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DEVELOPMENT OF THE EVALUATION MODEL OF TECHNOLOGICAL PARAMETERS OF SHAPING WORKPIECES FROM POWDER MATERIALS

Розглянуто системний підхід до технологічного процесу формоутворення (процес, машина, заготовка), що дозволило розробити математичну модель оцінки. На основі математичної моделі нечітких множин була виконана оцінка ефективності функціонування технологічного комплексу. Визначені зв'язки між параметрами підсистем на базі вібропресового обладнання з гідроімпульсним приводом для формоутворення заготовок з порошкових матеріалів

Ключові слова: нечіткі множини, формоутворення, рівнощільність, гідроімпульсний привод, вібропресове обладнання, порошковий матеріал

Рассмотрен системный подход к технологическому процессу формообразования (процесс, машина, заготовка), что позволило разработать математическую модель оценки. На основе модели нечетких множеств была выполнена оценка эффективности функционирования технологического комплекса. Определены связи между параметрами подсистем на базе вибропрессового оборудования с гидроимпульсным приводом для формообразования заготовок из порошковых материалов

Ключевые слова: нечеткие множества, формооброзование, равноуплотненность, гидроимпульсный привод, вибропрессовое оборудование, порошковый материал

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1. Introduction

Technologies that are characterized by processes of shaping workpieces, in which fluidity of materials with complex reology is implemented under conditions of complex loading, need new developments, learning and improvement. Vibrational and vibroimpact technological processes, as well as equipment for their implementation are becoming increasingly common [1–3]. It was found that the application of useful vibrations or impact pulses to the objects of treatment makes it possible to significantly intensify the course of a number of technological processes, provide optimum loading parameters and obtain a product with high quality parameters. In particular, when pressing workpieces of products made of powder materials (carbides, borides etc.), average density and equal density by the volume of workpieces increases by 60–70 % under conditions of waste-free production. That is why vibration equipment for shaping workpieces from powder materials should meet more serious requirements. It must have a relatively simple structure, high reliability,

low metal and energy consumption and provide high quality of the shaped product.

Therefore, development of effective method for estimating condition of the technological complex of shaping workpieces from powder materials on vibropress equipment is a relevant task.

2. Literature review and problem statement

When designing the processes for shaping workpieces from non–metallic powder materials [4, 5], authors in article [4] did not analyze the most effective way of shaping – vibroimpact pressing [1–3]. In paper [5], author did not note existence of a high degree of uneven density of workpieces at shaping in centrifuges. Technological equipment with hydropulse drive [6, 7] should meet basic requirements, such as reliability and efficiency. The original technological equipment, presented by authors in [6], because of its complexity, requires promising methods of technical evaluation. They include finding operation parameters of the condition of technological equipment at all stages. In article [7], authors did not mention the fact that the technological process consists of many stages. This leads to considerable uncertainty of the state of the system as a whole. Thus, using the method of fuzzy sets will provide effective prevention or termination of their subsequent possible negative development [1–3].

Currently, mathematical modelling of physical processes based on fuzzy sets is becoming more widespread [8, 9]. Moreover, authors in [8] limited the use of this method only to power industry. In paper [9], author pointed to the existence of stochastic processes in hydrology, which makes impossible the application of the method of fuzzy sets for studying technological processes of pressure treatment machines. This method can be applied for deep and full exploration of the impact of structural and operational factors on the basic characteristics of technological process of shaping workpieces in vibropress equipment with hydropulse drive. Method of estimation by fuzzy sets allows identification of specific ways of their improvement, significantly lowering the volumes of experimental research [10, 11]. Despite the complexity of calculation of mathematical description of the technology of comprehensive assessment of innovation effectiveness [10], the authors did not fully explore the possibilities of this method due to the review of only initial stage. Moreover, in paper [11], authors did not examine the impact of structural and operational factors on the stability in the supply chain in the metallurgical industry. Nevertheless, the impact of structural and operational factors on the efficiency of shaping workpieces on vibropress equipment with hydropulse drive [1, 3] may be specified during the experiment [8–11].

3. The aim and tasks of the study

The aim of the study is to increase efficiency of technological processes of shaping workpieces from powder materials by means of developing advanced mathematical models for vibropress equipment with hydropulse drive.

To achieve the set goal, the following tasks were to be solved:

– to analyze the process of shaping workpieces from powder materials using vibration and vibroimpact treatment based on the developed structure of vibropress shaping machines, types of drives and their characteristics;

– to develop a model, constructing and substantiating sets of input and output parameters for the evaluation of operational efficiency of technological complex;

– based on the developed model of fuzzy sets, to obtain dependences for quantitative characteristics of the examined process, with the help of which to select effective mode of vibroimpact pressing.

