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Research Article

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STUDY OF THE EFFECT OF HEAT TRANSFER DURING MOLDING OF TERMOPLASTIC BERYLLIUM OXIDE CERAMICS

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Abstract. *Beryllium oxide (BeO) ceramics formed with the use of ultrasound exhibit more intense sintering, lower shrinkage, and a reduced sintering temperature compared to ceramics produced without ultrasound. The effectiveness of ultrafast sintering is dependent on the cohesion of ceramic agglomeration and the proper arrangement of particles. Rheological properties thermoplastic slurry changed as a result of ultrasound activation. These changes are related to dispersion phase processes and mass transfer. Ultrasonic activation also slightly enhances the properties of the castings. The increase in the density and strength of castings is explained by the effective reduction of shrinkage under the influence of ultrasound during hardening. That is, compensation for the deposition of the Ingot is determined by filling with a liquid slurry and its compaction under the influence of pressure. For ultrasonic injection of thermoplastic beryllium oxide slurry, formulations with a binder content ranging from 9,5 to 11,7% are recommended. Because these binder compositions are mixed with beryllium powder, turning into a high-strength slurry, forming ceramics that can withstand large temperatures.*

Keywords: ultrasonic activation, beryllium oxide, thermoplastic slurry, molding process, viscous plastic state.

1. Introduction

Beryllium oxide powder is used to prepare thermoplastic slurry which is obtained using standard technology in serial production from beryllium hydroxide [1]. Beryllium oxide powder has a granulometric composition by fractions. This composition of BeO powder (Table 1) shows satisfactory casting properties of the slurry when the mass fraction of the binder changes from $\omega = 9.5\ to\ \omega = 11.7\%$. case of an increase in the finer fractions BeO in the powder composition, the required amount of binder increases. With an increase in the composition of larger fractions BeO in the powder, the ceramics become stained, which indicates the presence of micropores and cracks [2]. On the edges of beryllium oxide microcrystals and important physical and chemical processes occur in the layers, such as adsorption, changes in surface energy, etc. Therefore, the dispersion of beryllium oxide powder significantly affects the casting process of beryllium ceramics. All types of ceramic dispersed systems intended for molding are classified as coagulation structures. Coagulation structures are characterized by contacts between particles that are comparatively weak in terms of interaction strength. In dispersion systems, boundary layers of considerable extent are recorded. These layers, possessing specific deformation properties, are responsible for the thixotropic nature of the suspension flow. With regard to the dispersed system - thermoplastic slurry, the following main features of their structure can be formulated:

relatively high viscosity of the dispersion medium and low value of its dielectric constant; complex structure of the dispersion medium, the presence of supramolecular formations and low diffusion mobility of individual structural elements; weak lyophilic interaction at the phase boundary and absence of dissolution of the solid phase; significant dependence of the density and viscosity of the dispersion medium on temperature. The slurry is assumed to have certain rheological properties when studying its deformation behavior. Complete information in determining the relationship between the rheological properties of the dispersed system and the intensity of the ultrasonic effect on the slurry was obtained by constructing a complete rheological flow curve [1-5]. The flow curve allows to describe the viscous plastic and elastic properties of coagulation structures in the range of changes in these properties under ultrasound exposure.

The physical essence of the use of ultrasonic activation for processing slurry is reduced to the intensification of physical and chemical processes that facilitate the flow of mass and heat exchange processes throughout the entire volume, as well as the sound-capillary effect, which actively influences the processes occurring at the interface between the solid and liquid phases [3, 6-7]. As a result of the action of ultrasound, a whole series of secondary effects arise, accompanying the propagation of ultrasonic waves in the liquid slurry, depending on the rheological behavior. The most significant effect is structural destruction, which is expressed in a sharp decrease in the viscosity of the slurry due to the deep destruction of the coagulation structures [1-3].

The article [8-9] presents the results of calculations under the influence of ultrasonic vibrations and a comparison with the results of experimental data, the change in viscosity and ultimate stress depending on the temperature and duration of ultrasonic treatment.

The volume-phase characteristics of the highly heat-conducting dispersed system change during the casting process at a temperature of 59–40 ºC and the volume of the liquid phase increases. Increasing the volume of the liquid phase, which gives the slurry the necessary casting properties, does not allow achieving the desired effect, since during firing the “additional” amount of binder leads to the appearance of structural defects and deformation of the products. The migration mechanism of shrinkage compensation will work only in the liquid slurry layer, and at the interface between the liquid and solid phases, incomplete compensation of internal shrinkage is the cause of internal defects. Complete compensation of internal shrinkage is achieved using the mechanism of plastic deformation of the hardening layer of slurry in the forming volume of the casting mold under the action of a pressure gradient arising as a result of ultrasonic vibrations [1-3].

