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Setting of the Optimal Parameters of Melted Glass

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Abstract:

This research is focused on the problems of setting the optimal parameters of melted glass in real conditions. To achieve the best quality of glass products, the striae (inhomogeneity) value must be the smallest or ideally minimal. In this paper, the value of striae is minimized from aspect of parameters of melting process $p_1, ..., p_n$ *by constructing a regression model in the form* $y = f(p_1, ..., p_n)$*, where f is a polynomial of n variables. The description of the striae using a regression functions in glass industries is an original idea of the authors. This unique method has been developed in cooperation with developers in the development of a new innovative technology of production of glass. It is apparent that the optimal setting of parameters of melting process* $p_1, ..., p_n$ *has both economic and practical importance (the parameters* $p_1, ..., p_n$ *describe performance of electro – heating, the value of the actual off take of glass melt, the temperature of the front and rear zone of the gutter, the temperature at the bottom of the furnace etc.). Chemical striae have often negative effect on the glass properties, and the elimination of striae has been a key problem in glass science and technology. On the basis of the experiments and obtained results, it is possible to propose a method for minimizing the value of striae. Moreover, other important knowledge could be used for modernization and improvement of the process of industrial production of glass in practical application in military technologies.*

Keywords:

Striae, glass, glass melting, regression, optimal parameters

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Nomenclature:

A	constants
b	upper border of parameter *p*
f	polynomial of *n* variables
g	function
m, *l*	integer
p	parameters of melting process
p	vector
P	closed set
R^n	*n* dimensional space
y	value of regression function

1. Introduction

Nowadays the system requirements of setting the optimal parameters of melted glass are set up and evaluated in various manners. We have plenty of excellent options available taking about an item technical state. We can also consider other states by numerous diagnostic options [1]. One of them can be setting of the optimal parameters, such as the melting temperature of glass, the temperature of a dispenser homogenizer in several sites, the occurrence of defects, the electric boosting in melting aggregates and its ratio to the gas heating, the flow of glass in the dispenser etc., in real conditions.

Glass as an essential material can be found in many diverse areas of military technology. Infrared domes, lenses, reconnaissance windows, and windows of military vehicles must be transparent to radiation of certain wavelengths and must also resist damage from airborne debris and penetration from projectiles. They should retain a degree of transparency after a hit and should withstand multiple hits.

Glass windows can be produced in large sizes by the relatively inexpensive float glass process. Most windows consist of multiple layers of glass adhesively bonded to one another and backed by a polycarbonate layer. Care is taken to avoid flaws on the layer surfaces. Glasses can be toughened with thermal or chemical treatments that induce compressive stresses on their surfaces [2, 3].

Many viscous liquids contain a great number of bubbles, seeds, stress birefringence, chemical and optical inhomogeneity – striae, a consequence of their production process, undesired chemical reactions, ageing, intensive manipulation with them etc. [4]. The homogeneity of glasses is important to their physical properties, and hence, homogenisation of the melt is a crucial step in glass production [5]. Inhomogeneity is a complex term since it is influenced and determined by several factors. The melt produced in the initial stages of the batch melting is chemically inhomogeneous because of insufficient mixing of the raw materials and of the batch during melting and the reactions between the melted glass and the surrounding refractory materials. Therefore, a processing step follows the fining to homogenize the chemical composition of the glass melt. This homogenization process is of the particular importance for microstructuring, as its success depends on the local chemical composition of the glass piece [6].

Some types of striae are of physical origin, i.e. the difference is in cooling rate, while others are of chemical origin, i.e. the difference is in the chemical composition and/or redox state. As a stria is a three dimensional amorphous domain within the glass matrix, the striae can be described by different parameters, such as its volume (size), geometry and compositional difference. Due to the strong impact of inhomogeneities on glass performance, glass scientists and technologist have made considerable efforts in finding ways to characterize, understand and remove inhomogeneities from glass products [7, 8].