4. Materials and methods for examining technological parameters of shaping workpieces from powder materials

4. 1. Object of the study

The technological process of manufacturing products from new high- performance materials [1, 3, 12], based on powders of metals and non-metals, their alloys and compounds with fillers, can be represented by consequently performed operations of charge preparation (powder material), shaping workpiece and its heat treatment. The main technological operation is shaping workpieces that can be carried out by such methods as free filling into a shape, pouring suspensions and pastes, sealing by ramming and a number of their combinations. The most widespread workpiece shaping by the method of pressing is implemented in different ways: simple, stepping, isostatic, noozle, pulse, impact, vibration and vibroimpact [1, 2, 12].

Compared with other ways of pressing, vibration and vibroimpact pressing (VIP) provides keeping to technical requirements to the workpiece more efficiently. The latter is explained by a significant decrease in working force compared with force of static pressing, which leads to a decrease in wear of press-shape parts. It also provides the possibility to manufacture workpieces from products of complex configuration, large dimensions and thin walls. Their production used to be difficult or virtually impossible.

For the implementation of VIP pressing of powder materials, special equipment is used. This is due to different variants of recommended schemes of workpiece loading in treatment and a variety of types of drives of mechanisms, generating vibrations, or vibration exciters. Promising is application of inertial vibration press-hammers (IVPH) with hydropulse drive (HPD), which is attributed to the simplicity of construction, compactness, high power consumption, a wide range of adjustment of operating parameters and possibility of operation in automatic mode.

A new type of hydraulic IVPH was created at Vinnytsia National Technical University by the order of Brovary Plant of Powder Metallurgy (Ukraine) [13] (Fig. 1). A new type of equipment takes into account all requirements for the method of shaping workpieces with carbide-silicon powder materials.

The specific feature of this machine is existence of moving crossbeam 6 with alternating inertia load 5, intensifying the process of workpiece sealing 4. In axial bore of bed 1, there is plunger 2 of executive section, associated with bed 1 by the elements of elastic return 3. Guide columns 9 of crossbeam 6 are missing in the bore of the bed 1, and a cylinder of adjusting movements 11 is fixed at the bottom crosspiece 10. Depending on technology requirements, it is possible to provide a vibration or vibro-impact mode of pressing powder materials on the machine, created by this scheme. Pressing modes are defined by conditions of interaction of moving elements of the machine, as well as the method of connecting and adjusting the valve-pulser 7 and hydraulic HPD 8.
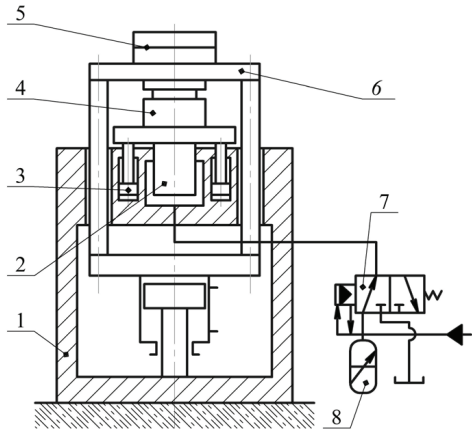
Fig. 1. Structural scheme of inertial vibropress-hammer

4. 2. Statement of research task

In the examined technological complex for vibroimpact pressing, we can distinguish three basic interconnected systems: object of treatment (system I), operation process (system II) and machine (system III), which are combined in the overall system of technological complex [1] (Fig. 2).
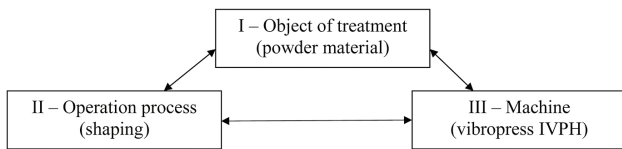

Fig. 2. Schematic of technological complex of vibroimpact pressing

In the case of IVPH, the object of treatment is powder material, which shows the properties of a metasystem. For the latter, the definition of intermediate states over time is a complicated and not always attainable task. That is why system I must be presented in the form of two subsystems and I.1 and I.2, characterizing respectively the initial (weighing of powder material) and resulting (workpiece of the product) states of the object of treatment (Fig. 3).

System II is functionally dependent on system I and is a technological pressing process. This process is described by two subsystems II.1 and II.2, which set the method of VIP and the accepted mode of its implementation (Fig. 4).
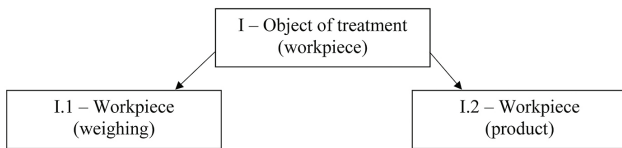

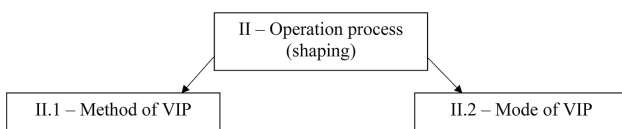Fig. 3. Schematic of system I — workpiece

Fig. 4. Schematic of system II — operation process (shaping)

