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Process Control and Quality Improvement of Plug - assist Thermoforming Process: a Case Study

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ABSTRACT. Problem recognition was obvious to the management body of the disposable cup factory as looking at the scrap bin and realizing that some specific part of the process is causing substandard and defected products. Fourteen types of defects were recognized and the problem solving approach combined with quality control charts and tensile testing was used to solve the problem and called Thermo-mechanical approach (TMA). The results of the TMA showed that an uneven distribution of temperature after preheating is the most effective variable in increasing the number of defects. Changing the design of the heating system from free convection to forced convection by adding fans helped in overcoming the heat distribution problem. An optimum temperature of 171 0C of the heating elements was also determined to give the best productivity results.

KEY WORDS: Plug-assist, Thermoforming, Thermo-Mechanical, Control Charts, Disposable.

1. Introduction

Plug assist thermoforming is one of the most process variants for thermoforming industry. Its purpose is to pre-stretch the heated polymer sheet prior to the application of pressure and/or vacuum during the final part formation. Just as the softened material can be forced into the mold by positive air pressure as is done in pressure forming, it can be forced downward by mechanical pressure. In this type of forming, a plug is used to force the material into the mold. Generally the plug will not push the material completely into the mold but, rather, only part way to positive seating. A pressure is then applied to draw the material against the cavity walls and complete the forming operation. This technique is shown in Figures 1 & 2.

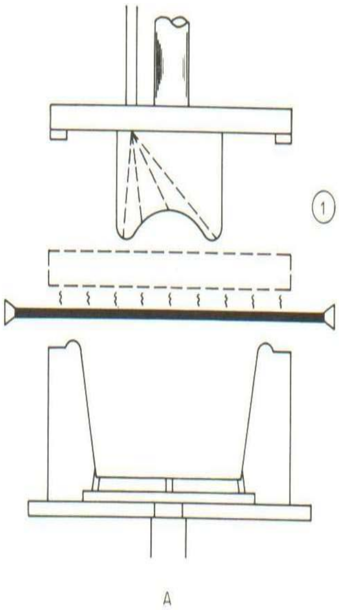


Figure 1: The pre-heating phase.

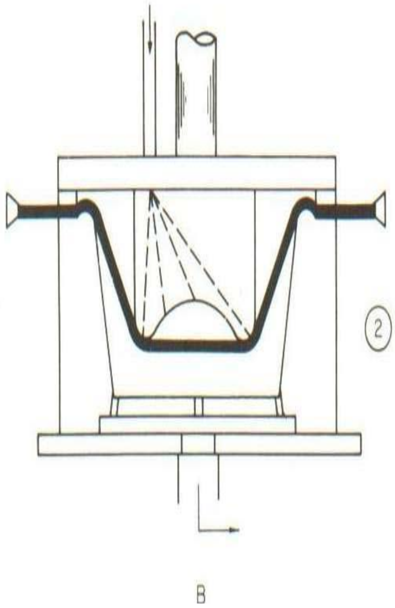


Figure 2: The forming and blowing phase.

Pressure technique is called plug-assist forming when a plug is used. The major advantage of plug-assist forming is that it gives a better wall thickness uniformity than can be obtained by other forming processes, especially for conical cup or box shapes. The plug can be used to carry material towards the areas that would have been too thin if just straight pressure forming is used. In plug-assist forming the initial sagging of the material is kept to a minimum. When the pressure is applied as a blowing process, the material moves outward off the plug and stretches uniformly until the material makes contact with the mold. As with straight pressure forming, this contact first occurs at the center of the bottom and along the walls. The thickness then becomes fixed at those locations and stretching occurs at the corners and other locations not yet in contact with the mold, all details of mold walls will print directly and smoothly on the product surface. The studied product is a disposable cup as shown in Figures 3a & 3b.

Figure 3a: Full disposable cup details.

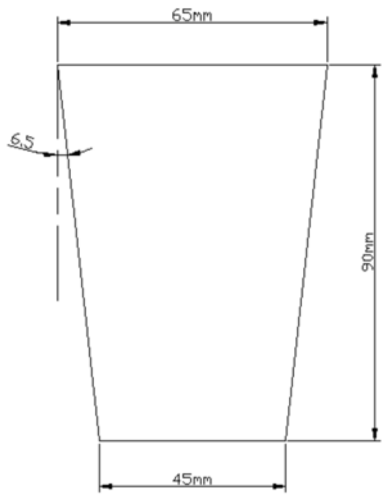


Figure 3b: Dimensions of disposable

The product and sheet specifications are shown in Table1. The schematic view of the Plug-Assist machine is shown in Figure 4, and its specifications are shown in Table2.