Striae are localized string regions in glass with sufficient difference in index of refraction to be detectable by shadowgraph (see Fig. 1) [9]. The shadowgraph is the simplest form of optical system suitable for observing a flow exhibiting variations of the fluid density. In principle, the system does not need any optical component except a light source and a recording plane onto which to project the shadow of the varying density field. A shadow effect is generated because a light ray is refractively deflected so that the position on the recording plane where the undeflected ray would arrive now remains dark. At the same time the position where the deflected ray arrives appears brighter than the undisturbed environment. A visible pattern of variations of the illumination (contrast) is thereby produced in the recording plane. From an analysis of the optics of the shadow effect, it follows that the visible signal depends on the second derivative of the refractive index of the fluid. Therefore, the shadowgraph as an optical diagnostic technique is sensitive to changes of the second derivative of the fluid density [10]. Striae grades are categorized on the basis of predetermined patterns [9].

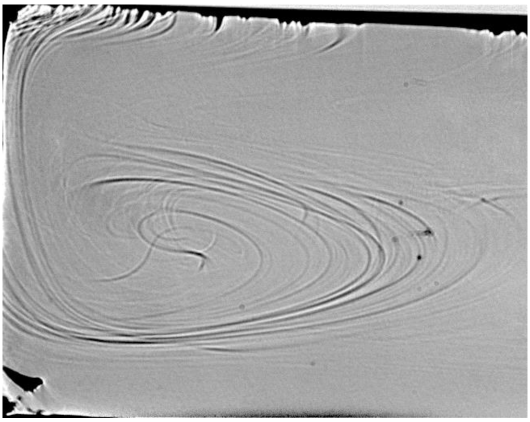

Fig. 1 Shadowgraph of chemical inhomogeneity [11]

The research has been closely related with the previous work [12] and with effort to find the form of the regression function $y = f(p_1, ..., p_n)$. The function f describes the dependence of value of the striae on the given parameters of melting process $p_1, \ldots, p_n$. This dependence can be used for subsequent determination of such parameter values $p_1, ..., p_n$ at which the value of the striae is minimal. Moreover, the given parameters $p_1, ..., p_n$ can be classified according to their influence on the creation of the striae. The problem of their classification is very simple from the mathematical aspect, to change each parameter and fix other parameters. Since this is not possible in practice, it was decided to create only a regression model, as well as to determine such parameter values (optimal setting of parameters), for which the regression function is minimal. To some extent, the shape of the regression function can be used for derivation of the influence of parameters on the creation of the striae.

2. Results and Discussion

The optimal point $\boldsymbol{p} = (p_1, ..., p_n)$ is determined from the closed set P, which is a subset of R_n, including all points of measurements in which value of regression function f is minimal.

It has been looked for a regression function $y = f(p_1, ..., p_n)$ in the form (1).

$$f = \sum_{i=1}^{n} A_i p_i + \sum_{i_1=1, i_2=1}^{n} A_{i_1,i_2} p_{i_1} p_{i_2} + \ldots + \sum_{i_1=1, i_2=1, .. i_m=1}^{n} A_{i_1,i_2,\ldots,i_m} p_{i_1} p_{i_2} \cdots p_{i_m} + A, \quad (1)$$

where A_i, $A_{i,j}$, …, A are unknown constants which can be determined by minimization of the function g in (2).

$$g(A_i, A_{i_j}, .. A) = \sum_{i=1}^{l} [y_i - f(p_{l_i}, .. p_{n_i}, A_i, A_{i,j}, .. A)]^2 \quad (2)$$

For all measurements $y_i, p_{1_i}, \ldots, p_n$, where $i = 1, \ldots, l(y_i, p_{1_i}, \ldots, p_n)$.

Then, points of minimum of (2) can be obtained as the solution of the following equations $\frac{\partial g}{\partial A_i} = 0$, $\frac{\partial g}{\partial A_{i,j}} = 0$, …, $\frac{\partial g}{\partial A} = 0$. Following this, we obtain equations (3).

$$\sum_{i=1}^{l} \left[y_i - f(p_{1i}, ..., p_{ni}, A_i, A_{i,j}, ..., A) \right] \frac{\partial f}{\partial A_s} = 0 \quad (3)$$

Coefficients A_i, $A_{i,j}$, …, A of the polynomial can be obtained as a solution of linear system of equations (3). Optimal value of parameters p_1, ..., p_n can be determined as point $\boldsymbol{p} = (p_1, ..., p_n)$ of the minimum of the function f on a closed set P, which is a cuboid in R^n, including all points of measurements $(p_{1i}, \ldots, p_{ni})$, where $i = 1, \ldots, l$. These points can be interior stationary points of set P or interior stationary points of the boundaries of set P or and the peaks of the cuboid P.