Ultrasonic activation has brought significant changes to thermoplastic slurry casting systems [3-5]. The intensity of ultrasonic processing allows you to effectively influence the Rheology of the thermoplastic Slurry. The mechanism of action involves managing the parameters that govern the relationship between the solid and liquid phases [3-5]. Optimal conditions for the interaction of casting systems were found within a temperature range of 63 - 68°C and with 7 - 10 minutes of ultrasonic processing [1, 3-5]. Ultrasonic processing with thermoplastic slurry showed a change in the properties of the microstructure of ceramics. Compared to samples made without ultrasound, ultrasonic samples have a uniform structure and have higher structural-mechanical and electrophysical parameters [1, 3-5]. The conducted comparative analysis of the thermal-physical characteristics of the slurry in the range of phase transformations in combination with experimental data reveals a detailed method of physicochemical analysis of the solidification depending on the cooling rate and the change in the position of the crystallization interval of the slurry in the cavity of the casting plant.

At the molding stage, the castability of the slurry depends on its viscosity, and the solidification temperatures and cooling rates are determined by its thermal conductivity. It has been established that the high thermal conductivity of beryllium oxide slurry at elevated temperatures is linked to the temperature-dependent variations in its viscosity and shear stress output. The changes in the structural and mechanical properties of the beryllium oxide slurry are determined by the relationship between the solid phase and the binder, as well as the stages of the casting process [1,6].

The article uses mathematical modeling to investigate distributions of velocity and temperature fields showing the dynamics, to track the change in temperature-phase fields during the solidification process, calculation and prediction of cooling and solidification of the casting system of ceramic products, necessary for the study of thermal processes and analysis of the formation of shrinkage defects.

2. Materials and methods

The movement and heat exchange of the thermoplastic slurry occur in flat configuration. Fig.1 shows a diagram of a flat forming cavity. The thickness of the flat cavity is 2H = 0,0015 m, width b = 0,03 m, length L = 0,071 m. the cooling circuit (Fig. 1) consists of two parts. A liquid slurry with an initial temperature of $t_0 = 75℃$ is introduced into the cavity. During the casting phase, the thermoplastic slurry undergoes cooling and hardening through heat exchange. As the slurry solidifies, its density increases. The movement of the thermoplastic slurry is laminar, with a Reynolds number Re < 1. Due to the high viscosity of the thermoplastic slurry, the Prandtl number Pr $= \mu c_p/\lambda$ is greater than one.

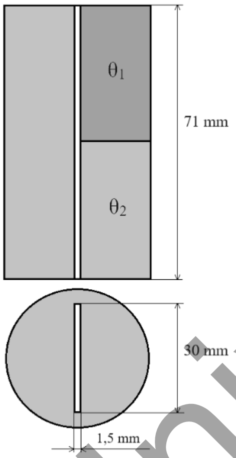


Fig.1. Diagram of a flat cavity die.

The thermoplastic slurry is a two-phase dispersion system, where the solid phase consists of beryllium oxide powder, and the liquid phase comprises organic compounds (binders) [1, 5]. The organic compounds are made up of three components: paraffin (0,82%), wax (0,15%), and oleic acid (0,03%). The beryllium oxide powder possesses a granulometric composition categorized by fractions (Table 1). The mass fraction of the organic binders varies between ω = 10% and 11,7% [6,7].

Table 1. Key properties of beryllium oxide powder [1]

Bulk Density $\rho_0 \times 10^3$ kg/m^3		0.75
Surface Area per Unit Mass, S × 10^{-3} m^2/kg		1.72
Granulometric Composition by Particle Size Fractions of Beryllium Oxide	Fraction, μm	Fraction, %
	up to 1.4	35.2
	1.4 - 4.1	52.7
	4.1 - 7.0	9.6
	7.0 - 9.7	1.7
	9.3 - 12.5	0.4
	12.6 - 15.3	0.3
	15.3 - 18.2	0.1

The composition of BeO powder (Table 1) demonstrates satisfactory flow properties of the slurry when the mass fraction of the binder ranges from ω = 9.5 % to ω = 11.7 %. An increase in smaller fractions of BeO in the powder necessitates a higher binder content. Conversely, an increase in larger BeO fractions in the powder results in ceramics exhibiting microcracks and defects. Viscoplastic slurry can be classified as a Bingham liquid, which has a thixotropic nature of the flow of $0.005 - 1200\ s^{-1}$, within the limits of a change in the shear rate [8,9]. The effective molecular viscosity of a liquid μ_{eff} is defined as [10-12]:

$$\mu_{eff} = \begin{cases} \mu_p + \tau_0|\dot{\gamma}|^{-1}, & \text{if } |\tau| > \tau_0 \\ \infty, & \text{if } |\tau| \le \tau_0 \end{cases}, \tag{1}$$

where τ_0 - yield strength, μ_p - plastic viscosity coefficient, $\tau = \mu_{eff} \cdot S$ - shear stress tensor, $S \equiv \sqrt{2S_{ij} \cdot S_{ij}}$ - strain rate tensor, $S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$- second principal invariant of the strain rate tensor. The Shvedov–Bingham model is a viscous plastic fluid model that linearly relates the shear stress of a simple viscous liquid to the viscosity [13 -15]. Ultrasonic treatment affects the rheological properties of the slurry. Experimental data of plastic viscosity and yield strength for mass fraction $\omega = 11.7\%$ of the slurry after treatment can be described as follows [1,3-5]:

$$\mu_p(t) = 293{,}6259 \cdot \exp\left(-0{,}05816 \cdot t\right), \text{ Pa·s} \tag{2}$$

$$\tau_0(t) = 11{,}4 + 11{,}41 \cdot \exp\left(-(t - 70{,}05)/5{,}47\right), \text{ Pa} \tag{3}$$