Table 1: Product and sheet specifications.

Product material	Polystyrene
Product weight	8.0 gm
Product dimensions	Upper diameter = 65 mm, Bottom diameter = 45 mm, and Height = 90 mm.
Heating temperature	160 – 180 ^{o}C
Sheet length	On average 115 m.
Sheet width	950 mm.
Sheet thickness	400 μm

The main parameters that control the Plug-Assist process are: feed rate, which is a character of the machine, preheating temperature which is about l50-170 ^{0}C (the temperature must be less than 180 ^{0}C because at this temperature the burning, degradation and bubbles or discolorations (spots) may occur in the sheet), wall thickness, cooling rate and preheating time which can be calculated by equation 1 below:

$$t = 10+3v \tag{1}$$

Where:

t- preheating time (s).

v- thickness of sheet (mm)

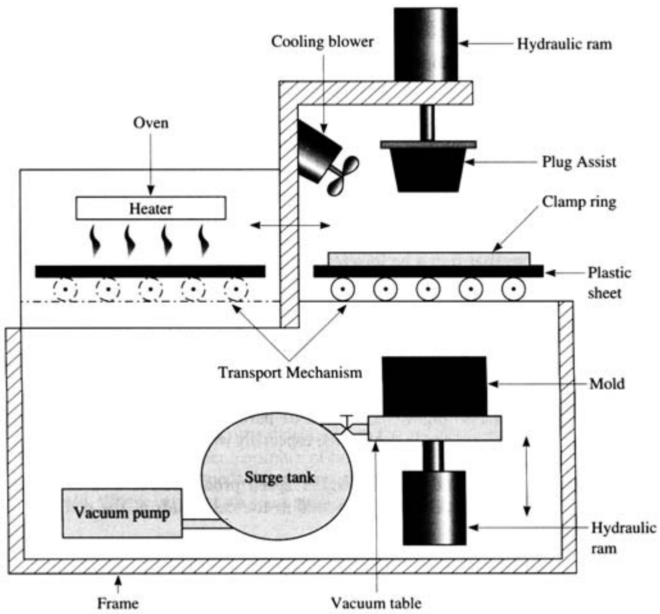


Figure 4: Illustrative drawing for Plug-Assist machine.

Table 2: Plug assist machine specifications

Dimensions	3.80× 2.25 × 1.70 cubic meter
Power consumption	25 Hp
Pneumatic pressure	4 – 5 bars
Production rate	About 25 cubic meters of polystyrene per hour
Slot width	950 mm (adjustable to 1200 mm)
Slot length	1000 mm
Refrigeration temperature	Up to 4 ^{o}C
PLC characteristics	Siemens
PLC input	12
PLC actuators types	Hydraulic & Pneumatic
Hydraulic pressure	4.0 bars

Previous studies concentrated on investigating the wall thickness parameters. For example, Aroujalian et al [1] studied the wall thickness distribution in plug assist vacuum forming and Wolf et al [2] studied the wall thickness of medical blisters while the optimization of wall thickness distribution was studied by Wolf et al [3] and Novotny et al [4]. Other researchers used finite element modeling to predict distortion of the sheets used for plug assist forming [5] and to model the plug assist thermoforming process as a whole [6]. Various plug assist materials and their effect on the thermoforming characteristics of polymer sheets were investigated [7] in addition to the rheological properties and processing parameters [8]. It is worth mentioning that the hot impact test was used in simulation of the plug assisted thermoforming process [9] and an attention was paid to the heat transfer in this process [10].

In this study, a real problem in the quality of the final disposable cup product in the disposable cup factory was studied. After defining, analyzing, and seeking the solution in a scientific manner, it was found that the distribution of temperature after preheating is behind this huge number of defected product. A modification in the design of the machine was suggested and applied to provide a better heat distribution. An improvement in the quality of the products and a reduction in the number of defects was achieved.

