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RESEARCH PAPER

Investigation of the use of variable pressure in the formation of sand-resin casting moulds

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ABSTRACT

Consumer demand increases the efficiency of the operation of cast parts of various equipment, necessitating the development of new technological processes for manufacturing castings. One of the important tasks currently facing the foundry is to increase the purity of the surface of castings and reduce defects due to casting defects. Such properties are possessed by castings obtained by casting into shell molds. Sand-resin mixtures are used for their manufacture. Molds from such mixtures allow the obtaining of high-quality castings from various alloys. The relatively high cost of a pulverbakelite binder prevents its widespread use in industry. In this regard, research aimed at improving the technological processes for manufacturing durable sand-resin moulds while reducing the binder content in the mixture without compromising other parameters is relevant. The disadvantage of the available technological modes of manufacturing shell moulds with the required strength is the high content of binder pulverbakelite (7-9%). Therefore, reducing the pulverbakelite content in the mixture by using the most optimal modes of shell formation, primarily variable pressure, to obtain high-quality castings of the widest range is very relevant.

Keywords: pulverbakelite, variable pressure, mode, sand-resin mixture, resin, casting, strength.

INTRODUCTION

Currently, the most common technological process for obtaining castings for casting mining equipment parts into sand-clay moulds does not fully meet modern requirements. Casting into sand-clay moulds (SCM) is characterized by various defects: gas porosity, burnout, shrinkage shells, blockages, hot and cold cracks, etc. In addition, casting in SCM does not always ensure the production of castings with the required structure and, accordingly, with the necessary mechanical properties [1]. The value of the yield characterizes the use of metal in foundry production. Improving cast blanks' accuracy reduces metal consumption per unit of output and reduces the cost of machining blanks [2].
SRM (sand-resin mixture) has more advantages than SCM, which does not look as attractive as in the past.
The main parameters of the mould are strength, hardness (mechanical properties), density, gas permeability, porosity, and roughness (technological parameters). For casting, the main quality parameters determined in the work are the absence of defects (fit, continuity) and roughness.
The factors influencing the shape parameters are the values of the pressing pressure, the temperature of the mixture formation (the heating temperature of the model plate) and the temperature and duration of sintering of the shell mould.
Shell moulds with resin as a binder can produce castings of a wide range from 0.2 to 300 kg with a wall thickness of 3-18 mm from a wide variety of alloys. Shell casting provides greater geometric accuracy, often eliminating the need for machining. They also have high strength and gas permeability, do not absorb moisture, are not prone to crumbling and shrinkage resistance, and solidifying alloy. Another advantage is that the moulds are easily destroyed after the casting solidifies. An additional advantage of shell moulds is that even with prolonged storage after manufacture, they do not lose their strength properties, allowing them to produce high-quality castings with high dimensional accuracy [3, 4].
Sand-resin mixtures have the properties of a viscous liquid and a loose body. When deformed, they exhibit viscous and dry friction. They are multiphase dispersed systems with a high concentration of dispersed particles, and after preparation, they consist of a solid phase (sand), resin, moisture, and air.
When a load is applied to the sand-resin mixture, solid phase particles (sand) converge due to removing a gaseous medium (air). During the heating process, the gaseous phase is filled with molten resin. The interaction of phases under static loading occurs with a volumetric change in the solid phase and its shape change. During the deformation of the shape, there is a movement of both individual solid particles and, directly, some volumes. The gaseous phase and the melting resin reduce internal friction, promoting sealing. The indoor air's direction of movement can increase the mixture's density.
Long-term experience shows that mould manufacturing technology is always based on the physicochemical and technological properties of binder compositions and mixtures; their study leads to the development of fundamentally new technological processes [5]. The physicochemical processes occurring in dispersed media are considered in [6-10]. The physical and physico-mechanical properties of moulding mixtures, which play an important role in sealing, include compressive strength, tensile strength, shear strength, density, porosity, mass, bulk weight, and humidity. There are several technological properties – fluidity, flowability, gas permeability, compactness, formability, etc. The strength of the mixtures varies in a wide range, from 0.04 MPa to 0.4 MPa [11].
Increasing the binder content at appropriate humidity increases the strength. The ratio of the moisture content of the mixture and the absolute binder content should be optimal. It varies between different binders, composition and properties of sand. With an increase in the content of pulverbakelite, the strength increases. However, the cost of the form increases significantly. The strength of the mixture, as well as the strength of the mould, have a direct relationship, all other things being equal. However, the same mix of equal strength will show different results for the strength of the mould and its areas with varying compaction methods. In general, we can say that the strength of the mould fully reflects the topography of the distribution of the mass (density) of the mixture in the volume of the mould. It should be borne in mind that the final density distribution of the mix is determined not only by the compaction method but also by its initial density and distributions in the tooling (determined by the filling method).
It has been revealed that in most studies on this topic, the formation of a sand-resin mixture occurs only under heating conditions. Some sources indicated the use of additional pressing to increase the strength and density of the sand-resin mould. At the same time, the peculiarities of the pressure effect on the mixture and technological properties (strength, hardness and gas permeability) of the finished casting mould and, accordingly, the characteristics obtained in them have not been studied.
In addition, the relatively high cost of binder (pulverbakelite compared to clay) hinders the widespread use of shell casting technology [12].

