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AUTOMATED PRODUCTION OF LARGE-DIMENSION ARTICLES OF COMPLEX GEOMETRIC SHAPE ON HYDRAULIC PRESS EQUIPMENT

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Analytical relationships that permit determination of interrelation between the basic characteristic of the material in a large-dimension article being formed into a complex geometric shape – density, and the production parameters of compaction force and embedment time during its production by the method of multiple-stage compaction, are derived.

Production processes and equipment for the treatment of solid disperse materials and compositions based on them (granular mineral fertilizers, construction materials, polymers, detergents, dyestuffs, etc.) and articles produced from them are in widespread use in the chemical and chemical-related industries.

Processes involving compaction under pressure are used for the production of a broad nomenclature of large-dimension articles of complex geometric shape.

In contrast to compaction of the simplest articles in the form cartridges, tablets, and briquettes, the shaping of large-dimension articles cannot, in the majority of cases, be accomplished by a single force-loading production procedure. The primary difficulty consists in attainment of the required density of the article being shaped at all of its points, which is virtually impossible under a single compactive effort. The required qualitative and quantitative characteristics of the article produced (strength, density, density distribution over the height and radius, absence of cracks, cleavages, and other defects) are achieved by selecting a separate compaction regime for each type of articles.

The modern procedure for compaction of articles of complex geometric shape calls for two steps. In the first step, one (or more) blank of the future article is formed from a free-flowing material by the cold-compaction method on hydraulic presses. In the second step, components of the article are assembled, and compacted (at an elevated temperature, if necessary) as a single unit.

Various designs of hydraulic presses are traditionally used to compact articles of complex geometric shape. A number of compactors equipped with control systems capable of implementing complex schemes of forced loading during compaction are currently under development [1, 2]. Figure 1 shows a segment of the circuit for a hydraulic press of the type in question.

The hydraulic press is equipped with a remote pressure-regulating system for compaction, which includes safety valve *6* with proportional electric control, analog pressure transducer *3*, cut-off hydraulic distributor *7* with throttles *8* and *9*, and a programmed controller, which consists of units *12–16*.

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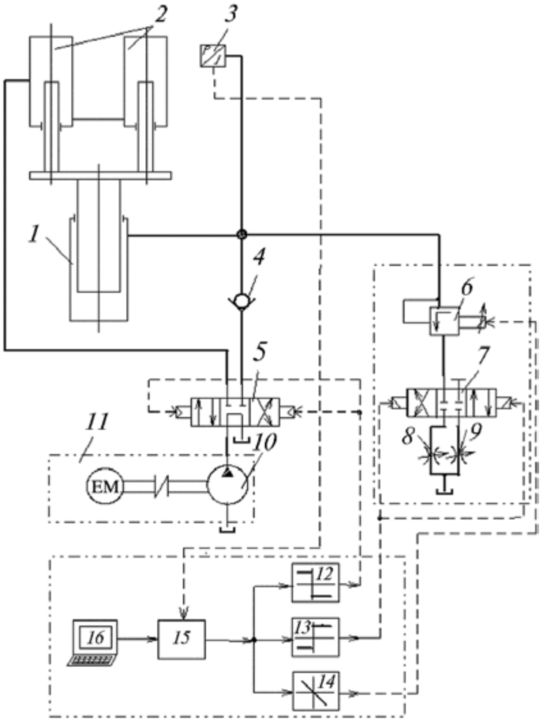

Fig. 1. Segment of circuit for automated 4000-kN Model 9636 hydraulic press: *1*) plunger type of working cylinder; *2*) return cylinders; *3*) analog pressure transducer; *4*) check valve; *5*) three-position hydraulic distributor; *6*) safety valve with proportional electric control; *7*) cut-off hydraulic distributor; *8*, *9*) throttles; *10*) pump; *11*) hydraulic station; *12*) control unit for hydraulic distributor; *5*, *13*) control unit for hydraulic distributor *7*; *14*) control unit for valve *6*; *15*) comparison unit; *16*) set-up unit.

