MINIMIZING OF SETUP ATTEMPTS ON KILNFORMING PROCESS WITH DOE

Vladimír SOJKA[1], Petr LEPŠÍK[1], Petra HENDRYCHOVÁ[2]

[1]Department of Design of Machine Elements and Mechanisms, Faculty of Mechanical Engineering, Technical University of Liberec, Liberec, Czech Republic
[2]Department of Research and Development, Preciosa – Lighting, Kamenický Šenov, Czech Republic

Abstract
Number of setup attempts on kilnforming process can be very high. Because each next attempt to setting up the process correctly is expensive, there is need to face off to this problem. Solution for it could be the Design of Experiment (DOE) method for describing the process in kiln and thereafter predicting the process results. This paper is focusing on use of DOE for glass slumping technology. After DOE is used number of setup attempts is reduced to minimum. That spare time and money on kilnforming technology. Application of DOE on glass kilnforming process was proven by case study on glass slumping technology in Preciosa – Lighting company also included in this paper.

Key words: *Design of Experiment; kilnforming; glass slumping; process setup optimization.*

INTRODUCTION
Kilnforming processes like glass fusing or glass slumping are good for making variety of different shapes from glass plates. These technologies are often used for art production, where is no need for high productivity. Setting up of kilnforming process is often only guessing from previous experiences with processes. That can lead to many wrong attempts before right dimension of product are done. In cases where kilnforming technologies are used in manufacturing there is need to have a process with a less waste and higher productivity. A cost of setup for production of new parts can be very high. This requires to do setups of processes better. Practically there are only two main parameters for setting up: forming temperature and forming time.
The biggest problem comes when kilnforming is used in a custom production. In a custom production of unique parts, there is need to often re-setup the kiln. If exact setup of a process is not known, it can take numerous of attempts to get a good result. One attempt can sometimes take up to a whole day, and when result is bad, the material and time used for this attempt are wasted and the final price is higher and higher with every try. A ratio between the number of setups and the number of products in custom production is close to 1:1. That all can lead to situations when more time is spent on wrong tries and kiln setups, than manufacturing itself. Either in a serial or custom production, there is need to reduce the number of setup tries to a minimum.
This calls for method determining how to setup the glass kilnforming process as few attempts as possible – in best case on the first attempt. That leads to a statistical method, the Design of Experiment (DOE), which is a great tool for describing of very complex systems. Positive results with DOE method were proved by many authors before. For example, design optimization of composite parts (*Lepšík & Kulhavý, 2017*), heat transfer optimization *(Das & Dwivedi, 2013)*, and others (*Weissman & Anderson, 2015*).
The aim of this paper is to use the DOE method for predictable setup of glass kilnforming process, including a case study from workshop producing unique kilnformed parts to chandeliers in the Preciosa – Lighting company.

MATERIALS AND METHODS
Glass kilnforming
Glass forming is an umbrella term for many techniques of glass manufacturing in a kiln. Most significant techniques of kilnforming are glass fusing and glass slumping. Glass fusing is a method when several parts (plates, fragments or shards) of glass are fused together by high temperatures in a kiln. Results depend on forming time and temperature, it can look only like joining of parts together or complete fusion of parts into one object (*Sadakova, 2015*; *Seward, 2003*). The glass slumping is instead, a method when a plate of glass is changing its shape by heat and gravitation. The plate of glass

is heated in kiln and it is becoming plastic. This plastic glass is falling down and copying the shape of the mold or form (*Stokes, 1997*). It can be step after glass fusing or it is possible to do both methods in one step. The plate of glass with smaller parts of glass are fused together and formed via mold in one step. Different time and temperature in kiln causes different results. On dropout forms there can be different depth of dropout of glass during forming temperature.

Design of Experiment (DOE)
The Design of Experiment is a statistical tool for describing of very complex systems, where a mathematical model cannot be applied. An experiment generally is a set of tries (runs) where a goal is to find the best work procedure or to gain a better knowledge about properties of a product or process.
The result of the Design of Experiment is significancy level of factor's effect on system outcome which are calculated by a statistical hypothesis testing. The next result is a regression function, which is calculated from correlation between factors, their significancy and the demanded response (*Anderson & Whitcomb, 2015; Condra, 2001; Weissman & Anderson, 2015*).