MATERIAL AND METHODS

The main components of the mixture are quartz sand and a binder – pulverbakelite. The most common is SF -011A pulverbakelite, a mixture of phenol-formaldehyde resin powder and urotropin [13]. In addition, the mixture includes kerosene and a solvent (industrial alcohol). Moulding mixtures based on quartz sands of grades 1K0315 and 1K02 were studied, where SF-011A pulverbakelite was used as a binder and additives: kerosene, white spirit, and boric acid.

Studies of forming a solid shell from SRM were carried out on experimental installations and devices of the original design. Industrial research was carried out at LLP "KMZ named after Parkhomenko" and LLP "Maker" (Karaganda, Republic of Kazakhstan).

According to the tested technology, the moulding machine for the manufacture of shell moulds has been upgraded based on the moulding semi-automatic model 51713. The scheme of the moulding machine of the 51713 brands is shown in **Fig. 1.**

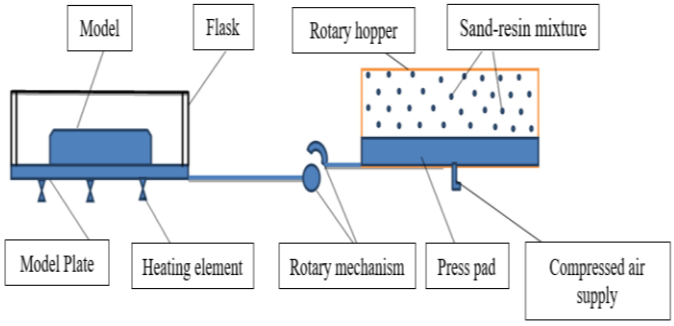

Fig. 1 The scheme of the moulding machine of the brand 51713

The forming machine consists of a hopper into which the sand-resin mixture is filled, an oven, a plate for additional static load application, and a table on which an electrically heated model plate with a model is mounted. A flask is installed on the model plate [14, 15]. **Fig. 2** shows a general view of the moulding machine.

a *b*

Fig. 2 The moulding machine of the brand 51713, retrofitted with a press plate in the hopper: a – from the side of the hopper and the model plate; b – from the side of the control panel

Models of castings were installed on the model plate, on the reverse side, of which there were spring pushers (to separate the finished shell half-mould from the model) and electric heating devices. There was also a thermal sensor, which controlled the stove's heating to 240-260 °C. A flask with a height of 100 mm and a perimeter coinciding with a hopper with a mixture was installed on a model plate with models of castings. In the initial position, the model plate with the models is covered with the body of the drying oven. A bunker was nearby, into which a mechanical mixture of quartz sand and pulverbakelite was poured. Before the operation of the machine, the model plate was covered with a separation compound, which consists of a mixture of water – 100%, dimethylpolysiloxane – 8%, and household soap – 3%. When applied to a model heated to 250 °C, the separation mixture forms a hard, thin, but heat-resistant film, which persists after several removal of the shells from the models. When the moulding machine was turned on, the furnace rose, and the mixture was filled from the hopper onto the model plate. At the same time, a plate was lowered onto the filling frame with the poured mixture, exerting a static load on the mixture. Then, the plate returned to its original state.

Under the influence of the heat of the model equipment, the pulverbakelite melts and wet sand grains in the layer of the mixture directly adjacent to the model plate. After the shell is formed, the model plate returns to its original position, and the model plate with the formed shell is covered with an oven, inside which the temperature reaches 350 °C. The thickness of the shell is 10-15 mm [14].