2. Methodology

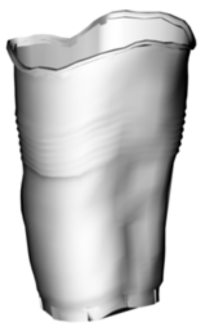
A logical, systematic approach to problem solving follows the basic sequence of problem recognition, problem definition, problem analysis, choice for action and problem solution was used in this investigation. The problem was recognized by the management of the factory while the other steps of sequence will be discussed in the following sections.

2.1. *Problem Recognition and Definition*

Problem recognition was obvious to the management of the factory since looking at the scrap bin reveals that some specific part of the process is causing substandard products. Classification of the defects enabled in defining the problems in the process. The main problems in the manufactured product can be summarized as follows:

1. Blisters/bubbles.
2. Incomplete Forming, poor Details.
3. Blushing or color intensity change.
4. Webbing, bridging, wrinkling.
5. Excessive sag.
6. Sag variation between sheet banks.
7. Chill marks, striations.
8. Shiny streaks on part.
9. Post-forming shrinkage, distortion.
10. Poor material allocation.
11. Very thin corners.
12. Part sticks in mould.
13. Sheet sticks to plug.
14. Sheet tears while forming.

Figure 5 shows the pictures that illustrate the above mentioned defects of the products.

		
Blisters/bubbles	Incomplete Forming, poor Details	Blushing or color intensity change
		
Webbing, bridging, wrinkling	Excessive sag	Sag variation between sheet banks
		
Chill marks, striations	Shiny streaks on part	Post-forming shrinkage, distortion

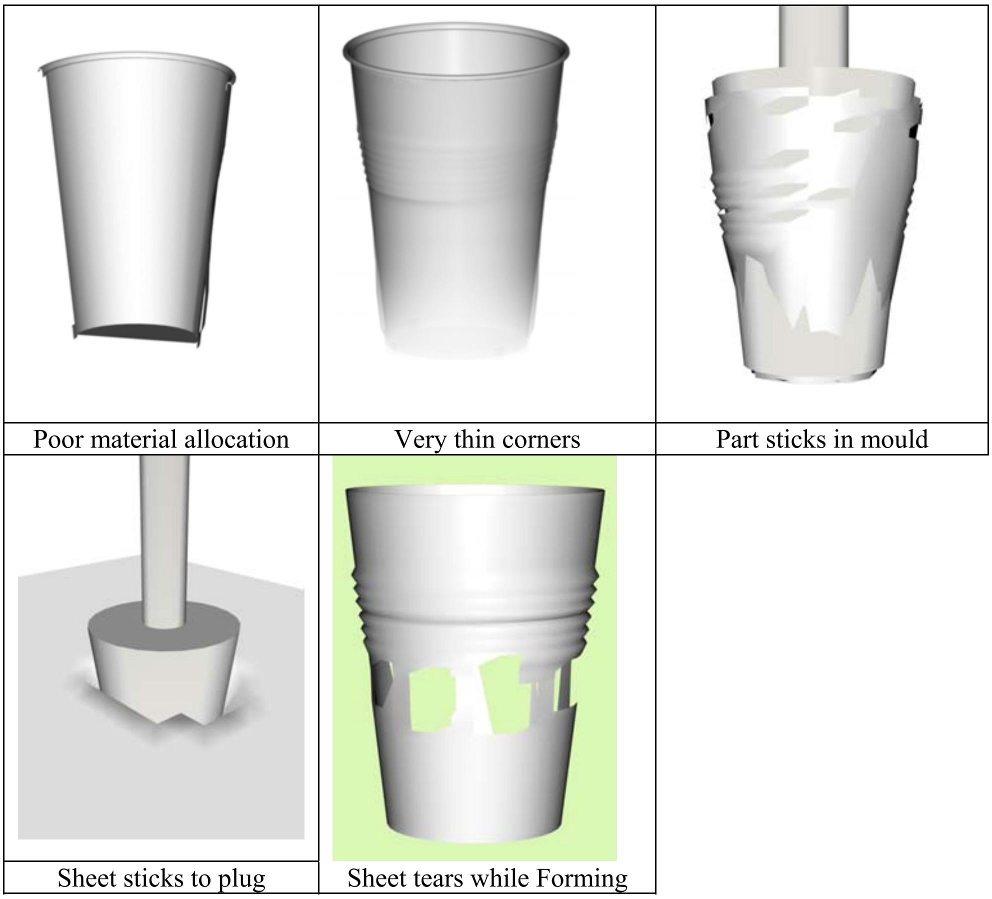


Figure 5: Illustrations of the detected defects in the factory.