2.1. Example for Real Condition

In this part of the paper, the example for $n = 3$, $l = 10$, $m = 2$ has been demonstrated. The measurements are:

$p_1 = [0.1, 0.2, 0.3, 0.4, 0.4, 0.2, 0.3, 0.4, 0.1, 0.3]$,

$p_2 = [0.1, 0.1, 0.3, 0.4, 0.2, 0.1, 0.3, 0.4, 0.3, 0.2]$,

$p_3 = [0.2, 0.2, 0.2, 0.2, 0.3, 0.3, 0.3, 0.1, 0.2, 0.3]$,

$y = [1, 2, 3, 2, 3, 2, 3, 6, 2, 3]$.

The data of parameters used in the demonstration example have been chosen as random values from the interval of $\langle 0, 1 \rangle$. For $n = 3$, $m = 2$, regression function (1) has the form:

$$f = A_1 p_1 + A_2 p_3 + A_3 p_3 + A_{12} p_1 p_2 + A_{13} p_1 p_3 + A_{23} p_2 p_3 + A_{111} p_1^2 + A_{222} p_2^2 + A_{333} p_3^2 + A \quad . \quad (4)$$

When the coefficient of polynomial f (4) was calculated by Matlab, the f was defined as follows:

$$f = 35 p_1 + 15 p_2 - 63.333 p_3 - 33.333 p_1 p_2 - 133.333 p_1 p_3 + 66.6667 p_2 p_3 + \\ + 16 p_1^2 - 50 p_2^2 + 166.6667 p_3^2 + 4 \quad . \quad (5)$$

The system of equations (3), where p_1, p_2, p_3 are variables is following

$$\frac{\partial f}{\partial p_1} = A_1 + A_{12}p_2 + A_{13}p_3 + 2A_{111}p_1 = 0$$
$$\frac{\partial f}{\partial p_2} = A_2 + A_{12}p_1 + A_{23}p_3 + 2A_{222}p_2 = 0 \qquad (6)$$
$$\frac{\partial f}{\partial p_3} = A_3 + A_{13}p_1 + A_{23}p_2 + 2A_{333}p_3 = 0 .$$

It can be written as (7) or (8).

$$\begin{pmatrix} 2A_{111} & A_{12} & A_{13} \\ A_{12} & 2A_{222} & A_{23} \\ A_{13} & A_{23} & 2A_{333} \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} = \begin{pmatrix} -A_1 \\ -A_2 \\ -A_3 \end{pmatrix} \qquad (7)$$

$$B \cdot p = A \qquad (8)$$

If the solutions $\boldsymbol{p} = \boldsymbol{B}^{-1} \cdot \boldsymbol{A}$ of the matrix equation (8) belong to the set P, it is necessary to compute $f(\boldsymbol{p})$. It is obtained from the equations (9) and (10).

$$y'_{p_2}(p_2, p_3) = A_2 + A_{12}a_1 + A_{23}p_3 + 2A_{222}p_2 = 0$$
$$y'_{p_3}(p_2, p_3) = A_3 + A_{13}a_1 + A_{23}p_2 + 2A_{333}p_3 = 0 \qquad (9)$$

$$\begin{pmatrix} 2A_{222} & A_{23} \\ A_{23} & 2A_{333} \end{pmatrix} \begin{pmatrix} p_2 \\ p_3 \end{pmatrix} = \begin{pmatrix} -A_2 & -A_{12}a_1 \\ -A_3 & -2A_{13}a_1 \end{pmatrix} \qquad (10)$$

This has been achieved by putting $y_{b_1}(p_2, p_3) = f(b_1, p_2, p_3)$ where b_1 is the upper border of parameter p_1. Now we solve the same equation one more time (11).

$$\begin{pmatrix} 2A_{222} & A_{23} \\ A_{23} & 2A_{333} \end{pmatrix} \begin{pmatrix} p_2 \\ p_3 \end{pmatrix} = \begin{pmatrix} -A_2 & -A_{12}b_1 \\ -A_3 & -2A_{13}b_1 \end{pmatrix} \qquad (11)$$

If the solutions $\boldsymbol{p} = (p_2, p_3)$ of the matrix equation (11) belong to the set P, we calculate $y_{b1}(\boldsymbol{p})$. Similarly we find interior stationary points also at other boundaries of set P. Now we select all points $\boldsymbol{p} = (p_1, p_2, p_3)$ for which the value of $f(\boldsymbol{p})$ is minimal. The corresponding parameters p_1, p_2, p_3 are the optimal setting of parameters.

