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Optimizing Thermoforming of High Impact Polystyrene (HIPS) Trays by Design of Experiments (DOE) Methodologies

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***Abstract* - The process of heating and reshaping plastic sheet and film materials has been in use since the beginning of the plastics industry better known as thermoforming [1]. Today this process is very ubiquitous for industrial products including signage, housings, and hot tubs [1]. It also produces much of the packaging in use today including blister packs, cartons, and food storage containers [1]. The process of thermoforming has many advantages over other methods for producing high-quality plastic products, with some limitations, which is resolved by implementing stringent quality control using scientific methods to improve process performance. Two areas of interest in today's industry of great concerns are lean manufacturing operations and environment [2]. Polystyrene scrap must be segregated from other materials in the waste stream before it can be recycled [3]. Thermoforming of high impact polystyrene sheets using Vacuum thermoforming technique requires technical knowledge on material behavior, mold type, mold material, and process variables. Research on various subjects documented but limited research focuses on the process optimization of HIPS (High Impact Polystyrene) [2]. The design of Experiments (DOE) approaches like those that the face-centered cubic central composite design used to refine the process to cut rejects [2]. This paper presents a case study on thermoforming of HIPS single use trays made on a semi-automatic machine using three criteria solely based on the FCC Design method. The optimization of HIPS tray forming using wall thickness distribution explored. Results show that ideal performance parameters achieved using Design Of Experiments [1].**

INTRODUCTION

The development of educational and industrial software and Thermoforming is an industrial process in which thermoplastic sheet (or film) transforms into a new shape using heat and pressure. Thermoforming is one of the earliest processes in the plastic industry since the mid-1800's beginning with the forming of cellulose nitrate sheet in [1]. The growth increased dramatically as new materials and applications developed [1]. For example, the need for aircraft canopies in World War II along with the development of poly-methyl-methacrylate (acrylic) created the perfect opportunity to advance thermoforming process technology. 5% to 6% growth rate of thermoforming process technology sustained over forty-five years.

Today this process produces many products from small blister packs to display AAA size batteries to large skylights and aircraft interior panels. End use of the manufactured products defines the market. "Industrial Products" include items with expected long life such as those used in the transportation and construction industries. "Disposable Products" (non- packaging) include items that have a short life expectancy but are not on the packaging side of the business [1]. This market includes disposable plastic plates and drinking cups. "Packaging Products" is a huge, high volume, an industry devoted to providing manufacturers with low-cost packaging to display, protect, and/or extend the life of their products [2].

Various new research technologies define new and exiting thermoforming processes and products. Process simulations using novel computer based software like COMSOL developed and well studied. Detailed new studies on process optimization of PET using Taguchi Method proposed [1], [2]. Taguchi Method works with a single qualitative characteristic or response. However, most products have several qualitative characteristics or responses of interest [4]. Process conditions and plug materials in plug-assisted thermoforming are well investigated [1], [2], [5]. Most thermoforming processes the important practical operating consideration is the ability to control the wall thickness distribution, since this will largely determine the physical properties of the final product. An uneven thickness distribution the thinnest regions will dictate mechanical strength of the formed part. Industry is very well focusing in trying to balance the wall thickness of thermoformed parts [6]. Although many studies conducted, none have investigated the process about the ideal processing settings that can produce the high yield with consistent part thickness and least processing time [2]. The face-centered cubic central composite Design of Experiments is an all-inclusive method that can be used to optimize product quality / trays by implementing suggested processing parameters while minimizing waste and process iterations.

HIGH IMPACT POLYSTYRENE (HIPS)

Polystyrene is the fourth biggest polymer produced in the world after polyethylene, polyvinyl chloride, and polypropylene. General-purpose polystyrene (GPPS) is a glass like polymer with a high processability [7]. Polystyrene modified with rubber known as high impact polystyrene (HIPS) encompassing characteristics, like toughness, gloss, durability and an excellent processability [8]. Polystyrene is one of the most versatile plastics. Whether packaging for food products, office and information technology, refrigerators, all sectors place high demands on the properties of the materials used. In its diverse variants, HIPS offers extraordinary property combinations, thus making a vital contribution to everyday life. High impact polystyrene is also used in many applications because of its excellent balance of properties and low-cost. HIPS have good impact resistance, dimensional stability, excellent aesthetic qualities, is easy to paint and glue, manufactured at a low-cost and approved by the U.S. Food and Drug Administration [8].