Density of the slurry taking into account the concentration of beryllium oxide powder and organic binder:

$$\rho = \frac{\rho_{BeO} \cdot \rho_{bin}}{(1-\omega)\rho_{bin} + \omega \cdot \rho_{BeO}}, \tag{4}$$

where ω - volume fraction of the binder, ρ_{bin} - density of the binder, ρ_{BeO} - density of BeO. The density of the binder for $\omega = 11.7\%$ is determined by the formula:

$$\rho_{bin}(t) = 0{,}852 + 0{,}0725 \cdot cos(0{,}05612 \cdot (t + 273{,}15) - 16{,}7361), \text{ kg/m}^3 \tag{5}$$

The density of organic binder in temperature range $t = 74 - 52$°C varies from 779.7 kg/m^3 to 901.0 kg/m^3 and at $\omega = 11.7\%$ the density of the slurry increases from 2260 kg/m^3 to 2370 kg/m^3.

The density of thermoplastic slurry is determined by the content of the solid phase of the studied dispersed system. The volume content of the solid phase, depending on the composition and temperature, varies in the liquid slurry 5% by volume and does not exceed 71%. In this case, the increment of the binder density during the cooling process is 1.20 including due to cooling to 55°C - 1.02, during crystallization 55÷40°C-1.03, in a solid-plastic state below 55°C-1.17. Based on the calculation results and in comparison with the experimental data presented in the article [5,16-17], it's possible conclude that the effect of ultrasound affects the change in the density of ceramics and shows the solidification front depending on the casting modes, the structure of the casting mass and the features of the configuration of the products.

The slurry's rheological characteristics undergo changes based on temperature variations, and heat release occurs during phase transitions involving shifts in the material's state. When the slurry cools, it can lead to non-uniform temperature distribution, influencing the mold's rheological properties. Solidification typically initiates from the walls, while the central portion of the cavity might remain liquid. As a result, slurry may flow into the cooled areas to compensate for internal volume shrinkage. Full control over the cooling of the slurry mass during forming products in a molding cavity is of great importance, since the solidification process inside the mass depends on the temperature distribution. Also, the change in the temperature field at the cooling process depends on the heat release in the phase transition region and the determination of boundary conditions. The experimentally established liquidus and solidus temperatures of the slurry make it possible to identify the nature of the phase distribution at different stages of crystallization and calculate the rate of solid phase release necessary for studying thermal processes [1,3,6]. The amount of heat released per unit mass during the phase transition is calculated based on the enthalpy ΔH in the transition zone [13].

In this phase, the slurry's heat capacity changes, and the increase in enthalpy can be measured through the apparent heat capacity method [14-20]. The specific heat capacity of the slurry is calculated by the equation [14,21]:

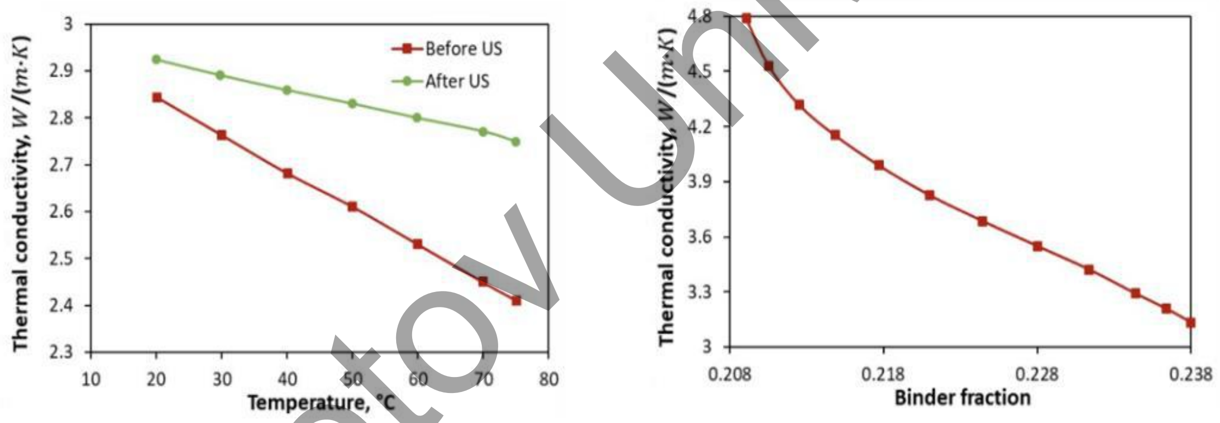
$$c_p = c_s \cdot \left(1-\alpha(\bar{t})\right) + c_l \cdot \alpha(\bar{t}) + H_{1\to 2}\frac{d\alpha}{dt} \tag{6}$$

where c_s, c_l - represent the heat capacities of the slurry in its solid and liquid states, respectively, $\alpha(\bar{t}) = 0$ for the solid-state slurry, and $\alpha(\bar{t}) = 1$ for the liquid-state slurry. Here, $\bar{t}$ denotes the dimensionless temperature of the slurry.

