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 plastics sheet and film materials has been in use since the beginning of the plastics industry better known as thermoforming. Today this process is very ubiquitous for industrial products including signage, housings, and hot tubs. It also produces much of the packaging in use today including blister packs, cartons, and food storage containers. The process of thermoforming has many advantages over other methods for producing high quality plastic products, with some limitations, which can be 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. Thermoforming of high impact polystyrene sheets using vacuum forming technique requires technical knowledge on material behavior, mold type, mold material, and process variables. Research on these various subjects is well documented but very limited research is done in process optimization of HIPS (High Impact Polystyrene). Design of Experiments (DOE) approaches like the face-centered cubic central composite design can be used to refine the process and to minimize rejects. In this paper, we present 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 tray forming and wall thickness distribution is explored. Results indicate that optimal performance parameters can be achieved using DOE methodology.

Introduction

Thermoforming is an industrial process in which thermoplastic sheet (or film) is processed into a new shape using heat and pressure. This was one of the earliest processes to be used in the plastics industry beginning with the forming of cellulose nitrate sheet in the mid 1800's. The growth increased dramatically as new materials and applications were developed. 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. A growth rate of approximately 5% to 6% has been sustained for over forty-five years.

Today this process is used to produce many products from small blister packs to display AAA size batteries to large skylights and aircraft interior panels. The market is often defined by the end use of the products being manufactured. “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 in the packaging side of the business. This market includes disposable plastic plates and drinking cups. “Packaging Products” is a huge, high volume, industry devoted to providing manufacturers with low cost packaging to display, protect, and/or extend the life of their products.

Research on thermoforming processes has been conducted on different aspects of the process. Process simulations using novel computer based software like COMSOL have been developed and well studied. Process optimization of PET using Taguchi Method has been investigated thoroughly [1]. Process conditions and plug materials in plug-assisted thermoforming have been investigated [2,3]. Although many studies have been conducted, none have investigated the process with regards to the optimal processing settings that can produce high yield with consistent part thickness and minimum processing. The face-centered cubic central composite Design of Experiments is an all-inclusive method that can be used to optimize the quality of product / 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 glasslike polymer with a high processability. When modified with rubber it is known as high impact polystyrene (HIPS) with a unique combination of characteristics, like toughness, gloss, durability and an excellent processability. Polystyrene is one of the most versatile plastics. Whether packaging for food products, in office and information technology or 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 also has good impact resistance, good dimensional stability, excellent aesthetic qualities, is easy to paint and glue, can be manufactured at a low cost and is approved by the U.S. Food and Drug Administration.

Face-Centered Cubic Central Composite Design

Face-centered cubic Central Composite Design is a Design of Experiments (DOE) method. It is used when you 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. That is where design of experiments comes in. DOE turns the idea of needing to test only 1 factor at a time on its head by letting you change more than a single variable at a time. This minimizes the number of experimental runs you need to make, so you can obtain 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. Some variables have more importance than others and some show important interdependence or interactions with others. A deep understanding of your current thermoforming process and equipment is essential prior to conducting the experiments in order to obtain robust results. A simple screening experiment is necessary to weed out which of these factors have the biggest effect on the part quality. This method provides a robust combination of process variables that need to be closely examined for an optimum part quality and minimum deviation from the target.

There is three distinct steps in this method: preparation of the trials, realization of the trials and analysis of results. 1. Preparation of Trials: The characteristic (response) to be analyzed is specified. Through some experimental runs and prior knowledge of equipment and processes the most important variables are identified and levels are determined. Then appropriate Face-centered cubic central composite design is selected with levels in the Minitab software. The orthogonal array table produced by Minitab is used to create the trials. Additional tables are created to facilitate analysis. After performing all trials and recording all relevant data, results are analyzed using adapted averages calculations and variance analysis. Minitab enabled us to gain a better graphical representation with contour plots of the results. An optimal combination of different variables at the right condition is obtained. A final trial is run, using this optimal combination for validation.

Equipment Setup

Thermoforming of HIPS Trays was 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 had to be installed and adjusted for the size of 16in X 20in blanks.
3. Several dry runs were performed to remove any kinks in processing steps.
4. Program on the controller was studied in detail to make sure it can accommodate our processing parameters.
5. Several wet runs were performed while changing parameters on the controller to make sure we get a good finished product.
6. All kinds of process variables from fan on and off time to vacuum and heating times were analyzed to detect which factors have a direct relationship with part quality.

Processing of HIPS Tray

Thermoforming of the HIPS trays was 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 was followed as listed in Table 1. Between the changes in temperature parameter the equipment was allowed to warm up between the runs. Processing steps are listed as 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 will be removed gently and a label will be applied to enter a sequence number, temperature settings and forming time along with sheet temperature.
15. Process will be repeated for the next sequence
16. 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 approximately 36” x 48” in size. The HIPS tray were made from a sheet stock of High Impact Polystyrene (HIPS) 16” x 20” and 0.040” thick. A female mold made of aluminum with 4 cavities is mounted with clamps on the bottom pneumatic holder. Molding is not used with plug assist but instead vacuum channels in the bottom female mold will assist in proper part formation. The equipment is a semi-automatic laboratory use machine. The main quality specifications (response) we selected are even wall thickness with least variance from one cavity to the next.

