UDC 621.74
DOI: 10.15587/2706-5448.2023.288152

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ADAPTIVE METHOD OF ESTIMATING THE DYNAMIC CHARACTERISTICS OF THE BOTTOM PRESSING PROCESS WHEN MAKING DISPOSABLE CASTING MOLDS

The object of research in the paper is the process of bottom pressing in the manufacture of disposable sand molds.

The existing problem is that in practical conditions it is almost impossible to determine the forces acting in the molding mixture in the process of lower pressing. This leads to the fact that in the real process, with the selected pressing modes, the requirements regarding the density of the mixture in the furnace during the manufacture of the half-form may not be met.

To solve this problem, it is proposed to build a method that does not require measurement of effort in the system, but allows to obtain dynamic characteristics of the pressing process based on an adaptive approach to determining the technological effort.

It is hypothesized that it is possible to evaluate the dynamic characteristics of the compaction process in an industrial process without measuring the forces acting in the system during lower pressing. This can be done regardless of which drive is used – pneumatic or hydraulic.

It is demonstrated how the kinematic characteristics of the process can be determined based on the use of D-optimal plans on a segment.

The proposed method includes 12 points that involve the implementation of experimental and industrial studies directly on the operating equipment based on the use of D-optimal plans and further adaptation of the process of finding the force acting on the molding mixture. The adaptation is based on a preliminary assessment of the kinematic characteristics of the pressing process and involves the calculation of the technological effort that ensures the achievement of the given time of the coordinate of the lower plane of the molding mixture obtained from the equation of kinetics.

The results of the implementation of the method make it possible to identify different stages of the pressing process and the distribution of the density of the mixture along the height of the column of the molding mixture.

The practical implementation of the method can help in setting up the control system of the lower pressing process depending on the equipment parameters. Therefore, the presented research will be useful for machine-building enterprises that have foundries in their structure, where shaped castings are made in one-time sand molds.

Keywords: *sand mold, press molding machines, compaction of molding mixture, bottom pressing, foundry equipment, D-optimal plans.*

Received date: 03.08.2023
Accepted date: 22.09.2023
Published date: 26.09.2023

How to cite
Lysenkov, V., Demin, D. (2023). Adaptive method of estimating the dynamic characteristics of the bottom pressing process when making disposable casting molds. Technology Audit and Production Reserves, 5 (1 (73)), 6–11. doi: https://doi.org/10.15587/2706-5448.2023.288152

1. Introduction

The quality of production of one-time sand molds largely determines the quality of the finished castings, along with the influence of the design of the gating system [1] and the quality of molding and core mixtures [2, 3]. Modern approaches to design and technological solutions are based on the use of CAD/CAM/CAE tools. However, in order to correctly use these tools, a qualitative analysis of the casting geometry is necessary for its complexity [4–6] and the possibility of finding the simplest and most economical technological solutions. This requires not only qualitative, but also quantitative analysis [7] of the complexity of the design embedded in the casting equipment. This is especially important in the case of machine molding.

It is important to note that, despite the promising expectations from 3D simulation modeling in relation to the prevention of casting defects [8], not taking into account the technological conditions of compaction will not live up to expectations. This is due to the fact that under- or over-compaction of the mixture will lead either to a violation of the geometry of the castings, in the first case, or to the formation of gas porosity, in the second case. Therefore, it is important to find rational compaction modes, which is difficult to do in the absence of automation systems with control of all necessary process parameters, especially if compaction is carried out on shaking-press machines. Even making design changes based on optimizing shaking processes with further pressing [9, 10] will not be effective.

A good solution would be to rationalize the compression compaction process, which is efficient in terms of productivity and the ability to use in automatic lines, but the restrictions on the height of the flask for such processes are an obstacle if the castings are oversized. However, even in the case of such restrictions, it is not always possible to carry out the process with the specified quality indicators, since it is practically difficult to estimate the forces acting on the mixture during the compaction process, taking into account the complex geometry of the equipment. This leads to some uncertainty regarding process control, regardless of whether the actuator is pneumatic or hydraulic.

The dynamic characteristics of the pressing process determine compaction control processes and are taken into account in automated solutions in ready-made molding complexes [11, 12] produced by global developers of foundry equipment. The corresponding solutions are, as a rule, a commercial secret and are not declared by the developers. Therefore, each enterprise equipped with compression molding equipment must find its own rational solutions. Such decisions must be based on knowledge of the dynamic characteristics of the process. However, it is quite difficult to describe such processes in production conditions, since this requires controlling a number of factors that are not subject to actual measurements.