Selection of system III is defined by system I and system II. System III is IVPH, which is divided into subsystems of HPD (III.1), moving sections (III.2), vibroexciter (III.3)

and press-shape (III.4). According to the system approach, each of the selected subsystems may be divided into sections. Since when building IVPM, the problems of designing HPD and its exciters are solved only in general form, and the press-shape consists of two main parts – matrix and symbol, it is sufficient to indicate in the schematic only subsystem III.2, which contains the bed and the foundation (section III.2.1), the vibration table (main operation section III.2.2) and additional operation section III.2.3. In this case, each of the specified sections is divided into parts if needed (Fig. 5).
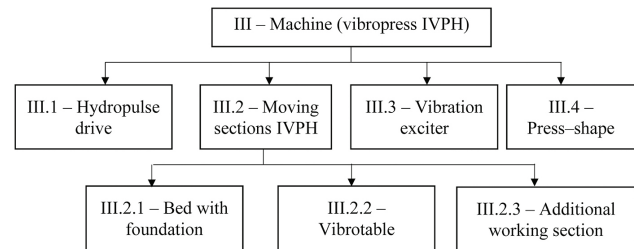

Fig. 5. Block diagram of system III — machine (vibropress IVPM)

To complete the system description of IVPH, presented in the form of block diagram, it is necessary to identify structural and functional relationships in it. In the analysis of IVPH, the source of incoming information is the information about the treated object, contained in sub-system I.1 and transferred to system II in the form of logical function of the VIP mode selection. The mode, in turn, determines the operation process, taking into consideration parameters of which, the choice of a machine of a specific type is made (system III).

Functional connection between the machine and the object in the form of force influence function is defined for a given period of time. This allows us to obtain output information, which, as well as input information, is associated with the object of treatment. But it is contained in sub-system I.2, which corresponds to the product workpiece. Functional connection between subsystem III.3 and section III.2.2 has the form of function of pressure generation in the cavity of the working cylinder, which periodically changes over time.

In further analysis of the designed vibropress equipment with the use of a systematic approach, it is also possible to distinguish intersystem functional relationships. The functional relationships of the components of systems I and II of vibro-press equipment in analytic form are a mathematical model of the operation process of VIP.

After developing the mathematical model for IVPH [14, 15] and assessing the work of its constituents, we turn to the generalized model of the entire complex based on input and output parameters.

Problem of making decision regarding assessment of functioning efficiency of the entire technological complex lies in choosing an adequate solution N from a set of solutions:

$$Z_j \ (\ j = \overline{1, J} \ ).$$

It is proposed to make choice by using effectiveness assessment of the technological complex functioning based of set X of estimation parameters:

$$x_i \ (\ i = \overline{1, n}, \ n \in N).$$

A specific feature of the mathematical model is that it takes into account the set of initial input parameters:

$K=(k_c)$ $(c=\overline{1,C})$.

A set of estimation parameters of the system:

$X=(x_i)$ $(i=\overline{1,n})$.

Function of transformation of initial parameters into estimation parameters:

$F_1: K \rightarrow X$.

A set of decomposition functions of convolution of parameters, by which identification of the system state is performed:

$D=(Y,...S, P)$.

To obtain results on the evaluation of functioning effectiveness of the shaping process, when making decision based of initial input parameters K, it is necessary to realize the above-mentioned functions in the following sequence:

$$K \xrightarrow{F_1} X \xrightarrow{D} Z_j.$$

To determine the final estimation of the state of technological complex Z_j, it is proposed to take into account a combination of complex functions – parameters $P_1...P_q$ – state, which estimate the groups of indicators of the highest hierarchy level [16, 17]:

$$Z_j = F(P_1, P_q). \tag{1}$$

In turn, the input data for calculation of complex parameters P_1 and P_q are the set of parameters that evaluate specific groups of indicators $(S_1...S_p)$, i. e.:

$$P_1 = F(S_1...S_t),\ P_q = F(S_e...S_p), \tag{2}$$

where $t, e, p \in M$, and M is the set of functionals of generalizing parameters of the P-th level.

Complex parameters of the last but one level $(Y_1...Y_m)$ are functions from the relevant evaluation parameters of x_i state:

$$Y_1 = f(x_1..x_l)...Y_m = f(x_k...x_n), \tag{3}$$

where $l, k, n \in N$, and N is the set of output parameters.

Thus, estimation parameters x_i are determined based on the set of initial input parameters K and transformation function

$F_1: X = F_1(K),\ K=(k_c),\ c=\overline{1,C};\ X=(x_i),$

$i=\overline{1,n}$.

Based on the constructed functions (1)–(3), it is necessary to form set X of the relevant parameters for evaluation of functioning effectiveness of the entire technological process. This set is formed with the help of a set of initial input parameters $K(k_1...k_e)$, where $e \in N$.

