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Effect of bagging configurations on vacuum bagging only-oven cured to the thickness variations for the complex- shaped laminate composite

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Abstract: In contrast to the current autoclave manufacturing process, out-of- autoclaved manufacturing process is a potential solution for achieving good part quality, especially for controlling the thickness variations of composites laminates. This work presents an analysis of the various bagging configuration in vacuum bagging only process. The study is based on full factorial method with three processing parameters and analysis of variance (ANOVA). In order to observe the thickness uniformity of the cured complex-shaped laminate composites, statistical contributions of the polytetrafluoroethylene (PTFE) application, edge breather application and intensifier application were determined. The degree of uniformity (DOU) is used as an indicator in order to assess the consistency of the thickness of the composite. The results indicated that the PTFE configuration produced negative effect to the thickness uniformity and contributed the value of DOU away from target value of 1 by 17.8% deviations. However, for the VBO and Intensifier bagging configuration, the value of DOU achieved is close to the target value of 1 with the value of 4.4% and 6.9% deviation respectively.

Key words: Vacuum Bagging Only; Thickness variations; Complex-shaped laminate

1. Introduction

In the complex-shaped manufacturing process for critical engineering application, prepreg is the most recommended material among the other dry fabrics with resin injected materials. This is due to the difficulties to control the resin distribution for the entire laminate especially at the complex region of the laminate structure. Therefore, the prepreg material ensures that the resin distribution in the entire laminate is consistent based on the desired shape. In the prepreg manufacturing process, the stringent control of the resin content and dispersion eliminates the risk of high variation in the fibre content and buildup of resin rich areas, i.e. the fibre resin ratio, and hence maximizing the combined materials performance (Chandrakala et al., 2009).

Usually, most of the complex-shaped structure is designed as a stiffener. The configurations of stiffeners are very much diverse in design, encompassing T-shaped, J-shaped, L-shaped, and hat-shaped (Williams and Mikulas, 1975, Williams and Stein, 1976). The L-shaped, which is the simplest unit of a stiffened panel, is extensively used in aircraft wings where it is utilized at the wing spar-to-skin and stiffener-to-skin interfaces. Hence, the quality characteristic of the L-shaped plate should be in the point of interest to ensure that the integration process is executed smoothly thus resulting in a perfect end-product.

The critical sub processes required to be extended focused at and carefully examined on the manufacturing processes of the prepreg materials include the lay-up, bagging and curing processes. The effect of the various processing parameters, such as the cure cycle, mould design, flange length, bagging configuration, stacking sequence (ply orientation) and resin type system on the thickness variation and void content, were largely investigated in the previous researches. Nevertheless, the compaction behavior of the L-shaped laminate is extended required to be investigated using either theoretical analysis or experimental approach to provide the important guides for manufacturing the stiffener-to-skin structures with the integral molding process.

The crucial problems that normally occur in the manufacturing of complexed-shaped laminate is to control the thickness uniformity for the laminate structure whereas, the thickness variations between the flat and curved regions are the common issues in compaction of complex-shaped laminates. It was established that the highest thickness gradient is localized at the corner (Hubert and Poursartip, 2001, Fernlund et al., 2002, Naji and Hoa, 2000, Li, 2001, Hubert, 1996, Naji and Hoa, 1999) and the compaction behavior (i.e. thinning or thickening) is dependent upon the mould design and fibre ply orientation. Hence, from the non-uniformity thickness it would obstruct and give a higher impact to the assembly process.

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To date, a fundamental knowledge of the effect of the processing parameters on the quality characteristics of the cured composite laminates has been attained based only on the study on the autoclave manufacturing process. The challenge now consists of applying, evaluating and expanding this knowledge to determine the significant contribution of each and combined parameters to the development of the new Vacuum Bagging Only (VBO)-Oven Cure process of the complex-shaped laminates using prepreg materials.

Hence, the current study presents the optimization of the processing techniques in the VBO-Oven Cure for producing the complex-shaped composite structure as an alternative solution to replace the autoclave manufacturing process which contributes to the high cost technology. An autoclave prepreg material roll was used and then the laminates are cured in the oven curing processing. Without a high compaction pressure during curing process, it was expected that varying the VBO configuration, especially in the vacuum bagging process, will contribute to the control the thickness variation. In addition, the percentage of influences of the single and combined processing parameters on the degree of uniformity (DOU) is also examined.