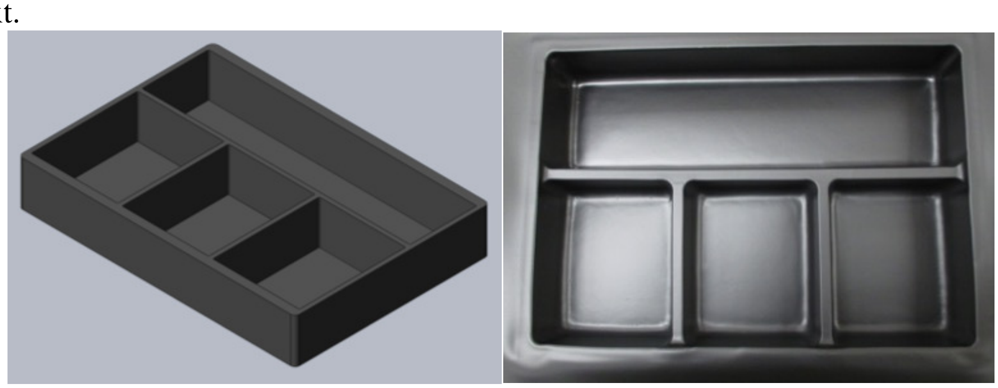

Figure 1. The CAD model of HIPS tray (left), actual HIPS tray (right).

Figure 2. MAAC thermoforming machine and aluminum mold with vacuum holes.

After some brainstorming and some trial runs, it was decided that the optimization study would consider the effect of three process variables on quality specifications. Each variable will be tested at three different levels. Selected variables and levels are listed in Table 1.

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.

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

Preparing HIPS Tray for Analysis:

Before any analysis can begin the processed Trays need to be cut in half and sand off edges to make it ready for measurements. The trays were cut into to halves on a regular band saw machine available in manufacturing labs. The reason to cut the trays was to expose the profile, which will make it easier to measure thicknesses at different locations with a vernier caliper. As shown in Figure 3, the thickness measurements were performed at 11 different locations.

Figure 3. HIPS tray cut in half – top view and side view.

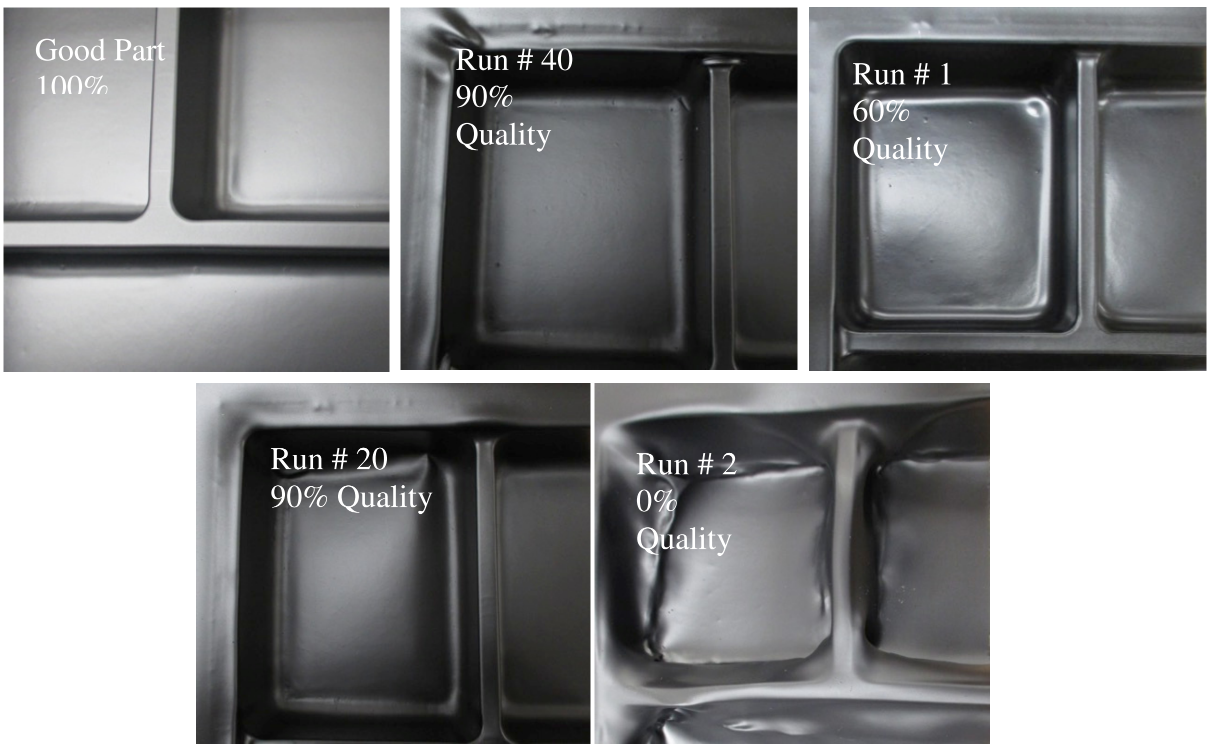

Figure 4. Assigned visual part quality based on draw down, formation of sharp edges & radii.

