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Methodology of Designing Statistical Design of Experiment (SDE) to Study Wrinkles and Delamination on Composite Panels

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Abstract

Composites are two or more dissimilar materials, such as fibre and resin, working together to create a product with exceptional properties not present in the original materials. There are various technologies used in the process of molding this material such as resin transfer molding (RTM), liquid infusion molding (LIM) and autoclave molding (ACM). Many composite manufacturing systems are manual, and hence, due to difficulty in controlling manual processes, quality of the product is compromised. At a manufacturing plant in Kedah, there is a hand-lay-up manual system in the manufacture of a certain high technology composite product line. It has been observed that process control is rather difficult due to a high number of process parameters involved. Thus, a study using 'statistical design of experiment' (SDE) will be performed to aid process optimisation, which should result in getting minimum number of defects on the final product. In this paper, an overview of the process will be given, and the experimental strategies will be discussed in detail. The aim of the study is to reduce two dominant mode of failure on the product, namely delamination and wrinkling. This is done by optimising several controllable and uncontrollable variables such as temperature, pressure, soaking time, heat up rate, cool down rate, and the geometrical dimensions of the part. It is proposed that SDE is a useful technique for the investigation of shop floor problems and the setting up of the process parameters that ultimately lead to reduced variability in the final product. Instead of running many combinations of parameters in real life, SDE enables only a few combinations to be run before optimum process set-up can be determined. As a result, the time taken to determine optimum process set-up is greatly reduced. This also allows experimenters to get much more and much better data per experimental run. This in turn results in tremendous cost savings.

Key Words: *Composite manufacturing process, wrinkles, delamination, statistical design of experiments, process optimisation.*

Introduction

Composite sandwich panels are widely used in aerospace, marine, automotive, rail and recreational industries because of their high specific strength and stiffness, corrosion resistance and stability and simple manufacture methods (Shokrieh *et al.,* 2006). There are various manufacture technologies used in the process of molding this material such as resin transfer molding (RTM), liquid infusion molding (LIM) and autoclave molding (ACM) (Lang, 2005). What so ever the composite fabrication technique is used to produce the parts still there are several possible failures for composite panels? For instance wrinkles, edge delamination, cracks, war page and edge effect are the most common manufacturing defects in composite materials. Composite panels for aerospace industry are produced with hand lay-up and autoclave curing (Mccracken).

According to Gutow Ski the most important manufacturing process of composite panels applied to aerospace industry is the hand lay-up of prepregs and autoclave cure. Although the manufacturing process have been undergoing constant technical changes and improvements, the HAND LAY-UP still persists as the method in use for more than half of all advanced aerospace composite structures. It's large use results from the extreme flexibility which allows the manufacturing of a large variety of panels in flat and highly contour shapes. Additionally, hand lay-up is a labour intensive manufacturing but at the same time does not require large capital investments (Avila *et al.,* 2005).

In this type of manufacturing two distinct steps can be established; the first one consists of fiber glass impregnation and its stacking sequence, and the second one is the cure procedure. As mentioned by Jones that autoclave cure is the best procedure of curing for honeycomb sandwich structures in the presence of vacuum (vacuum bagging) under compression (pressing) and controlled cure temperature. He stated that the composite materials performance is directly related to the manufacturing process used to produce the composites. In his study he evaluated five different processes, namely, autoclaving, resin transfer moulding (RTM), resin film infusion (RFI), pultrusion and compression moulded sheet. Moreover, the process selection must be based not only on the materials used but also the component geometry, sizes and required mechanical properties. In this regard the work done by Bader is a comprehensive study on composite manufacturing although he does not consider process problems, issues and manufacturing defects such as wrinkles and delamination generated during the manufacturing of composite materials (Avila *et al.*, 2005).

During the last two decades most researchers focused on the composite's mechanical, physical and chemical properties estimation. The manufacturing process was somehow neglected to a secondary place. Moreover, the mould process was considered a simple hand lay-up process while cure process was treated for a long time as if it was a mere recipy, but this behaviour is changing owing to composite materials peculiar properties and important role in the daily lives of most people in the industrialized societies. Each year, composites find their way into hundreds of new applications, from golf clubs and tennis rackets to jet skis, aircraft, missiles and aircraft. (Ahmad *et al,* 2006). Therefore, to improve the composite overall performance it is needed not only to consider the mechanical, physical and chemical properties estimation models but also the manufacturing process improvement and optimization with a view to minimize process defects and make process best cost effective (Avila *et al.*, 2005).

Daniel and Abot also lay emphasis on the improvement of composite manufacturing process with its advantages and limitations. They linked the two areas by taking into account the problem of wrinkles formation on laminated and sandwich composites. According to them wrinkles and voids can be formed either by air entrapment, broken fibers, air pockets, nods bond damage of core and blisters created during the composite lay –up (Avila *et al.*, 2005).

