A Case Study in the Structured Application of Statistical Design of Experiments and FMEA to Reduce Wrinkles and Delamination on Composite Panels

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Introduction

Occurrence of wrinkles and delamination in composite sandwich panels is yet to be understood. Hence, reliable strategies for manufacturing high quality panels are not yet available. In this paper the authors describe a structured statistical approach which identifies key inputs and outputs of a composite sandwich panel manufacturing process. Process improvement methods such as Statistical Design of Experiment (SDE) and Failure Mode Effect Analysis (FMEA) have been shown [1], [2], [3] to be very useful. The following steps are taken: (1) developing statement of the problem; (2) data mining; (3) applying SDE and FMEA; (4) validation of the results. The goal of the study is to apply this structured statistical approach to minimize the formation of defects, namely, of wrinkles and delamination.

Experimental plan

A screening design is selected to reduce the number of impact factors while still allowing interactions between the factors to be detected. This is a $2^{(4-1)}$ fractional factorial resolution IV design in 8 runs, augmented with 2 center points to allow a test for possible curvature (Block 1 in Table 2). If active interactions are not clear due to confounding with two-factor interactions, then another 8 runs, with 2 center points, would be carried out in a fold-over design (Block 2 in Table 2), making this experiment a total of 20 possible runs. If curvature is indicated, then an additional 10 runs consisting of 2 axial points for each of the 4 factors, along with 2 additional center points would be run (Block 3 in Table 2) to allow a central composite design (CCD).

Each experimental run takes one production day. Hence, a total of 10 production days are used for Block 1. After the completion of 10 runs (i.e. run no 1, 2, 3, 4, 7, 8, 9, 10 in Table 2), preliminary analysis is performed to determine the next course of action.

Table 2: Planning of Experiments Using Design Expert

			Factor 1	Factor 2	Factor 3	Factor 4
Std	Run	Block	A:Temperature	B:Pressure	C:Heat-up- rate	D:Curing time
15	1	Block 1	180	20	7	60
3	2	Block 1	180	20	0.5	15
9	3	Block 1	180	10	0.5	60
2	4	Block 1	200	10	0.5	15
18	5	Block 1	190	15	3.75	37.5
17	6	Block 1	190	15	3.75	37.5
8	7	Block 1	200	20	7	15
5	8	Block 1	180	10	7	15
12	9	Block 1	200	20	0.5	60
14	10	Block 1	200	10	7	60
1	11	Block 2	180	10	0.5	15
11	12	Block 2	180	20	0.5	60
10	13	Block 2	200	10	0.5	60
6	14	Block 2	200	10	7	15
4	15	Block 2	200	20	0.5	15
16	16	Block 2	200	20	7	60
13	17	Block 2	180	10	7	60
7	18	Block 2	180	20	7	15
19	19	Block 2	190	15	3.75	37.5
20	20	Block 2	190	15	3.75	37.5
22	21	Block 3	200	15	3.75	37.5
29	22	Block 3	190	15	3.75	37.5
28	23	Block 3	190	15	3.75	60
23	24	Block 3	190	10	3.75	37.5
27	25	Block 3	190	15	3.75	15
25	26	Block 3	190	15	0.5	37.5
24	27	Block 3	190	20	3.75	37.5
30	28	Block 3	190	15	3.75	37.5
21	29	Block 3	180	15	3.75	37.5
26	30	Block 3	190	15	7	37.5

If only some of the factors show to be active but no curvature, then a reduction in the number of factors would be made, new factor levels determined, and a new experimental plan (e.g. a CCD) developed for possible optimization. If it is not clear which two-factor interactions are present, and there is no curvature, then Block 2 would be run. If curvature is indicated after Block 1, then Block 2 and Block 3 would be run to complete the CCD and determine optimum settings from the modeled curvature.

Results and Discussion

For the first run of experiments, a total of 39 production run panels on Temperature =180°C, Pressure = 20 psi, Heat-up Rate = 7 °F/min, and Curing Time = 60 min (Run 1 in Table 2) are monitored. Upon completing the normal 10-hour autoclave cure cycle, it is noticed that the heat-up reading for this batch of production is 0.2 °F/min for 8 panels, 0.3 °F/min for 6 panels and 0.4 °F/min for 6 panels. This rate is well below the rate permissible by specs, which is 0.5 °F/min minimum and 7 °F/min maximum. Hence, even without inspecting for wrinkles and delamination, the parts concerned are considered as rejects and are immediately quarantined. In other words, 51% of the parts are considered “rejects” due to the low heat-up rate.

