Accuracy Verification of Glass Kilnforming Process after Improvement by DOE

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Abstract DOE (Design of Experiment) is a great tool for the reduction of the number of setting attempts to a minimum. Setting up complex processes can be time-consuming and lots of attempts are often made until a demanded result is achieved. That is why DOE is a good tool for the improvement of glass kilnforming processes. After the DOE is applied to the process to find the equation for the determination of parameters to set up the process. There should be considered the accuracy of this method. Results from the regression equation and real output are not the same. For preventing defects by misunderstanding accuracy of setting, the accuracy of the regression equation should be known. This paper deals with verification measurements after the application of DOE on the case study of setting up a glass kilnforming process.

Keywords DOE, kilnforming, verification

1. INTRODUCTION

Glass kilnforming manufacturing is a very complex process. The technology of kilnforming allows us to produce a high variety of different products, which is beneficial for art or custom production. When there is a demand for precise shapes and dimensions with repeatable results, too many custom products. Problems with re-setting up of process parameters occur. Glass properties are hard to predict and in combination with many process parameters, it can lead to lots of failures during often attempts to re-setup the kilnforming process. The solution for that can be the use of DOE (Design of Experiment) to describe the process more precisely. DOE was used for many complex systems before, for example [1], [2], and [3]. The use of DOE on a practice example of glass kilnforming was described in [4].

This paper aims to a description of the accuracy of results after the DOE application. For that, the same case as in [4] is used.

2. BACKGROUND

2.1 Glass kilnforming

Glass forming or glass kinlforming is an umbrella term for glass manufacturing techniques in the kiln. It contains techniques and methods as glass fusing, glass slumping, or kiln casting. Glass slumping is a method when a glass plate is shaped by gravitation and heat in the kiln. The shape is defined by mold under glass plate [5]. Glass fusing is when several glass parts are fused together. This could be combined with glass slumping when the glass plate changing its shape by mold and at the same time it is fused with different glass particles [6], and [7]. For both methods, temperature and time are crucial parameters of the forming process.

2.2 DOE (Design of Experiment)

DOE (Design of Experiment) is a statistical method for the description of complex systems. If a mathematical model cannot be applied DOE can be used for the understanding of the system and its parameters. An experiment is compound from a set of tries or runs, where the main goal is to find the best set of process parameters to achieve demanded results. The goal can be to maximize or minimize output or get to a specific value. The Design of Experiment is an experiment with a plan. The procedure of an experiment is well organized to get a minimum of runs and preserve the quality of the gained information. One of the goals of the Design of Experiment is to find factors that have a significant effect on the outcome of the process. There is also a need to find connections between factors and their effects. The second goal of the Design of Experiment is to find optimal values of factors to get the required level of response.

The Design of Experiment is good for processes without a mathematical or physically-technical model. The plan of the experiment is setting: number of runs, conditions of each run, and order of runs. For the reduction of systematic mistakes, all runs must be done in randomized order. For the reduction of mistakes by measurements can be doubled the measurement in one try. When it is impossible to do all runs in one day or with constant conditions of the experiment, all runs can be divided into blocs. Blocs are

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sequences of runs with constant conditions of the experiment, where random influences are reduced by the scheduling of runs.

Phases of Design of Experiment method are. Choice of factors with an influence on the outcome. Choice of lower and upper values for each factor. Crafting the plan of the experiment. The experiment itself – a measurement of all runs. Finding of significant factors. Generating of the regression model. Application of results into a real problem.

The outcome from the DOE is a level of significance of the factor's effect on system output. This is calculated by statistical hypothesis testing. The next outcome is the regression function. Regression function describes the system and its calculated from the correlation between factors, significance, and response [8], [9], and [3].