Safety valve *6* is the determining element of the remote pressure-control system, which provides the assigned loading regime generated by the programmed controller.

Set-up unit *16*, which is an automated work place for an operator or process engineer, is based on a personal computer (PC), and is designed to input initial compaction parameters to the program, and process them. Time parameters for compaction are used directly by the programmed controller, and force parameters are converted to the pressure of the hydraulic system of the press with allowance for its characteristics. Curves of the compaction pressure versus time t in the form of a function $p = f(t)$, which reflects the force-loading scheme (Fig. 2), where p is the pressure in working cylinder *1* of the press, are plotted on the basis of the compaction parameters.

The PC managing the automated control system of the press utilizes the compaction parameters in developing algorithms for implementation of a loading scheme as an assignment to the control and regulating units.

Use of modern hardware and software makes it possible to create an electronic catalogue listing a broad range of articles that can be compacted. A set of compaction parameters, which define the force-loading scheme, corresponds to each type of articles. In selecting the type of article, these parameters are automatically rewritten from the catalogue to the programmed controller for implementation. Moreover, the catalogue stores a library of archival files with a record of assigned, and actually implemented parameters in the compaction process; when necessary, this makes it possible to recall the production history of each article.

Despite the high level of automation of the compaction equipment, however, the initial compaction parameters are, as before, determined experimentally, and there are no computed characteristics. The operator inputs the initial compaction parameters to the compaction-cycle program separately for each type of articles.

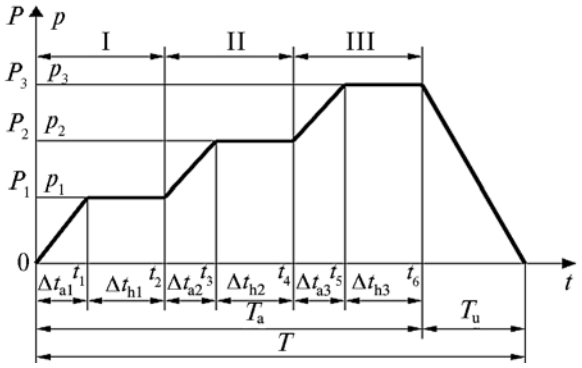

Fig. 2. Dependence of compaction pressure p during three-step compaction of large-dimension article of complex geometric shape on compaction time t: I–III) compaction steps.

Experimental investigations of the compaction of articles of complex geometric shape indicate the feasibility of enhancing their qualitative characteristics by use of the so-called stepwise (repeated) loading scheme, which is governed by alternation of increasing pressure and subsequent holding under a constant pressure; this contributes to a reduction in the resistance of the material being compacted to elasto-plastic deformation, occurrence of relaxation processes, and a reduction in internal stresses [3].

At the present time, however, there are no data in the literature, which make it possible to determine the quantitative interrelation between the parameters of multiple-step compaction and the final characteristics of the compressed article with allowance for the rheologic and physicomechanical characteristics of the material being compacted.

In formulating a theoretical approach to solution of the stated problem, it is necessary to consider the two most critical production characteristics relative to the compaction of articles of a complex geometric shape.

The first production characteristic consists in repeated alternation of compaction steps during force loading with increasing pressure and subsequent holding at a constant pressure. The step of active material deformation where the basic change in its density occurs by a magnitude $\Delta\rho_a$, and holding at a constant pressure ensures an additional increase $\Delta\rho_h$ in the material's density as a result of bulk creep, is characterized by a pressure that increases over time. The final density ρ_f on completion of the compaction process can then be represented as

$$\rho_f = \rho_0 + \sum_{i=1}^{n_s} (\Delta\rho_{ai} + \Delta\rho_{hi}),$$

where n_s is the number of compaction steps, and ρ_0 is the initial density of the material (at the start of loading).