For the binder content, the function at $\omega = 11.7\%$ is expressed as follows. This heat capacity method is advantageous because the transition zone does not need to be predefined; it is instead determined by calculating the temperature of the slurry [20 - 23]. The thermal conductivity of the slurry is temperature-dependent and can be calculated using the following formula when the binder content is $\omega = 11.7\%$ [7]:

$$\lambda = 1{,}6 + 4{,}8 \cdot exp(-0{,}017 \cdot t),\ \text{W/(m·K)} \tag{7}$$

The aggregate change of the liquid slurry during the molding process, the transition of the slurry to a viscous-plastic state is governed by temperature-dependent formulas (2) - (7), which define the properties of the slurry. Thermal conductivity, heat capacity and melting heat are the main parameters for calculating the model of the process by injection casting ceramic products [24]. In scientific literature, the data on thermophysical properties of the dispersed system are limited, and they theoretically confirm that mechanical failures of the dispersed system structure do not affect thermophysical properties, i.e., the value of c_p heat capacity and λ thermal conductivity [5]. The change of thermal conductivity before (1) and after (2) ultrasonic treatment of the slurry in the temperature range of 20 - 80 °C are given (Fig. 2a).



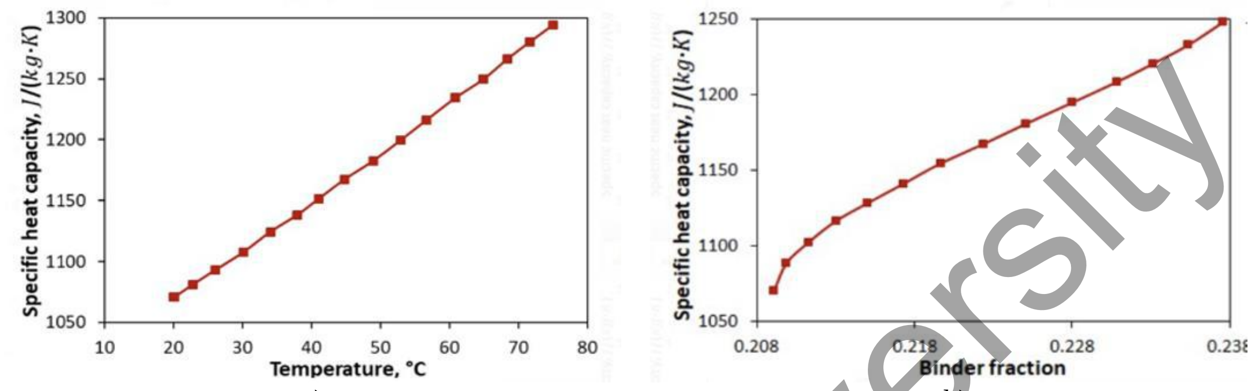
a) b)

Fig.2. The dependence of the thermal conductivity of the slurry on the temperature (a) and the volume fraction of the binder (b).

With an increase in the content of the binder, the thermal conductivity of the slurry decreases, that this is natural, given the large difference in the thermal conductivity of the binder. A comparison of the high thermal conductivity of beryllium oxide with the low thermal conductivity of the the binder indicates that when considering the slurry as a structured dispersed system, its thermal conductivity depends, first of all, on the thermal conductivity of the binder, especially free, unsolvated, since the particles of the dispersed phase practically do not contact each other and cannot have a significant effect on the thermal conductivity of the system. This phenomenon is clearly visible when considering the dependence of thermal conductivity on the volume fraction of the binder content in slurry (Fig.2b).

As well as density, the thermal conductivity of slurry in the solid state is higher than in the liquid state, which is entirely consistent with the idea of higher thermal conductivity of substances [1-5]. With a decrease in the volume content of the binder below 40%, the thermal conductivity of the slurry begins to increase sharply due to the increase in the possibility of direct contact between particles [1-5, 26]. In the work [7,16] the results of studies of heat transfer in suspensions under shear flow are published. It follows from them that for a viscoelastic dispersed system, the linear dependence of thermal conductivity and heat capacity on temperature is preserved. This dependence is not observed only more in a homogeneous liquid state of the dispersed phase. The thermal conductivity coefficient of the casting was determined at a temperature of 20-25°C using the onedimensional heat flow method according to the industry standard (OCT 48-91-7-75) on the IT-02Ts device. The measurement method is based on comparing heat flows through the sample under study and standards with known thermal conductivity. The measurement error in this method is known to be $\pm 10\%$.

The heat capacity of beryllium oxide slurry with an increase in temperature and binder content naturally increases [13]. The graphs show that the heat capacity of the slurry depends only on density and does not depend on viscosity and shear stress (Fig.3).



a) b)

Fig.3. The dependence of the heat capacity of the slurry on the temperature (a) and the volume fraction of the binder (b)

In the structure of the slurry on the surface of solid particles, the adsorbed molecules of liquids significantly change some physical properties, in particular, the melting point and density increase. The slurry mass has a higher heat capacity than other liquids, due to the latent heat of phase transition, it can increase the volume of heat transfer at an equivalent volume flow rate in the mold cavity.