2.3 Minimizing the number of setup attempts on kilnforming process with DOE method

Glass manufacturing is a complex process with many variables. When there is a need to lower the number of setup attempts, DOE is a good tool [4]. As a result of DOE, an equation (1) describing the kilnforming process appears.

$$Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + \\ + b_5 \cdot x_1 \cdot x_2 + b_6 \cdot x_1 \cdot x_3 + b_7 \cdot x_1 \cdot x_4 \quad (1)$$

Where Y is measured outcome (response), $b0 – b7$ are coefficients of regression, and $x1 – x4$ are factors. From equation (1), there is easily possible to calculate demanded values for parameters to set up the process and get the requested result on the first attempt. When a description of the whole kilnforming process is needed, the DOE must be done for all types of forms and glass.

3. THEORETICAL BASIS

After the Design of Experiment for glass, kilnforming is made. Setup attempts are reduced to a minimum. Problems can occur when a request for more and more accurate results appears. There is a need to know the kilnforming process better. If the accuracy of the setting is not known, even that DOE was used defect could be made. That is why this paper is focused on the accuracy of the regression function. From this equation, we are able to determine a degree of accuracy whit which setting for parts can be made on a minimal number of attempts. This is more described in a case study below.

4. CASE STUDY

The case study was made on the same process and the same experiment as in [4]. It is a glass slumping process in a Czech company where custom glass parts are produced. Final products are glass-metal assemblies, that is why good accuracy of slumped parts is needed. The experiment was done on a circle dropout form, where before glass a separator was applied as can be seen in Figure 1.

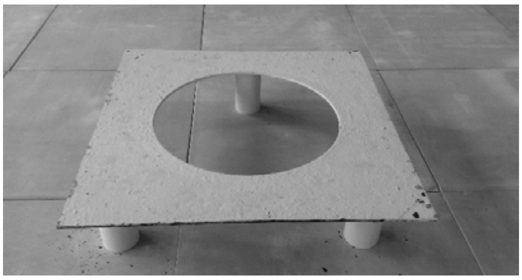

Figure. 1: Dropout form with separator.

To minimize setup attempts by DOE, several process parameters are defined as constants. Type of glass, kiln, shape of dropout form, position in the kiln, and orientation of tin layer. The experiment runs followed the temperature curve where forming temperature and forming time were parameters for change, as other parameters for change glass thickness and diameters of a hole in form were chosen. The outcome of the process is the depth of glass dropout.

Lower, upper and middle points for the experiment were set based on experiences from previous work with the kiln. See Table 1 below.

Table 1: Lower, upper and middle points for the experiment.

Factor	Lower point	Upper point	Middle point
Forming temperature	620 °C	720 °C	670 °C
Forming time	300 s	2700 s	1500 s
Glass thickness	4 mm	12 mm	8 mm
Diameter of hole in form	150 mm	500 mm	325 mm

Based on table 1, the experiment was created. Runs were generated by statistical software Minitab. For each run, a depth of dropout was measured and written into the software. After all runs were made, the software calculated a regression equation. The whole experiment with the outcome is summed in Table 2.

Table 2: Complete Design of Experiment plan with a response and regression values

Run order	Forming temperature (A) [°C]	Forming time (B) [s]	Glass thickness (C) [mm]	Diameter of hole in form (D) [mm]	Depth of dropout (Y) [mm]	Regression value [mm]
1	620	300	4	150	1.1	1.0064
2	720	2700	4	150	14.0	15.1564
3	720	2700	12	500	115.2	114.5522
4	620	300	12	500	20.8	19.5582
5	670	1500	8	325	28.1	33.1283
6	620	2700	12	150	1.4	1.4672
7	670	1500	8	325	30.3	33.1283
8	720	300	12	150	13.5	13.7052
9	720	300	4	500	70.0	69.1074
10	620	2700	4	500	30.0	30.4735
11	620	2700	12	150	1.1	1.4672
12	720	2700	4	150	15.8	15.1564
13	620	300	4	150	0.9	1.0064
14	620	300	12	500	18.4	19.5582
15	720	300	12	150	13.9	13.7052

16	620	2700	4	500	30.6	30.4734
17	670	1500	8	325	30.7	33.1283
18	720	2700	12	500	113.5	114.5522
19	670	1500	8	325	29.5	33.1283
20	720	300	4	500	68.3	69.1074

All parameters of the experiment are significant, a review of regression coefficients is summed in the Table 3.