Use of DOE for setup of Kilnforming process
A glass manufacturing itself is a complex process with many variables (*Seward, 2003*), that is why the Design of Experiment is good for use in kilnforming processes. This paper is focusing on glass slumping. To setup a process properly it is important to find how to set the parameters of the process to get the result which is needed. In case of glass slumping, it could be a depth of dropout of glass or an angle of bending. At first it is needed to find the intended result, then factors, which have an effect on the process results, are chosen. Here it is simple because factors are parameters of process. The kiln and the material must be the same for each experiment. The factors are: the forming temperature, the forming time, the thickness of the glass plate and the dimension of the mold (for example the diameter of a hole in the mold). After factors are chosen, it is needed to define their upper and lower values. The next step is to make the experiment plan. In basic, a simple plan is enough. For four factors, a solution can be a half plan with one repeating and with middle points.
After a real experiment, which means measurement of each run results, is done, a software calculates which of factors are significant and which are not. The software also calculates a regression model of the process. The main outcome of the Design of Experiment is a regression equation (1) and regression coefficients describing kilnforming process.

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

In the regression equation Y is measured outcome (response), $b_0 - b_7$ are coefficients of regression (-), and $x_1 - x_4$ are factors.
From this equation it is possible to calculate parameters for a setup of process to get required results with necessary conditions of final product.
For example, to make a particular part, a needed material, its thickness and shape of mold is usually in description of part's parameters. Kiln is defined by workshop. Only parameters which is possible to change are forming temperature and forming time. These two are easy to calculate from the equation (1).

Case study
For the case study experiment, a glass slumping technology in the Preciosa – Lighting company was chosen. The Preciosa – Lighting is company in Czech Republic, which makes luxury chandeliers in custom type of production. The goal of experiment was to find values of parameters for setup of a glass slumping process to get a requested depth of dropout of the glass plate. An equation for calculation of values used for slumping of unique parts in future on first attempt. Parameters of glass slumping process are: the forming temperature, forming time, thickness of the glass plate, diameter of a hole in the form. Factors which have an effect on the outcome (a depth of dropout of a glass plate) are: the glass type and its manufacturer, shape of dropout form, position of form in kiln, orientation of tin layer on glass, temperature curve, thickness of glass plate, dimension of dropout hole in form, forming temperature and forming time. Conditions of the experiment were set in a way that the glass manufacturer

was the Pilkington company, type of glass was optifloat, shape of dropout form was circle, orientation of tin layer was upside, position was in the center of kiln, temperature curve is shown in Tab. 1.

Tab. 1 Temperature curve for experiment

Step	Temperature	Time
1.	555 °C	70 min
2.	Forming temperature	30 min
3.	Forming temperature	Forming time
4.	555 °C	50 min
5.	500 °C	120 min
6.	400 °C	120 min

The next step in experiment was to find upper and lower values for experiment factors. These values are shown in a Tab. 2.

Tab. 2 Temperature curve for 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

Values of factors were written into a statistic software and a plan of experiment was automatically generated. The design of experiment used was a half plan with repeating. The next was the experiment itself. Dropout form was a metal plate with round hole. Before measurement, a separator was applied on surface of the form. The separator was Bullseye Shelf Primer which is a mixture with kaolin as a main ingredient. Separator was applied in form of water solution. When separator was dry, Glass plate was putted on a form, and main kilnforming process could began.
Each run taken whole workday and at the end, results was measured. Depth of dropout of glass from each run was collected. After all experiment runs were done, results were written into the software (Minitab®). The software calculated significancy of factors and a regression function. Deformation of the glass after one of experiment runs is shown in Fig. 1.