3. Mathematical model

The casting speed is directed vertically downwards along the axis OX, and there is also a transverse velocity component due to the addition of liquid slurry from the wall side until the casting has completely solidified (Fig.1). The mathematical model of the flow process includes equations of motion, continuity and energy, taking into account the dissipation of kinetic energy, temperature dependence of rheological properties and heat of crystallization:

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{dp}{dx} + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial y}(\tau) + \rho g$$

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \qquad (8)$$

$$\rho u c_p \frac{\partial T}{\partial x} + \rho v c_p \frac{\partial T}{\partial y} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + L_k \frac{d\rho}{dt}(\tau) + \mu \left(\frac{\partial u}{\partial y}\right)^2$$

Based on the results of the experiments, the thermophysical properties of the thermoplastic beryllium oxide slurry were found using ultrasonic activation at $30\ ^\circ\mathrm{C} \leq T \leq 80\ ^\circ\mathrm{C}$, which are described by empirical formulas (2-7). The pressure gradient in the equation of motion is determined from the condition of conservation of mass flow rate:

$$\int_0^h \rho_j^{n+1} u_j^{n+1} dy = \dot{m} \qquad (9)$$

The values of velocity and temperature at the inlet section of the cavity are constant, and accordingly all thermophysical characteristics of the slurry are constant:

Boundary conditions

at $x = 0$: $u = u_0$, $v = 0$, $T = T_0$

$$\text{at } x > 0,\ \ y = 0:\ \ \frac{\partial u}{\partial y} = \frac{\partial T}{\partial y} = v = 0. \tag{10}$$

when the thermoplastic slurry moves, the wall sliding of the solid phase is observed. It is practically known that a layer of dispersion medium is formed near the wall, along which the dispersed system moves. At the same time, the condition of adhesion of the slurry mass complied with the wall, but only for its continuous phase [27-29]. And for the entire casting system, the actual conditions at the cavity wall combine the effects of internal and boundary friction. At calculating the velocity profile and flow rate, the slurry condition on the wall is as follows:

$$\text{at } \ x > 0,\ \ y = h:\ \ \frac{dp}{dx} = \left(\tau_{ow} + \left(\mu_0 \frac{\partial u}{\partial y}\right)_w\right)$$

The heat exchange on the outer wall is determined in accordance with the temperature in the cooling circuits of the channel. Specifying the water temperatures in the hot, warm and cold circuits $T_1,\ T_2,\ T_3$, respectively, there are boundary conditions for the temperature on the outer wall:

$$\begin{aligned} &\text{at } 0 \le x < l_1,\ -\lambda \frac{\partial T}{\partial y} = k^{'}(T_m - T_1), \\ &\text{at } \ l_1 \le x < l_2,\ -\lambda \frac{\partial T}{\partial y} = k^{'}(T_m - T_2), \\ &\text{at } l_2 \le x < l_3,\ -\lambda \frac{\partial T}{\partial y} = k^{'}(T_m - T_3) \end{aligned} \tag{11}$$

To determine the average mass temperature, the distribution of temperature and longitudinal velocity over the cross section of a flat cavity is used

$$T_m = \frac{\int \rho u T dA}{A \rho_m u_m} \tag{12}$$

where $dA -$ cross-sectional area, $A\rho_m u_m$- mass flow. Product of $\rho_m u_m$ is expresses the average mass flux density, u_m- average velocity, which is determined by the expression

$$u_m = \frac{\int u dA}{A} \tag{13}$$

Heat exchange calculations were considered using the boundary condition of the third kind in the form of expression (11) for a flat forming cavity. This means that the heat flux density is taken to be proportional to the difference between the temperatures of the coolant T_w and the average mass temperature of the slurry T_m. In the stationary mode, heat flux density q_w can be represented as

$$q_w = \alpha_1(T_m - T_w) = k^{'}(T_w - T) = k(T_m - T) \tag{14}$$

where $k^{'}$- heat transfer coefficient from the inner surface of the wall to the coolant; k – heat transfer coefficient from the slurry flowing in the cavity to the cooling liquid; α_1- coefficient of heat transfer from the slurry flowing in the cavity to the inner surface of the wall.

The coefficients $\alpha_1, k,\ k^{'}$are related by the relation

$$\frac{1}{k} = \frac{1}{\alpha_1} + \frac{1}{k^{'}} \tag{15}$$

For flat forming cavities:

$$\frac{1}{k^{'}} = \frac{d_e}{\lambda_s} + \frac{1}{\alpha_2} \tag{16}$$

where $d_e = \frac{4A}{s}$ - equivalent diameter; s - cavity perimeter; λ_s - thermal conductivity coefficient of the wall material; α_2- coefficient of heat transfer from the outer surface of the wall to the coolant:

