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CONTENTS

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
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RHEOLOGICAL MODEL OF MOLDING MIXTURES IN FOUNDRY MACHINES

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Abstract. The proposed paper deals with the actual problem of molding mixture density control under dynamic loading, which plays an important role in foundry production. The study is based on a five-element rheological model that takes into account elastic, viscous and plastic properties of the mixture. The model is formed in the form of a system of differential equations, which allows to realize it in the form of a numerical algorithm and to predict the change of the mixture density in time at given loads. The model is oriented for application in conditions of real foundry production. Numerical methods of calculation based on differential equations and experimental data were used for analysis. The main hypotheses of the work are that the density of the molding mixture is determined not only by the applied stresses, duration of their action, but also by the rheological parameters of the medium. The obtained dependences allow predicting the change of the mixture density in time under different types of dynamic loads. The conducted studies confirm that the five-element rheological model more accurately predicts the dynamics of compaction compared to traditional three-element models. The developed methodology and calculation algorithm can be applied in the foundry industry to optimize the composition of mixtures, improve the quality of castings and develop new compaction technologies. The application of machine learning can be integrated into foundry machine control systems to adjust and optimize operating parameters in real time and improve production efficiency. The obtained results provide a basis for further research in the field of rheology of molding mixtures and can be used in the design of equipment for foundry production.

Keywords: rheological model, molding mixture, foundry machines, modeling

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ҚҰЙЫП-ҚАЛЫПТАСТЫРАТЫН МАШИНАЛАРДЫҢ ҚАЛЫПТАСТЫРУ ҚОСПАСЫНЫҢ РЕОЛОГИЯЛЫҚ МОДЕЛІ

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Аннотация. Ұсынылған мақалада құю өндірісінде маңызды рөл атқаратын динамикалық жүктеме кезінде қалыптау қоспасының тығыздығын басқарудың өзекті мәселесі қарастырылады. Зерттеудің негізі қоспаның серпімді, тұтқыр және пластикалық қасиеттерін ескеретін бес элементті реологиялық модель болып табылады. Модель дифференциалдық теңдеулер жүйесі түрінде қалыптасады, бұл оны сандық алгоритм түрінде жүзеге асыруға және берілген жүктемелер кезінде қоспаның тығыздығының уақыт бойынша өзгеруін болжауға мүмкіндік береді. Модель нақты Құю өндірісі жағдайында қолдануға бағытталған. Талдау үшін дифференциалдық теңдеулер мен эксперименттік мәліметтерге негізделген сандық есептеу әдістері қолданылды. Жұмыстың негізгі гипотезалары — қалыптау қоспасының тығыздығы қолданылатын кернеулерден ғана емес, олардың әсер ету ұзақтығынан да, қоршаған ортаның реологиялық параметрлерінен де анықталады. Алынған тәуелділіктер әртүрлі динамикалық жүктемелер кезінде қоспаның тығыздығының уақыт бойынша өзгеруін болжауға мүмкіндік береді. Жүргізілген зерттеулер бес элементті реологиялық модель дәстүрлі үш элементті модельдермен салыстырғанда тығыздау динамикасын дәлірек болжайтынын растайды. Әзірленген есептеу әдістемесі мен алгоритмін құю өнеркәсібінде қоспалардың құрамын оңтайландыру, құю сапасын жақсарту және жаңа тығыздау технологияларын әзірлеу үшін қолдануға болады. Машиналық оқытуды қолдану нақты уақыт режимінде жұмыс параметрлерін реттеу және оңтайландыру және өндіріс тиімділігін арттыру үшін құю машиналарын басқару жүйелеріне біріктірілуі мүмкін. Нәтижелер қалыптау қоспаларының реологиясын одан әрі зерттеуге негіз береді және құю жабдықтарын жобалауда қолданылуы мүмкін.