In the production of articles of complex geometric shape, the number of alternating loading steps is usually assumed equal to three, provisionally with respect to the number of phases in the deformation process [4]. The first phase is characterized by the displacement and mutual binding of the particles, the second phase by brittle and plastic deformations of these particles, and the third by their three-dimensional compression.

The second production characteristic consists in the fact that since the material of the article is compacted by the assignment of a rate of compaction (as, for example, in the rapid-action press of a rotary type of equipment), and the force-loading scheme in the form of the function $p = f(t)$, since the rate of bulk deformation is an arbitrary quantity that can be defined by the current pressure, and varies at each point in time t. Its average value in each load step can be represented as

$$\langle \dot{\varepsilon}_V \rangle = \varepsilon_V / \Delta t, \quad (1)$$

where ε_V is the expected deformation, and Δt is the deformation time.

TABLE 1

Compaction step	Loading stage	Time period, sec	Compactive pressure		
			initial	current	final
I	Compaction	$\Delta t_{a1} = 0–t_1$	0	$p(t) = K_1(t - 0)$	$p_1 = K_1 t_1$
	Holding at p_1 = const	$\Delta t_{h1} = t_1–t_2$	p_1	p_1	p_1
II	Compaction	$\Delta t_{a2} = t_2–t_3$	p_1	$p(t) = p_1 + K_2(t - t_3)$	$p_2 = p_1 + K_2(t_3 - t_2)$
	Holding at p_2 = const	$\Delta t_{h2} = t_3–t_4$	p_2	p_2	p_2
III	Compaction	$\Delta t_{a3} = t_4–t_5$	p_2	$p(t) = p_2 + K_3(t - t_4)$	$p_3 = p_2 + K_3(t_5 - t_4)$
	Holding at p_3 = const	$\Delta t_{h3} = t_5–t_6$	p_3	p_3	p_3

Figure 2 shows a graphic, and Table 1 an analytical representation of the dependence of the pressure p on time t for three-step compaction, where K_1–K_3 are proportionality factors in the law governing the change in pressure p in the stages of active loading, and t_1–t_6 are the times that determine the boundaries of active and passive loading. Here, it is necessary to note that modern control systems of automated compaction equipment can actually implement any forced-loading algorithm. Implementation of a rectilinear scheme of pressure variation, which ensures the attainment of guaranteed accuracy and reliability of reproducibility of the compaction algorithm adopted is most widespread and acceptable in technical respects.

The limiting-equilibrium theory has found practical application for investigation of the stress-train state of solid disperse media, the density and physicomechanical characteristics of which are varied during compaction under pressure; this is inherent to the shaping of articles formed from powder materials. Basic positions of this theory can be used for the analytical modeling of stepwise loading during the forming of an article of complex geometric shape. According to Generalov [5], the average normal stress σ_{avg} is the basic parameter in the computational scheme of compaction under a static force effect, since it is precisely this stress that causes a change in volume, and is invariant with respect to shaping density of the material being compacted. Using the relationship $\rho = f(\sigma_{\text{avg}})$, the stress σ_{avg} is selected with respect to the density ρ, which must be achieved in conformity with technical specifications relative to the article in questions. The relationship between the selected stress σ_{avg} and compactive pressure p (compaction force P) will depend, in turn, on the method and conditions of compaction, the geometric dimensions of the article, and the rheologic properties of the material being compacted. Generalov [5] has derived expressions establishing the quantitative interrelation between σ_{avg} and p for certain types of articles, for example, large-dimension articles with a characteristic conical recess. As a result, it is possible to calculate the required compactive force P that will ensure development of the required average normal stress σ_{avg} at any point of the material undergoing compaction in an article of complex geometric shape.

The compactive force (pressure) determined in this manner will provide for the required density of the article, which can be achieved under a static load. Since under real conditions, the article is compacted at a certain rate, and the shaping regime differs from the static, the remaining parameters of the process must be selected and analyzed, proceeding from considerations of maximum approximation of the final density obtained for the article to a density invariant to the selected stress σ_{avg}.