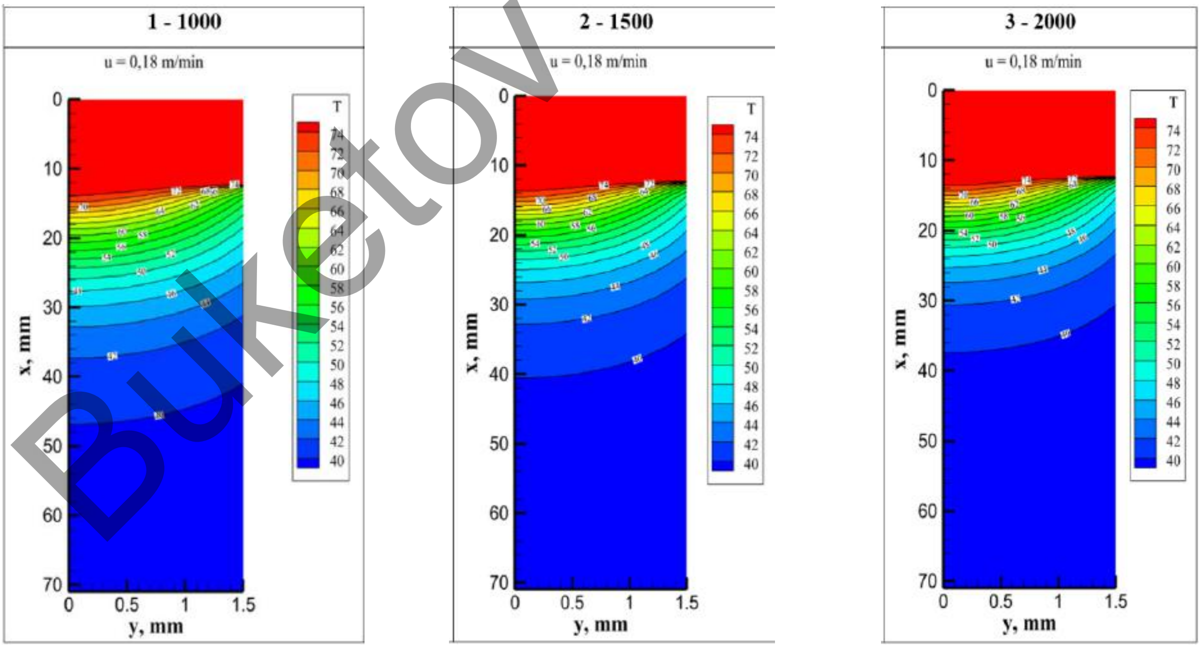
$$\alpha_2 = \frac{2\lambda_b}{d_3 ln(4d_3/d_e)} \tag{17}$$

Numerical methods are used to solve the model of motion and heat transfer of thermoplastic slurry in a flat cavity [25].

4. Calculation results and discussion

The effect of ultrasonic treatment on the properties of the casting was assessed by changes in apparent density and mechanical strength. Ultrasonic treatment allows us to obtain castings with a finer grain structure and apparent density compared to samples obtained without ultrasound. According to experimental data, it is known that castings with maximum density are obtained with an ultrasound power of 60-80% from N_{max}, which corresponds to an ultrasound intensity $0.4 - 1.6\frac{W}{cm^2}$. A decrease of the density of castings at a level above 60-80% from N_{max} leads to the formation of shrinkage and cracks in castings during the process of forming their structure [3-4]. The increase in the density of the casting indicates a change in the volume-phase relationships during the structure formation of the casting under the influence of ultrasound. Considering the insignificance of the gas phase content in the liquid slurry and equal cooling of the casting in all experiments, the increase in the density of castings formed with ultrasound is a more effective compensation for shrinkage during casting hardening. In this case, compensation for shrinkage is achieved both by adding liquid slip and by deformation compaction during the structure formation of the casting. A comparative analysis of the structural and mechanical properties of products, with and without the use of ultrasound, showed that castings with ultrasound had a 7-10% higher apparent density. The universal strength limit for flexible products obtained using ultrasound exposure is 1.3-1.7 times greater than for products obtained without ultrasound.

Dynamic viscosity of slurry $\mu_p(t)$, density ρ(t), and shear stress $\tau_0(t)$ the temperature increases as it decreases. In the second cooling circuit, the water temperature is set at θ_2 = 40 ^{0}C. Through the heat exchange process between the slurry and the water, the slurry's temperature is reduced to 40 ^{0}C (Fig.4 a,b,c), and the density increases from 2270 kg/m^3 to 2370 kg/m^3 (Fig.5 a,b,c).

