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Одним з найбільш енергоємних виробництв є виробництво вуглецевих виробів, тому підвищення ефективності даного виробництва є актуальною науково-технічною задачею. Одним із шляхів розв'язання поставленої задачі є створення сучасної системи керування виробництвом.

У роботі розглядаються питання створення системи керування одним з визначальних технологічних процесів виробництва вуглецевих виробів – процесом їх формування. В основу роботи системи керування покладений критерій оптимальності на основі питомої собівартості продукції з урахуванням показників її якості. Як метод керування використовується MPC-керування (Model Predictive Control). Результати проведеного дослідження залежності критерія оптимальності від параметрів налаштувань MPC-регулятора дозволили визначити оптимальні значення горизонтів прогнозування та керування, які забезпечують мінімізацію питомої собівартості продукції. Розроблена структура запропонованої системи керування у середовищі Simulink, що дозволяє досліджувати дану систему керування шляхом комп'ютерного моделювання.

Дослідження ефективності запропонованої системи керування процесом формування вуглецевих виробів здійснювалось шляхом порівняння якості керування даної системи та системи, яка використовує класичний ПІД-закон керування. З цією метою у середовищі Simulink синтезовано трьохконтурну систему керування на основі ПІД-регуляторів. Налаштування кожного з регуляторів проводилось за методом Пауела на мінімальне значення інтегрального критерію. Результати порівняльного дослідження продемонстрували, що на кожному циклі роботи значення критерію оптимальності у системі керування з MPC-регулятором на 8,8 % менше, ніж у системі з ПІД-регуляторами при однакових показниках якості продукції. Це говорить про покращення техніко-економічних показників процесу формування. Особливого значення ця обставина набуває з урахуванням циклічності технологічного процесу формування вуглецевих виробів

Ключові слова: виробництво вуглецевих виробів, процес формування, гідравлічний прес, система керування, критерій оптимальності, MPC-керування

SYNTHESIS AND INVESTIGATION OF THE CONTROL SYSTEM FOR THE PROCESS OF CARBON ARTICLE MOLDING

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1. Introduction

The properties of graphite products, in particular their high thermal stability, electrical conductivity, and mechanical strength [1–4] resulted in their widespread use in various branches of industrial production. At present, they are used in steelmaking, ferroalloy electro arc furnaces at metallurgical and machine-building enterprises, as the cathodes and

anodes for electrolyzers, other equipment for industries that require the use of electrothermal technological processes.

The production of carbon-graphite articles consists of a series of technological processes and operations [5–8] and is characterized by significant resource and energy intensity. In addition, there is a tendency to the constant increase in the requirements for the products' qualitative indicators; therefore, it is a relevant task to improve the efficiency of this production by introducing optimum operating modes at key technological stages.

One of the basic technological processes of carbon article production is the process of their molding by pressing an electrode mass through a mouthpiece of the appropriate shape in a hydraulic press. It is at the stage of pressing the electrode blanks that the main hereditary properties that determine the quality of finished products are laid [2, 3]. In particular, pressing substantially affects the shape of a workpiece, its length, porosity, and mechanical strength.

The entire process of molding can be conditionally divided into the following stages: loading, additional pressing of material, and the actual pressing of carbon articles. In terms of the quality of the finished products, the most responsible stage is the stage of actual pressing, which is why we shall focus on this particular stage in the process of forming carbon products.

The pressing process is carried out within the mouthpiece and the mass cylinder. The pre-loaded and additionally pressed electrode mass is pressed out under pressure through the forming and calibrating zone of the mouthpiece. In this case, the surface of the molding and calibrating zone is heated by appropriate inductors while the edges of the calibrating zone are additionally heated by candles (Fig. 1).
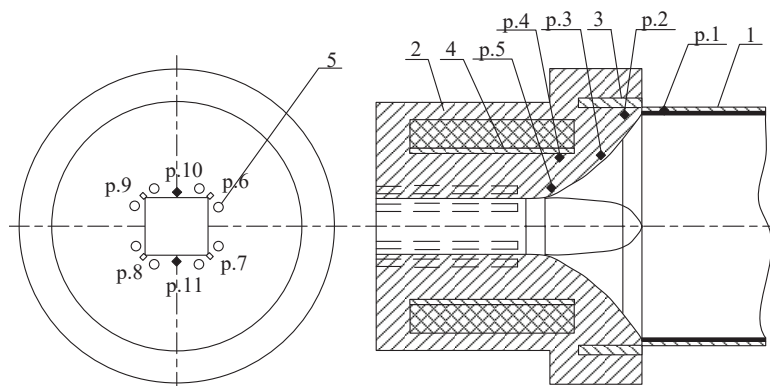