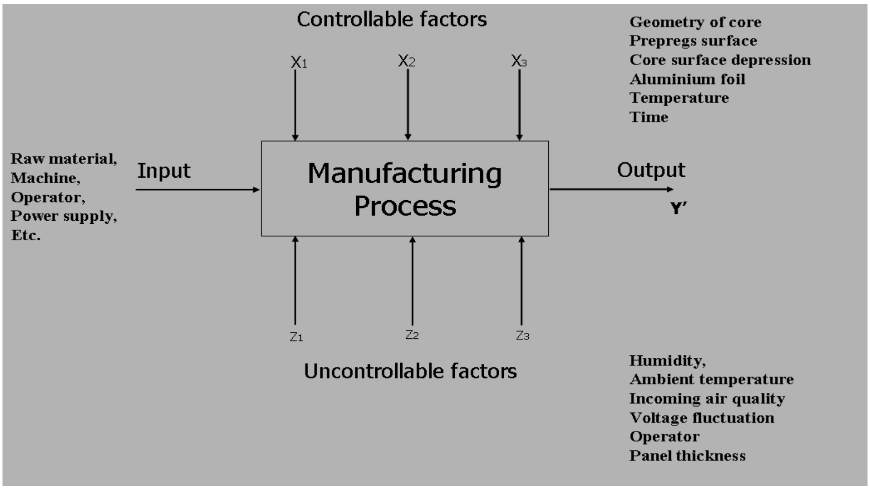
As recognized by Mallick voids and wrinkles formation causes stiffness and strength reduction of composite materials. He went further trying to correlate voids and wrinkles formation with two key factors i.e., time and temperature during autoclave cure. In some composite manufacturing, processes, e.g., RTM, RFI, LMC, and HAND LAY-UP, the problem of wrinkles formation is also related to the manufacturing process parameters such as fiber volume fraction, resin viscosity, geometry of honeycomb core, dry core and not dry core, prepregs surface, core surface depression, aluminium foil and temperature, etc. In all cases RTM, RFI, LMC, and HAND LAY-UP, wrinkles formation can be induced in certain shapes, size, location and direction due to the manufacturing processes. For example, a bad selection of plies with blisters, core with nods bond damage and plies design sequence can lead to narrow resin path that can trim down the resin flow which can direct to a series of voids and wrinkles in a preferential direction (Avila *et al.*, 2005).

Taking into consideration all the points discussed above, it is possible to conclude there is a need for a study on manufacturing process effects on the formation of wrinkles, voids and delamination. The purpose of this paper is to study and optimize HAND LAY-UP composite manufacturing process with autoclave cure by using Statistical Design of Experiment (SDE). As SDE is a very useful tool for the manufacturers to speed up their product development and optimization of manufacturing processes with a small number of cost effective set of experiments (Rhyder, 1997).

The Concept of Statistical Design of Experiment

In this study, statistical design of experiments (SDE) will be used to optimize composite manufacturing process to minimize variation in wrinkles formation. Usually, experiments are performed to gain insight about a process so that conclusions and decisions can be made to improve process, and to reduce waste, defects, and cycle time. Statistically designed experiments make it possible to test several process input variables simultaneously in order to assess the effect of each on the process output. At composite manufacturing, processes are geared towards high-cost parts and low production runs. This dictates the need for efficient experiments that capture the greatest amount of information in the fewest runs. A useful approach in this context is to use a series of small experiments, with knowledge gained in previous experiments being used to design small but efficient new experiments. This approach is known as "sequential experimentation". Figure 1 is the basic model of process whereby showing the various input factors affect the manufacturing process. (Montgomery, 2005).

Figure 1: Various Inputs Affect the Manufacturing Process



Factors at composite manufacturing that influence the quality of final product that can be called –controllable- and they include:

1. Geometry of core material
2. Prepregs surface quality
3. Core surface depression
4. Aluminium foil porosity
5. Temperature
6. Time
7. Pressure
8. Dry vs. not dry core
9. Nod bonds damage of core material
10. Tool surface finish

Factors at autoclave curing process that influence the quality of final product are as follow:

1. Vacuum
2. Heat up rate

3. temperature tolerances
4. Cure time
5. Cooling rates
6. Disabling of thermocouples
7. Soaking time
8. Parts location
9. Machine warm up conditions

There are also in put variables in composite manufacturing and autoclave curing Process (es). That can not be controlled and called –uncontrollable-

1. Humidity
2. Incomming air quality
3. Voltage fluctuation
4. Operator
5. Panel thickness

Following are the response variables of composite manufacturing

1. Wrinkles
2. Edge Delamination
3. Blisters, cuts, nods
4. Panel surface finish
5. Panel thickness
6. Edge effect
7. Warpage