This general structural model (Fig. 6) of estimation of functioning efficiency of the process of shaping workpieces from powder materials on vibro-press equipment with hydropulse drive was proposed [12].
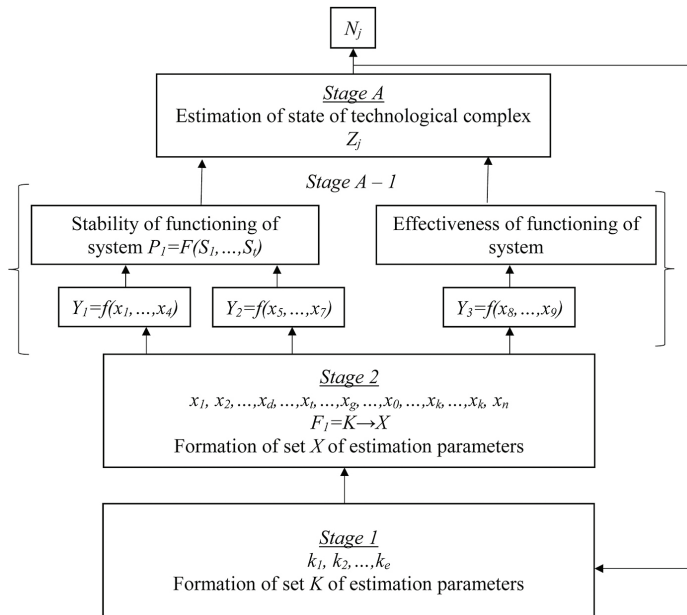

Fig. 6. General structural model of process of effectiveness evaluation of the process of shaping workpieces on vibropress equipment with hydropulse drive

At the first stage, formation of set K of initial input parameters of the whole technological complex is carried out. The second stage implies formation of set X of estimation parameters of the state of each system based of set K of initial input parameters [12]. At the third and subsequent intermediate stages, in particular S and P, formation of complex generalized indicators of evaluation of functioning efficiency of each system $Y_1...Y_m$; $S_1...S_p$; $P_1...P_q$ is carried out. At the highest stage A, the solution is identified:

$$Zj,\ j=\overline{1,J},$$

that determines functioning efficiency of the entire technological complex.

To define functions (1)–(3), it is necessary to establish a set of input and output parameters. These sets should cover a wide range of parameters of influence, as well as meet conditions of completeness, effectiveness and minimality.

The object of treatment (powder material) is included in our technological complex, which we designated as system I. System I shows that a number of them (with index «i») in the process of VIP varies from the values that characterize the initial state of the workpiece (i=0) in sub-system I.1 to the values that characterize its final state (i=k) in subsystem I.2 (Fig. 3).

The basic parameters of system I, which form a set of input and output values:

– ρ – average density of workpiece, kg/m^3;
– a – linear average dimensions of particles of material, m;
– R_0 – geometric factor for initial state of workpiece, m;
– S_0 – area of the open surface from symbol's side, m^2;
– h_w – height of workpiece, m;
– K_w – dynamic module of conditional elasticity, MPa.

Then a reduced set of parameters of system I will be written down in the form of $\{\rho, a, R_0, S_0, h_w, K_w\}$.

The mode of vibro-impact pressing in this research is system II (operation mode), which describes the method and the mode of force impact of system III on system I. We will

distinguish the basic parameters of system II. These parameters of system II include:

– τ_0 – duration of impact pulse, c;

– $P_{ст}$ – forces of additional static loading of workpiece, H;

– $F_{l.max}$ – maximum force of loading of workpiece in the process of HPD of workpiece, H;

– n – total number of strokes of working table of IVPH;

– f_p – their frequency, Hz.

Moreover, parameters n and f_p, may be combined and described by one parameter that characterizes the full time of operation process

$$t_{VIP}=n\cdot f_p^{-1}.$$

A set of basic parameters of system II may be represented in the form of $\{F_{l.max}, P_{ст}, f_p, t_{VIP}\}$.

Since IVPH is a system of a technological complex, based on the analysis of structural system III (Fig. 7), we distinguished parameters, which are characterized by basic parameters of HPD:

– E_a – energy of one-cycle hydroaccumulator, J;

– W_a – volume of hydrosystem, m^3;

– K_S – elasticity coefficient, Pa;

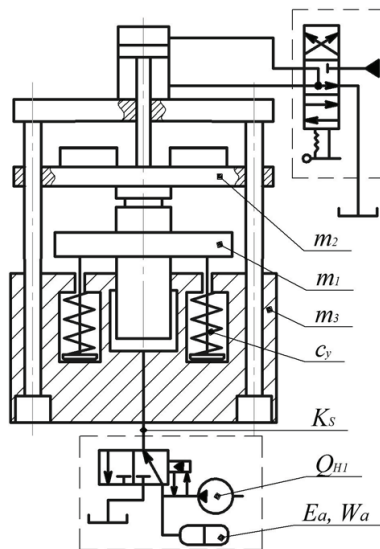– Q_{H1} – feeding of working liquid from the pump, m^3/s.

Fig. 7. Schematic of IVPH

As well as parameters of vibration exciter and the system of moving sections:

– p_1, p_2 – pressure of vibroexciter operation, Pa;

– m_1, m_2, m_3 – weight of moving sections, kg;

– c_y – stiffness of elastic elements, H/m).