A preliminary investigation into the cause of the low heat-up rate shows that the use of a steel mould is related to the problem. Production uses two types of moulds - aluminum and steel. Aluminum is much preferred because of its high coefficient of thermal expansion (CTE = 205 W/m-K) which matches with the CTE of the parts. This results in a better interaction between the mould and the curing part along the interface. But the steel mould which has a low CTE (50.2 W/m-K) is also used because it takes less time for lay-up preparation, is cheaper, and has exceptional durability. Due to these differing CTEs, panels with aluminum moulds are placed in area of the autoclave with better air circulation, while steel moulds are located at locations where the circulation of air is not as effective.

In this study, the heat-up rate for Run no. 1 is too low for the steel mould as indicated by the excessive number of rejects. The decision of management after the first production run is to discontinue the experiment as rejects are costly.

Use of FMEA

As part of the investigation using FMEA, top fast cooling rates, steel lay-up-mold (LM), discontinued compaction, un-pre-cured silicon sheets, moisturized fiberglass and lesser thickness of heat resistant layering material are identified as causes of rejects. Hence, a thorough study is carried out to identify the actions to reduce the rejects. The findings are shown in Table 3.

Subsequent actions taken result in a break-through decrease of number of rejects.

Conclusion

A low heat-up rate causes an excessive reject rate which, in turn, leads management to terminate the experiment. This causes attention to shift to another line using FMEA. The experience gained from the SDE planning is applied to the FMEA. As a result, a break through improvement is made to the process in that the failure rate is substantially reduced.

Table 3: Identification of risks, actions taken and results achieved

Identification of Risks	Actions Taken	Results Achieved
Different cooling rates between top and bottom surface of the panel during autoclave curing process	Putting heat resistant layering material around the panel periphery	Reduced wrinkle failure rate from 29% to 20%
	Apply increased silicon pad thickness (top) to 0.08" for steel LM	37 panels were tested and found acceptable
	Increase fluoroelastomer layer thickness (bottom) to 0.04" for steel LM	11 panels were tested and found acceptable
	Every 20mils increase in fluoroelastomer layer thickness reduces autoclave peak temperature by 1.5°F	Tested 40mils, 60mils and 80mils.
	Found fluoroelastomer layer on top of silicon sheet gives higher heat resistance	Thicker fluoroelastomer of 80mils higher heat resistant
	Use aluminum pocket to quicken heat conductivity	Recommended but not feasible to be implemented
	Place thermocouple under silicon sheet & on LM surface to detect cooling rates	LM with silicon pad improved cooling down rates and reduced delamination
Problem seen with steel Lay-up Mould (LM) more than Aluminum LM.	Use aluminum LM only because of higher thermal conductivity	398 panels were tested and 181 not accepted due to wrinkle, 4% variation is accounted for by Aluminium LM, 45% contributed by Steel LM
	Thermal conductivity of steel is only quarter 50.2 W/mk, while Aluminum conductivity is 205 W/mk	Found that peak temperature for Aluminum LM higher about 16°F compare to steel LM
	Test performed on application of pressure plate made by fiber glass material	Ten numbers of panels were tested no wrinkle appeared but encountered another defect bridging between core edge and faying area of the panel
	The top cooling rates must be slowed to match the slower cooling rate of the bottom in contact with the steel LM	Used 0.060" thick silicon sheet and failure rate reduced 0.2% to 0.5%
Lack of contact between ply, LM and the pressure pad before and during the resin transformation from the state of liquid to solid	Aluminum LM peak temperature is 16°F which is higher than the steel LM	Higher thermal conductivity Aluminum LM should be preferred for fabrication of panels
	Use compaction effectively during Lay-up process. Apply compaction process before the last ply to reduce air entrapment before applying aluminum foil as per Resident Work plan RWP.	Compaction Process specs has been incorporated in PRWP and implemented reduced failure rate 0.1% to 0.2%
	Use continuous compaction during autoclave staging	Reduced failure rate 0.1% to 0.5%
	Reduce back pressure in auto clave by replacing pressure hoses and their clamps	Reduced failure rate of wrinkle and delamination 0.3% to 0.5%
	Use Yellow sealant at final bagging to reduce back pressure	Yellow sealant was compared with Black sealant and tested 100 panels. Observed 19 panels with back pressure effect with yellow one. While 37 panels affected with back pressure layed up with black sealant.

References

1.Guillaumat, L. et al, Contribution of experimental designs for a probabilistic dimensioning of impacted composites, *Int’l J of Impact Engg*, (2005), 31, pp. 629 – 641.

2. Grove, SM et al, An investigation of the skin/ core bond in honeycomb sandwich structures using statistical experimentation techniques, *Comps part A: Appl Sci, and Manu,* (2006), 37, pp. 804 – 812.

3. Sutherland, LS & Soares, CG, Effects of test parameters on the impact response of glass reinforced plastic using an experimental design approach, *Compos Sci, and Tech,* (2003), 63, pp. 1 – 18.