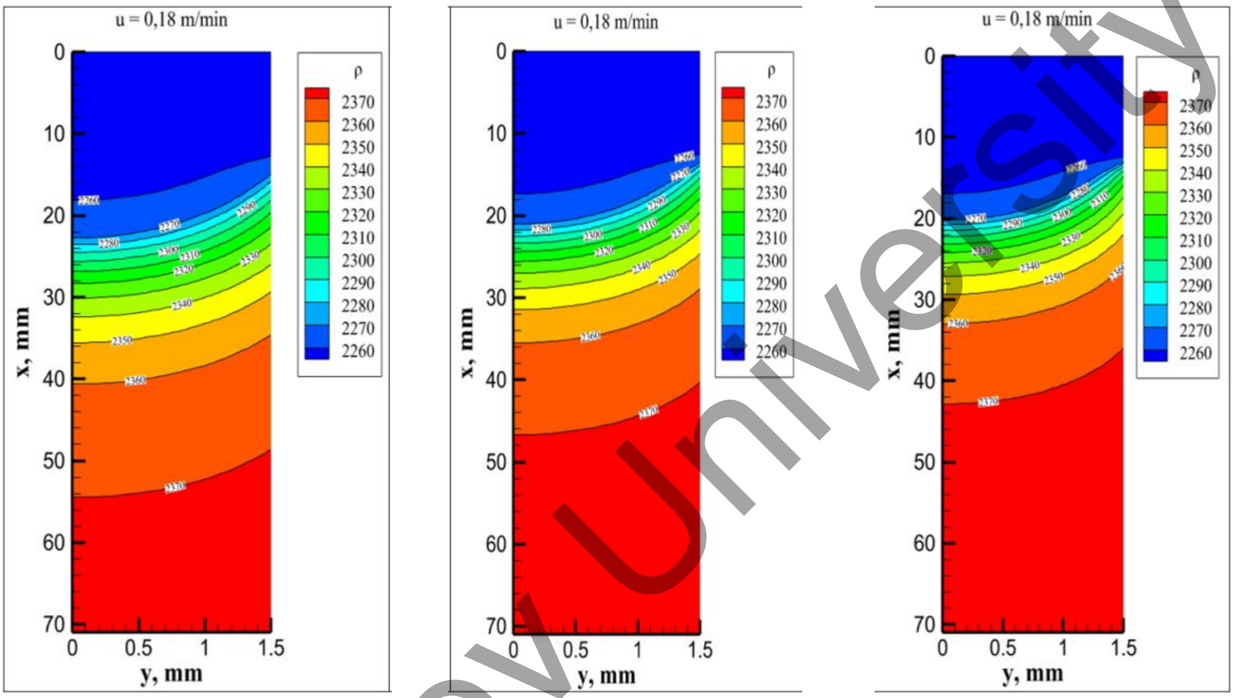


a) b) c)

Fig.4 Changing the temperature of the slurry depending on the value of the heat exchange coefficient: $a)\ k = 1000\,J/(m^2 \cdot ℃),\ b)\ k = 1500\,J/(m^2 \cdot ℃),\ c)\ k = 2000\ \ J/(m^2 \cdot ℃)$

After ultrasound exposure, calculations were made for slurry with rheological properties. The computation results for the slurry movement in a planar die, given a cavity thickness of 2h = 0.0015 m, a casting speed of $\vartheta = 0.18$ m/min, and an initial temperature of $t_0 = 75℃$, are illustrated in figure 4. In the initial cooling circuit, the temperature of the water is θ_1 = 75 ^{0}C. The temperature field shows a decrease in temperature to 72 °C (Fig. 4 a, b, c), and the density increases from 2260 kg/m^3 to 2270 kg/m^3 (Fig.5 a, b,c).

Transitioning from the first to the second region involves a shift from an amorphous state to a viscous-plastic state, during which the temperature and density fields change, eventually stabilizing to uniform values. Experimental data [1,6] indicate that an increase in the transition zone between states can lead to shrinkage of the slurry, the formation of cavities and voids, and a decrease in casting strength. The smaller the transition zone between states, the less the slurry will shrinkage. Ultrasonic treatment, by improving rheological properties, results in a reduction in the transition zone and consequently a decrease in the shrinkage of the beryllium oxide casting.



a) b) c)

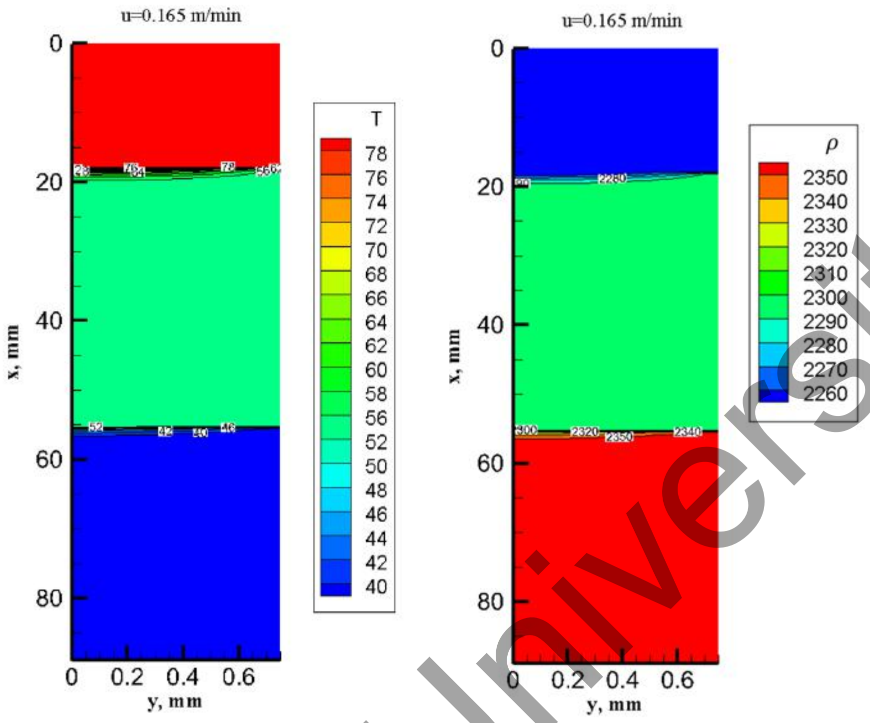
Fig.5 Changing the density of the slurry depending on the value of the heat exchange coefficient: $a)\ k = 1000\,J/(m^2 \cdot {}^\circ\mathrm{C}),\ \ b)\ k = 1500\,J/(m^2 \cdot {}^\circ\mathrm{C}),\ \ c)\ k = 2000\ \ J/(m^2 \cdot {}^\circ\mathrm{C})$

