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Top Surface Quality Analysis of Aluminum Structured: Lean Six Sigma Methodology

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Abstract

Bubbles in lamination is a significant defect that has been extensively examined in various studies. Lamination involves applying High-Pressure Decorative Laminate (HPDL) to tabletops using Hot Met Adhesive (HMA). In this research, the tabletops are aluminum tabletops (AT), a unique subject due to the lack of data on the compatibility of HPDL with AT using HMA, particularly concerning the different rates of dimensional change for AT and HPDL and the required environment and curing time. To identify potential root causes, we applied the Lean Six Sigma (LSS) methodology and analyzed one year of process data using the Xbar-R chart in IBM SPSS. Our findings indicate that environmental conditions are a source of special variation, with the process going out of the specific control limits suggested by H.B. Fuller, the Hot Melt Adhesive supplier. Notably, the occurrence of bubbles increases during hot weather. We conducted a Design of Experiments (DoE) to validate or refute those potential root causes. This research aims to establish the specification limits for the environment and curing time for laminating HPDL to AT using HMA and provide a solution to the bubbling defect issue.

Keywords
Lean Six Sigma, DMADV, Bubbles, Laminate Aluminum tabletops, Hot melt, HPDL.

1. Introduction
Many organizations are committed to improving product quality and process performance in an attempt to achieve a set of bottom-line and strategic goals, including profitability, market share, and competitiveness, Ilesanmi Daniyan et al. (2022). Furniture manufacturing is a specific industrial sector with a high human labor demand, a wide range of materials processed, and short production runs caused by high customization of end products Skorupińska, E. et al. (2024a). This type of manufacturing is more labor-intensive than other manufacturing systems due to the complexity of furniture products, making it less automatable in the production process Turbański, W. et al. (2021). Several methodologies and tools of quality control are used in manufacturing Daniyan. et al., (2022a). and Six Sigma is one of the tools that is effectively used mainly for continual improvement. Six Sigma is about collecting data on a process

to be used to analyze and interpret what type of problem that process has so the process can be improved (Kano and Taguchi). By following the improvement plan of the Six Sigma process, the entire system will be under observation to reduce variation and reducing waste, with the result of increasing productivity Kubiak, T. M., & Benbow, D. W. (2016). Lamination is the technique/process of manufacturing a material in multiple layers so that the composite material achieves improved strength, stability, sound insulation, appearance, or other properties Fung, W. (2002). Southern Aluminum is a company in Magnolia, AR, USA, developed a special type of table which is laminate aluminum tabletops, The lamination process is where the HPDL is adhered to the AT in the following order of processes: the coat roller, fitting, and pinch roller (Figure 1). The HMA is deposited by the coat roller machine to join the HPDL and AT. The factors surrounding the process can lead to bubbles in the top surface Figure 2.

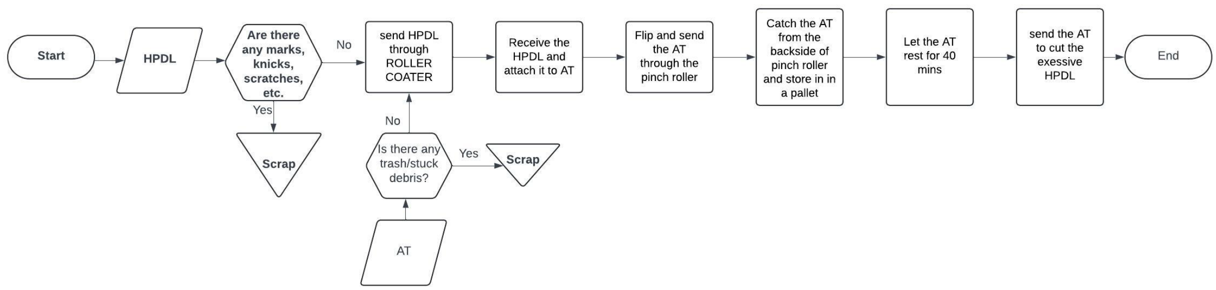

Figure 1. lamination Flow chart

Figure 2. Defects tables (bubble)

1.1Objectives

The objective of this research is to understand significant factors in laminating aluminum tabletops bubbling and explore methods for reducing the bubbles from occurring or developing past acceptable standards. This will be accomplished by an analysis of existing data regarding the process likelihood of bubbles and physical studies of product manufacture with resulting of bubbles. The physical studies will look at factors in components (HPDL, HMA, AT), the physical application process, and the post-application environment.