Face-Centered Cubic Central Composite Design

Design of experiments (DOE) is a statistical technique introduced by Sir R. A. Fisher in early 1920s [7]. Face-centered cubic Central Composite Design is a Design of Experiments (DOE) method [3]. FCC Design can have many factors that affect your process outcome simultaneously. Studying each factor one at a time would be very expensive and time-consuming, and you would not get any information about how different factors interact with each other [3]. That is where the design of experiments comes in. DOE turns the idea of needing to test only one factor at a time on its head by letting you change more than a single variable at a time [3]. This minimizes the number of experimental runs you need to make, so you can get meaningful results and reach conclusions about how factors affect a response as efficiently as possible.

Oven % On Time, Heating Time, and Vacuum Time, are the three process variables of interest [2]. Some variables have more importance than others and some show important interdependence or interactions with others [1]. A deep understanding of your current thermoforming process and equipment is essential prior conducting the experiments to get robust results [2]. A simple screening experiment is necessary to weed out which of these factors have the biggest effect on the part quality [1]. This method provides a robust combination of process variables that examines for best part quality and least deviation from the target [2].

There is three distinct steps in this method: preparation of the trials, the realization of the trials and analysis of results as shown in figure 1 [2]. 1. Preparation of Trials: The specific characteristic (response) analyzed [2]. Through some experimental runs and prior knowledge of equipment and processes, the most important variables identified and levels determined. 2. Then, the right Face-centered cubic central composite design selects levels in the Minitab software. Minitab software produces the orthogonal array table to create the trials. Additional tables created to ease analysis [1]. After performing all trials and recording all relevant data, results analyzed using adapted averages calculations and variance analysis. Minitab enabled us to gain a better graphical representation with contour plots of the results [2]. An optimal combination of different variables at the right condition obtained. Using the suggested optimal combination of process parameters, a final vacuum thermoformed part made for validation.

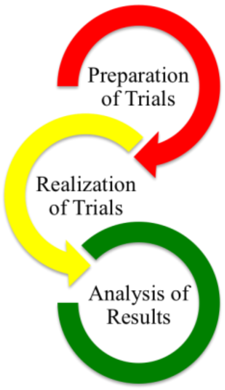

Figure 1. Design of Experiments process flow chart

Equipment Setup

Thermoforming of HIPS Trays performed on a MAAC thermoforming machine. Several adjustments were necessary in order to perform thermoforming of trays successfully which are listed below:

1. The vacuum connection was modified with a connector to facilitate easy disconnect of hose.
2. Pneumatic clamps that hold blanks adjusted for the size of 16in X 20in blanks.
3. Several dry runs helped remove any kinks in processing steps.
4. Software on controller did accommodate our processing parameters.
5. Several wet runs while changing parameters on the controller helped to get a good finished product.

All kinds of process variables from a cooling fan on and off time to vacuum and heating times analyzed to detect which factors have a direct relationship with part quality.

Processing of HIPS Tray

Thermoforming process involves a large and rapid deformation of a sheet and process is a common technique in forming of thermoplastic sheets. A pre-manufactured thermoplastic sheet is clamped in a place and is heated to its softening temperature. In the next step, the softened material is formed into a female/male mold by applying atmospheric pressure against a vacuum [9]. The heating stage is of primary importance in the thermoforming process [10] along with cycle time, because it has influence on the pieces final thickness distribution [11]. Thermoforming of the HIPS trays performed over a time of 4 weeks in the summer afternoons to minimize effects of the room temperature, humidity and other uncontrollable factors. The processing sequence followed as listed in Table 1. The equipment allowed warming up between the runs when temperature settings changed.

Table 1. Process variables and their levels

Process Variables	Letter	Levels		
		L1	L2	L3
% Oven On (Temp. Setting)	A	30 (310°F)	35 (335°F)	40 (370°F)
Heating Time (Sec.)	B	30	40	50
Vacuum Time (sec.)	C	2	4	6

Note: % Oven On process variable results in corresponding even oven temperatures that resulted in HIPS sheet temperatures shown in parenthesis.