Fig. 1. An industrial pressing tool to mold large carbon work pieces:
1 — mass cylinder with a heater; 2 — mouthpiece; 3, 4 — main inductors;
5 — additional heaters; points 1—11 — temperature measurement points

Given the above-mentioned circumstances, it is a pressing issue to create and investigate such a system of control over the carbon product formation, which would improve the technical and economic efficiency of a given technological stage and, ultimately, of the overall production of carbon articles.

2. Literature review and problem statement

At present, there are several known systems to control the pressing of carbon products.

The authors of work [2] propose using, as a controlled parameter, the pressing intensity (efforts to extrude a single volume of mass per 1 s). The disadvantage of this method is the impossibility to measure the parameter directly, which leads to the indirect control over it and, consequently, to the possible control errors caused by the inaccuracy in the calculation of a given indicator.

A study of the impact of various parameters on the quality of the pressed workpieces [4] showed that it is necessary, in order to obtain the defect-free products, to ensure that the conditions for medium continuity are observed during pressing. These conditions could be met by adjusting the temperature at the «control» points on the surface of the pressing tools [4]. Such a control system enables or disables the heating elements depending on the temperature at the «control» points and the temperature of carbon loam softening T_{soft}. A significant drawback of this control system is its relay nature, which significantly degrades the quality of control.

Paper [9] describes an algorithm for designing the optimal control over the press inductors with an optimality criterion for minimizing the energy costs to heat the surface of a mouthpiece. Since the required temperatures at control points are set in the form of a constraint for the optimization problem, the control, based on this algorithm, does not ensure the optimality of the process technological parameters. Consequently, the products obtained under such control will have not the optimal but permissible quality indicators. In addition, the cited paper does not describe the algorithm for selecting the constraints on temperature and does not account for the impact of the pressing rate on the course of the technological process.

The authors of [10] described a model of the viscous-plastic material extrusion and proposed a control system that considers the change in the rheological properties, which are calculated by a given model. However, they outlined only the concept of such a control system, with neither the structure nor the algorithm for developing this system given.

Patent [11] was given to the designed extrusion machine with an improved temperature control system. The essence of the improvement is only the arrangement of a temperature sensor almost at the edge of contact between the press wall and the material which is subjected to extrusion. According to the authors, this innovation makes it possible to quickly acquire information about the temperature of the material, which, in turn, could improve the efficiency of the temperature control system. However, this advancement has not any proof of the expediency of such a modification in terms of costs to introduce it; the authors did not investigate its effect on the strength of the inside part of the pressing tool at the place of sensor installation.

The authors of [12] reported a supervisor control system for the process of hot-melt extrusion. The basic idea of the developed system is that the control is executed based on the acquisition and analysis of the main technological parameters of the process. The control itself is carried out based on the quality indicators of the output products and is executed by means of an MSPC (multivariate statistical process control) method.

Although a given system ensures high quality indicators of products, it cannot be used as a basis for creating a control system for the formation of carbon articles as one of the requirements for the application of a given system is the continuity of the process whereas molding is a periodic process.

Study [13] proposed a two-screw extruder control system for powdered substances extrusion based on the MPC-controller (Model Predictive Control). The designed system showed high efficiency. Therefore, the general approach to the synthesis of a control system, demonstrated by the cited study, can be applied taking into consideration the features in the process of carbon product molding.

Works [14, 15] report a neural fuzzy temperature control system in the process of plastic extrusion. The disadvantage of this system is that the temperature dynamics model in a press is represented in the form of an aperiodic link of the first order with the lag; therefore, the devised control system does not take into consideration the distribution of material properties for volume and the possible non-linearity of an object. This fact may have a significant negative impact on the efficiency of the developed system operation when it is used at an actual object.