2. Experimental study

2.1. Design of experiment

This research study was constructed using the two-full factorial design with eight experiments study, which was developed by using Design Expert DX9 software. There are 3 input parameters of PTFE application; edge breather application and intensifier application were selected to observe the thickness uniformity of the cured composites. All the input parameters were investigated at two different levels (YES and NO). Tables 1 and 2 explain the details of the control factor and the configuration of the experiment for this research study.

Table 1: Level of control factors for selected processing parameters

Symbol	Control factor	Type	Level 1	Level 2
A	PTFE application	Categoric	NO	YES
B	VBO application	Categoric	NO	YES
C	Intensifier application	Categoric	NO	YES

Table 2: The design of experiment using 2 full factorials design

std	run	PTFE application	VBO application	Intensifier application
1	6	NO	NO	NO
2	5	YES	NO	NO
3	8	NO	YES	NO
4	1	YES	YES	NO
5	3	NO	NO	YES
6	2	YES	NO	YES
7	7	NO	YES	YES
8	4	YES	YES	YES

2.2. L-shaped laminate preparation

A plain weave glass fibre Cycom 7668/7781-1 prepreg from Cytec Engineered Materials Inc. was used in the study. The Cycom 7668 epoxy resin content is 36±2% and contains 177oC flame impeded formulated properties for use with glass fibre in structural laminates and sandwich panels for aircraft exteriors. Next, the prepreg was cut into dimension of 305 mm x 250 mm and 8 plies of were laid up together to produce a composite panel. After the knitting process, the plies were then stacked on the convex mould with a [0^0] lay-up order (warp direction) for each part to be manufactured. After completing lay-up of eight plies, the laminate was debulked at room temperature using a single stage vacuum pump at ultimate vacuum of 5 Pa, using a hose and vacuum port connected to the vacuum bagging setup. The bag was then sealed under an approximately 3.86kPa (29mmHg) of low vacuum pressure for 45 minutes. This operation was performed to compact the plies and to remove most of the entrapped air between the plies. In order to complete the vacuum bagging process, the combination of the bagging configuration was performed as per Table 3. The schematic and actual image for the bagging configuration of the preparation of L-shaped laminate is shown in Fig. 1. Lastly, the laminate was cured at the recommended cure cycle includes three phases: 1) 1st ramp with 20C/min, 2) dwell for 120 minutes at 180±120C, 3) cool down to room temperature with 60C/min. During the curing process, a vacuum pump was connected to the vacuum bag and with a supply of 1 kPa to evacuate the entrapped air from the composite laminates.

2.3. Thickness measurement

The cross section of angled laminate was divided into five measurement points along the perimeter as shown in Fig. 2, with the lengths between the adjacent stations fixed at 20 mm. Point H3 was located at the corner region, whilst the others were in the flat region including flange and web sections. Thickness measurements of the flat region were performed using micrometers with an accuracy of ± 0.001 mm while profile projector was used to measure the corner region at 20 X magnification.

Table 3: Details of the bagging configuration for initial study

Configuration	Description
BASE	Reference panel (without PTFE, VBO and Intensifier).
PTFE	Applications of PTFE function as release film.
VBO	Application of glass fibre as an edge and a top breather during bagging system.
VBO PTFE	Only edge breather was used and PTFE at the top of laminate.
Intensifier	Application of aluminium plate at the top of laminate.
PTFE Intensifier	Application of PTFE with aluminium plate at the top of laminate.
VBO Intensifier	Application of edge breather with aluminium plate during bagging system.
COMBO B	Combination between PTFE, VBO and intensifier together into one bag system.

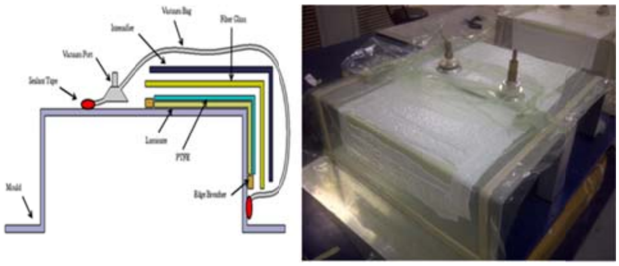

Fig. 1: Schematic diagram of the bagging configuration and the actual image of the completed bagging configuration

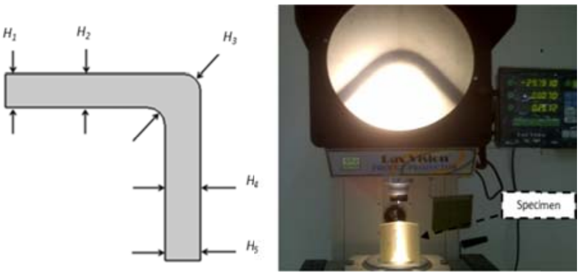

Fig. 2: Locations of the L-shaped laminate for thickness measurement

To quantify the thickness difference between those two regions, a criterion of degree of uniformity (DOU) has been introduced as shown in Equation 1.

$$DOU = \frac{h_3}{h_{flat}} \quad (1)$$

Where h_3 is the thickness of the curved region at point H3 and h_{flat} is the average thickness of the flat regions at points H1, H2, H4 and H5.