During multiple-step shaping, the compactive pressure p_i and stress $\sigma_{\text{avg}i}$ in each intermediate ith load step can be expressed in terms of the maximum pressure p and stress σ_{avg} using a load factor $C_{li} \le 1$:

$$p_i = C_{li} p; \quad \sigma_{\text{avg}i} = C_{li} \sigma_{\text{avg}}.$$

With the same load increase in each step of the three-step compaction, we then obtain: $C_{l1} = 0.33$, $C_{l2} = 0.66$, and $C_{l3} = 1$.

For a linear change in compactive pressure over time with a constant loading rate in all steps of the compaction, the pressure is determined from the formula $p = Kt$ (see Table 1), where $K = K_1 = K_2 = K_3$, and the time of the active loading in the ith step of the compaction Δt_{ai} from the formula

$$\Delta t_{ai} = \frac{p_i - p_{i-1}}{K} = p\left(\frac{C_{li} - C_{li-1}}{K}\right).$$

It is known that the bulk deformation of solid disperse materials under the action of external loads qualitatively brings to mind the behavior of nonlinear bulk-hardening systems, while the structural bonds – both rigid, and also viscous – exert a major influence on the character of the deformation [5]. In this connection, Boltzmann's superposition principle can be applied to the theory of viscoelasticity, according to which the overall stress-strain state of the pressing is determined by the stresses that developed during viscous bulk deformation.

The relationship between the stress and strain parameters can then be expressed by a rheologic equation of the form

$$\sigma_{\text{avg}} = E_{\text{com}}\varepsilon_V + \chi\frac{d\varepsilon_V}{dt}, \tag{2}$$

where E_{com} is the bulk-compression modulus of the material, χ is the viscosity of the material, and ε_V is the relative bulk deformation of the material.

Using Eq. (1), the dependence of the relative bulk deformation ε_{ai} in the stage of active loading on the average normal stress can be derived from Eq. (2):

$$\varepsilon_{ai} = \frac{m\left(\dfrac{\sigma_{\text{avg}}}{\sigma_0}\right)^n \left(C_{li}^n - C_{li-1}^n\right)}{1 + \dfrac{\lambda_i}{\Delta t_{ai}}},$$

where m and n are rheologic parameters characterizing the static deformation of the material being compacted (determined by experimental means); λ_i is the retardation time, which depends on the rate of bulk deformation $\dot{\varepsilon}_{ai}$ in the ith step of the stage of active loading; and $\sigma_0 = 0.1$ MPa.

The density of the article in the stage of active loading can be determined from the formula

$$\rho_{ai} = \rho_{\text{h}i-1}\frac{1}{1 - \varepsilon_{ai}},$$

where $\rho_{\text{h}i-1}$ is the density of the material, which is obtained in the holding stage at the constant pressure of the preceding step (the initial density ρ_0 should be used for the first active loading in lieu of the density $\rho_{\text{h}i-1}$).

Since two stages exist simultaneously in the same step of the material's deformation – active loading and holding at a constant pressure – the relationship between them is determined in the following manner.

The maximum (static) bulk compressive deformation ε_V for a given stress σ_{avg}:

$$\varepsilon_V = \sigma_{\text{avg}}/E_{\text{com}}. \tag{3}$$

Here, the final density of the article is determined by the expression

$$\rho_{\text{f}} = \rho_0\frac{1}{1 - \varepsilon_V} = \rho_0\frac{1}{(1 - \varepsilon_{\text{a}})(1 - \varepsilon_{\text{h}})}.$$

For this reason, it follows that when a stage of active loading exists, the maximum deformation in the stage of holding is limited to the quantity

$$\varepsilon_{\text{h max}} = \frac{\varepsilon_V - \varepsilon_{\text{a}}}{1 - \varepsilon_{\text{a}}}. \tag{4}$$