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Optimization Plot Overlays of Results

All contour plots indicate that a vacuum time of approximately 4.75 seconds is optimal. Contour plots were then reformulated using a vacuum time hold value of 4.75 seconds.

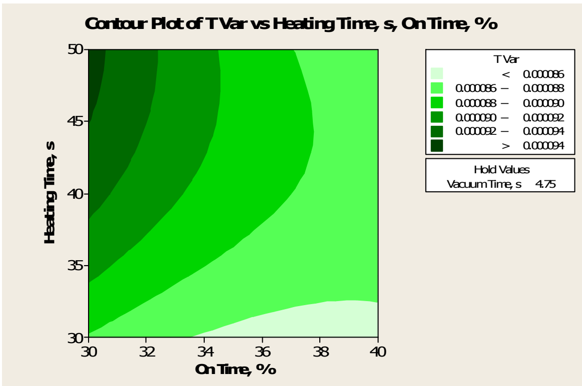

Figure 5. Contour plot of variance vs. heating time and % oven on time.

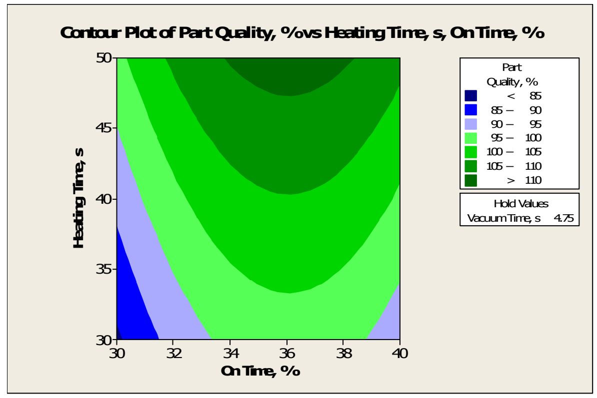

Figure 6. Contour plot of part quality vs. heating time and % oven on time.

Finally, contour plots were overlaid to minimize thickness variance and maximize part quality as shown in Figure 7. And considering extreme (robust) possibilities the optimized plot is shown in Figure 8 below.

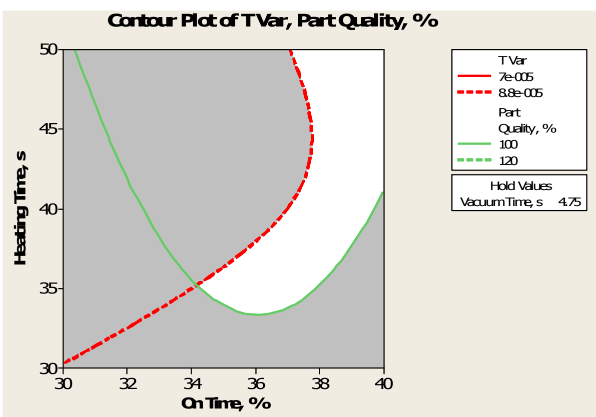

Figure 7. Contour plot of variance and part quality vs. heating time and % oven on time.

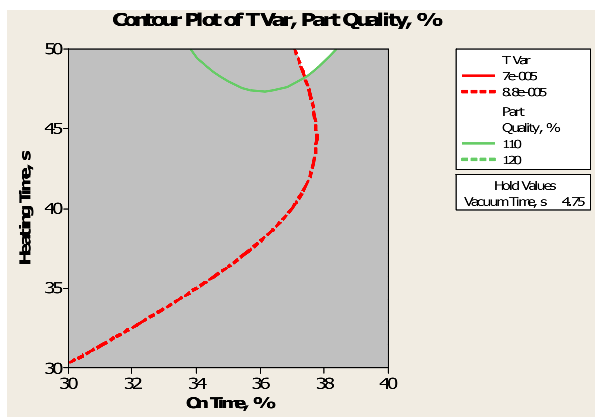

Figure 8. Optimized contour plot of variance and part quality.

Recommended Vacuum Thermoformed Part Process Parameters

Table 2. Recommended Vacuum Thermoforming Parameters

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

Conclusions:

A Face-centered cubic central composite design was used to optimize vacuum thermoforming of HIPS trays. The MAAC thermoforming equipment was used and optimal combination of process variables for the trays were obtained. This method is a simple and efficient approach that can be performed on an industrial production if needed. It resulted in short production times (< 120 seconds) and yields a robust product quality, minimizing waste and reprocessing. 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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