been carried out to extended study the effect of different types of intensifier (aluminium and natural rubber) and VBO areal density (109 g/m^2 and 244 g/m^2). It has been observed that, as the intensifier stiffness and the areal density of VBO type increased, the void content at the corner region of laminate also increased by 13.48 and 4.36% respectively. On the other hand, the increase in the intensifier stiffness has achieved close to the target value (1) with the deviation value of 1.55%. The increase in the areal density of VBO type provided the worst result with a reduction of the DOU value by 2.37%.

CHAPTER 1

INTRODUCTION

1.1 Composite in general

Advanced composite materials have been increasingly used in a wide range of industrial applications due to the excellent properties such as high specific strength, specific stiffness and fatigue characteristics. Especially in civil aviation aircraft, the weight proportion of the composite materials in relation to the whole weight of the airplane has significantly increased for the past 30 years. According to Soutis (2005a), the significant reduction in weight without comprising the mechanical strength that can be achieved by this materials, provides the main driver for the increasingly use of carbon fibre reinforced plastic in high-performance applications over the conventional metal alloys. Composite materials were initially limited to secondary structures such as movable wing components (rudder, flaps, and spoilers), but with the rapid development in testing and inspection's techniques nowadays, composite materials are used also for primary structures such as complete empennage, wings and fuselage on many modern aircraft (Soutis, 2005b, Soutis, 2005a).

Primary structure is a critical load-bearing structure of an aircraft. If this structure is severely damaged or failed, the aircraft could experience fatal accident to the passengers. On the other hand, secondary structure acts as a structural element, mainly to provide enhanced aerodynamics features to the assembly (Christos, 2013). In aircraft industry, level of void content for the primary structure should be less than 1% whilst void content less than 5 % is acceptable for secondary structure.

The structural composite parts could be typically categorized into three main groups prior to the assembly process, based on their shapes and geometries, which are flat laminate, sandwich and complex-shaped laminate (Callister, 2003). The application of flat laminates and sandwich composite structures are wide used mainly in secondary structures due to the wide-range of advantages and potentials, which will lead to extended weight and cost saving. Hence, there are many researches that propose the utilization of the flat laminate and sandwich composite structures in the primary applications (Herrmann et al., 2005). Most developments in the research work are focused mainly on the flat laminate, and sandwich composite structure rather than the complex-shaped laminates (Long, 2005). It was established that, the manufacturing defects were easy to form at the complex section. Thus, the region of high stress concentration is easily developed, and subsequently, increasing the tendency of laminate to fail.

The fabrication of composite materials in the aircraft industry, where the resin is combined with the fibre materials, is available via three methods (Joshi, 2009); wet resin lay-up, resin infusion and pre-impregnating processes (Karlsson and TomasÅström, 1997). Due to the low material cost, wet resin lay-up may still be used in the fabrication of the composite components for the general aviation industry, however this process has reduced in its application over the recent years. The advanced composite materials used for commercial and military aircraft industries focuses on the later two, especially on the pre-impregnating process that will be discussed in detail in the next section.

1.2 Autoclave manufacturing

Autoclaves are pressure vessels with heating capability; in essence they are pressurized ovens. They are equipped with vacuum systems into which the vacuum integrity of the vacuum bag bagged composite laminate is maintained during the cure cycle. The integrity of the vacuum is essential to ensure the trapped volatiles, moisture and air are removed prior to the cross-linking of the thermosetting resin.

The curing pressures are generally in the range of 50 to 100 psi (350 to 700 KPa) and cure cycles normally involve long hours where the time required for pressurization and de-pressurization are accommodated. Autoclave molding is a modification of vacuum bag molding, however it is superior to vacuum bagging processing methodology as this advanced process produces denser, void free composite parts as a result of the pressure used during the curing. It is widely used methodology in the aircraft industry to fabricate high strength to weight ratio parts; this method is able to accommodate higher temperature matrix resins such as epoxies and thermoplastics.

For the resin to achieve full cure to develop the required physical and mechanical properties, cross-linking reaction must be chemically initiated through the application of heat and completed to form a solid and rigid cured matrix. In the autoclave process, high pressure and heat are applied to the curing resin through the autoclave atmosphere. An additional atmospheric pressure is applied via the vacuum bag used on the curing parts, where it is also served to protect the laminate from the autoclave gases. The autoclave cure cycle for a specific application is usually determined empirically; this is applicable especially to thick laminates and laminates with complex shapes. As a result, several cure cycles may be developed for a single material system in order to account for these variables that will affect the cure in producing good quality composite parts (Yan, 2006, Yang and Lee, 2002).