Integrating rheologic equation (2) and making use of Eqs. (3) and (4), it is possible to obtain the relative bulk deformation in the holding stage at a constant pressure $\varepsilon_{\mathrm{h}i}$ as a function of the holding time $t_{\mathrm{h}i}$:

$$\varepsilon_{\mathrm{h}i} = \frac{\left[(\sigma_{\mathrm{avg}} / E_{\mathrm{com}}) - \varepsilon_{\mathrm{a}i}\right] C_{li}}{1 - \varepsilon_{\mathrm{a}i}} \left[1 - \exp\left(\frac{t_{\mathrm{h}i}}{\lambda_i}\right)\right].$$

The density of the material on completion of holding is determined from the formula $\rho_{\mathrm{h}i} = \rho_{\mathrm{a}i}/(1 - \varepsilon_{\mathrm{h}i})$, where $\rho_{\mathrm{a}i}$ is the density of the material, which is obtained in the stage of active loading during the previous step.

In generalized form, the expression for calculation of the final density of the article after n_{s} compaction steps will assume the form

$$\rho_{\mathrm{f}} = \frac{\rho_0}{(1 - \varepsilon_{\mathrm{a}1})(1 - \varepsilon_{\mathrm{h}1}) \ldots (1 - \varepsilon_{\mathrm{a}n})(1 - \varepsilon_{\mathrm{h}n})}. \tag{5}$$

Expression (5) can be used to solve the inverse problem – determination of the holding time at the maximum pressure required to obtain the density ρ_{f} of the material.

In addition to achieving the assigned density of the material, the most important problem in the production of articles of complex geometric shape on automated compaction equipment is the high quality of these articles.

Internal (residual) stresses may cause various defects in a compacted article in the form of cracks between layers, or a change in its shape and geometric dimensions. A characteristic feature of stress relaxation in solid disperse bodies consists in the fact that they do not drop to zero, but merely diminish to a certain value, and remain constant thereafter. It is experimentally established that during holding at a constant pressure, the absolute residual stresses are reduced, and the character and direction of their propagation within the article are changed. Here, holding over a period of time commensurate with the relaxation time – a rheologic parameter of the article's material – leads to a reduction in the level of dangerous residual tensile stresses, and a continued increase in the holding time will not have a significant effect.

With an exponentially approximated curve of stress reduction, it is possible to derive an expression for determination of the holding time at a constant pressure in the *i*th step of the compaction stage in the form

$$t_{\mathrm{h}i} \geq t_{\mathrm{r}i} \ln \left[\frac{\dfrac{3\sigma_{\mathrm{avg}} K_{li}}{1 + 2\xi} - \sigma_\infty}{[\sigma_{\mathrm{t}}] - \sigma_\infty} \right],$$

where σ_∞ is the minimal residual stress that will not vary over time, ξ is the coefficient of lateral pressure for the material being compacted, $[\sigma_{\mathrm{t}}]$ is the ultimate tensile strength of the pressing, the density of which corresponds to the maximum compactive stress, and $t_{\mathrm{r}i}$ is the relaxation time.

To determine the time $t_{\mathrm{r}i}$, it is possible to make use of the dependency of the relaxation time (as a rheologic parameter) on the density of material being compacted. In the general case, the relaxation time $t_{\mathrm{r}i}$, as determined by the increase in density in the *i*th step, is defined as $t_{\mathrm{r}i} = t_{\mathrm{r}}(\rho_i) - t_{\mathrm{r}}(\rho_{i-1})$, where $t_{\mathrm{r}}(\rho_i)$ and $t_{\mathrm{r}}(\rho_{i-1})$ are the relaxation times for the densities ρ_i and ρ_{i-1}.