Processing steps as listed below:

1) Turn On main power
2) Turn On power to equipment and vacuum pump
3) Turn On shop air half way and make sure the pressure gauge reads 15 PSI on the equipment (used for pneumatic clamps)
4) Turn control panel power on by releasing the red button
5) Go to main settings and change temperature and time as per your requirement
6) Turn oven On and wait till oven reaches the required set point and room temperature stays uniform
7) Put the HIPS blank in the holder and adjust to keep it in the center
8) Start the thermoforming process by pressing 2 green buttons on control panel
9) The clamp will close and the pneumatic lift will move the clamped HIPS blank into the oven
10) Blank will start to get hot and will reach a molding temperature as set by user
11) Measure sheet temperature right before it is moved down to thermoforming station
12) Now the bottom mold will get lifted to the desired stop and vacuum will turn on
13) After the sheet is molded it will get ejected by air pressure and clamp will release while the fan will turn on to cool down mold and formed parts
14) The thermoformed HIPS tray removed gently and a label applied to match a sequence number, temperature settings and forming time along with sheet temperature.
15) Process will be repeated for the next sequence

A reasonable delay time of 5 minutes was added to get the oven back to the set point temperature

Process Variables: HIPS Tray

For this research, the equipment used is a MAAC Thermoforming System –Single Station Model # ASP, Serial # 03904, having a total molding and clamping area of 30” x 36” and an oven of about 36” x 48” in size. The HIPS tray made from a sheet stock of High Impact Polystyrene (HIPS) 16” x 20” and 0.040” thick. Figure 2 and 3 shows the CAD model and thermoformed tray respectively. A female mold made of aluminum with four cavities mounted with clamps on the bottom pneumatic holder. Vacuum channels in the bottom female mold assist in proper part formation. The equipment is a semi-automatic laboratory use machine. The main quality specifications (response) selected are even wall thickness with least variance from one cavity to the next. Figure 4 and 5 shows MAAC thermoforming machine and aluminum mold with vacuum holes.

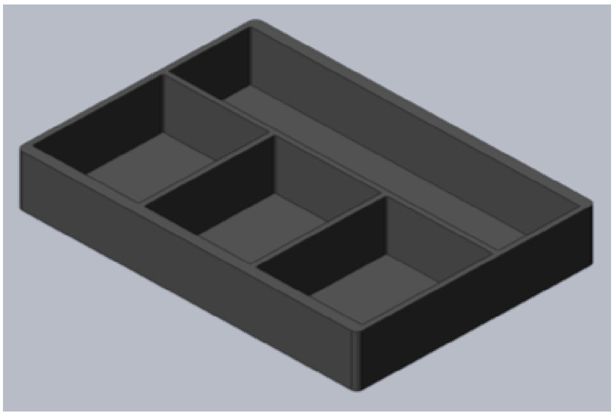

Figure 2. CAD model of HIPS tray

Figure 3. Thermoformed HIPS tray

Figure 4. MAAC Thermoforming Machine

Figure 5. Aluminum mold with vacuum holes

After some brainstorming and some trial runs, the optimization study would consider the effect of three process variables on quality specifications [12]. Each variable tested at three different levels [12]. Selected variables and levels as listed in Table 1.

The 40 trials completed consecutively for about 5 minutes of production time for each trial, which includes loading of blank sheets, clamping of blank sheets, processing, measuring the temperature of HIPS sheet with an infrared thermometer, removal of the finished tray and changing settings on the controller of the MAAC machine [2]. Wall thickness of the bottom, sides and corners were measured. Total of 11 measurements per tray recorded in Minitab. Wall thickness measurements analyzed to get mean thickness per tray; the standard deviation of each tray and the variance analysis performed for each tray. There were 10 instances where the processed sheet did not result in a part that analyzed for the thickness measurement so a zero part quality and a max variance of 0.00011 assigned as shown in figure 7.

Preparing HIPS Tray for Analysis

Before any analysis can begin, the processed trays cut in half and edges sanded to make it measurement ready. The reason to cut the trays was to expose the profile as shown in figure 6, which will make it easier to measure thicknesses with a vernier caliper.