2.2. *Problem Analysis*

The first step of analysis is dividing the variables that influence the quality of the product into four categories. The first category is the manufacturing route. It consists of feeding, preheating, forming force, pressure and cooling rate. The second category is the input and output design variables. They include the design of the product and the design of the sheet. The third category concerns material and mold design variables. It comprises the plug size, pattern design, drawing ratio and the type of the material used. The fourth category is the control system of the process which contains heating, punching and ejection.

The second step is the evaluation of the process by constructing the control charts which help in analyzing the potential causes for the out-of-control situations. There are two types of control charts, attributes control charts and variables control charts [11]. In this project, the attributes np-control charts were used because the product was judged according to the conforming or non-conforming base.

It was assumed that the roll coming out of the extruder has no effect on the quality of the product. Twenty samples (m=20) were taken from the roll, each sample was taken every hour with a sample size of twenty cups (n=20).
The control chart for the sample which was taken at the beginning of the manufacturing process is shown in figure 6 below while figure 7 shows the control chart for Plug-Assist process in normal operation conditions. Chart in figure 6 shows a pattern of points that are steadily falling. This decreasing trend suggests that something in the process is changing gradually. Also this downward trend signals process improvement. As this trend occurs at the beginning of the process until the heating and other variables are settled, Figure 7 indicates that the plug assist process is getting better after reaching the steady state. Points 16, 17, 18, 19, and 20 in this Figure show what is called an extreme unlikely occurrence as they form a long run of five consecutive points above the center line. This unlikely condition leads to consider process out of control.

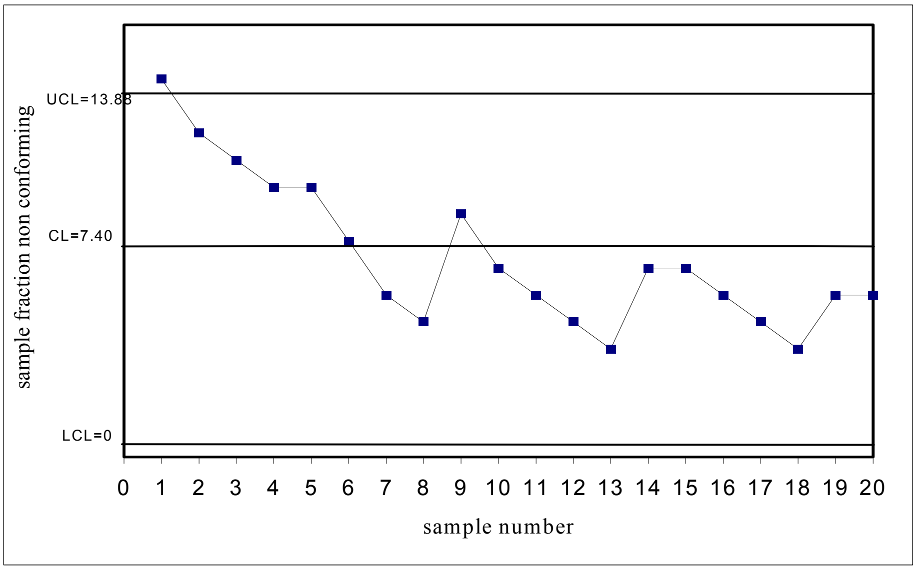


Figure 6: The np-control chart just at the begining of the manufacturing process. CL (center line)=7.4, UCL (upper control limit)=13.88, and LCL (lower control limit)=0.92