Түйін сөздер: реологиялық модель, қалыптастыру қоспа, құйып-қалыптастыратын машиналар, модельдеу

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РЕОЛОГИЧЕСКАЯ МОДЕЛЬ ФОРМОВОЧНЫХ СМЕСЕЙ ЛИТЕЙНЫХ МАШИН

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Аннотация. В предлагаемой статье рассматривается актуальная проблема управления плотностью формовочной смеси при динамическом нагружении, играющая важную роль в литейном производстве. В основу исследования положена пятиэлементная реологическая модель, учитывающая упругие, вязкие и пластические свойства смеси. Модель сформирована в виде системы дифференциальных уравнений, что позволяет реализовать ее в виде численного алгоритма и прогнозировать изменение плотности смеси во времени при заданных нагрузках. Модель ориентирована на применение в условиях реального литейного производства. Для анализа использовались численные методы расчета на основе дифференциальных уравнений и экспериментальные данные. Основные гипотезы работы заключаются в том, что плотность формовочной смеси определяется не только от приложенных напряжений, длительности их действия, но и от реологических параметров среды. Полученные зависимости позволяют прогнозировать изменение плотности смеси во времени при различных видах динамических нагрузок. Проведенные исследования подтверждают, что пятиэлементная реологическая модель более точно предсказывает динамику уплотнения по сравнению с традиционными трехэлементными моделями. Разработанная методология и алгоритм расчета могут быть применены в литейной промышленности для оптимизации состава смесей, повышения качества отливок и разработки новых технологий уплотнения. Применение машинного обучения может быть интегрировано в системы управления литейными машинами для регулировки и оптимизации рабочих параметров в режиме реального времени и повышению эффективности производства. Полученные результаты обеспечивают основу

для дальнейших исследований в области реологии формовочных смесей и могут быть использованы при проектировании оборудования для литейного производства.

Ключевые слова: реологическая модель, формовочная смесь, литейные машины, моделирование

Introduction. The production of complex metal products often requires casting, one of the most common methods of forming metal workpieces. In order to obtain quality castings with a minimum number of defects, it is necessary to use appropriate molding compounds (Major-Gabryś, 2019: 2).

Molding mixtures are compositions used to create molds into which molten metal is poured. These mixtures consist of a basic binder, sand and additives that improve their properties. (Davis, 1979: 1). The binder can be clay, water or a polymer material. Various types of sand are used in molding mixtures, such as quartz sand, granular sand or chromite sand. The type and particle size distribution of sand determine key properties such as strength, hardness and porosity. Additives in molding mixtures can be organic or inorganic, including waxes, grease, graphite, silicates, metal powders and other substances. (Isagulov, et al., 2006: 3; Hoque et al, 2010: 73). Additives improve the properties of molding compounds: heat resistance, ease of separation from the casting, and reduction of deformation.

Molding compounds are used in various types of casting machines, including cold casting machines, continuous casting machines and rotary table machines. Each machine type has its own specific requirements for the properties of the molding compound. An important factor in selecting a molding compound is the metal from which the casting is made, since different metals have different requirements for the composition of the molding compound For example, rotary table machines require a highly stable molding compound that does not deform as the table rotates. Gravity casting machines require a molding compound with high plasticity to produce long castings without fractures. Most castings are made in disposable sand molds. The quality of these molds directly affects the dimensional accuracy and surface quality of the castings (Zhang, 2017:34). The main factors affecting the quality of castings are the composition of the molding mixture, its density, and the density distribution over the height of the mold. Increasing the density of the mixture increases mold strength, improves surface quality, reduces gas permeability and decreases the likelihood of mold erosion. Analyzing the compaction process is necessary to ensure casting quality and to design efficient equipment by adjusting parameters such as power, pulse duration and frequency (Matveenko et al, 1998: 25).

Materials and methods of research. A characteristic feature of dynamic compaction is the induced stresses, which reach high values but last for a very short time. As a result, the mixture is not fully compacted in one impact and repeated impacts are required to achieve the required density (Boldin, 2003: 264; Boldin, et al., 2024: 179). Consequently, the final density of the mixture depends not only on the level of stresses, but also on the duration of their continuation, which requires analyzing the viscous properties of the medium.