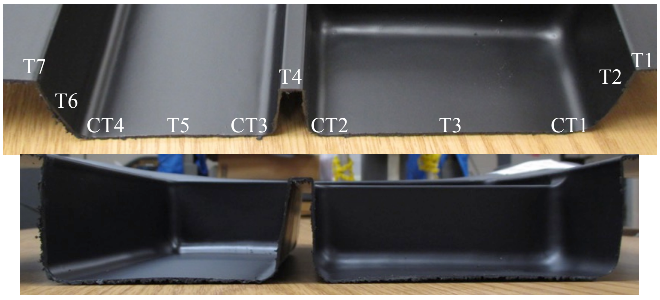

Figure 6. HIPS tray profile top and side view

The measurements were performed at 11 different locations. A visual part quality assigned as shown in figure 7.

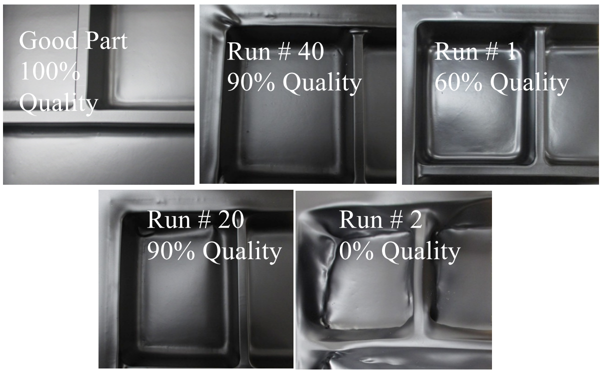

Figure 7. Visual part quality rating of thermoformed trays

Optimization Plot Overlays of Results

Residual plots for thickness variance and part quality of all thermoformed trays. Results plots as in figure 8 and 9.

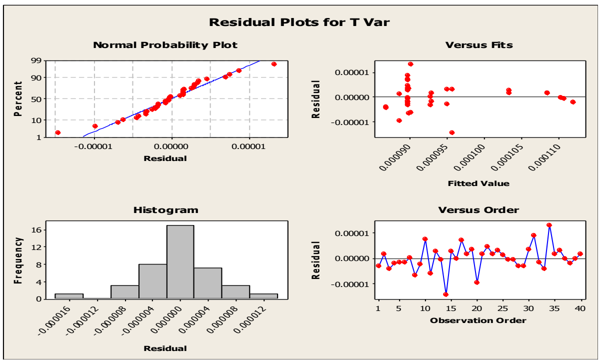

Figure 8. Residual plots for thickness variance data

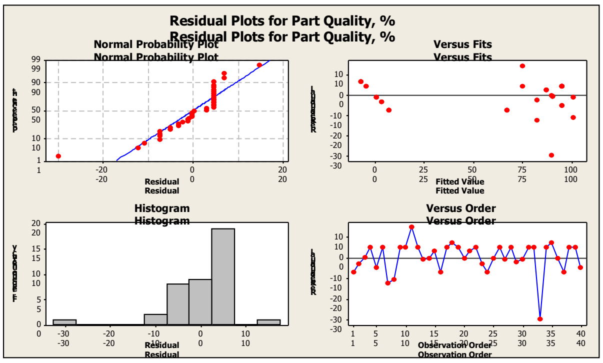

Figure 9. Residual plots for Part Quality

Contour plots as shown in figure 10 and 11 indicate that a vacuum time of approximately 4.75 seconds is optimal.