The strength test samples were manufactured according to a technological process corresponding to the manufacturing process of shell moulds for castings of mining equipment. The thickness of the samples *h* depended on the thickness of the pre-filling of the sand-resin mixture, the holding time on the plate, the pressure value, and the degree of heating of the model plate. The arithmetic means of the obtained results was considered an indicator of strength. If the data of one sample differed from the arithmetic mean by more than 10%, then the tests were repeated [14].

The tensile strength of sand-resin mixtures was determined on standard samples (**Fig. 3**). Individual parts of the shell experience the dynamic pressure of the metal jet, the value of which is proportional to the velocity and cross-sectional area of the jet. The remaining parts of the mould perceive the static pressure of the metal.

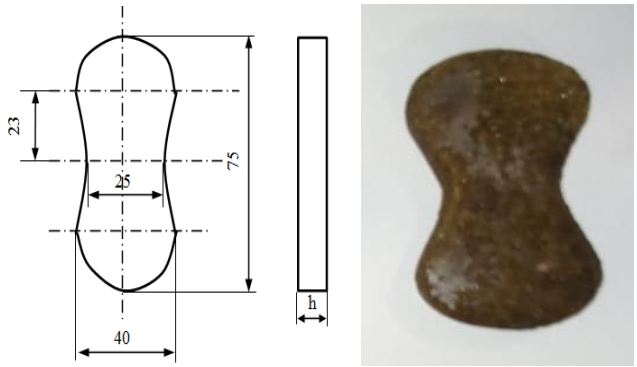

Fig. 3 The shape and dimensions of the rupture test samples

The samples were made using shell mould manufacturing technology. The strength test samples were manufactured using a technological process similar to manufacturing shell moulds and rods. The thickness of the samples *h* depended on the pressure value, the degree of heating of the model plate, the holding time on the plate, and the thickness of the pre-filling of the sand-resin mixture. The arithmetic means of the obtained results was considered an indicator of strength. If the data of one sample differed from the arithmetic mean by more than 10%, then the tests were repeated [14, 16].

The height of the samples depends on the pressing pressure, the temperature of the model plate, and the period of temperature exposure to the mixture. The arithmetic means of the obtained results was considered an indicator of strength. If the values of the parameters of one sample differed by more than 10% from the arithmetic averages, the tests were repeated.

After cooling, samples of 30×30×15 mm were cut out of them with a disc cutter to determine the rough surface of the castings. The plane of the samples was cleaned from an easily separated lump of the moulding mixture. The remaining residue (difficult to separate) was removed in a molten caustic soda at a temperature of 500 °C for 4-6 hours (after reaching a constant weight of the sample). The ratio of the prig's weight to the sample's surface area (g/cm^2) was taken as the quantitative characteristic of the prig.

Samples for determining gas permeability were made on a device for the 04315M brand. According to the accepted technology, samples with a diameter of 50 mm were produced.

To determine the burn after cooling the castings, samples with a size of 30×30×15 mm were cut out of them with a disc cutter. The plane of the samples was cleaned from an easily separated lump of the moulding mixture. The remaining residue (difficult to separate) was removed in a molten caustic soda at a temperature of 500 °C for 4-6 hours (after reaching a constant weight of the sample). The ratio of the prig's weight to the sample's surface area (g/cm2) was taken as a quantitative characteristic of the prig [17].