Experimentation Strategy

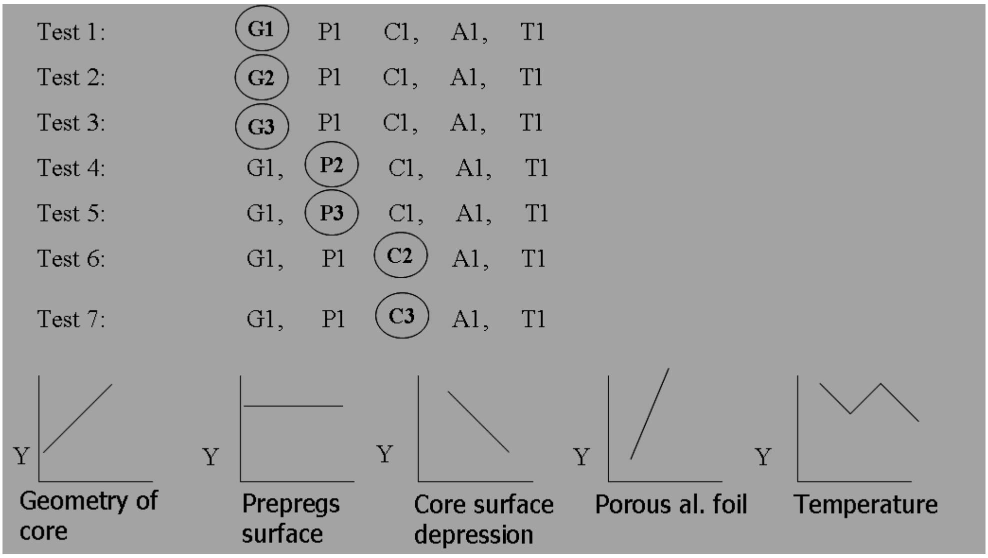
The design describes the process input factors that will be systematically changed, the settings for the input factors, the number of factor combinations (runs) to be tested, and the order in which the runs will be tested. Experiment design will be selected from the following list of designs.

- One-factor-at-a time approach
- Factorial approach
- Fractional factorial design
- Central composite design (CCD)

One-factor-at-a-time approach

This method consists of set of levels for each input factor; only one factor varies while others factors held constant (Montgomery, 2005). Many combinations – hence, too costly and too long. Results of the one factor at a time approach can be seen from the figure 2

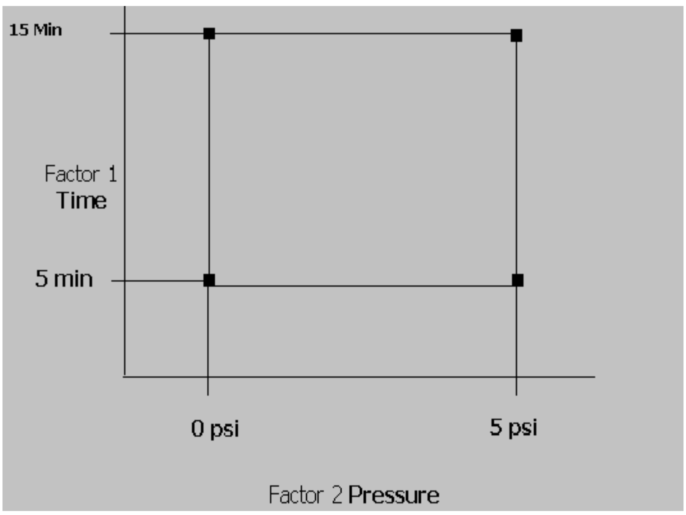
Figure 2: Results of the one Factor at a Time Strategy for the Experiment



Factorial approach for the experiment

In this experiment approach factors are varied together, not one at a time 2^2 factorial designs (2 factors each at 2 levels) $2^2 = 4$ runs minimum. Factorial design (4 factors, each at 2 levels) $4^2 = 16$ runs minimum (assuming each combination is not replicated). If there are 10 factors, each at 2 levels, the no. of run could be $10^2 = 1024$ runs (Still, too large). Factorial approach can be seen in Figure 3.

Figure 3: A Two Factor Factorial Experiment



Fractional Factorial and Central Composite Design
These are the most widely used types of designs for process optimization and also called screening experiments. Experiments are performed in the early stages of the experiment for identifying those factors that have large effect on the product quality. In these design methods usually not necessary to run all possible combination of factor levels. Only subset of the runs is made. This can save both time and cost (Montgomery, 2005).