All this allows to talk about the feasibility of research devoted to methods for indirectly assessing the parameters of the pressing process, on the basis of which it would be possible to identify dynamic characteristics and choose rational or optimal control of the pressing compaction process.

The object of study is the process of bottom pressing in the manufacture of one-time sand molds.

The aim of study is to develop a method that allows indirect assessment of the dynamic characteristics of the mixture compaction process in flasks.

2. Materials and Methods

The research hypothesis was that the dynamic characteristics of the compaction process can be assessed directly in the industrial process, without measuring the forces acting in the system during bottom pressing. This can be done regardless of whether the drive is pneumatic or hydraulic.

A diagram of the research object was used based on the well-known diagram of the bottom pressing process [13], but in a simplified representation for a pneumatic drive (Fig. 1).

To determine the kinematic characteristics of the process, the method of constructing D-optimal plans on a segment was used. This approach was justified by the fact that with a small height of the filling frame, the trajectory of the work table, the stroke of which is equal to the height of the filling frame, can be represented by a second-degree equation. To do this, taking into account the D-optimality of the experimental plan on the segment, it is enough to determine the values of the current coordinate for three moments of time – the initial, the end of the full movement of the table, the return of the table to its original position, that is, at $t=t_0$ ($x=x_{\min}=0$), $t=t_1$ ($x=x_{\max}=h$), $t=t_2$ ($x=2x_{\max}=2h$).

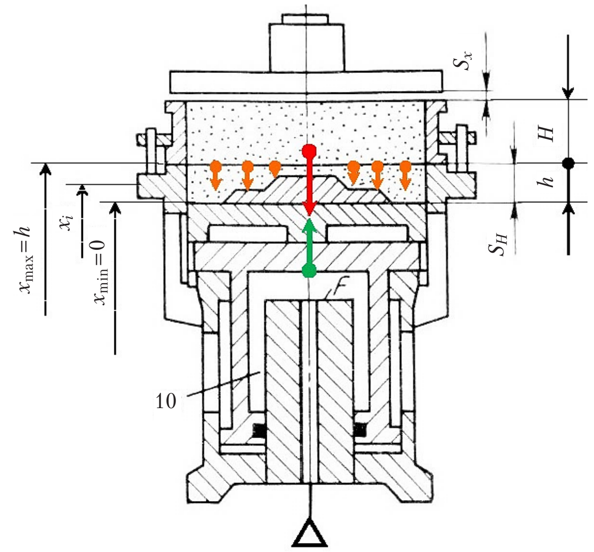

Fig. 1. Diagram of the bottom pressing process: x – current coordinate along the height of the filling frame; H – height of the flask; $h=S_H$ – height of the filling frame; S_x – gap between the press plate and the top of the flask; F – diameter of the pressing plunger; ↑ – lifting force table with modeling equipment and molding sand created by pressure from the line; ↓ – gravity force created by the weight of all lifted parts; ↓ – resistance forces from the compacted mixture (shown conditionally), the friction force in the seals of the press cylinder is not shown

For simplicity, it was assumed that a stroke equal to the gap S_x had already been completed. From the point of view of developing a method for determining characteristics, such a simplification does not affect the result, and the value of S_x can be taken into account in the components of the forces acting in the system.

Dynamic characteristics were determined based on the basic equation of dynamics in projection onto the x axis:

$$m_{\Sigma}\ddot{x} = \sum_{i=1}^{n} P_{ix} = P_{tech}, \tag{1}$$

where m_{Σ} – the mass of the parts being lifted; P_{ix} – the i-th force acting in the system (Fig. 1) (in the future, the index x is omitted, taking into account the unidirectionality of the movement); P_{tech} – the technological force, which is the resultant of all forces acting in the system during the process seals (Fig. 1).

3. Results and Discussion

The proposed method consists of the following steps:

1. An industrial workshop experiment is carried out – on an operating pressing machine, readings are taken of the time spent on the forward movement of the table, equal to the height of the filling frame, and on the reverse movement of the table, i. e. $t=t_0$ ($x=x_{\min}=0$), $t=t_1$ ($x=x_{\max}=h$), $t=t_2$ ($x=2x_{\max}=2h$). In this way, a triple of values x_i–t_i is formed.

2. The input variable is the table stroke value x, which is normalized by the formula:

$$x_{norm} = \frac{x-\bar{x}}{I}, \tag{2}$$

where x – the natural value of the input variable; $\bar{x}$ – the average value of the input variable; x_{norm} – the normalized value of the input variable; I – the interval of variation of the input variable:

$$I = x_{\max} - \bar{x} = \bar{x} - x_{\min}. \tag{3}$$

Operation (2) transforms the natural values of the input variable into the normalized range [–1; +1].