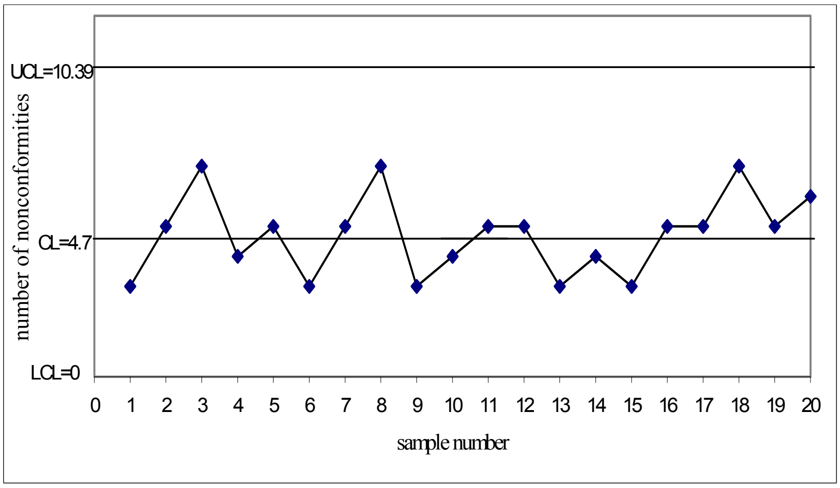


Figure 7: Control Chart for Plug-Assist process in normal operation conditions. CL =4.7, UCL =10.39, and LCL =0.

The third step of the analysis is the building of a relationship between the defects and the above mentioned categories to point out the reasons behind each of the problems. As a result of this step, the defects and their probable causes are shown in Table 3. It is clear from the underlined reasons in Table 3 that temperature and its distribution is the main reason behind most of the problems. For more assurance, it was decided to conduct a tensile test over different places of the sheet before and after preheating. As the property of the sheet before and after heating will have a great effect on the quality of the product, the results of the test for plastic sheet are good indicators for both design and quality assurance. The tensile test was conducted according to the standard ASTM D 638. The test is used to see the effect of temperature on the strength, it was called Thermo – Mechanical Test (TMA).

The Thermo-Mechanical Test (TMA) was performed to measure the changes in mechanical behavior of the sample as the temperature is progressively raised. TMA data can also be used to determine the heat distribution of the sheet. To check the uniformity of heat distribution along the sheet length, test specimens were taken from the sheet after the matrix arrangement for locating the specimens. The matrix dimension is [10,10] which mean that for 1-meter length 10 specimens in vertical dimension and 10 in horizontal dimension will be examined. The curves of heat variation were constructed after taking the dimensionless form of the tensile test data by dividing the results by the highest tensile test value for each matrix. The results of this TMA are shown in Tables 4 and 5 before and after preheating respectively. The following requirements were considered to guarantee getting good results are:

Table 3: The defects and their probable causes.

Defect	Probable Cause
Blisters	Heating too rapidly, Excess Moisture, and Uneven heating
Incomplete forming	Sheet too cold, Clamp frame Cold prior to sheet insertion, and Applied pressure too low
Blushing or color density change	Insufficient heating, Excessive heating, Mould too cold or hot, Assist too Cold, Sheet is stretched too far, Sheet cools before fully Formed, and Poor mould design
Webbing, bridging, and wrinkling	Sheet too hot, drape into forming area, Resins melt strength too low, sheet sag. Orientation mismatch, Excess draw ratio, and poor mould design/layout
Excessive sag	Sheet too hot, Sheet area excessive, and Melt index too high
Sag Variation	Wide sheet gage Variation, and Sheet made from different resins or not a homogeneous mixture
Chill marks and striation	Plug assist temperature too low, Mould temperature too low, Poor mould temperature control, Sheet too hot, and Wrong forming Techniques
Shiny streaks on product	Sheet over-heated in this Area
Post forming shrinkage	Time on mould too short or Mould too hot
Poor material allocation	Improper sheet sag, Sheet thickness variation, Cold mould, and Sheet pulls from rails
Very thin corners	Sheet too thin, Sheet temperature Variation, and Variation in mould Temperature
Part stick in mold	Part temperature too high, Inadequate draft, Mold undercuts, and Sticking in one spot
Sheet sticks to plug	Plug temperature too High, Wooden plug, Plug speed too high
Sheet tears while forming	Mould design, Sheet too hot, Sheet too cold , Improper polymer, and Forming conditions Improper

1- Each test specimen was cut according to engineering specimen dimensions indicated by the standard.
2- The specimen's direction with respect to the sheet is fixed in Y-axis to prevent the error due to anisotropic properties.
3- Several preparations were done before performing the test such as: clean, dry, smooth surface of sheet.
4- Constant heating time for sheet is verified by fixing the feed rate along sheet length.
5- The two sheets (before pre-heating & after pre-heating) taken from same roll to guarantee similarity in resin mixing percentage.