Of the existing many experimental models that describe the change in mixture density under different types of dynamic effects such as impact, compaction with impact, shaking and pulsation (Sheklein et al., 2004: 13). These models are only suitable for certain loading conditions and certain types of sandy clay mixtures (SCMs). The development of universal analytical models requires consideration of the compaction process using rheological models that best describe the elasticity, viscosity, and plasticity of the medium (Verbitsky et al., 2024: 2). One of the well-known models is a semi-empirical formula proposed by G.M. Orlov, which is based on a three-element model without taking into account elastic deformations (Orlov, 1988: 201).

This study employs a five element rheological model to calculate the density of the molding mixture under dynamic loads. A schematic representation of the five element rheological model is shown in Figure 1.

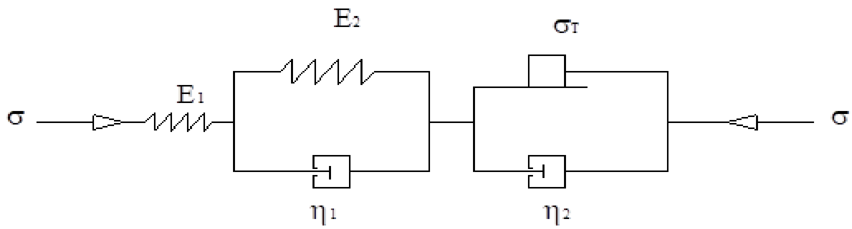

Figure 1– Five element rheological model

The first element of the model is Spring 1, with an elastic modulus E1, representing the material's ability to undergo instantaneous elastic deformation. The second component consists of Spring 2 and Damper 1, connected in parallel, with a viscosity coefficient η_1, describing the viscoelastic properties of the medium, which manifest as elastic aftereffects. The last element includes Damper 2 and a Saint-Venant plastic body, accounting for the viscoplastic properties of the material, which activate only when stress levels exceed the yield strength σ_T. Experimental data indicate that the medium's ultimate strength varies depending on the current density of the mixture, as described in prior empirical studies.

The governing equations for this model are written as follows:

$$\varepsilon = \varepsilon_1 + \varepsilon_2, \quad \sigma = E_2\varepsilon_2 + \eta_1\dot{\varepsilon}_2 \quad when \quad \sigma \le \sigma_T; \tag{1}$$

$$\sigma = \sigma_T + \eta_2\dot{\varepsilon} \quad when \quad \sigma > \sigma_T. \tag{2}$$

where, ε_i – spring deformations; σ – total stress; σ_T – total deformation.

Let's consider the first part of the model, which consists of two Springs and a Damper 1. Let's find the relationship between stress and deformation. From equation (1) under boundary conditions $t = 0, \varepsilon_2 = 0$, we get:

$$\varepsilon_2 = \sigma[1 - exp(- E_2 t/\eta_1)]/E_2.$$

Considering that $\varepsilon_1 = \sigma/E_1$ from the first relation we obtain:

$$\varepsilon = \sigma(E_c^{-1} - E_2^{-1} e^{\mu t}), \quad E_c^{-1} = E_1^{-1} + E_2^{-1}. \tag{3}$$

where, $\mu = E_2/\eta_1$, and Ec – static modulus of elasticity.