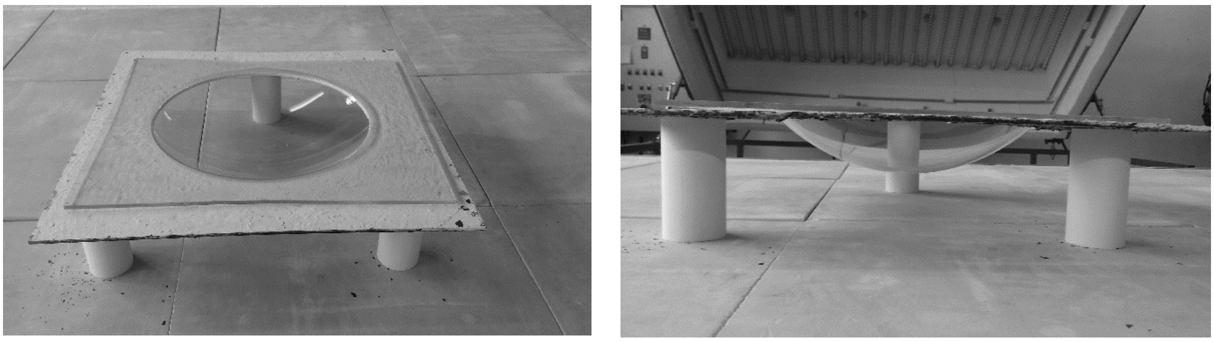

Fig. 1 Deformation of glass plate after experiment

RESULTS AND DISCUSSION

After all measurements, the software calculated a regression function of the kilnforming process. The factor's effects are shown in Fig. 2. As it is seen, every chosen factor had a significant effect on the process outcome which is the depth of the glass dropout. That means that every effect which was included in the DOE has a significant influence on kilnforming process. Factor with biggest effect on response is factor *D*, which is the diameter of dropout form, followed by forming time (factor *A*). Main effects of factors are shown in Fig. 3. Plots shows that all factors are rising types, that means that when higher value of depth of glass dropout is needed, all factor must be set to its maximum value. From the report also occurs that chosen factors are describing the slumping process with 99.95% of accuracy.

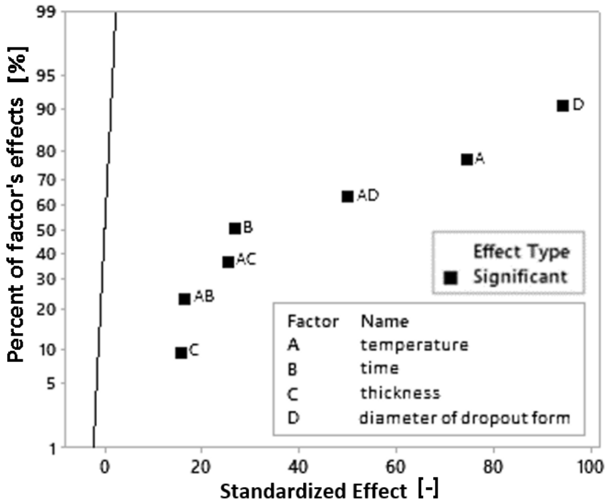

Fig. 2 Normal plot of the standardized effects

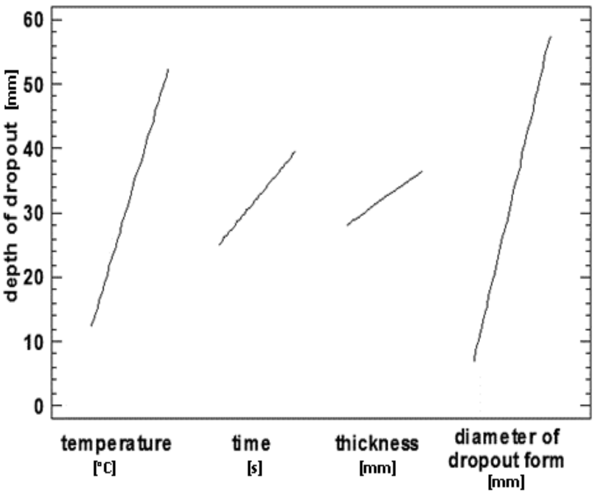

Fig. 3 Main effects plot for depth of dropout

The regression function is visualized by response surface plot shown in Fig. 4.

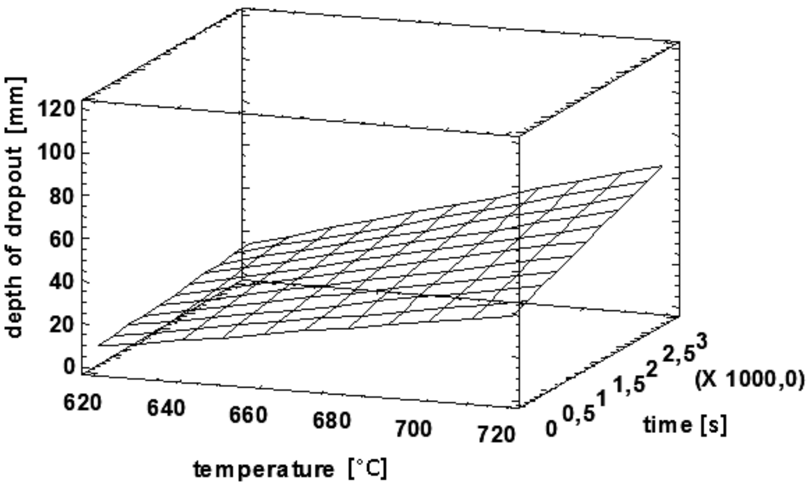

Fig. 4 Estimated response surface (thickness = 8, diameter of dropout form = 325)