To evaluate the distribution of temperature using the data shown in Tables 4 and 5, the range of variation was calculated as the difference between the highest and lowest values of the raw. The same was also done for to evaluate the distribution of temperatures along the columns. The range of variation among the data for the rows is 0.022 – 0.045 before heating (Table 4) and 0.043 – 0.092 after heating (Table 5). While for the data in the columns, the range is 0.016 – 0.045 before preheating and .202 – 0.282 after heating. This indicates that the pre-heating created a wide range of an uneven distribution of temperature which is translated into uneven distribution of the tensile strength.

Table 4: The strength ratio for plastic sheet before pre-heating done.

	1	2	3	4	5	6	7	8	9	10	Column Variation
1	0.992	0.992	0.976	1.000	0.980	0.994	0.978	0.992	0.990	0.998	0.024
2	0.994	0.984	0.992	1.000	0.992	0.992	0.992	0.982	0.986	0.994	0.018
3	1.000	0.978	1.000	0.992	0.976	1.000	0.965	0.992	0.978	0.992	0.035
4	0.971	0.971	1.000	0.976	0.990	1.000	0.955	0.978	0.982	0.978	0.045
5	0.961	0.965	0.984	0.971	0.992	0.998	0.963	0.990	0.994	0.984	0.037
6	0.965	0.998	0.992	0.978	1.000	0.973	0.980	1.000	1.000	0.990	0.027
7	0.998	0.996	0.994	0.996	1.000	0.976	0.992	0.971	0.994	0.998	0.029
8	0.986	0.992	0.990	0.990	1.000	0.992	0.996	0.984	0.994	1.000	0.016
9	1.000	0.986	0.976	1.006	0.971	1.000	0.994	0.994	1.000	1.000	0.029
10	0.976	0.978	1.000	1.000	0.992	0.971	1.000	1.000	0.994	1.000	0.029
Row Variation	0.039	0.033	0.024	0.029	0.029	0.029	0.045	0.029	0.022	0.022	

Table 5: The strength ratio for plastic sheet after pre-heating done.

	1	2	3	4	5	6	7	8	9	10	Column Variation
1	0.965	0.941	0.867	0.751	0.800	0.763	0.816	0.837	0.955	0.984	0.233
2	0.982	0.957	0.843	0.780	0.786	0.790	0.837	0.816	0.931	0.945	0.202
3	0.992	0.955	0.898	0.767	0.765	0.769	0.827	0.827	0.929	0.961	0.227
4	1.000	0.971	0.888	0.751	0.751	0.778	0.857	0.857	0.941	0.971	0.249
5	0.984	0.984	0.904	0.737	0.773	0.698	0.837	0.878	0.916	0.955	0.282
6	0.976	0.955	0.896	0.753	0.778	0.737	0.855	0.888	0.949	0.980	0.243
7	0.986	0.990	0.894	0.757	0.759	0.743	0.829	0.867	0.959	0.971	0.247
8	0.963	0.965	0.859	0.751	0.778	0.735	0.857	0.880	0.941	0.935	0.228
9	0.949	0.941	0.857	0.714	0.788	0.759	0.888	0.855	0.924	0.965	0.251
10	0.937	0.935	0.878	0.706	0.773	0.759	0.829	0.847	0.922	0.949	0.243
Row Variation	0.063	0.055	0.061	0.074	0.049	0.092	0.072	0.072	0.043	0.049	

Based on TMA data and control charts, the following results can be found:

1. The process seems in control but it has a run of five consecutive points above the center line.
2. The largest number of defects occurred at the beginning of the process due to non-compatibility between different control system. For example: the control system inside the machine that helps in reaching the right speed or the right feed rate, the control system of the heating, …etc. and also the die and sheet doesn't reach the operating temperature.
3. Distribution of heat on the sheet mainly affected the quality of the product

2.3. *Choice of appropriate action*

As a result of the analysis, it was decided to modify the design of the machine to get a better distribution of temperature after preheating and to define the optimum temperature for production. To achieve a better distribution of temperature it was decided to change radiation and free convection heat transfer environment to a forced convection by adding fans to the heating system. Figures 8 and 9 show the design of the heating system before and after modification respectively. The parameters used to decide the appropriate action are:

1. Softening temperature range is 140-150 ^{o}C
2. Temperature of heating zone (heaters) range is 160-180 ^{o}C
3. The dimensions of the sheet is 900 mm x 0.4 mm.
4. Fixed distance of about 150 mm between the sheet and the heaters was kept
5. Fixed feed rate during the conduction of the test was taken.