3. Result and discussion

3.1 Analysis of thickness variations

Among the eight bagging configurations of the bagging, the base configuration was used as a baseline to compare with other configurations. Fig. 3 shows the measured thickness from point H1 to H5 of the cured L-shaped laminates processed using different bagging configurations. An important mechanism behind the thickness variations in complex-shaped laminates lies in the difference in reaction stress between the corner and the flat section (Hubert et al., 1996). It clearly shows that the corner thinning occurs at the corner section of laminates with the thickness variation of the flange (H1 and H2) and the web (H4 and H5) are relatively within 0.15-17.02% variation as shown in Table 4. The uneven compaction of the fibre bed has a close relationship with the uneven compaction force exerted on the L-shaped laminates (Xin et al., 2011).

Table 4: Percent of the deviation of thickness between the flat and the corner reagion for all bagging configurations

Thickness, mm	Point	Base	PTFE	VBO	Intensifier	VBO PTFE	PTFE Intensifier	VBO Intensifier	COMBO
	H1	2.4	2.3	2.4	2.3	2.3	2.3	2.3	2.3
	H2	2.4	2.4	2.4	2.3	2.4	2.3	2.3	2.4
	H3	2.1	2.0	2.3	2.4	2.2	2.2	2.3	2.3
	H4	2.4	2.4	2.4	2.3	2.4	2.3	2.3	2.4
	H5	2.4	2.4	2.4	2.3	2.3	2.3	2.3	2.3
	H_{AV}	2.4	2.4	2.4	2.3	2.4	2.3	2.3	2.3
Deviation, %		12.5	17.0	3.5	-5.2	6.5	5.7	-0.2	3.4

The intensifier is used to control the uniformity of the compaction force during the curing process. The experimental analysis (Fig. 3) demonstrates that the corner thinning at the corner of the L-shaped laminate is apparent for the Base and the PTFE configurations is due to a deviation in the value of the thickness at point H3 from the point at the flat region (H1,H2,H4 and H5). Fig. 4 illustrates the mechanism of pressure exerted for base and PTFE configuration. It indicated that when the bagging configuration was exposed directly to the vacuum bagging film, the stress of mould side (Sm) is less than stress of pressure side (Sp) that would give higher corner thinning (Brillant, 2010; Hurbert, 1996). However, by applying the VBO and Intensifier, the uniformity of the thickness between the flat section and the corner section is controllable. As proven by (Fernlund et al., 2002), the use of the intensifier/caul-sheets improves the uniformity of the complex shape in the convex mould by reducing the amount of the corner thinning when compared to those without the caul-sheet.

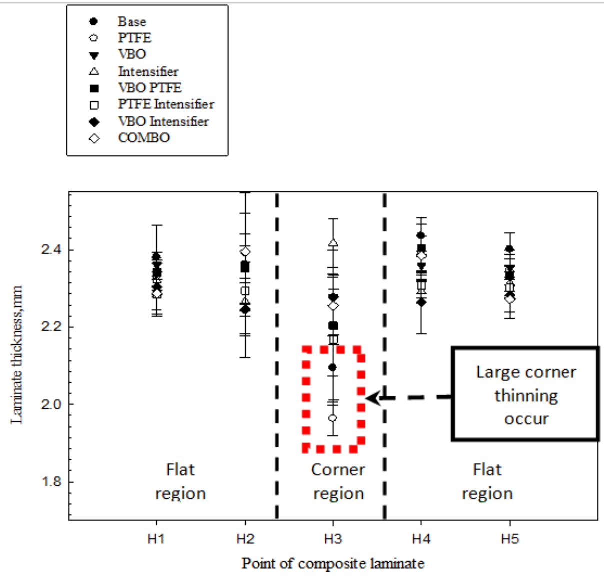

Fig. 3: Thickness measurement of the L-shaped laminate for different bagging configurations