The density of the molding mixture is determined through its deformation. If the initial length of the sample l_0 is reduced to length l, then the relative compression of a section of length x will become equal to dx/x, where dx is the absolute compression of the section under consideration. Then, summing up the relative compressions of individual sections, we find the total relative deformation:

$$\varepsilon = \int_l^{l_0} dx/x = ln\, l_0 - ln\, l.$$

It follows that dε = - dl / l. Considering that $l = m/A\rho$, where m – mass, ρ – density and A – cross-sectional area of the sample, we substitute l and dl into the previous relation. We get:

$$d\varepsilon = d\rho/\rho. \tag{4}$$

Solving this equation. We find $\rho = \rho_0 e^{\varepsilon}$, where ρ_0 is the initial density of the medium (at $\varepsilon = 0$). Taking into account expression (3), we obtain:

$$\rho = \rho_0\, exp[\frac{\sigma}{E_c}(1 - \frac{E_c}{E_2} e^{\mu t})], \quad \sigma \le \sigma_T. \tag{5}$$

If the stresses exceed the yield strength, then from equation (2) it follows:

$$\varepsilon = \varepsilon_T + \varepsilon_{ПЛ} = \varepsilon_T + (\sigma - \sigma_T)\Delta t/\eta_2, \tag{6}$$

where, ε_T – the deformation corresponding to the yield strength is determined by formula (3);

$\varepsilon_{ПЛ}$ – plastic deformation;

Δt – the difference between the current moment and the beginning of plastic flow.

Now equation (2), taking into account (4), can be written $\sigma = \sigma_T + \eta_2 \rho/\rho$.

Next, solving this equation, we get:

$$\rho = \rho_T \, exp[\,(\sigma - \sigma_T)\Delta t/\eta_2], \tag{7}$$

where, ρ_T is the density at stress σ_T, which is determined by formula (5).

Density depends on the current value of stress, and yield strength depends on density. This interdependence requires step-by-step calculations to determine the time variation of density. Therefore, the current density and stress values must be replaced by the values obtained at the previous time step in formula (7) and the corresponding time change must be used.

The stage of viscoplastic compaction continues until the plastic deformation stabilizes, after which unloading begins. In order to determine the density, it is necessary to record the stress values and the maximum values of strain and density before unloading starts.

The unloading process follows Hooke's law: $\varepsilon - \varepsilon_p = (\sigma - \sigma_p)/E_1$.

Taking into account the conditions $\rho = \rho_p$ for $\varepsilon = \varepsilon_p$, as well as expressions (4) and (8), we obtain:

$$\rho = \rho_p \, exp(-\varepsilon_p)e^{\varepsilon} = \rho_p \, exp[(\sigma - \sigma_p)/E_1]. \tag{8}$$

This process will continue until the stress becomes zero.

Numerous studies show that the physical and mechanical characteristics of the mixture depend not only on its composition and humidity, but also on its density (Karpov, 2001: 11). Analysis of experimental data allows us to establish a relationship between rheological parameters and density. Since the stress and density of the mixture change along the height of the mold during shaking, for a correct calculation of density it is necessary to discredit the data not only in time, but also in the height of the layer.

Let us now consider the method of layer-by-layer calculation of the density of the molding mixture during the shaking process. At the moment of impact of the table on the frame with a certain initial speed, V_0 a sharp braking of the table and the flask with the mixture contained in it occurs, as a result of which inertial forces arise in all layers of the mixture, causing compressive stresses (Ivanov et al, 1994: 97). Using the contact-classical theory of impact, we determine the speed of the table by the formula:

$$V_c = V_0 e^{-\varepsilon t}(cos\,p\,t - \frac{\varepsilon}{p} sin\,p\,t), \tag{9}$$

where, ε – is the damping coefficient of oscillations;

$$p = \omega_0\sqrt{1 - n^2}; \quad n = \varepsilon/\omega_0,$$

where, ω_0 – is the oscillation frequency.

The duration of the impact is determined by the formula: $t_y = \{\pi + arctg[-2n\sqrt{1-n^2}/(1-2n^2)]\}/p.$

Under the influence of compressive stresses, the mixture is compacted along the entire height of the flask to the ultimate density ρ_{max}. In this case, each layer decreases in thickness, and all sections move downwards with certain speeds and accelerations (Sutton et al., 2017: 5), Let us divide the height of the flask H into k -1 layers.