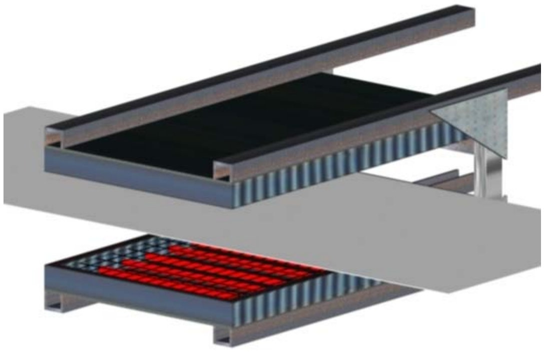


Figure 8: Heating system before modification

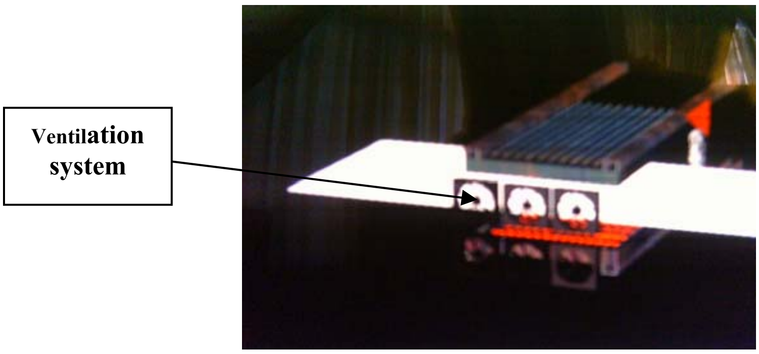


Figure 9: Heating system after modification

To determine the optimum temperature, which gives the minimum number of defects, the sheet was allowed to pass between the heaters at a predetermined fixed temperature within the 160 – 180 ^{o}C range with an increment of 5 ^{o}C. An increment of 1 ^{o}C was taken after coming nearer to the optimum value of temperature. Control charts were used as a measure of the performance of the process.

2.4. *Problem Solution*

The measured behavior of the process in the previous section showed that the design action and an optimum temperature of 171 ^{o}C of the heating elements can be used to improve the plug assist process and to get the best results by reducing the number of defects. To be sure of the taken actions, quality control charts were constructed and the tensile test, after preheating by the forced convection, system was conducted. It is clear from Figures 10 and

11 that the process is within the control limits of the process and also the variance was decreased. Comparing these ranges of variance to those measured after the modification of the design of the heating system (0.01 – 0.020), in Table 6, shows the huge improvement in the performance of the system because the ventilation system gave a better distribution of heat.

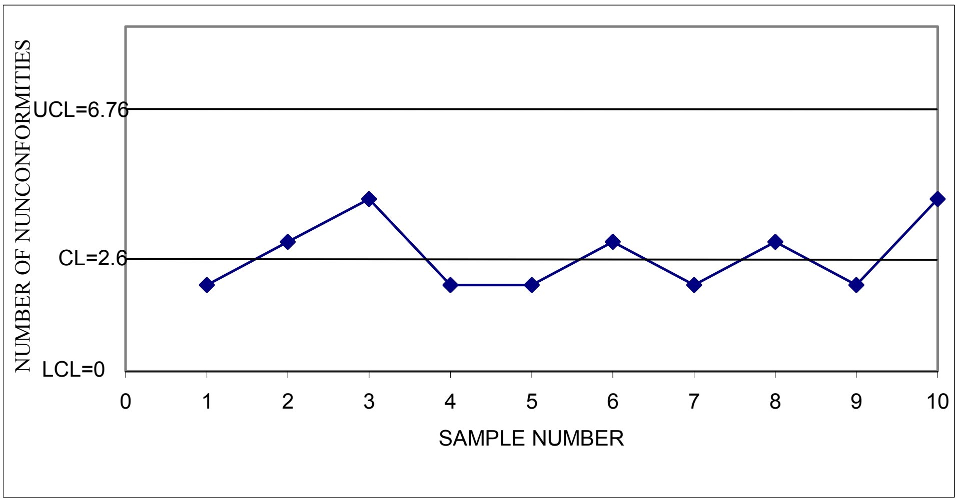


Figure 10: The control chart just at the beginning of the manufacturing process after modification. CL =2.6,UCL =6.76, and LCL =0.0