3. Based on three points $x_{\min}=-1$, $x_{\max}=+1$, $\bar{x}=0$, a D-optimal plan is constructed and these three values of the input variable are assigned experimental values of the time spent on traveling this path ($x_1=0$, $x_2=h$, $x_3=2h$). The structure of the equation obtained from these three points is as follows:

$$t = a_0 + a_1 x_{norm} + a_2 x_{norm}^2, \tag{4}$$

where a_i – the coefficients to be determined.

In its natural form, equation (4) is presented as follows:

$$t = a_0 + a_1 \frac{x-\bar{x}}{I} + a_2 \left(\frac{x-\bar{x}}{I} \right)^2. \tag{5}$$

Based on this equation structure:

– the matrix of the D-optimal plan has the form:

$$\mathbf{F} = \begin{pmatrix} 1 & -1 & 1 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \end{pmatrix};$$

– the transposed matrix of the D-optimal plan has the form:

$$\mathbf{F}^{\mathrm{T}} = \begin{pmatrix} 1 & 1 & 1 \\ -1 & 0 & 1 \\ 1 & 0 & 1 \end{pmatrix};$$

– the normalized dispersion matrix has the form:

$$\mathbf{D} = \begin{pmatrix} 3 & 0 & -3 \\ 0 & 1.5 & 0 \\ -3 & 0 & 4.5 \end{pmatrix}.$$

Estimates of the coefficients of equation (4) are calculated using the formula:

$$\mathbf{A} = \frac{1}{3} \mathbf{D} \mathbf{F}^{\mathrm{T}} \mathbf{X}, \tag{6}$$

where $\mathbf{A}$ – a matrix of coefficient estimates; $\mathbf{X}$ – a column vector of values of the output variable.

The resulting equation (4) allows to determine the dependence $t=f(x)$ in normalized form, which has the form of a polynomial of the second degree.

4. The input and output variables are swapped and 3 values of the variable t are selected according to the three points of the D-optimal plan $t_{norm\_\min}=-1$, $t_{norm\_\max}=+1$, $\bar{t}_{norm}=0$, having previously normalized t using formulas (2), (3), substituting in these formulas instead of natural values $x_{\min}$, $x_{\max}$, $\bar{x}$ natural values $t_{\min}$, $t_{\max}$, $\bar{t}$, obtained from an industrial experiment.

5. Three quadratic equations (5) are solved – for each of the three values of t: $t_{\min}$, $t_{\max}$, $\bar{t}$. The resulting roots of the equation form the values x_i for three points of the D-optimal plan $t_{norm\_\min}=-1$, $t_{norm\_\max}=+1$, $\bar{t}_{norm}=0$, and represent the output variables for constructing a dependence inverse to $t=f(x)$, i. e. $x=\varphi(t)$.

6. Using formula (6), the coefficients of the equation $x=\varphi(t)$, which is a second-degree polynomial of the form (4), but with coefficients b_0, b_1, b_2, are calculated.

7. The operation of converting the normalized form of the equation into a natural one is carried out according to formula (5), with the only difference that not the coefficients a_0, a_1, a_2, but the coefficients b_0, b_1, b_2 are used.

8. The final equation $x=\varphi(t)$ is written, describing the trajectory of the working table and, accordingly, the movement of the lower plane of the molding sand.

9. Differentiating the equation $x=\varphi(t)$ the first time, the pressing speed is obtained, differentiating the second time, the pressing acceleration is obtained. Thus, a complete system of equations was obtained that describes the kinematics of the pressing process:

$$x = \beta_0 + \beta_1 t + \beta_2 t^2, \tag{7}$$

$$\dot{x} = \beta_1 + 2\beta_2 t, \tag{8}$$

$$\ddot{x} = 2\beta_2, \tag{9}$$

where

$$\beta_0 = b_0 - b_1 + b_2, \tag{10}$$

$$\beta_1 = \frac{b_1}{I} - \frac{2\bar{t} b_2}{I^2}, \tag{11}$$

$$\beta_2 = \frac{b_2}{I^2}. \tag{12}$$

10. Equation (1) is integrated:

$$x = \frac{1}{m_\Sigma} P_{tech} \frac{t^2}{2}. \tag{13}$$

11. Numerical modeling selects P_{tech} values that ensure at time t that the coordinate x is equal to that obtained from equation (7).

P. 11 is an adaptation of the process of finding the force acting on the molding sand, based on a preliminary assessment of the kinematic characteristics of the pressing process.