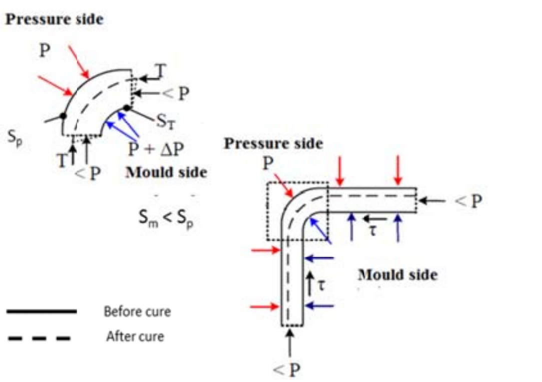

Fig. 4: Pressure distribution along L-shaped composite laminate during curing process

To quantify the different thickness variation between the flat and the corner region of L-shaped laminates, an indicator of degree of uniformity (DOU) was implemented to observe the similarity ratio between both regions. In general, most DOU is found to be less than 1 due to the type of mould used of the convex mould. High tendency of the corner thinning occurs at the corner section of laminate with the lay-up on the convex mould due to the difference in reaction pressure between the mould and the bag side. In this case, the surface at the mould side is smaller than at the bag side, so, higher laminate radial compressive stress was developed and caused a corner thinning because of the higher compaction and resin migration away from the corner (Hubert, 1996; Brillant, 2010).

From Fig. 5, individually, the VBO and Intensifier configurations provided the best performance of the DOU in achieving the target value of 4.4% and 6.9% respectively. Collectively, the best manufacturing process is the combined VBO and Intensifier with the DOU 0.2% closer to the target value. Good correlation between the VBO and Intensifier was observed in controlling the corner thinning of the L-shaped laminated. The intensifier in that configuration helps the pressure distribution along the laminate during the curing process (Fernlund et al., 2002).

In a similar case, the use of the VBO at the top of the laminate gave a good barrier between the laminate and the pressure contact. Therefore, the distribution of pressure and the resin flow along the laminate are better controlled through breather. However, the use of the PTFE alone gave the worst result with 17.8% deviation from the target value as the laminate was exposed directly to the bagging pressure. So, the reaction pressure exerted on the laminate was more difficult to control when compared to the bagging configuration used in the VBO and intensifier application.

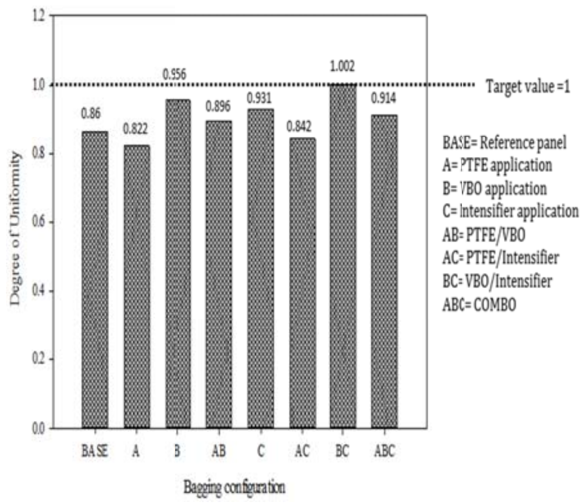

Fig. 5: Bar plot of degree of uniformity towards different bagging configurations

3.2. Analysis of variance (ANOVA)

Similar analysis was applied on the response of degree of uniformity (DOU) with the resulting ANOVA for the models shown in Table 5. The value of "Prob.>F" in Table 5 for those models was also less than 0.05 (i.e. α=0.05, or 95% confidence), indicating that these models are statistically significant. For the DOU responses, the significant model terms includes the factor A (0.0009), factor B (0.0007) and factor C (0.0053), and interaction effect of A-C (0.0355).

The R^2 value for the DOU was calculated 0.994 with the adequate precision value of this reduced model is well above 4. Based on the value of Sum of Squares, the percentage of influence was analysed and extended summarises in Fig. 6. From the analysis, it was found that the factor B takes the highest value of percentage of influence of 47.21% followed by factor A (37.97%) and factor C (11.35%). In addition, the combined factor A and C has also influenced the DOU value by 2.84%.