The current systems of control over the carbon articles pressing process are the systems of stabilization (typically, a temperature at control points) or program control (the rate of pressing); moreover, the laws of change in the technological parameters are typically determined empirically.

A significant drawback of the above-mentioned control systems is that they do not take into consideration the economic indicators of operation at a given technological stage of production, which typically leads to a decrease in the effectiveness of its functioning.

Work [16] proposed a technical-economic criterion (1) whose minimization in the control process should provide the minimum cost of a unit of production subject to the specified qualitative indicators:

$$K_{opt} = \frac{\left(P_e\left(W_p + W_t\right) + P_m G_m\right)}{t_e v_p F_m \rho_{mat}\left(\dfrac{1}{1+\dfrac{I}{V_p t_e}}\right)} \to \min \qquad (1)$$

where K_{opt} is the variable component of a production unit cost, a. u./kg; V_p is the value of the working volume of a mouthpiece, m³; P_e is the tariff for electricity; W_p, W_t is the electricity consumption; P_m, G_m are the price and consumption of raw materials, respectively; t_e is the duration of the process; v_p is the pressing rate; F_m is the cross-sectional area of a mouthpiece; ρ_{mat} is the density of a material.

In expression (1), I is the integrated criterion for determining the quality of the pressed workpieces, which is mathematically described as follows:

$$I = \int_0^T\int_0^L\left[\begin{array}{l}Q\left(R_{\min}-R_z\right)^2 + S\left(R_{\max}-R_z\right)^2 + \\ + h_1\left(R_{\min}\right) + h_2\left(R_{\max}\right)\end{array}\right]\mathrm{d}l\mathrm{d}t, \qquad (2)$$

where T is the pressing time; L is the length of a mouthpiece; Q, S are the weight matrices; R_z is the preset workpiece radius; $R_{\min}$, $R_{\max}$ are, respectively, the minimum and maximum core radius with a structural motion mode; l is the coordinate lengthwise of a mouthpiece in the cylindrical coordinate system; t is time.

The cited work did not pay attention to the issues directly related to the construction of a control system and the analysis of its effectiveness.

3. The aim and objectives of the study

The aim of this study is to synthesize a control system that would ensure the improvement of the technical and economic indicators of the carbon articles molding process.

To accomplish the aim, the following tasks have been set:
– to construct the structure of a control system for the carbon articles molding process based on criterion (1);
– to study the efficiency of the proposed control system in comparison with existing systems using a computer simulation method.

4. The structure of the control system with an MPC-controller

One of the modern formalized approaches to the analysis and synthesis of control systems, based on the mathematical optimization methods, is the theory of dynamic objects management that employs forecasting models – Model Predictive Control (MPC) [17–19].

The main advantage of the MPC-approach, which predetermines its successful application in the practice of building and operation of control systems, is the relative simplicity of the basic scheme of feedback formation, combined with high adaptive properties.

The latter circumstance makes it possible to manage multidimensional and multi-threaded objects of a complex structure, including the nonlinearity, to optimize processes in real time within the constraints on control and controlled variables, to take into consideration the uncertainty of objects and disturbances.

The results reported by recent studies [20–23] indicate the high efficiency of MPC under conditions of constraints. This circumstance is of special importance in the synthesis of a system of control over the process of carbon articles pressing when compliance with limitations largely determines the quality of control in general.

Based on the peculiarities of the carbon articles molding process, forecasting the object's behavior (predicting the radii of a workpiece) in a few steps ahead and taking into consideration the projected variables during control calculation is expedient. It is advisable then to use an MPC controller to manage this object. In addition, the MPC-controller computes a controlling signal based on the projected parameters, for which the value of the optimality criterion is calculated. This means that by setting (1) as such a criterion and by adjusting the controller properly, we could obtain such a control system that would at each step minimize (1).

The MPC-controller-based pressing control system has been implemented in the MATLAB Simulink programming environment, which includes the software tool MPC Toolbox that makes it possible to flexibly adjust all parameters of the controller, as well as an optimality criterion, and technological constraints.

The circuit of the control system with an MPC-controller, implemented in Simulink, is shown in Fig. 2.