Table 3: Values of regression coefficients

Coefficient	Value of coefficient [-]
b0	291
b1	-0.4811
b2	-0.04351
b3	-21.752
b4	-0.8819
b5	0.000074
b6	0.03403
b7	0.001532

When regression coefficients from Table 3 are put into an equation (1), a final regression equation (2) appears.

$$Y = 291 - 0.4811 \cdot A - 0.04351 \cdot B - 21.752 \cdot C - 0.8819 \cdot D + \\ + 0.000074 \cdot A \cdot B + 0.03403 \cdot A \cdot C + 0.001532 \cdot A \cdot D \tag{2}$$

In equation (2) Y is a depth of glass dropout in millimeters, A is forming temperature in [°C], B is forming time in seconds, C is the thickness of glass plate in millimeters, and D is the diameter of the hole in the form in millimeters.

5. RESULTS AND DISCUSSION

For setting accuracy, real measured output values and regression values must be compared. The difference between measured depths and depths calculated from the regression equation are residuals. Distribution and other plots of residual are seen in Figure 2.

From plots in Figure 1, there is seen that residual distribution is symmetric around the regression function, which means the equation describes the system well. A sit is seen biggest residual values are up to 2 millimeters, which is quite good for custom glass production. For verification several other runs were made, where different values of parameters were set. These runs are summed in Table 4

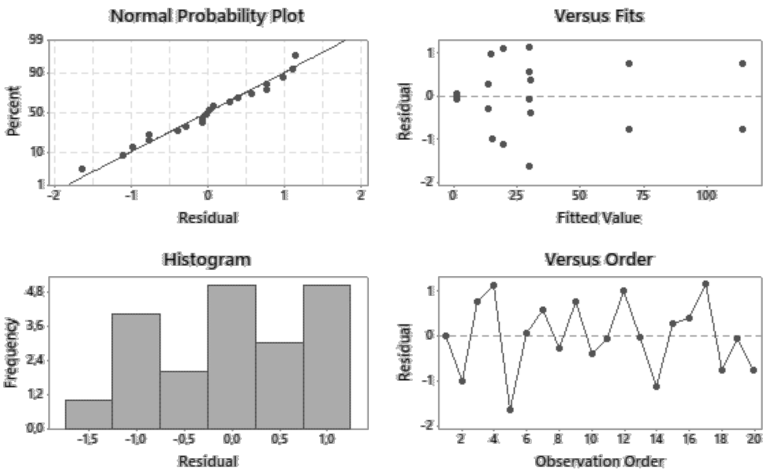

Figure 2: Residual plots for the depth of glass dropout

Table 4: Verification runs

Forming temperature (A) [°C]	Forming time (B) [s]	Glass thickness (C) [mm]	Diameter of hole in form (D) [mm]	Position of form in kiln	Depth of dropout (Y) [mm]	Regression value [mm]
695	450	8	225	Center	17.7	16.5293
625	1200	4	325	Center	16	16.2375
625	1500	8	225	Center	7.2	7.5665
625	1500	8	225	Side	7.5	7.5665

From Table 4 there is clear that the Regression function works well, and the difference between real depth and calculated values is 1.2 millimeters on maximal. These measurements verify the equation but also show us that accuracy of setting works too. After DOE verification measurement should be done to verify the functionality of the equation.

6. CONCLUSION

DOE (Design of Experiment) is a powerful tool, and it can be very useful for minimizing or optimizing process settings. As was seen before the use of DOE is beneficial even for Glass manufacturing processes as glass kilnforming. Sometimes just do DOE itself is not enough, several verification runs should be made to ensure the regression equation works well. During verification and experiment itself, we should focus also on the accuracy of process outcomes in comparison with demanded values. When request on very accurate production appears even DOE is sometimes not enough and first the accuracy of process setting should be considered.