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Samples were studied using standardised methods and modern equipment of accredited laboratories (GOST ISO 17025-2009 "General requirements for the competence of testing and calibration laboratories") of the International Center for Materials Science and the "KORMS" Engineering Type Testing Laboratory of the Abylkas Saginov Karaganda Technical University.
Shape parameters such as compressive strength, tensile and bending strength, porosity, gas permeability, roughness, and the size of the fit and the roughness of the casting were determined. A floor installation was used to determine the compressive strength and the mechanical properties of INSTRON-100.
The roughness of the samples and cast blanks was determined after cleaning using a roughness measuring device TR-220 [18].
The dependence of the moulds gas permeability on the pressure applied during hardening was determined. A well-known test method for sand-clay mixtures was used to check the gas permeability of the sand-resin mixture (PSS) [19]. Samples with a diameter of 10 mm were tested and manufactured using copra in a sleeve. Also, a different fractional composition of sand was used in the mixture [14].
The gas permeability of the sand-resin mould was determined using a well-known technique on a device for determining the gas permeability of the 04315M brand. Porosity studies were carried out on a PASCAL 400 mercury porosimeter, which allows the detection of pores with a radius of up to 2 nm [14, 20]. This PASCAL porosimeter module will enable you to reach pressures up to 400 MPa and make it possible to study materials of different degrees of hardness. High resolution and high analysis speed are the main features of the PASCAL 440, which is designed to solve the most complex analytical tasks in laboratories working with new materials such as ceramics or pressed metals and requires porosity studies at the micropore level. Sintering was carried out in a Nabertherm furnace.
Previously [14], the following was recognized as the most effective use of variable pressure: quartz sand with the optimal composition for shaping grade 1K0315 – 65.4%, quartz sand grade 1K02 – 28%; pulverbakelite SF-011A – 4.2%; kerosene – 0.3 %; white spirit – 2%, boric acid – 0.1%.
Five pressing modes with three pressure values, MPa, were used during the research. The pressure value P1 corresponds to the end of filling the mixture onto the model plate, pressure P2 corresponds to the transition of the resin to a liquid state in the layers adjacent to the model plate, pressure P3 corresponds to the transition of the resin in the same layers to a solid state: 1) P1 = 0.25; P2 = 0.25; P3 = 0.25; 2) P1 = 0.25; P2 = 0.35; P3 = 0.20; 3) P1 = 0.25; P2 = 0.30; P3 = 0.10; 4) P1 = 0.25; P2 = 0.20; P3 = 0.35; 5)P1 = 0.25; P2 = 0.20; P3 = 0.30.

RESULTS AND DISCUSSION

An important indicator of moulds is their gas permeability. A certain relationship exists between the shell's gas permeability and porosity. At the same time, it should be emphasized that, in this case, we should not talk about porosity in general but only about open porosity since it is obvious that the gas permeability process will be determined only by the parameters of open porosity.
An example of the results received is shown in **Fig. 4.**
The presence of an open porosity of the shell contributes to the transition of gases from the solidifying casting, as a result of which such a type of casting defect as gas porosity is practically excluded [21]. It should also be noted that it is important to know the cumulative volume of open porosity and the size distribution of open pores. This is because not all open pores are accessible to the penetration of gases, but only pores of a certain radius [22]. For air, this value is about 20 nm. However, the composition of the exhaust gases during the combustion of pulverbakelite is mainly represented by phenol and ammonia; CO is formed when pouring the melt, etc. gases. The molecules of these gases are about 3 times larger than the oxygen molecule: for example, the size of the phenol molecule is 0.8 nm, and the size of the oxygen molecule is 0.3 nm. Therefore, we will conditionally consider the available size to be pores with a radius exceeding 60 nm. As can be seen from the above data, the size of the available pores is not equal to that of the molecule because the average pore size is fixed. In contrast, the pore may have a complex "bottle" type structure, i.e. the input size may be lower than the average. It should also be noted that pores with a radius exceeding 1000 microns are potentially "dangerous" pores; their presence in the structure is highly undesirable. Pores with a radius greater than 1000 microns reduce the shell's strength, worsen the casting surface's quality, and violate the conditions of uniform heat exchange [23]. Thus, a group of pores is of interest, with an average size of 60-1000 nm. For convenience, we denote this range with the symbol A.