It is well know that the minimum value of f is 1, optimal setting of parameters is $p_1 = 0.1$, $p_2 = 0.4$, $p_3 = 0.1$. This program has been also used for plotting graphs in Fig. 2.

The graphs show cross-sections of our regression model – the plots demonstrate, how the striae depends on parameters p_1, p_2, p_3 in special cases (the model is four-dimensional, thus we have chosen untracked parameters as constants equal to average values of data, $p_1 = 0.27$, $p_2 = 0.24$, $p_3 = 0.23$).

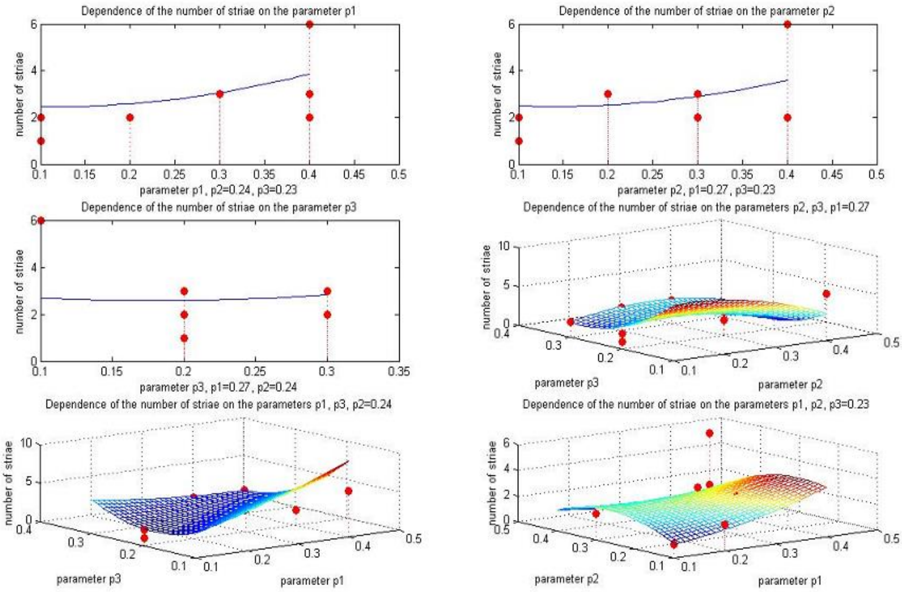

Fig. 2 Dependence of the striae on given parameter or parameters

3. Conclusion

This paper focuses on minimization of the parameters of the melting process, which allows us to reach a chemical homogeneity in the glass production. Chemical inhomogeneities lead to occurrence of internal stresses during solidification. These are manifested by striae in the glass product. Extensive approach to solving the problem is determined by the technological process of the production of glass. In this case, the composition and also the thermal expansion of the chemical inhomogeneity differ from the surrounding glass. This difference in thermal expansion leads to higher local tensions during the cooling, which can cause cracking of the material. In this way it can be recognized the true size of the internal stresses and chemical inhomogeneities and their harmfulness.

It is known that parameters of temperatures whose absolute values of coefficients of the regression function are large have a major influence on the creation of the striae (inhomogeneity). On the other hand, parameters with small absolute values have a minor influence on the creation of striae. The shape of the regression function in our example shows that parameter p_3 has more significant influence on the creation of the striae than the remaining parameters p_1, p_2 (the absolute value of p_3 is larger than the absolute values of p_1 and p_2). More precise results of our method can be obtained by an adjustment of the regression function. This can be accomplished by increasing the integer values *m* (number of coefficients in the model) and *l* (number of measurements).

Optimal parameters of the melting process have been found out which should minimize the occurrence of defects (such as the striae). Obtained knowledge should be confronted with industrial glass production. So, the theoretical results can make the industrial process more effective, which is important for practical application of military technologies.

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