As

$$m_2/m_1=\alpha \ (m_2=\alpha\cdot m_1),$$

then for system III, the reduced set of basic parameters

$$\{E_a, m_1, \alpha m_1, c_y, p_1, K_S\}.$$

Therefore, the set of estimation parameters X provides formation of such complex parameters that evaluate system I: (workpiece) – (Y_1), system II (operation mode) – (Y_2), system III (machine) – (Y_3).

Parameter

$$Y_1=f(x_1...x_4).$$

is characterized by estimation parameters: x_1 is the mean density of the workpiece (ρ, kg/m^3); x_2 is the dimensions of the particle of material (a, м); x_3 is the geometrical factor for the initial state of workpiece (R_0, м), x_4 is the area of the open surface from the side of symbol (S_0, m^2).

Parameter

$$Y_2=f(x_5...x_7)$$

is characterized by estimation parameters:

– x_5 – specific static force (P_s, H);

– x_6 – duration of impact pulse (τ_0, s);

– x_7 – full time of working stroke (t_{vsp}, s).

Parameter

$$Y_3=f(x_8...x_9)$$

is characterized by estimation parameters: x_8 is the power of one-cycle hydroaccumulator (E_a, J), x_9 is the total weight ($m_0=m_1+m_2+m_3$, kg).

The mean density of the workpiece is function $x_1=f(k_1...k_5)$ and is determined using the parameters:

– $k_1=m_W$ – mass of weighing of powder material;

– $k_2=S_W\cdot h_{si}$ – workpiece volume after shaping completion;

– $k_3=a$ – average dimensions of a particle of material;

– $k_4=R_0$ – geometrical factor for the initial state of a workpiece;

– $k_5=S_W$ – area of the open surface from the side of symbol.

Specific static force is function $x_5=f(k_6...k_8)$ and is determined using parameters: $k_6=m$ is weight, $k_7=g$ is acceleration of free fall, $k_8=S_a$ is the area of the open surface.

The duration of impact pulse, which is function $x_6=f(k_9...k_{13})$ is defined by a set of parameters:

– $k_9=h_{si}$ – height of workpiece at the initial moment of VIP;

– $k_{10}=h_{sf}$ – height of workpiece at the final moment of VIP;

– $k_{11}=H_{ei}$ – module of conditional elasticity at the initial moment of VIP;

– $k_{12}=H_{ef}$ – module of conditional elasticity at the final moment of VIP;

– $k_{13}=\rho_0$ – average density of workpiece at the initial moment of VIP;

– $k_{14}=\rho_k$ – average density of workpiece at the final moment of VIP.

Full time of working stroke $x_7=f(k_{15},k_{16})$ is determined with the help of parameters: $k_{15}=n$ – total number of strokes of working table, $k_{16}=f$ – frequency.

Energy, which is function $x_7=f(k_{17},...k_{19})$ and is determined with the help of parameters: $k_{17}=p$ – pressure; $k_{18}=W_0$ – volume of hydrosystem, $k_{19}=K_S$ – elasticity coefficient.

Inertial mass is function $x_9=f(k_{20})$ and is determined with the help of parameter: $k_{20}=m_0$ – total mass.

Based on these input parameters, set X of quantitative parameters of the whole process is formed (Table 1).

Thus, we will define a set of estimation parameters x_i i = $\overline{1,9}$, namely: x_1,...,x_9 – the values of which are calculated based of input parameters $k_1...k_{20}$.

Table 1

Set of parameters of technological complex

Name of parameter	Designation of parameter	Input parameters
System I (workpiece)	Y_1	$Y_1 = f(x_1...x_4)$
Mean density of workpiece, kg/m^3	x_1	k_1/k_2
Linear average dimensions of particles of material, m	x_2	k_3
Geometric factor for initial state of workpiece	x_3	k_4
Area of the open surface, m^2	x_4	k_5
System II (operation mode)	Y_2	$Y_2 = f(x_5...x_7)$
Specific static force, MPa	x_5	$k_6 \cdot k_7/k_5$
Duration of impact impulse, s	x_6	$\dfrac{2k_7 \cdot k_8}{k_8 \cdot \sqrt{\dfrac{k_{10}}{k_{12}}} - k_8 \cdot \sqrt{\dfrac{k_{11}}{k_{13}}}}$
Full time of working stroke, s	x_7	$k_{14} \cdot k_{15}$
System III (machine)	Y_3	$Y_3 = f(x_8...x_9)$
Power of one-cycle hydroaccumulator, J	x_8	$k_{16} \cdot k_{17}/2k_{18}$
Inertial mass, kg	x_9	k_{19}

We define a set of output parameters $Z=(Z_1,...Z_j)$ according to the criteria of completeness and effectiveness, which makes it possible to fully satisfy the needs of consumers of the system [12, 18]. Let us look at each of

$$Z_j \ (j=\overline{1,3})$$

decisions Z_1 – excellent; Z_2 – normal; Z_3 – satisfactory; Z_4 – critical; Z_5 – unsatisfactory.