After implementing the control system in Simulink, we adjusted its settings. The main parameters of the MPC-controller configuration are the prediction horizon and the control horizon [17], which is why our further research was aimed at determining their optimum values taking into consideration the feasibility criterion (1).
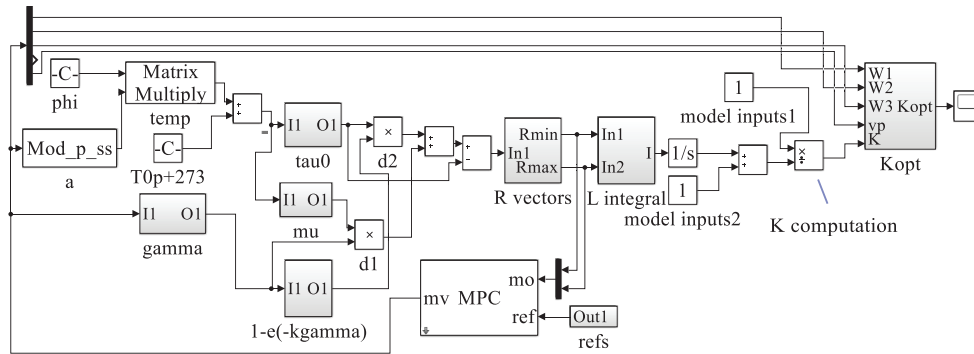
Fig. 2. A circuit of the MPC-controller-based control system, implemented in Simulink

Given that the dynamics of the feasibility criterion (1) becomes negative (the criterion value starts to increase) at values 15 for the prediction horizon and 10 for the control horizon, these values were selected as the maximum ranges of appropriate changes in setting the MDC-controller configuration parameters.

The existence of an extremum point for the function of the dependence of the feasibility criterion on the MPC-controller settings can be explained in the following way. On the one hand, an increase in the prediction horizon and control horizon makes it possible to calculate an optimal (for the predefined criterion) control by several steps forward instead of calculating the control at the current step, based only on the previous data acquired from the object. On the other hand, the MPC-controller uses a simplified mathematical model of the object and, for complex nonlinear objects, which is the pressing process, the longer the prediction horizon the larger the discrepancy between the values of the model and the object, which compromises the quality of control. An extremum point defines the moment when the negative impact exerted by the divergence in the model and object values exceeds the positive impact from the optimal control calculation.

To determine the optimum settings of the MPC-controller, we performed a series of computer simulations in order to clarify the dependence of the feasibility criterion (1) on setting the controller parameters. The study involved the production of electrodes, EGGP/UHP brand (diameter – 229 mm, length – 1,500 mm, volumetric density – 1.72 g/cm³, electrical resistivity – 6 μOhm·m) at the hydraulic press D6248. The simulation was based on the mathematical model [22] whose error in reproducing the actual data does not exceed 2.7 %. The simulation results are given in Table 1.

As the above data imply, the best result was demonstrated by setting the prediction horizon of 13 steps and the control horizon of 3 steps. Under such settings, the performance increased by 6 % compared to the performance of the press that complies with the regulations.

Table 1

The optimality criterion value (USD/kg) depending on the prediction horizon (P. H.) and control horizon (C. H.)

P. H. \ C. H.	1	2	3	4	5	6	7	8	9	10
1	0.394	–	–	–	–	–	–	–	–	–
2	0.388	0.379	–	–	–	–	–	–	–	–
3	0.368	0.367	0.366	–	–	–	–	–	–	–
4	0.367	0.364	0.364	0.363	–	–	–	–	–	–
5	0.361	0.359	0.356	0.358	0.332	–	–	–	–	–
6	0.354	0.353	0.350	0.353	0.301	0.332	–	–	–	–
7	0.349	0.338	0.329	0.338	0.284	0.314	0.328	–	–	–
8	0.346	0.310	0.311	0.324	0.262	0.305	0.310	0.315	–	–
9	0.339	0.295	0.290	0.306	0.259	0.293	0.292	0.302	0.319	–
10	0.334	0.280	0.275	0.289	0.259	0.282	0.284	0.298	0.302	0.320
11	0.342	0.270	0.258	0.279	0.262	0.274	0.280	0.285	0.297	0.306
12	0.344	0.279	0.244	0.266	0.267	0.266	0.271	0.293	0.311	0.338
13	0.349	0.285	0.230	0.251	0.274	0.265	0.284	0.302	0.325	0.359
14	0.350	0.287	0.243	0.253	0.280	0.275	0.298	0.319	0.342	0.373
15	0.352	0.291	0.245	0.254	0.288	0.291	0.311	0.341	0.368	0.389

5. Studying the efficiency of the control system for a carbon article pressing process

Our study of the efficiency of the proposed control system with an MPC-controller implied comparing the quality of control by a given system to the actual system with PID-controllers. The dynamics of change in the minimum and the maximum radius of a workpiece in the output cross-section using the configured MPC-controller for setting $R=0.23$ m are shown in Fig. 3.