Typically, autoclave cure cycle is a two-step process; first, vacuum and pressure are applied while the temperature is ramped up to an intermediate level and held there for a short period of time. The heat reduces the resin viscosity, allowing it to flow and making it easier for trapped air, moistures and volatiles to escape. Also, the resin begins wetting the fibres at this stage.

In the second ramp up, the temperature is raised to the final cure temperature and is held for a sufficient length of time to complete the cure reaction. During this step, the viscosity continues to drop, but the pre-set temperature and hold time stabilize the viscosity at a level that permits adequate consolidation and fibre wetting, while avoiding excessive flow and subsequent resin starvation. These control factors are also required for slowing the reaction rate, which prevent excessive heat generation from the exothermic polymerization process.

Although autoclave process is well established, besides offering excellent reliability and part quality, autoclave processing requires high capital investment (Buehler and Seferis, 2000), maintenance and energy costs. In addition, part size is limited to the size of the autoclave. Like any manufacturing processes, autoclave curing methodology has its advantages and disadvantages, as summarised in the following Table 1. 1.

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Table 1. 1: Advantages and disadvantages of autoclave process

ADVANTAGES	High fibre content laminates can be achieved, thus highest strength to weight ratio is achievable for the cured laminates.
	Pressurized curing reduces voids within the resin.
	With modern monitoring and control technologies, pressure and heat can be controlled very closely to achieve the customized curing that meets individual component complexity requirement.
DISADVANTAGES	High equipment investment cost.
	High operating cost typically applicable to the machinery that generates compressed air or the alternative nitrogen gas supply, which serve as pressurized air supply.
	High on the associated consumable costs, energy usage and waste generated.
	As the continuous feeding of parts for curing is not possible until the autoclave curing cycle is completed, autoclave curing process usually becomes the bottle neck for the composite part manufacturing.

1.3 Out of Autoclave manufacturing- Vacuum Bag Only- Oven Cure

In the drive for a low manufacturing cost and the solution for large component size constraint, a considerable amount of efforts have been put into the areas, focusing on the capability of composite parts manufacturing moving away from the high-cost and size constrained autoclave process (Campbell, 2003, Hernández et al., 2011). Out-of-autoclave (OOA) composite component manufacturing processes have emerged as alternate processing techniques to autoclave processing in the 90s.

Vast majority of advance composite structures in production today are still cured using autoclaves (Hernández et al., 2011). With autoclave curing method, the autoclave pressure compresses the trapped air, moisture and volatiles within the resin of the composite material into smaller size at micro level and extendedly diluted into the resin before the cross-linking phase of resin. With proper process management, autoclave curing process is able to produce cured laminate with very low voids (porosity) content. OOA process means the absent of the pressure, and therefore the method of removing trapped air, moisture and volatiles will depend solely on the vacuuming through the air path ways within the vacuum bag system. Figure 1. 1 shows the difference between the cure cycles of autoclave and vacuum bag only cure.

With the availability of the OOA prepreg materials, out-of-autoclave curing processes especially VBO- oven curing and automated-tape-placement (ATP) are the newer alternatives processing techniques for aircraft composite parts manufacturing (Kratz and Hubert, 2011, Lukaszewicz and Potter, 2011). VBO prepregs are manufactured by hot melt process, therefore the solvent content is negligible, and volatiles released by the evaporating solvent are therefore negligible.

On the other hand, the resin content of a VBO material is optimized with its reactivity to allow the prepreg material to be cured at a lower temperature, where lower temperature will prevent the emission of any volatiles. Modern hot melt pre-pregging process is designed with Engineered Vacuum Channels (EVaC); the prepreg is engineered for air removal using partial impregnation (Sequeira Tavares et al., 2011, Centea and Hubert, 2011) and is also identified as semipreg as shown in Figure 1. 2.