12. Assessing the position of the middle plane of the molding mixture in the flask and filling frame (ξ) at the actual position of the lower plane of the mixture $x=x_i$ (Fig. 1) using formula (14), the density of the mixture at the level ξ is calculated.

$$\xi = (H + h - x)/2. \tag{14}$$

The value ξ is measured from the top plane of the flask.

Below is a hypothetical example of using the adaptive method 1–12.

Initial data are shown in Table 1.

Let the data from industrial experiments record the average time values for the forward motion of the table ($x_2=h$) and the reverse motion of the table ($x_3=2h$), given in Table 2.

Table 1

Initial data for assessing the dynamic characteristics of the pressing process

Parameter	Designation	Dimension	Data
Clear height of the flask	H	m	0.3
Clear width of the box	B	m	0.4
Flask length	L	m	0.5
Filling frame height	h	m	0.2
Bulk density	δ_0	kg/m^3	960
Required mold density	δ	kg/m^3	1560
Gap	S_x	m	0
Model kit volume	V_m	m^3	0.00384
Mass of particles lifted during pressing	m_Σ	kg	317

Table 2

Data from industrial experiments to determine the time to lift the table and return it to its original position

Experimental point according to D-optimal plan				Time	
Natural value		Normalized value			
Designation	Value, m	Designation	Value	Designation	Average value based on the results of k experiments for each point of the D-optimal plan, s
x_1	0	x_{1norm}	−1	$\overline{t}_1$	0
$x_2=h$	0.2	x_{2norm}	0	$\overline{t}_2$	3
$x_3=2h$	0.4	x_{3norm}	+1	$\overline{t}_3$	5

The coefficient matrix **A**, calculated using formula (6), is equal to:

$$\mathbf{A}=\begin{pmatrix} 3 \\ 2.5 \\ -0.5 \end{pmatrix}.$$

Therefore, the equation $t=f(x)$ in normalized form is presented as follows:

$$t=3+2.5x_{norm}-0.5x_{norm}^2. \quad (15)$$

Then the equation $t=f(x)$ in natural form (5) is presented as follows (Fig. 2):

$$t=4E\text{-}15+17.5x-12.5x^2. \quad (16)$$

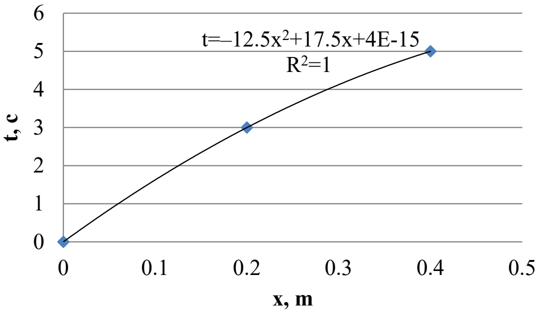

Fig. 2. Dependence $t=f(x)$ in natural form

Completing steps 4–8 leads to the final equation $x=\varphi(t)$ in natural form:

$$x=0.0496t+0.00608t^2. \quad (17)$$

The results of the calculation using formula (17) for the time interval of the pressing process, that is, the forward motion of the table, are presented in Table 3.

The principle of implementation of clause 11 is demonstrated in Table 4.

Table 3

Results of calculating the coordinates of the lower plane of the mixture on the forward motion of the table

t, s	x, m
0	0
0.5	0.026
1	0.056
1.5	0.088
2	0.124
2.5	0.162
3	0.204

Table 4

The principle of adapting the process of finding the force acting on the molding sand

P_{tech}					
66	35.5	1020	455	243	147
x, m					
0	0	0	0	0	0
0.026	0.014	0.001	0	0	0
0.104	0.056	109.959	0.008	0.004	0.003
0.234	0.126	0.088	0.039	0.021	0.013
0.416	0.224	0.278	0.124	0.066	0.04
0.651	0.35	0.682	0.304	0.162	0.098
0.937	0.504	1.413	0.63	0.337	0.204

In Table 4, the x values corresponding to the data in the table are indicated in Table 3, and describing the coordinate of the lower plane of the molding sand obtained from the kinetics equation (17).

The results of the calculation using formula (14) and the calculation of the density of the mixture at this level are shown in Fig. 3.