Table 2 presents experimental data on the casting performance and mechanical strength of the cast, as a function of binder composition and casting speed.

Table 2. The dependence of the strength of ceramics on the velocity of casting in a flat cavity [1].

Mass fraction of mass	Slurry's viscosity, Pa*s at $T_0 = 75°C$	Slurry casting ability, mm	Casting velocity, mm / min	Mechanical strength of the casting at bending, mPa
0.117	4.16	88	165	8.18

The calculation data were obtained at the experimental values of the filling velocity $u_0 = 0.165\ m/min$ at ω = 0.117 in a flat cavity (Fig. 6). In the initial configuration, the cooling water temperature is set at θ_1= 75 ^{0}C, while in the second configuration it is θ_2= 59 ^{0}C, and in the third configuration, it is θ_3= 40 ^{0}C. The liquid slurry flows into the uniform cavity at an initial temperature of t_0 = 75 ^{0}C. As depicted in Fig. 4, the transition between one cooling circuit and the next shows fewer voids. The casting speed ensures a uniform temperature distribution across the cross-section of the cavity. This even temperature distribution results in uniform rheological and thermophysical properties of the slurry across its cross-section. Consequently, the shrinkage of the thermoplastic slurry is consistent, preventing the formation of voids and defects that could compromise the strength of the beryllium oxide casting. The slurry solidifies within the molding cavity, indicating that the beryllium oxide (BeO) ceramic product acquires a structural shape suitable for further processing.



a) b)

Fig.6 The temperature and density field of a Slurry in a flat cavity: u_0 = 0.165 m/min, ω = 0,117 %

5. Conclusion

Ultrasonic treatment improves the rheological properties and enhances the fluidity of the thermoplastic beryllium oxide slurry within the molding cavity. The maximum values of apparent density and mechanical strength were obtained at an ultrasound intensity of 0.4÷1.6 W/ cm^2. A further increase in the impact power leads to a decrease in density due to the formation of porosity in the castings due to an increase in the size of the cavitation region, the number of newly formed cavitation cavities and the entry of part of the cavitation region into the cooling zone of the die. The increase in density and strength of castings is an effective compensation for shrinkage under the influence of ultrasound during pressing. In this case, shrinkage compensation occurs both according to the classical scheme by feeding with liquid slip, and by means of deformation compaction under the action of static and radiation pressure.For ultrasonic casting of thermoplastic slips based on beryllium oxide, it is advisable to use compositions with a binder content of 11.0-11.7% by weight, since these compositions achieve better shrinkage compensation and, accordingly, a denser casting.

Through the analysis of experimental data, empirical formulas were developed to relate the plastic viscosity and the critical shear stress of the slurry to temperature. It was established that the phase transition of the thermoplastic beryllium oxide slurry occurs within a defined temperature range. The heat generated during the phase transition was accounted for by considering the increased heat capacity over this temperature range.

Based on the calculation results, the following main conclusions can be made:

- a mathematical model of the formation of ceramic processes by the hot casting method includes a system of equations of motion of a non-Newtonian fluid, continuity and energy, taking into account the release of heat during the state of aggregation changes as the slurry cools in the mold cavity;

- the calculations received distributions of velocity, temperature and rheological properties, showing the internal structure of the slip in the mold cavity. The change of temperature and density of the slurry depending on the value of the heat exchange coefficient at a given value of the casting velocity is uniform across the cross-section of the mold cavity. This is explained by the fact that the conduction mechanism plays a predominant role in heat transfer due to the high thermal conductivity of beryllium oxide.The heat of crystallization released during this process is quickly dissipated due to the high thermal conductivity of beryllium oxide;

- the density of the slurry mass increases with a change in the state of aggregation, the calculation explains the mechanism for compensating for volumetric changes during the formation of ceramics by the hot casting method and is in satisfactory agreement with experiment.

Comparative calculations with experimental results help define the conditions for the hot molding process, facilitating the production of hardened beryllium oxide ceramics with a uniform structure.

Conflict of interest statement

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

CRediT author statement

Sattinova Z.: Conceptualization, Funding acquisition, Supervision; **Turalina D.**: Methodology, Data curation, Validation, Editing; **Yesbol Zh.:** Investigation, Analysis of results, Writing- Reviewing and Editing; **Mussenova E.:** Writing Reviewing and Editing, Resources, Data curation. The final manuscript was read and approved by all authors.

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