2.Literature Review

Motorola developed Six Sigma to enhance product quality, addressing the issue of high component counts leading to a high probability of defective final products (Arnheiter & Maleyeff, 2005). Six Sigma enhances productivity by reducing process variation. It is defined as a business strategy that minimizes defects and failures, increases productivity, and reduces cycle time and production costs. This statistical method for reducing process variation has ebeen utilized in numerous studies (Kubiak et al., 2016), (Burch V et al., 2014), (Skorupińska et al., 2024), (Turbański et al., 2021), (Basem, 2024; Simanova et al. 2020). (Anderson et al., 2014), (Megawati et al., 2020). Six Sigma achieves cost reductions in manufacturing and services, contributes to bottom-line savings, enhances customer satisfaction by measuring defects, improves product quality, and reduces defects to 3.4 parts per million opportunities within organizations. This methodology highlights variations in the manufacturing process and mitigates them through its statistical tools and techniques (Vinodh & Swarnakar, 2015). Limited public literature exists regarding the occurrence and characterization of bubbling in industrial settings. Some studies have examined bubbling in contexts such as paper labels or wood tabletops, but not aluminum tabletops (e.g., those produced by Southern Aluminum). In this study, we aim to identify the specification limits compatible with the lamination process and materials to address this issue.

3. Methods

This study aimed to identify the root cause of the bubbling issues observed in Southern Aluminum's laminate tables. The investigation began with an analysis of existing defect rate data to determine if the problem could be linked to a specific time period, manufacturing line, or table size. The study then focused on two potential contributing factors to table bubbling: glue application and environmental conditions.

Data collected by the quality team from April 2023 to April 2024 included information on the number and type of tables, glue weight (indicating glue thickness), pinch roller settings (indicating pressure), temperature, humidity, and the number of defective tables.
The study utilized the Lean Six Sigma methodology, dividing the work according to each phase as shown in Figure 3. improve and control phases were not implemented, as the design of experiments has not been completed yet.

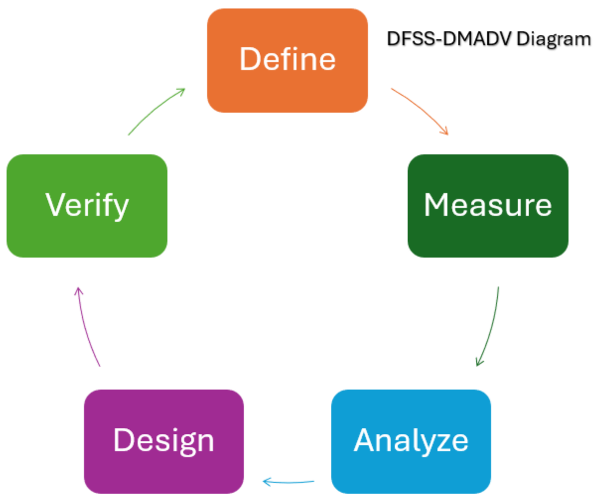

Figure 3. DFSS-DMADV Diagram

3.1. Define Phase

The first step of the DMAIC approach is to define the problem through a value flow map and quality analysis of the process. This involved observing the process over several days, reviewing all standard work instructions, machine manuals, and data sheets for the substances used. Following this, a process flow chart (as shown in Figure 2) and a SIPOC diagram (Suppliers, Inputs, Process, Outputs, Customers) were developed (as shown in Figure 4).
The primary materials involved in the process are Aluminum Tabletops (AT), Hot Melt Adhesive (HMA), and High-Pressure Decorative Laminate (HPDL). The key machines used are the coat roller and the pinch roller. The HPDL is supplied by Wilsonart, and the HMA (Rapidex® 1011) is supplied by H.B. Fuller. These materials are processed in-house to produce the final laminated tabletops.