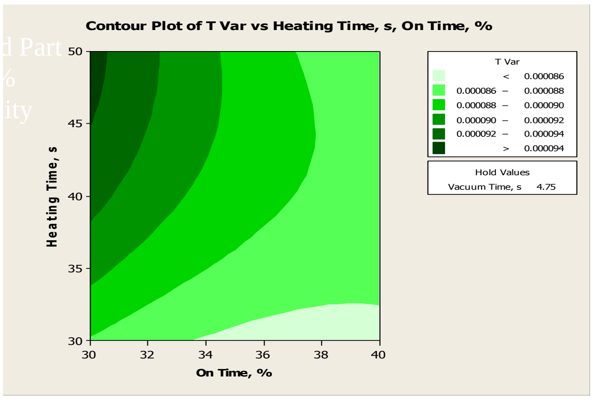

Figure 10. Contour plot of thickness variance vs. heating time and % on time

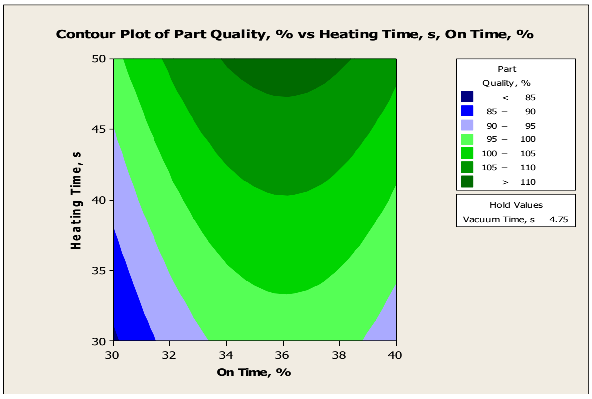

Figure 11. Contour plot of part quality vs. heating time and % on time

Contour plots reformulated using vacuum time value of 4.75 seconds as recommended by the analysis. Contour plots overlaid to minimize thickness variance and maximize part quality as shown in figure 12. Finally, considering extreme (robust) possibilities the optimized results plot is shown in figure 13 below.

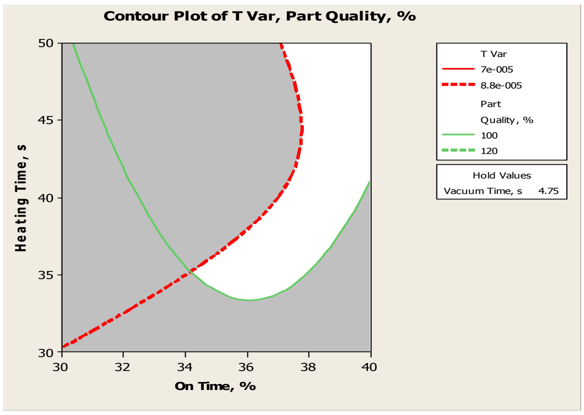

Figure 12. Contour plot of thickness variance vs. part quality

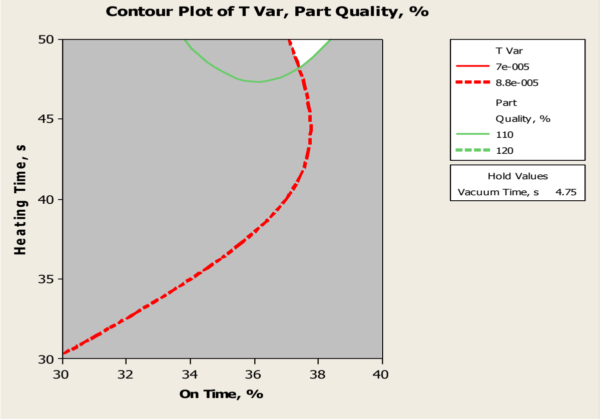

Figure 13. Optimized Contour plot of thickness variance vs. part quality

Recommended Vacuum Thermoforming Process Parameters

The recommended vacuum thermoforming parameters to improve part quality by minimizing thickness variance are shown in table 2.

Table 2. Recommended vacuum thermoforming process parameters

Process Variables	Letter	Recommended Thermoforming Parameters
% Oven On (Temp. Setting)	A	37
Heating Time (Sec.)	B	50
Vacuum Time (sec.)	C	4.75

CONCLUSION

A Face-centered cubic central composite design used to optimize vacuum thermoforming of HIPS trays [2]. The MAAC thermoforming equipment used and optimal combination of process variables for the tray obtained [2]. This method is a simple and efficient approach if adopted can yield significant process improvements in an industrial production setting [2]. It resulted in short production times (< 120 seconds) and yields a robust product quality, minimizing waste and reprocessing [2]. A well-prepared test will bring relevant and useful results for economical production cycle. Systematic process optimization by the DOE enabled defect-free and uniform wall thickness and radii.

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Biographies

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