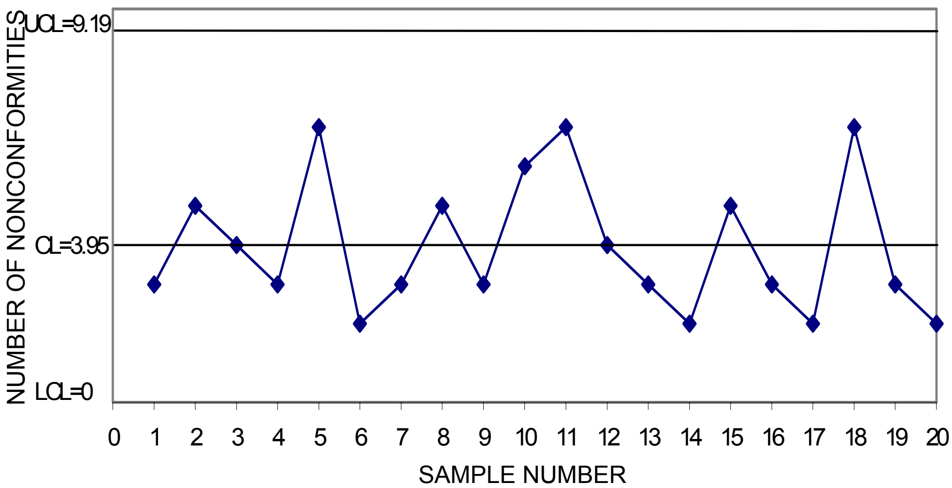


Figure 11: Control Chart for Plug-Assist process in normal operation conditions after modification. CL =3.95,UCL =9.19, and LCL=0

Table 6. The strength ratio for plastic sheet after pre-heating and after modification.

	1	2	3	4	5	6	7	8	9	10	Column Variation
1	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.01
2	0.99	1.00	0.99	1.00	1.00	0.99	0.99	1.00	0.99	0.99	0.01
3	0.99	0.98	1.00	0.99	1.00	1.00	0.99	0.99	1.00	1.00	0.02
4	0.98	0.99	1.00	0.99	0.99	0.99	0.98	1.00	1.00	0.99	0.02
5	1.00	0.99	0.98	0.99	0.98	1.00	0.99	0.99	0.99	0.98	0.02
6	1.00	1.00	1.00	0.99	1.00	0.99	1.00	1.00	1.00	0.99	0.01
7	0.99	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	1.00	0.01
8	0.98	0.99	1.00	1.00	0.98	0.99	1.00	0.99	0.99	1.00	0.02
9	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.99	1.00	0.98	0.02
10	0.99	0.99	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.99	0.01
Row Variation	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	

3. Conclusions

1. Problem solving approach combined with quality control charts and tensile testing serves as a good tool in solving real industrial production problems.
2. Temperature distribution within the sheet was the most effective variable in plug assist thermoforming process.
3. Forced convection of heat is better than free convection to get a better temperature distribution
4. The temperature 171 ^{o}C was the optimum temperature for plug - assist thermoforming.

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ضبط عملية التشكيل الحراري بمساعدة القابس وتحسين نوعيتها: مصنع كاسات البولسترين المستهلكة كحالة دراسية

عصام جلهم

أستاذ مشارك، قسم الهندسة الصناعية، كلية الهندسة والتكنولوجيا، الجامعة الأردنية

المستخلص: لقد كانت مشكلة البحث واضحة لإدارة مصنع الكاسات المستهلكة عند النظر إلى حاويات المخلفات الممتلئة بالمنتجات غير الصالحة. أربعة عشر نوعًا من المنتجات تم تصنيفها واستعملت طريقة حل المشكلة العلمية مجتمعة مع خرائط ضبط الجودة وفحص الشد للتغلب على المشكلة وأطلق عليها اسم الطريقة الحرارية الميكانيكية. وقد تبين أن المشكلة الرئيسية في ازدياد عدد المنتجات غير الصالحة يعود إلى توزيع الحرارة غير المتجانس أثناء التسخين ما قبل التصنيع. وبتعديل نظام التسخين من التوصيل الحر إلى التوصيل الإجباري بإضافة مراوح إلى نظام التسخين ساعد في التغلب على هذه المشكلة. وقد تم كذلك تحديد الحرارة 171 م لتكون الحرارة المثالية لإعطاء أفضل نتائج للإنتاجية.