The main result was a regression equation which is describing a regression function (2),

$$Y = b_0 + b_1 \cdot A + b_2 \cdot B + b_3 \cdot C + b_4 \cdot D + b_5 \cdot A \cdot B + b_6 \cdot A \cdot C + b_7 \cdot A \cdot D \tag{2}$$

where Y is depth of glass dropout (mm), $b_0 - b_7$ are regression coefficients (-), A is the forming temperature (°C), B is the forming time (s), C is the thickness of glass plate (mm) and D is the diameter of the hole in the form (mm).

Regression coefficients are: b_0 = 291, b_1 = -0.4811, b_2 = -0.04351, b_3 = -21.752, b_4 = -0.8819, b_5 = 0.000074, b_6 = 0.03403, and b_7 = 0.001532. When regression coefficients are put into equation (2), final regression equation (3) appears.

$$Y = 291 - 0.4811 \cdot A - 0.04351 \cdot B - 21.752 \cdot C - 0.8819 \cdot D + 0.000074 \cdot A \cdot B + \\ + 0.03403 \cdot A \cdot C + 0.001532 \cdot A \cdot D \qquad (3)$$

From equation (3), it is possible to calculate the setup for the process. Because the shape and materials are given by specification of the product, only parameters which are allowed to change are forming temperature and forming time. When one of these is set, the other one can be easily calculated. That can be used for setting up the process of manufacturing of a new product by kilnforming techniques. Residuals – a difference between real measured depths of a glass dropout and depths calculated form the regression function, was good. It is because of distribution of residuals is symmetric around the regression function. The biggest difference between the regression function and the real depth is approximately 2 millimeters, which is a very good result in a glass industry focused on art manufacturing.

That all means, that it is possible to get really precise results from kilnforming processes on first setup of a process, when the DOE was used before.
For verification of results another measurements were done. In those verifying measurements were values of forming temperature and forming time changed in a way to not be same as upper, lower, or middle value from experiment. In last try the form was not set into the center of kiln to know if position in kiln is also significant or not.

Results from verifying measurements have shown that difference between calculated and real depth is on maximal value 1.2 millimeters. That proves that the experiment was done the right way and the results are usable for next production. These measurements were done only for practical verification, there is no need for this verification every time when DOE is used.

Equation (3) is used for setting up of glass slumping process with maximal dimension differences of 2 millimeters. This results are better than before the DOE was used. Results are better even in comparison with results for setting up the kiln from other authors, for example (*Sadakova & Safin, 2015*), or in comparison with recommendations from manifold guidebooks.

Beside of original state, the number of setup attempt could be reduced to minimum. Use of DOE for kinforming processes optimization is very practical. For more complex shapes there is possibility that final results will have bigger dimension differences than simple shape parts. With very high probability the DOE is good for optimization of all glass manufacturing processes.

CONCLUSIONS

It was proved that the Design of Experiment (DOE) is a great tool for describing of a kilnforming process. When the DOE is done, results can be used for predicting of a process setting, to get a correctly manufactured part on the first try. For every kiln or specific technique particular DOE must be done, because every machine and technique can have different conditions and the final regression equation have different regression coefficients. The number of setup attempts was minimized to few tries in many cases to setting up on first try. With more complex shapes there can be bigger differences between calculated dimension and final outcome.
To describe a whole kilnforming process there is needed to do the DOE for all categories of forms and for many glass types.

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Corresponding author:
Ing. Vladimír Sojka., Department of Design of Machine Elements and Mechanisms, Faculty of Mechanical Engineering, Technical University of Liberec, Studentská 1402/2, Liberec, 461 17, Czech Republic, phone: +420 485353326, e-mail: vladimir.sojka@tul.cz