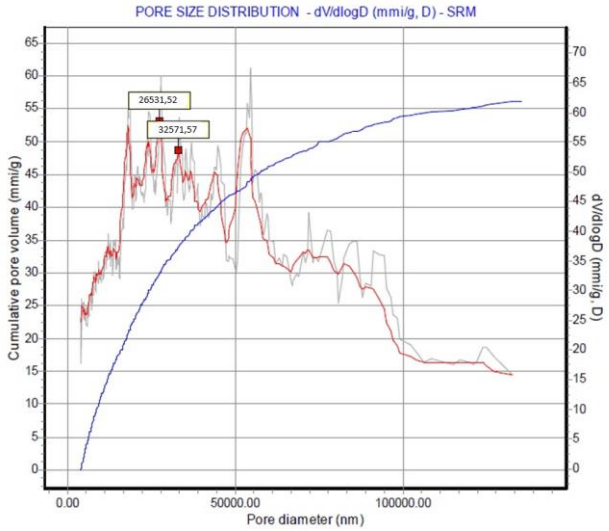

Fig. 4 The distribution of pores in the shell form obtained at variable pressure

Shell samples obtained under different pressing conditions were analysed (**Table 1**). During the experiment, the total porosity, the nature of the size distribution, and the volume of pores with a radius exceeding 60 nm were controlled.
As can be seen from the data in **Table 1**, changing the pressing mode has a significant effect on the parameters of the porous structure. Using non-stationary pressure leads to a slight decrease in the total porosity from 38% to 32%. Still, the main effect of using non-stationary pressure is manifested in a change like porosity [24, 25]. In the reference sample, the proportion of pores in the A range is 38%, i.e. most of the porosity is represented by pores with a radius greater than 1000 nm. Using non-stationary pressure increases the proportion of pores in the A range to 61%. However, a further increase in pressure leads to a decrease in the total porosity and a reduction in the proportion of pores in the A range. Such a tendency is undesirable. Therefore, a further increase in pressure when pressing the mould is impractical.
The available porosity in the A range and gas permeability should be correlated.

Table 1 – Parameters of the porous structure depending on the pressing mode

Pressing mode	Total porosity, %	The proportion of pores, range A, %
1	39	42
2	38	62
3	34	46
4	37	59
5	34	45

The shells obtained under different pressing conditions were analysed for gas permeability. The effect of pressure changes applied to the mixture on gas permeability was also investigated. 0.25 MPa was taken as the base pressure, and after 10 seconds, the pressure was reduced to 0.2 MPa, and then, after another 10 seconds, it was increased by ΔP.
It was determined (**Fig. 5**) that the pressure change at the last stage slightly affects the decrease in gas permeability; in all samples, it was more than 100 units.
If we compare the data on the proportion of pores in range A and gas permeability, it can be seen that an increase in the proportion of pores in range A does not significantly change gas permeability. Thus, introducing non-stationary pressure to the critical mode (mode 4) does not pose a danger from the point of view of gas permeability. However, the nature of the pore distribution towards an increase in the proportion of small pores (with a radius less than 1000 nm) should have a positive effect on the level of mechanical properties [22].

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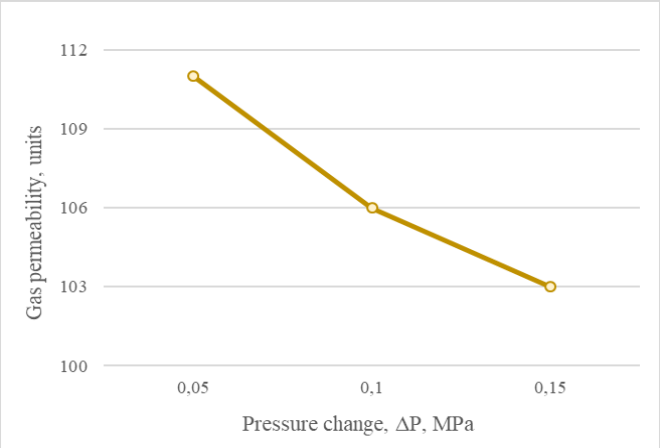

Fig. 5 Gas permeability of the sand-resin shell depending on the pressure variability

Studies have been conducted on the dependence of the gas permeability of a mixture with various grain compositions on the pressure parameters at the SRM (**Fig. 6**).

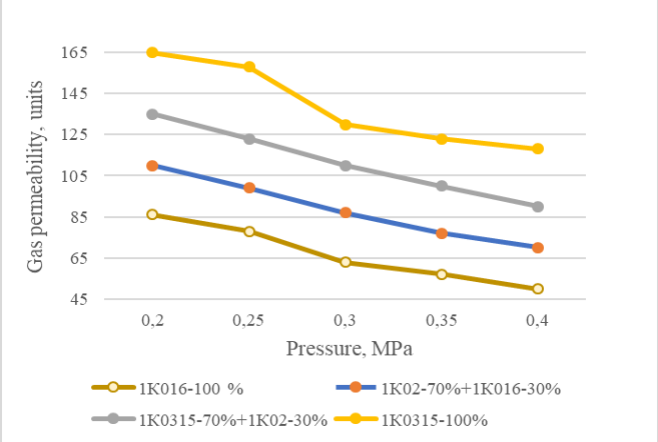

Fig. 6 The effect of the base pressure parameter on the gas permeability of the shell