To construct the method of evaluation of the state of the technological complex based of a set of fuzzy sets, we will define set T of estimating linguistic terms, which is a set of values of linguistic variables. A linguistic variable is a variable that takes values from a set of words or word combinations of any language [19]. In our case, a linguistic variable is effectiveness of the technological complex (workpiece – operation process – machine). For many problems, which are solved within the human-machine system, the accuracy of the resulting decision in terms of the level of the working state of the system allows us to identify the adequacy of:

– three – L (low), M (medium), H (high) (T=3);

– five linguistic terms – L (low), LM (lower than medium), M (medium), HM (higher than medium), H (high) (T=5).

This quantity T allows optimization (both by time criterion and by complexity) of the work of experts. Next, we will define polynomic membership functions μ^{Z_j}, $j=\overline{1,J}$ of values of parameters $(x_1,...,x_9)$ to linguistic terms.

$$\mu^H(x) = \begin{cases} 1, & x \in [a,a_1); \\ \left(\dfrac{k_1 - x}{k_1 - a_1}\right)^{0.8}, & x \in [a_1, k_1]. \end{cases} \quad (4)$$

$$\mu^{HC}(x) = \begin{cases} \left(\dfrac{x-a}{b-a}\right)^{1.2}, & x \in [a,b]; \\ 1, & x \in (b,b_1); \\ \left(\dfrac{k_1 - x}{k_1 - b_1}\right)^{0.8}, & x \in [b_1, k_1]. \end{cases} \quad (5)$$

$$\mu^{C}(x) = \begin{cases} \left(\dfrac{x-a}{c-a}\right)^{1.2}, & x \in [a,c]; \\ 1, & x \in (c,c_1); \\ \left(\dfrac{k_1 - x}{k_1 - c_1}\right)^{0.8}, & x \in [c_1, k_1]. \end{cases} \quad (6)$$

$$\mu^{BC}(x) = \begin{cases} \left(\dfrac{x-a}{d-a}\right)^{1.2}, & x \in [a,d]; \\ 1, & x \in (d,d_1); \\ \left(\dfrac{k_1 - x}{k_1 - d_1}\right)^{0.8}, & x \in [d_1, k_1]. \end{cases} \quad (7)$$

$$\mu^{B}(x) = \begin{cases} \left(\dfrac{x-a}{k-a}\right)^{1.2}, & x \in [a,k]; \\ 1, & x \in (k,k_1). \end{cases} \quad (8)$$

where a, a_1, b, b_1, c, c_1, d, d_1, k, k_1 are the values of characteristic points, which are defined by individual vision of involved experts.

Aggregated value of parameters $a,...,k_1$ for each of the indicators is calculated by the formula:

$$A_V = \sum_{s=1}^{d} k_{ns} \cdot EX_V, \quad (9)$$

where k_{ns} is the competence of the s-th expert; EX_V is the value of a parameter, given by the s-th expert.

We will calculate aggregated values of A_V parameters $(a...k_1)$ for indicator x_1 (average density of a workpiece ranges from 2.1 to 2.9 g/cm^3).

Parameter a: $A_V=2.1$; parameter a_1: $A_V=2.3$; parameter c: $A_V=2.5$; parameter c_1: $A_V=2.7$; parameter k: $A_V=2.8$; parameter k_1: $A_V=2.9$.

Similarly, we determine aggregated values of these parameters for all other indicators.

For more accurate efficiency estimation of process of shaping workpieces from powder materials on vibropress equipment with hydropulse drive, we will raise polynomic membership functions $\mu(x_i)$ to power α_i.

Then values of membership functions take the form:

$$\mu^{Z_j}(x_i) = \mu^{Z_j}(x_i)^{\alpha_j}, \quad j=\overline{1,J}(J=5), \ i=\overline{1,n} \ (n=16). \quad (10)$$

The final result is the highest of the values of membership functions μ^{Z_j}, i.e.:

$$\mu^{Z_j} = \max\{\mu^{Z_1}, \mu^{Z_2}, \mu^{Z_3}, \mu^{Z_4}, \mu^{Z_5}\}. \quad (11)$$

Extreme values of polynomic membership functions (11) for a set of output parameters $Z=(Z1,...,Zj)$ characterizes the optimality of group $Y_1...Y_3$ of parameters of efficiency of functioning of technological complex by the criteria of completeness and effectiveness.

5. Results of examining parameters of technological process of shaping workpieces from powder materials

To receive dependences of characteristics of the studied technological process, we select the quality of a workpiece as the major criterion for evaluation of the method of shaping. Quality of workpiece of the product should be achieved through relevant parameters: average density and uneven density of a workpiece by the volume under conditions of waste-free production, excluding further mechanical treatment.