It is known [4, 10–13] that in the systems of control over the molding of carbon articles the controlled variables are the temperatures at the control points of each zone of a mouthpiece (the thermocouples are installed at these points) while the controlling variables are the current power of the heaters.

In this case, the pressing rate is typically defined only by technological regulations.

Fig. 1 shows that the points 3 and 5 are located directly near the inner surface of the forming and calibration zone of the mouthpiece and, therefore, characterize to the largest degree the temperature of an electrode mass in these regions. That is why they were chosen in the control system as control points for the inductor in the molding and calibration zone, respectively.

As for additional heaters, they are switched on synchronously, so in order to accurately provide the necessary slippage conditions, it is necessary to keep control in accordance with the minimum value of temperatures in t. 6–11.

The control system would then consist of three temperature control circuits. The pressing rate is set according to the technical regulations [8]. The assigned radius of a workpiece in the output cross-section is $R = 0.23$ m.

The scheme of the proposed three-circuit control system, implemented in Simulink, is shown in Fig. 3.

In a given scheme, in addition to the model for calculating temperatures at control points and feedback to the PID-controllers, in order to run a comparative analysis of the quality of control by the two examined systems (MPC and PID), there is a unit that calculates vectors R_{min}, R_{max}, and the criterion (1) value. The PID-controllers were set based on a Powell method [24]. We used, as the assigned temperature, the values of temperature at the control points derived from experimental data [8].

During the simulation, the values of temperature at selected points were calculated by using a mathematical model [25]. The simulation results are shown in Fig. 4 (MPC-controller) and Fig. 5 (PID-controller).

Fig. 4, 5 show that the control system with PID-controllers, in contrast to the MPC-controller-based control system, demonstrates the overshooting for R_{min} by 8 %. This means that in the process of heating the machine (the mouthpiece), a first control system (MPC) would produce articles of the required quality, starting at minute 100. A second control system (PID) would start making articles of the same quality only at minute 125, due to the overshooting. As a result, the criterion (1) value for the system with PID-controllers is USD 0.25/kg, which is 0.02 larger than that for the system with an MPC-controller.
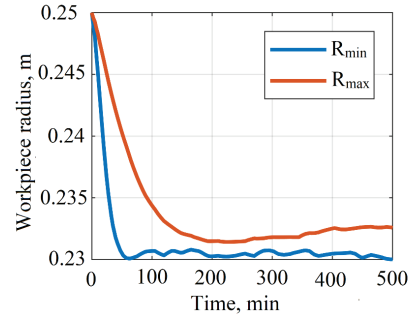

Fig. 4. The dynamics of a workpiece radius in the system with the configured MPC-controller
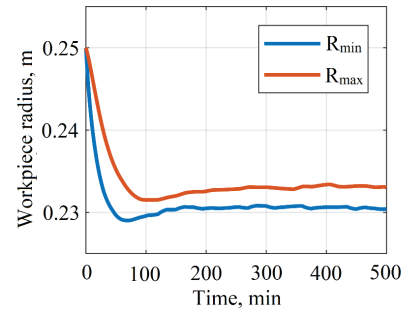

Fig. 5. The dynamics of a workpiece radius in the system with PID-controllers

6. Discussion of results of studying a control system

The current systems of control over the process of carbon product molding do not ensure the desired quality of control. Besides, the economic indicators are left unaddressed; given this, taking into consideration the significant energy intensity of the molding process becomes very important.