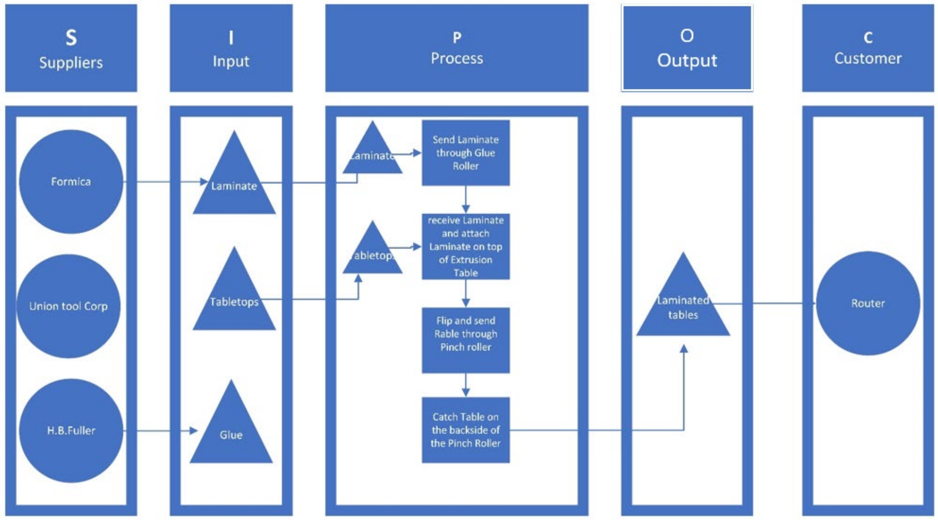

Figure 4. SIPOC Diagram for Lamination process

3.2. Measure Phase

The aim of this phase is to quantify and understand the main quality problems and to design a system for measuring quality and process variation. The primary quality issue identified was intermittent bubbling, although the data did not provide precise percentages for rework, scrap, or returns. Several process variations were noted. While a Standard Work Instruction (SWI) from Union Tool Corp (the supplier of the coat roller and pinch roller) existed, it lacked instructions for environmental conditions. The glue thickness, measured in grams for a specific dimension of HPDL, was identified but not tested. Additionally, the cure time was set at 40 minutes before the laminated tabletops were routed to remove any excess laminate, but there were no specified environmental requirements during the cure time. The term substrate (substratum), as it applies to High Pressure Decorative Laminate (HPDL), refers to the structurally supportive material that a laminate is bonded to. To understand Laminate. HPDL is composed of resin impregnated kraft paper with decorative paper face material and a clear protective top layer which are fused under high heat and pressure. HPDL sheets are primarily composed of more than 70% alpha-cellulose (wood) fibers! In selecting the appropriate Substrate for Laminate, it's smart to consider the typical dimensional characteristics of wood. Other materials such as plywood, steel, or aluminum may be used in some applications, but their dimensional characteristics (movement during climatic change) are significantly different than the laminate that will be applied to them. This can create issues after installation. (Technical Services, 2012) Steel/Aluminum are used for high structural/ performance demand projects. Although internal bond is not an issue, metal substrate dimensional change is completely relative to temperature. In contrast HPDL dimensional change is primarily humidity driven (hygroscopic). As a result, ambient conditions may make components move in opposite directions. Additionally, there are specific challenges when bonding the metal and HPDL. The nonporous nature of steel limits the use of adhesives that require evaporation. Oxidation can occur after bonding. (Technical Services, 2012). The dimensional change of aluminum and its alloys with a change of temperature is roughly twice that of ferrous metals. The average CTE for commercially pure metal is 24 × 10–6/K (13 ×10–6/°F). Aluminum alloys are affected by the presence of silicon and copper, which reduce expansion, and magnesium, which increases it. (ASM International, 2024).

The coefficient of thermal expansion in the direction of wood fibers is between 3.5 and 5.0 × 10-6/K.
The most common cause of bubbling laminate is dimensional incompatibility between the laminate and the substrate. To prevent the problem, the substrate and the laminate must be compatible — they must respond to humidity changes by expanding and contracting at the same rates — and they must both be acclimated to the indoor environment before they are bonded. If the laminate is dry and the particleboard is wet, the laminate will bubble when the laminate grows and the substrate either shrinks or stays the same size. It takes laminate about two days to acclimate, if air can get to both sides of the material. For a piece of 3/4-inch particleboard substrate, it takes about a week. (Gros, 2000) Solvent-based adhesives are preferable to water-based adhesives. When it comes to dimensional movement, wood reacts with moisture, not with solvent. Even with proper acclimation, if you use water-based contact adhesive, the water can

disrupt the humidity balance by introducing water into the laminate or the substrate. Solvent-based adhesives tend to be more forgiving than water-based adhesives, and do not induce dimensional change problems. (Gros, 2000).

3.3. Analyze Phase

The aim of this phase is to identify the specification limits for cure time relative to humidity and temperature, as well as the optimal glue thickness for this process. To achieve this, a Design of Experiment (DoE) approach was employed. DoE provides a systematic method to evaluate the effects of variables on the output and their interaction effects. Unlike the one-factor-at-a-time approach, DoE allows for the assessment of multiple variables simultaneously, revealing interaction effects. Each variable (k) is assigned two or more levels (l), and all combinations of these levels are tested, generating l^k experiments. The output is normalized based on the level of each variable, determining the variables' effects on the output. Significant influences are identified in a normal probability plot as deviations from the error line. A first-order response can be created to capture individual and interaction effects for each response (Box et al., 2005; Montgomery & Runger, 2010). As discussed by Joseph Lloyd Andrus et al. (2022), DoE was applied to environmental factors affecting bubbles, testing temperature, humidity, and pressure. Each group was placed in the test environment for 24 hours, inspected, and then left for one week before another inspection. Measurements of bubble width along the parting line were taken for direct comparison (Figure 5, 6, 7, 8, 9 and 10).