For the theoretical study of technological shaping process, four samples of powdered materials were selected [12]:

– M1 – mineral powder NEF (humidity 13 %, lipid bond 3,2 %);

– M2 – mineral powder NEF (humidity 2 %, bond is missing);

– M3 – silicon carbide green No. 4, 10, 12, M28 – 80 % (bakelite 10 %, coke 10 %);

– M4 – fire-resistant chammote (humidity 13,8 %, clay bond 31,2 %).

Therefore, based on the above-developed models of fuzzy sets, we devised an algorithm [20, 21] to determine mean density of a workpiece for three kinds of modes of treatment of VIP (Fig. 8), which depends on changes in the energy of one-cycle hydraulic accumulator E_a, as well as on frequency of vibration of workpiece f.
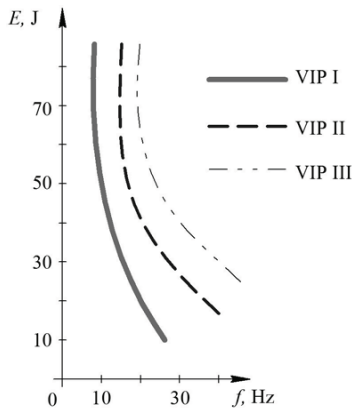

Fig. 8. Graph of types of modes of treatment VIP of workpieces from powder materials

This algorithm was implemented on computer, the results of which are presented in Fig. 9. As a result of calculation, we obtained graphs (Fig. 9) of dependence of change in average density of a workpiece depending on:

– static load of a workpiece – P, MPa;

– frequency of vibration of a workpiece – f, Hz;

– energy of one-cycle hydraulic accumulator E_a, J;

– uneven density of a workpiece – ε_ρ, %.

Graphical interpretation (Fig. 9) by the method of fuzzy sets in the environment MAPLE 10.0 received the following estimation values of input parameters:

– M1 – $\mu_{M1}^{Z_j} = \max \mu^{Z_{1,...5}}(x_1,..,x_9) = 0.836$;

– M2 – $\mu_{M2}^{Z_j} = \max \mu^{Z_{1,...5}}(x_1,..,x_9) = 0.842$;

– M3 – $\mu_{M3}^{Z_j} = \max \mu^{Z_{1,...5}}(x_1,..,x_9) = 0.901$;

– M4 – $\mu_{M4}^{Z_j} = \max \mu^{Z_{1,...5}}(x_1,..,x_9) = 0.768$.

Based on extreme values of polynomic membership functions for each type of powder material, we identified the most effective modes of vibroimpact pressing, namely for M1 and M2 – VIP–1, for M3 – VI –III and M4 – VIP–II.
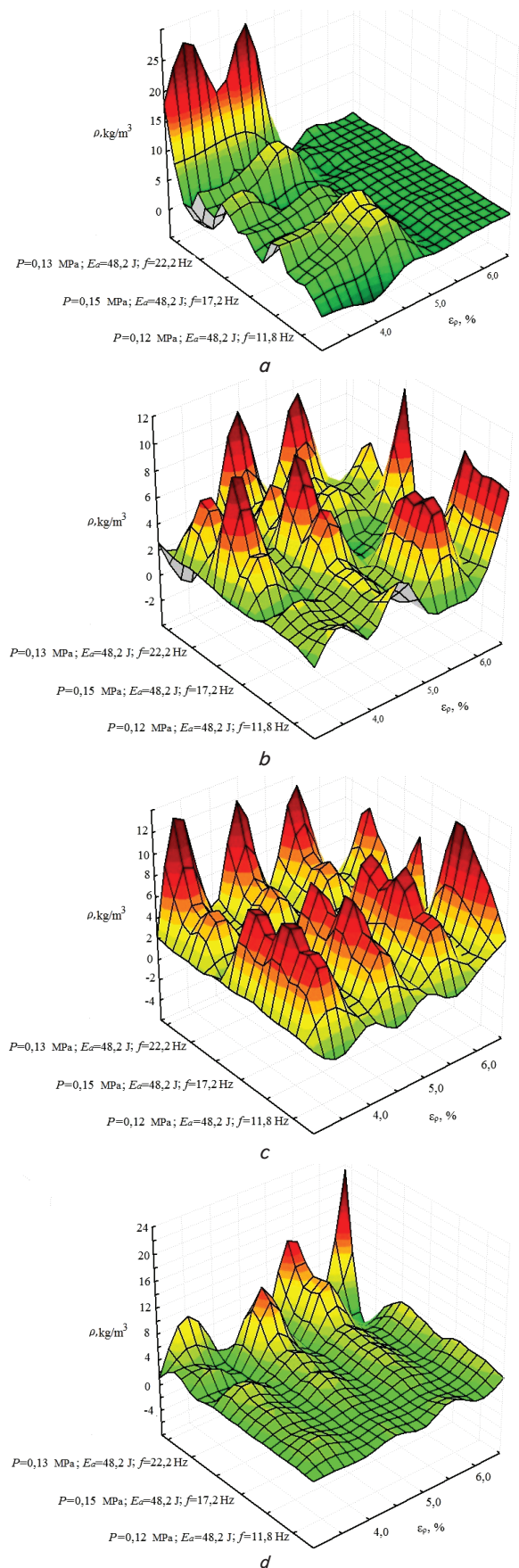