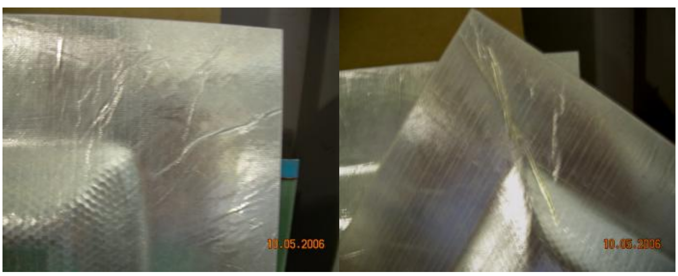
Statement of the problem: "Wrinkles"
A ridge or fold on the surface of sandwich composite material panels is called wrinkle (Pourboghrat *et at.*, 2005). Processing and completed parts should meet the acceptable limits. The specified requirements of wrinkling on sandwich panels are as follow:

1) Faying surfaces of sandwich panel: 0.005 inch maximum height is allowed in 4 inch area
2) Non-faying surfaces: 0.100 inch maximum height is allowed in a 4 inch area

If the part exceeds these limits it shall be reworked in accordance with specified requirements or otherwise will be rejected.

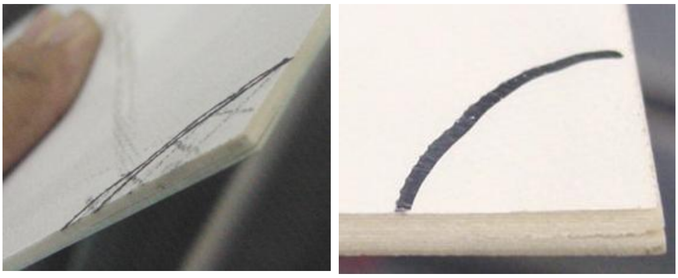
Data depicts that wrinkles in terms of shape, location, and size are detected in a number of panels (approx 0.5 %) after the autoclave curing process. It is believed that a number of factors contribute to this condition. This study aims to identify the 5 of the main factors (-controllable, -uncontrollable) and determine the range of whereby the factors are to be set so as to get the smallest number of wrinkles as possible. Figure 4 below are the examples of various types of wrinkles and delamination over of sandwich material.

Figure 4: Wrinkling Formation on Sandwich Panels



Delamination is another mode of rejection for sandwich composite materials. Normally this kind of problem occurs on the panel surfaces due to expired material introduced to production line, inconsistent resin content over prepregs, poor surface of the tool, and operator hand contact with prepregs during lay up process, improper compaction and finally the water jet cutting. Figure: 5 showing the various type of delamination on the panels.

Figure 5: Delamination on Sandwich Panels



Choice of Factors and Factor Levels

The factors will be selected from the list given above of factors controllable and uncontrollable. However response variable could be either wrinkle or delamination and Warpage. Table 1 is the example of input factors and factor levels for a designed experiment.

Table 1: Examples of Factors Levels for a Designed Experiment

Input factors	Levels	
Time (minutes)	120	140
Temperature (ºF)	395	410
Mould Type	1	3
Dry vs. not dry core	A	B
Parts location	C	D

Performing the Experiment

Planning is very crucial to experiment success, care should be taken to follow the experiment procedure exactly because errors in conducting the experiment can invalidate the results (Ryan, 1989). The data will be collected on the specified formats. Everything will be done according to time line and plan laid down in gantt chart. Any unexpected event that would occur during the experiment will be noted on the log.

Statistical Analysis of Data

In the analysis step the input factors and interactions (joint effects of input factors) that have significant effects on the response variables are identified along with their best settings. Statistical tools will be used for data analysis, and the interpretation of experimental results. In this way the best operating conditions can be discovered by running only a small fraction of the possible conditions. After data analysis the following ***final steps*** will be made in the experimental process:

1) Run the experiment and verify new conditions
2) Draw conclusions from the experimental results
3) Recommend course of action
4) Perform follow-up runs and confirmation tests to verify the conclusions from the experiment
5) Set process parameters on the basis of the experimental results
6) Experimentation approach should be iterative to achieve the ultimate objective of the experiment

Conclusions

The aim of this paper was the understanding and knowledge of composite materials manufacturing process (es) namely hand lay-up and autoclave curing. Further to introduce the concept of statistical design of experiments (SDE) in order to determine the optimal conditions for the processing of composite materials with a view to minimize wrinkles and delamination on the final product after curing. In fact, SDE enables only a few combinations to be run before optimum process set up and also facilitate the experimenter to get much more and much better data per experimental run.

The approach pointed out that five of the process parameters such as geometry of core, prepregs surface quality, and core surface depression, aluminium foil porosity and elevated temperature are playing leading role in the formation of wrinkle and delamination on composite panels.

The future development of the present research is to quantify effect of each of the input parameters on the final product quality, root cause analysis, and setting process parameters on the basis of the experimental results and to aid process optimization.

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