In the lamination process, the main factors identified were cure time relative to humidity and temperature, and glue thickness, as shown in Table 1. Based on the Xbar-R chart analysis of one year of historical data (April 2023 - April 2024) and information from the SWI and HMA data sheet (Figure 11), the glue thickness specification limit is 8 grams +1 / -0.25 grams. The upper and lower specification limits for temperature are 70°F and 50°F, respectively, while for humidity, the limits are 50% and 25%. To determine the compatible specification limits for cure time relative to humidity and temperature, we will conduct experiments on eight samples with three replications, as shown in Table 2. The samples will be produced in the morning using the standard size (10x7 inches) for the glue thickness test, then placed in a Benchtop Humidity Chamber, Model: BHD-205 (Figure 12 and 13). This chamber can control a temperature range from -85°F to +392°F and a humidity range from 20% to 98% RH. Each group will be subjected to the test environment for 24 hours, inspected, and then left for one week before a final inspection. During inspections, pictures and measurements of bubbles in the tabletops will be taken, focusing on the number and area of the bubbles.as shown in Table 2.

Table 1. Factorials and levels

Factorials and Levels 3^2			
Levels	Factors	High	low
X1	Glue thickness (gm)	9	7.75
X2	Temperature (F)	90	50
X3	Humidity (%)	75	25