As a result, the duration T_{a} of the entire cycle of multiple-step compaction of the entity (when $n_{\mathrm{s}} = 3$) can be determined from the formula

$$T_{\mathrm{a}} = \sum_{i=1}^{n_{\mathrm{s}}=3} (\Delta t_{\mathrm{a}i} + \Delta t_{\mathrm{h}i}).$$

The concluding step of the compaction is an unloading operation, which consists in a stepwise reduction in pressure from maximum to zero. Here, the unloading scheme (a smooth or stepwise curve), and, of course, also the time required to

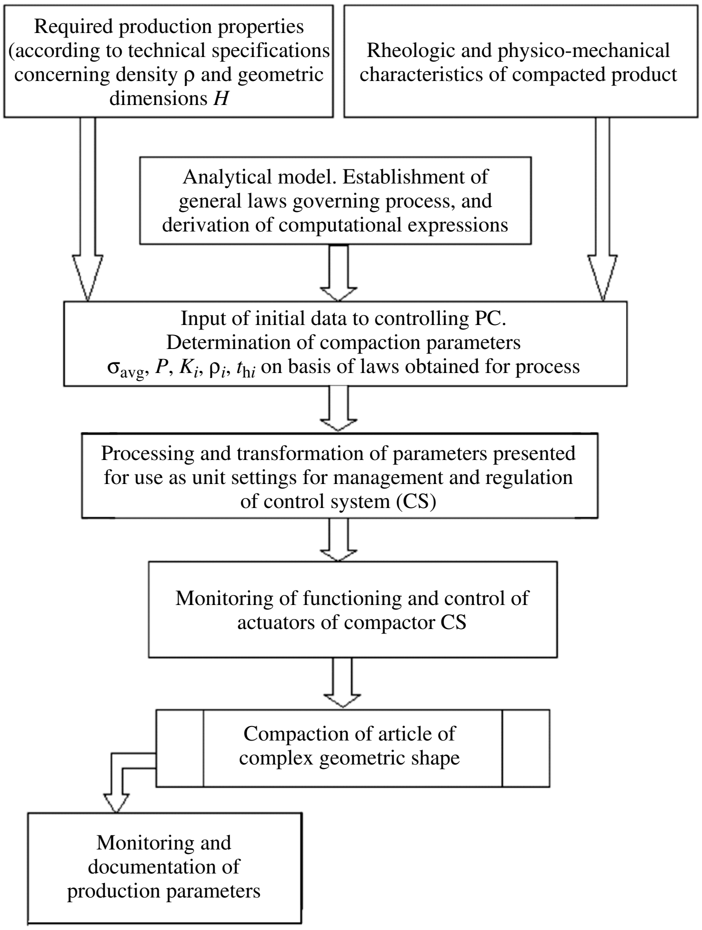

Fig. 3. Algorithm for calculation and implementation of production parameters required to form articles of complex geometric shape.

complete the operation in question T_u (see Fig. 2) must be selected proceeding from the condition whereby elastic deformations are smoothly restored as a result, and do not cause the article to crack.

Expressions that make it possible to link one of the key characteristics of the material in the article being formed – density – with the following multiple-step compaction parameters are derived as a result of these investigations: the maximum and intermediate compactive forces (pressures), the time (rate) of active loading, and the holding time at a constant pressure in each of the intermediate steps, and at the maximum pressure. Use of modern control systems for a hydraulic type of compactive equipment will permit the creation of a closed, completely automated production cycle for large-dimension articles of complex geometric shape. Here, the program controlling the press determines the force and time parameters of the shaping on the basis of a developed computational procedure and ensures their implementation in conformity with the algorithm presented in Fig. 3.

Conclusions

1. Analytical relationships permitting determination of the interaction between the basic characteristic of the material being formed within a large-dimension article of complex geometric shape – density – and the following production parameters of the compaction, are derived: the force and loading time during its production by the method of multiple-step compaction.

2. Computed production parameters can be defined directly in the computer controlling the automated compaction-control system, where an electronic catalogue of types of compacted articles is created; this catalogue includes a database of compaction parameters that can be used in assignments given to control and regulation units, and an archival library as well.

3. The results obtained are used in algorithms for the operation of automated hydraulic presses, which have the capacity to implement complex force-loading schemes for the production of large-dimension articles of complex geometric shape with a given material density, and which provide for the production of a broad listing of quality articles with different production characteristics.

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