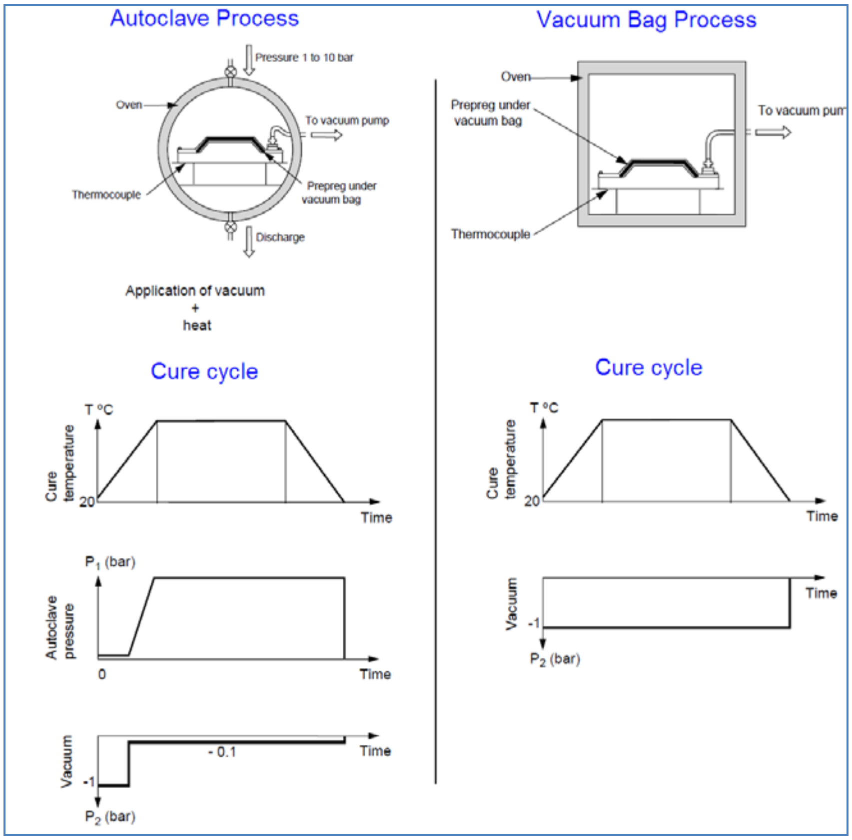

Figure 1. 1: Comparison between the Autoclave and the vacuum bagging process (Hexcel, 2005)

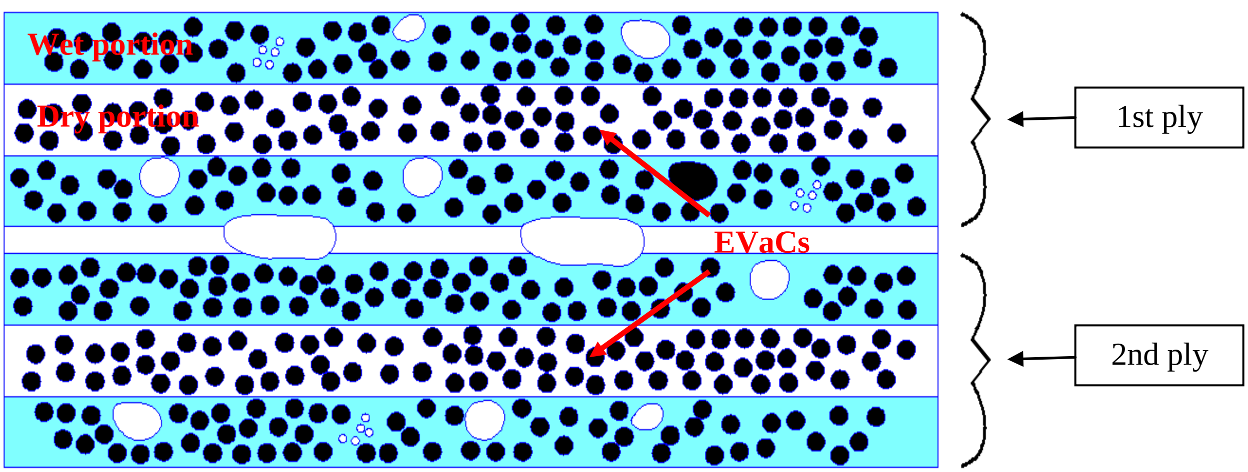

Figure 1. 2: Two ply of Engineered Vacuum Channels (EVaCs) in OOA prepreg (Wysocki et al., 2009)