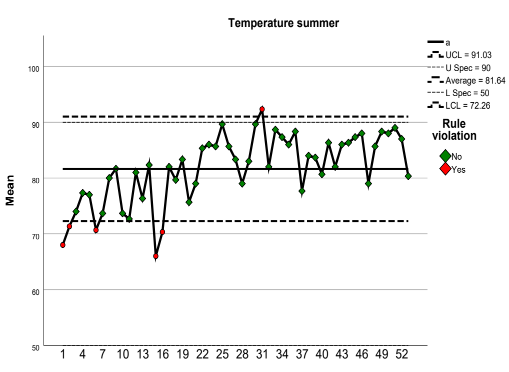

Figure 5. Xbar-R chart for temperature during summer

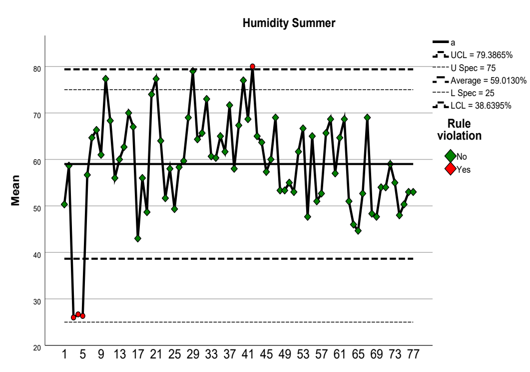

Figure 6. Xbar-R chart for Humidity during summer

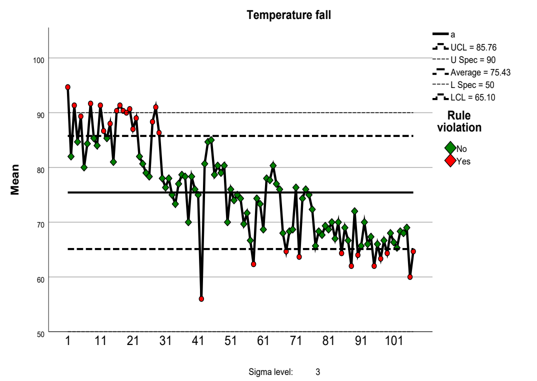

Figure 7. Xbar-R chart for temperature during fall

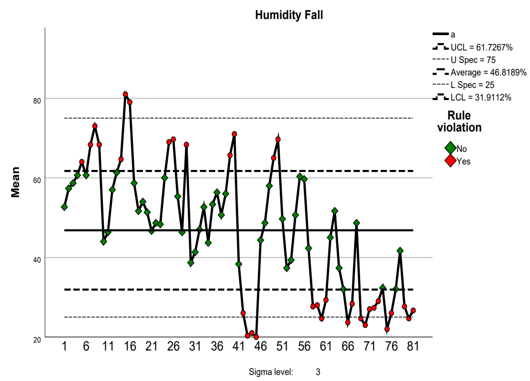

Figure 8. Xbar-R chart for Humidity during fall

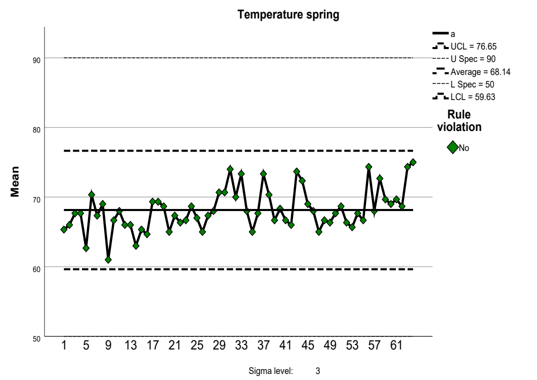

Figure 9. Xbar-R chart for temperature during spring

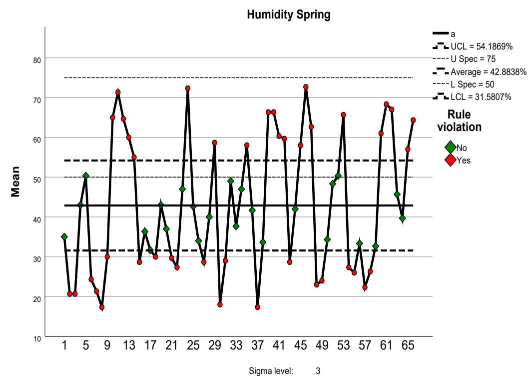

Figure 10. Xbar-R chart for Humidity during spring

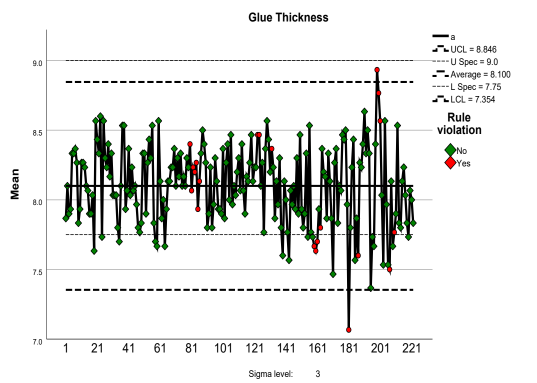

Figure 11. Xbar-R chart for Glue thickness

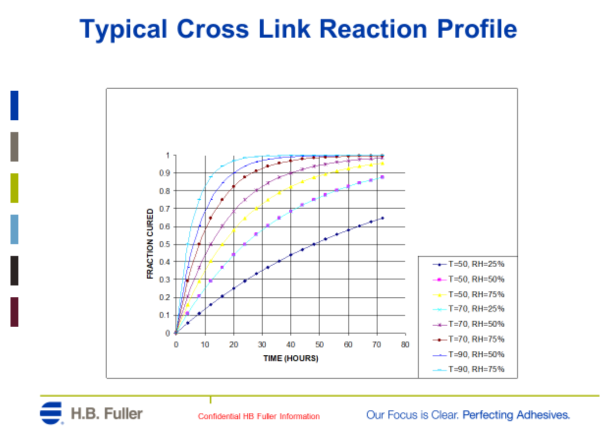

Figure 12. Cure time in relevant T&H

Figure 13. Benchtop Humidity Chamber

Table 2: Design of Experiment

	X1	X2	X3	#bubbles	Dimension	Description
1	high	Low	low			
2	Low	Low	low			
3	high	High	low			
4	low	High	low			
5	high	Low	high			
6	low	Low	high			
7	high	High	high			
8	low	High	high			

3.4. Design phase

Depending on the result of the DoE we will be able to set the specification limit for the cure time with relative temperature and humidity and the glue thickness required for this process.

3.5. Verify Phase

In verify phase control chart will be conducted to monitor the process and make sure that the process is in control.

4. Result

The potential root causes of the bubbles in the aluminum tabletops are identified and depending on the result of the DoE we will be able to set the specification limit that compatible with the process.

5. Conclusion

The results of this article document that even today it is possible to achieve a significant improvement in quality and increase the efficiency of processes in the company with the help of correctly designed methods and procedures, with the use of consistently formulated goals and with an active approach of the whole team. This study focused on this area using the Six Sigma methodology within the DMAIC steps with an emphasis on the competence of furniture production processes, specifically the critical process of laminating tabletops.

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