Since the mass of each layer remains constant during the compaction process, the thickness of the j-th layer at time i can be determined using the following formula:

$$h_{i,j} = h_{i-1,j}\rho_{i-1,j}/\rho_{i,j}. \quad (10)$$

Distance from the origin to the upper boundary of the j-th layer:

$$y_{i,j} = y_{i,j-1} + h_{i,j-1}. \quad (11)$$

The absolute values of acceleration and velocity of the upper boundary of the layer are equal to:

$$a_{i,j} = (V_{i,j} - V_{i-1,j})/\Delta t;$$

$$V_{i,j} = V_{c,i} + (y_{i,j} - y_{i-1,j})/\Delta t, \quad (12)$$

where, Δt – is the time step.

When performing a calculation from top to bottom, it is necessary to specify the velocity of the upper layer: $V_{i,1} = (V_{c,i} + V_{i-1,1})/2.$

The correctness of the selected speed is checked by the lower limit of the following condition:

$$|V_{i,k} - V_{c,i}|/V_{c,i} \le \Delta, \quad (13)$$

where, Δ – is the permissible error in speed.

The coordinate of the upper face is determined by the following formula:

$$y_{i,1} = y_{i-1,1} + (V_{i,1} - V_{c,i})\Delta t. \quad (14)$$

The rate of change of stresses in sections is determined by the expression (1):

$$(\partial\sigma/\partial y)_{i,j} = -(a_{i,j} - 9{,}81)\rho_{i,j} - \xi f P\sigma_{i,j}/A, \quad (15)$$

where, P – is the perimeter of the flask;

ξ – is the lateral pressure coefficient;

f – coefficient of friction of the molding mixture against the wall of the flask; A – area of the flask.

Then the stresses arising in the layers:

$$\sigma_{i,j+1} = \sigma_{i,j} + (\partial\sigma/\partial y)_{i,j} \cdot h_{i,j}. \quad (16)$$

The algorithm for layer-by-layer calculation of molding sand compaction is shown below.

1. Setting the initial data:
$H,\ P,\ A,\ f,\ \xi,\ \rho_0,\ \rho_{max},\ k,\ \Delta t,\ V_0,\ \omega_0,\ n,\ t_y,\ \Delta;$

2. Setting initial conditions: $\rho_{1,j} = \rho_0;\quad \sigma_{1,j} = 0;\quad h_{1,j} = H/(k-1)$
$y_{1,j} = (j-1)H/(k-1);\quad V_{1,j} = V_0;\quad \varepsilon_{1,j} = 0,$

where, $\varepsilon_{i,j}$ – are plastic deformations.

3. Setting the time cycle: $t_i = 0 \div t_y$ through $\Delta t.$

4. Calculation of table speed using formula (9): $V_{c,i}.$

5. Setting conditions on the surface of the molding mixture: $\sigma_{i,1} = 0;\quad V_{i,1}.$

6. Calculating the coordinates of the upper face using (14): $y_{i,1}$

7. Assigning a cycle by layers: $j = 1 \div k$.

8. Calculation of model parameters using empirical formulas depending on the layer density $\rho_{i-1,j}$: $E_1, E_2, \eta_1, \eta_2, \sigma_T.$

9. Calculation of the density of the mixture in sections according to (5), (7), (8): $\rho_{i-1,j}$.

10. Calculation of coordinates, accelerations and velocities of sections, as well as layer thicknesses according to (10), (11), (12): $h_{i,j}; y_{i,j}; V_{i,j}; a_{i,j}.$

11. Calculation of stresses in sections according to (15) and (16): $\sigma_{i,j+1}.$

12. Setting the end of the cycle by layers: $j = k.$

13. Checking the condition (13). If the condition is true, then continue the calculations; if the condition is not met, then change the speed $V_{i,1}$ and repeat the layer-by-layer calculation starting from point 6.