The proposed system to control the process of carbon product formation, based on an MPC-controller, resolves the specified issues. A given system implies the calculation, when executing the control process, of both the criterion of optimum control, the cost of a unit of production, and an integrated indicator of its quality, the radius of a workpiece.
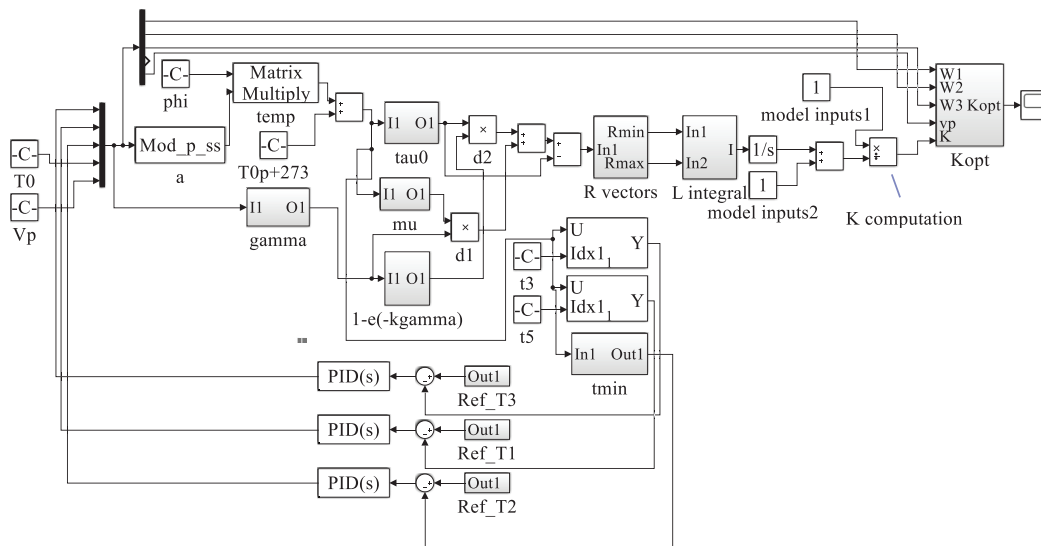

Fig. 3. Scheme of the PID-controller-based control system implemented in Simulink

The important role belongs to the proposed MPC-controller-based control system structure (Fig. 2), implemented in the Simulink programming environment, which makes it possible to conduct a comprehensive study of a given control system.

An important result of our study is determining the extreme character of the dependence of an optimality criterion (1) on the parameters of the MPC-controller configuration (Table 1), which allowed the optimal settings for an MPC-controller to be determined: a prediction horizon of 13 steps, a control horizon of 3 steps.

The efficiency of the control system with an MPC-controller was examined by comparing it to the conventional system with the PID-controllers. To this end, we have developed, and implemented in the Simulink programming environment, the structure of the control system based on PID-controllers (Fig. 3).

The simulation results (Fig. 4, 5) indicate better quality of MPC without overshooting, which enables the production of articles of the required quality (the considered size) by 25 minutes earlier than the system with PID-controllers, which, in terms of the cost of production, saves USD 0.51/kg.

We have investigated the efficiency of the proposed system of control over the process of carbon products molding for the hydraulic press D 248 when making electrodes of EGGP/UHP brand (diameter – 229 mm, length – 1,500 mm, volumetric density – 1.72 g/cm^3, electrical resistivity 6 μOhm·m). Therefore, there is no reason to argue about the versatility of the devised control system. Research must be undertaken involving other control objects in the industrial production of various carbon articles, which could be subject of our studies in the future.

7. Conclusions

1. We have devised the structure of a control system for carbon articles molding, built on an MPC-controller. In order to refine it, the structure has been implemented in the Simulink programming environment. The result of our study is determining the optimal settings for an MPC-controller, namely, a prediction horizon of 13 steps and a control horizon of 3 steps. The developed system ensures the specific cost of a production unit at the level of USD 5.77/kg while maintaining the required quality. In addition, using the synthesized system has increased the performance by 6 % compared with the performance of the press operated in line with regulations.

2. A comparative study of the synthesized system and the PID-controller-based system has been carried out. It has been determined that the specific cost of a unit of production for the system with the PID-controllers is USD 6.28/kg, which is 0.51 larger than for the system with an MPC-controller. This, in its turn, demonstrates the higher economic efficiency of the synthesized control system with the MPC-controller.

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