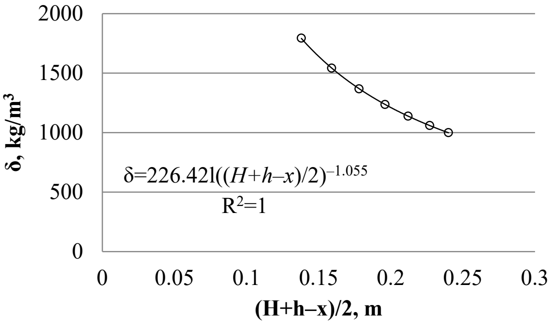

Fig. 3. Distribution of mixture density according to the position of the middle plane of the mixture during the pressing process

Combining the results shown in Table 4 and Fig. 3 leads to the final results of assessing the dynamic characteristics of the pressing process (Table 5).

Table 5

Summary results of calculating the dynamic characteristics of the pressing process

t, s	x, m	v, m/s	δ, kg/m^3	$(H+h-x)/2$, m	P_{tech}, N
0	0	0.0496	1000	0.24	66
0.5	0.026	0.05568	1060	0.227	35.5
1	0.056	0.06176	1138	0.212	1020
1.5	0.088	0.06784	1236	0.196	455
2	0.124	0.07392	1368	0.178	455
2.5	0.162	0.08	1542	0.159	243
3	0.204	0.08608	1794	0.138	147

Approximation of the results obtained allows to identify different stages of the process, identifying the fate of plasticity and elasticity of the mixture (Fig. 4).

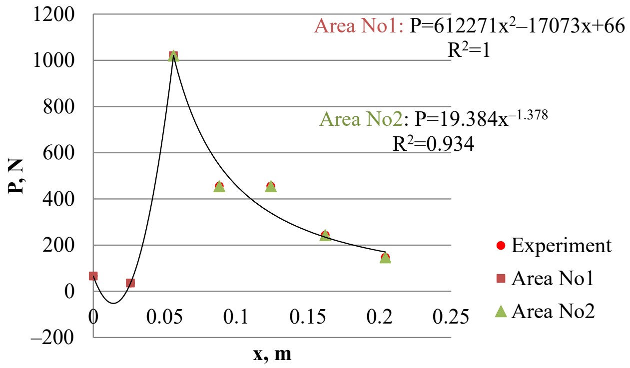

Fig. 4. Graph of the pressing process with areas of plasticity and elasticity of the mixture

So, from Fig. 4 it is possible to see that at the first stage, corresponding to the section $x\approx(0-0.03)m$, the mixture is deformed with virtually no resistance and virtually no effort from the pressing piston. The section $x\approx(0.03-0.06)m$ characterizes the deformation of the mixture without resistance, that is, the section of plasticity. Starting from $x\approx0.06m$, the mixture begins to exhibit elastic properties, creating a resistance force that increases as the working table moves upward.

In addition, the results obtained make it possible to assess the achievability of the specified requirements for the density of the mixture at the height of the flask. So, as follows from Fig. 3, the specified density of 1560 kg/m^3 corresponds to approximately half the height of the flask. This suggests that it is impossible to ensure high-quality compaction over a flask height of 0.3 m.

The advantage of the proposed method is the simplicity of assessing the actual parameters of the pressing process – the effort and density of the mixture and their distribution along the height of the mixture column. This approach also makes it possible to estimate the resistance values on the side of the mixture in dynamics, if the pressure supplied to the press piston is known. This may be interesting from a theoretical point of view for identifying the mechanism of deformation of the mixture, the magnitude of its elasticity under various technological pressing modes and for various equipment parameters. From a practical point of view, this can be useful for calculating the correction value of the pressing pressure, which can be taken into account and included in the control system for the lower pressing process.

A limitation of the study is the assumption that the coefficients of equations (4), (5), (7) are constant.

The disadvantage of the study is that the system is considered from the perspective of the movement of a solid body, which is a work table with a model kit, but not molding sand. Therefore, it is likely that when using the method in practice, the results obtained may differ from the theoretical ones. This will require further adaptation for specific production conditions.

The development of this research is possible in the direction of collecting and processing the results of practical tests of the method, identifying the factual validity of the assumptions and simplifications made.

4. Conclusions

The proposed method makes it possible to quite simply evaluate the dynamic characteristics of the bottom pressing process. This is achieved by implementing experimental industrial research directly on existing equipment based on the use of D-optimal plans and subsequent adaptation of the process of finding the force acting on the molding sand. Adaptation is based on a preliminary assessment of the kinematic characteristics of the pressing process and involves the calculation of the technological force, which ensures that at a given point in time the coordinates of the lower plane of the molding sand, obtained from the kinetics equation, are reached.

The results of the method implementation make it possible to identify the various stages of the pressing process and the distribution of mixture density along the height of the molding sand column.

The practical implementation of the method can help in setting up a control system for the bottom pressing process depending on the equipment parameters.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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