14. Setting the cycle completion time: $t = t_y.$

15. Printing the obtained calculation results: $\rho_{i,j}$; $h_{i,j}; y_{i,j}; V_{i,j}; a_{i,j}$, $\sigma_{i,j}$.

Results. According to the given algorithm, a program for calculation was written in Python language and the calculation of the density of the sand-clay mixture was performed with a moisture content of 3.2% and a raw strength of 0.07 MPa. Initial density ρ_0= 1000 kg / m^3, initial speed = 1 m / s. The dimensions of the flask are 400 × 300 × 200 mm. V_0. The parameters of the shaking molding machine model 271 were used as characteristics of the mechanical system: $\omega_0 = 257c^{-1}$; $n = 0{,}18$; $t_y = 0{,}011c$.

With the number of layers equal to 10, Figure 2 shows the calculation results for the first impact. Curve 1 describes the lower plot and curve 2 describes the seventh plot. The intensity of density growth is the higher the lower the plot is located, and it also strongly depends on the initial density. For example, with an initial density ρ_0 = 1500 kg / m^3 it will be equal to only 1%, while with ρ_0 = 1000 kg / m^3 it is 8.5%.

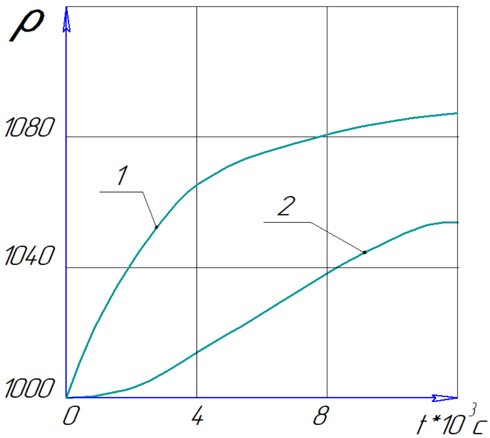

Figure 2 – Graph of density change over time

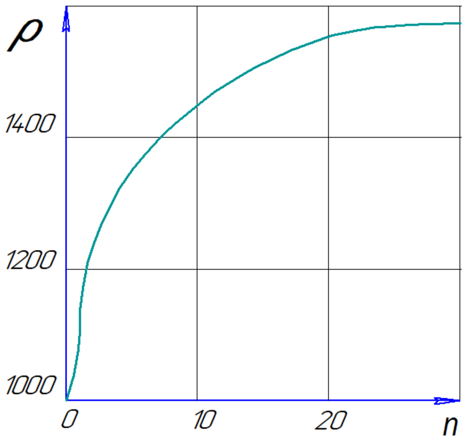

Figure 3 – Dependence of mold density on the number of strokes

As the number of blows increases, the density of the sand-clay mixture at first grows rapidly, then the growth slows down in growth and stops completely when a certain number of blows is reached. The graph of density variation in the lower part (on the mold) from the number of blows is shown in Figure 3.

Discussion. A number of studies confirm that the physical and mechanical properties of the mixture depend not only on the composition and moisture content, but also on the density. The analysis of experimental data allows to reveal the relationship between rheological parameters and density. Since stress and density change along the mold height during shaking, accurate density calculation should take into account both temporal and height changes. Several numerical experiments were conducted to test this model against empirical data from previous studies of sand-clay mixtures. As a result, we obtained a five element rheological model that shows the compaction dynamics more accurately than traditional three-element models.

The results of this study provide valuable information for optimizing the selection of molding mixture and improving the efficiency of foundry processes. The proposed model can be integrated into foundry machine control systems to adjust operating parameters in real time, ensuring optimal mold density.

Conclusion. This study presents an improved five element rheological model for predicting the compaction behavior of molding mixtures under dynamic loads. The model accounts for viscoelastic and plastic properties, providing a more accurate representation of mixture behavior compared to existing three-element models. The results suggest that implementing this model in foundry processes can lead to improved mold quality and more efficient production.

Future research should focus on experimental validation using different types of molding mixtures and the integration of machine learning techniques for real-time optimization of compaction parameters. In this paper, some artificial intelligence capabilities have been utilized to verify the validity of the results obtained.

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