Table 5: Summary of the ANOVA for degree of uniformity (DOU)

Source	Sum of Squares	df	Mean Square	F Value	Prob > F
Model	0.0253	4	0.006	116.69	0.0013
A	0.0097	1	0.010	178.35	0.0009
B	0.0120	1	0.012	221.77	0.0007
C	0.0029	1	0.003	53.32	0.0053
AC	0.0007	1	0.001	13.33	0.0355
Residual	0.0002	3	0.000		
Std. Dev.	0.0074		R^2		0.99361
Mean	0.9033		R^2 adjusted		0.9851
C.V. %	0.8148		Predicted R^2		0.95459
PRESS	0.0012		Adequate Precision		31.7955

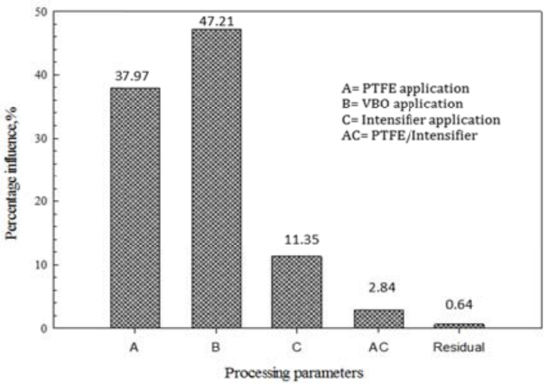

Fig. 6: Percentage of influence factor towards processing parameters for the degree of uniformity values

The main effects of processing parameters towards the DOU of the L-shaped laminates are illustrated in Fig. 7. It was found that the use of VBO and Intensifier in the bagging configuration has achieved close to the target value (1) with the increasing value of 8.96% and 4.26%, respectively. However, the PTFE application had shown a worst result by reducing the DOU value as much as 7.41%. As mentioned before, the use of VBO and Intensifier contributed to the good performance of controlling the thickness variation in the L-shaped laminate structure.

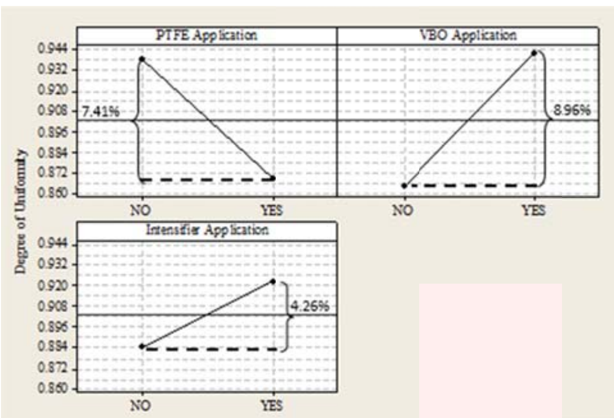

Fig. 7: The main effects plot of processing parameters towards degree of uniformity

Fig. 8 indicates the interaction plot of the combination between two processing parameters towards the DOU criteria. It was observed that the PTFE-Intensifier (A-C) interaction has contributed as much as 2.84% to the influence factor. The influence of the Intensifier application (from NO INTENSIFIER to YES INTENSIFIER) is stronger at the YES PTFE line. It indicated that the application of PTFE film with the Intensifier application in bagging configuration was influenced the value of DOU value away from target value. However, there was not has any an interaction for PTFE-VBO (A-B) and VBO-Intensifier (B-C) since the lines connecting the point at the same level are parallel.

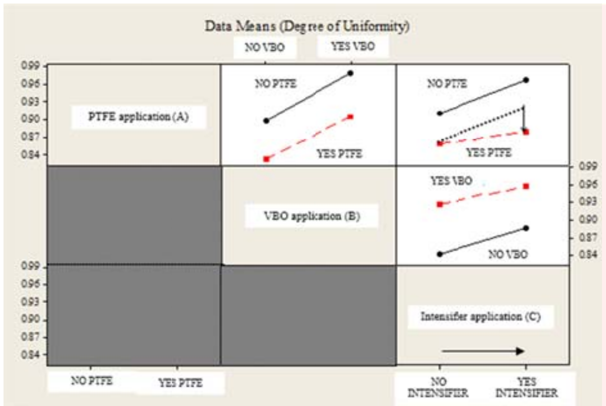

Fig. 8: General factor interaction plot for combination of two processing parameters towards degree of uniformity (DOU)

4. Conclusion

The use of VBO and intensifier were achieved close to the target DOU value of 1 with the value of 4.4% and 6.9% deviation respectively. However, the PTFE has shown a worst result by reducing the DOU away from the target value by 17.8%.

For the ANOVA study, it was found that the factor B which is VBO application has the highest value of percentage of influence of 47.21% followed by factor A; PTFE application (37.97%) and factor C; Intensifier application (11.35%). In addition, the combination between factor A and C has also influenced the DOU value by 2.84%.

The combination between PTFE and VBO application will deviate the DOU value from 1 while the combination between the VBO and intensifier will help the DOU value approaching 1.

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