Fig. 9. Graph of change in the mean density of obtained workpiece from processable materials depending on changes of technological parameters of VIP: *a* — material M1; *b* — material M2; *c* — material M3; d — material M4

6. Discussion of results of examining technological parameters of shaping workpieces from powder materials

For theoretical examination of effectiveness of the technological process of shaping workpieces, we used a method of fuzzy sets [11, 12–20]. The value of membership functions

$$\mu^{Z_j} = \max\left\{\mu^{Z_1}, \mu^{Z_2}, \mu^{Z_3}, \mu^{Z_4}, \mu^{Z_5}\right\},$$

for a set of output parameters

$$Z=(Z_1,...,Z_5),$$

by the criteria of completeness and effectiveness, we identified concentration of minimum values average density and ineven density of output workpieces from the studied materials. For the material from mineral powders M1, the set of optimal technological indicators in mode VIP-1 makes for average density of material ρ=2.3 kg/m^3 for uneven density ε_ρ=6.5 %. Evaluation of the treated material from mineral powders M2 is slightly separated compared with the data, obtained in mathematical model, namely, presents appropriateness of applying a combination of technological modes VIP-I and VIP–II, in which qualitative characteristics gain the values: in the case of analysis of average density, its minimum value ρ=1.9 kg/m^3 is observed at VIP-II, in the case of analysis of uneven density, the minimum value ε_ρ=2.3 % – VIP-I. Studying the output samples, formed at M3, showed that optimal values of average density of material ρ=4.7 kg/m^3 and uneven density ε_ρ=3.9 % are observed at mode III of vibroimpact pressing. In the case of assessment of qualitative characteristics of pressed materials from fire-resistant chamotte M4, it should be noted that the minimum value of average density and uneven density, respectively, ρ=3.8–4.2 kg/m^3 and ε_ρ=2.5–2.9 % are observed at VIP–I and VIP–II.

An analysis of matrix of knowledge for evaluating groups of parameters $(Y_1,...Y_3)$ of qualitative characteristics of the studied materials showed that optimal technological parameters of treating material M1, M2 is pressure P=0.12 MPa, M3 – P=0.15 MPa, M4 – P=0.13 MPa. However, we should note an increase in the studied indices of average density and uneven density of treated material at an increase in power characteristics of treatment and a decrease in frequency of technological impact.

The value of qualitative parameters of material M1 (density and uneven density of the treated material) under conditions of operation mode P=0.12 MPa; E_a=85.8 J; f=8.2 Hz is accompanied by significant energy consumption under conditions of a decrease in quality characteristics.

Changing the magnitude of energy E_a within a particular mode of VIP, one can provide an increase or a decrease in average density of a sample from any given powder material, to its underpressing or overpressing [1, 3, 12]. For constant magnitude of energy E_a, an increase in duration of VIP process allows us to increase the average density of workpieces only to a certain boundary. Further increase in average density of a sample practically remains the same, while the quality decreases significantly as a result of overpressing and destruction.

7. Conclusions

1. We analyzed the process of shaping workpieces from powder materials and defined an increase in average density of workpieces by 60–70 % relatively to static pressing, by vibration or vibroimpact method of treatment based on the developed structure of vibropresss shaping machines, types of drives and their characteristics.

2. Based on the systems approach and formulated set of design parameters of technological equipment, a mathematical model for determining the mean density of workpiece was developed. It was shown that it is a set of original input design and estimation technological parameters (workpiece, operation process, machine) and functions of transformation of initial parameters to evaluation function. Based on the sets of estimation parameters, we derived polynomial membership functions for assessing characteristics of vibroimpact loading mode of the process of shaping workpieces from powder materials.

3. Using an extremum of the array of values of membership functions as a criterion of completeness and effectiveness, effective modes of vibroimpact loading were chosen for the sets of mean density of workpiece from four samples of powder materials. For types of pieces:

– mineral powder NEF (humidity 13 %, lipid bond 3.2 %), and mineral powder NEF (2 % humidity, bond is missing) – vibroimpact mode of type I (average power of hydraulic accumulator E_a=55.3 J, frequency of vibration of a workpiece – f=11.2 Hz);

– silicon carbide green No. 4, 10, 12, M28 – 80 % (bakelite 10 %, coke 10 %) – vibroimpact mode of type I (average power of hydraulic accumulator E_a=55.3 J, frequency of vibration of workpiece – f=11.2 Hz) and type II (average power of hydraulic accumulator E_a=62.8 J, frequency of workpiece vibration – f=17.28 Hz);

– fire resistant shammot (humidity 13.8 %, clay bond 31.2 %) – vibroimpact mode of type I (average power of hydraulic accumulator E_a=55.3 J, frequency of workpiece vibration – f=11.2 Hz) and type III (average power of hydraulic accumulator E_a=62.8 J, frequency of workpiece vibration – f=17.28 Hz).

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