As a result, it was determined (**Fig. 6**) that the combination of filler (quartz sand), which ensures the gas permeability of the mould of more than 90 units under specified technological conditions, is as follows: grades 1K02-30% + 1K0315-70%. It has been experimentally determined that when using a base pressure on a mixture of 0.27-0.36 MPa and its proper regulation, the densest laying of sand grains of different fractions is ensured. The dependence of the gas permeability of the shell form on the pressure used in its formation is almost linear. It is determined that the technologically necessary gas permeability value is provided if the mixture is initially pressed between 0.2 and 0.4 MPa, which should then be adjusted according to the technology described above. If you continue to increase the pressure (above 0.4 MPa), the gas permeability of the shell form drops to less than 90 units. The deterioration of gas permeability occurs due to the extrusion of filler grains and their "clogging" of pores in the hardened shell. An experimental study of the dependence of the strength of the shells on the holding time on the model plate at different pressure values on the mixture showed that increasing the holding time of the mixture on the plate increases the strength. The data of this series of experiments are presented in **Table 2** [14].

Table 2 The dependence of the compressive strength of the shell on the holding time of the mixture on the model during the shaping process under various loads

The holding time of the mixture on the model, seconds	Pressure on the mixture P, MPa	The strength of the resulting shell is σ_c, MPa
10	0,25	8,2
20		11,3
30		12,5
40		13,1
50		13,9
10	0,35	8,7
20		11,3
30		13,7
40		14,1
50		14,7

In another series of experiments, the effect of the expediency of increasing the pressure on the mixture during the forming process was investigated. It was determined that with an increase in pressure during the forming process of 0.03-0.05 MPa relative to the initial pressure (0.25 MPa), the roughness of the shells decreases while the gas permeability remains within 90-100 units. A decrease in gas permeability of less than 100 units is observed with a further increase in pressure. and a slight increase in roughness due to the extrusion of grains in the already-formed shell. **Table 3** shows experimental data on determining the optimal pressure on the mixture. A graph of the dependence of the roughness of the mould on pressure changes during the formation of the shell is shown in the **Fig. 7**, and the strength of the mould on pressure changes during the formation of the shell is shown in **Fig. 8**, respectively.

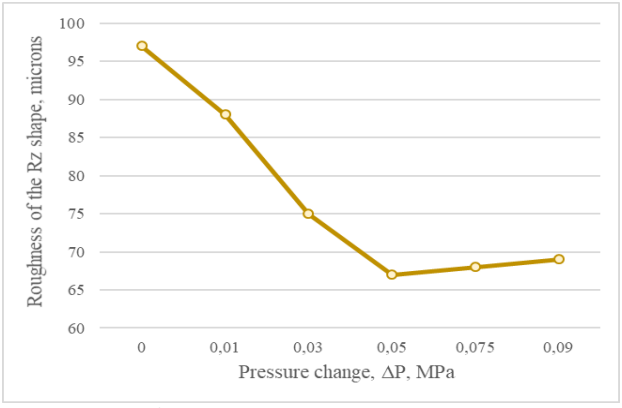

Fig. 7 Dependence of the shape roughness on pressure changes during shell formation

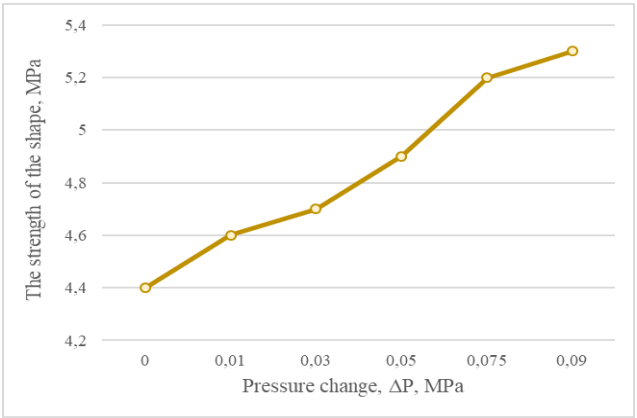

Fig. 8 The dependence of the strength of the mould on pressure changes during the formation of the shell

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Table 3 The dependence of the strength and roughness of the shell on the pressure on the mixture during the formation of the shell

Experience number	Pressure change ΔP, MPa	Roughness of the shape Rz, microns	Shape strength σ_{st}, MPa	The moment of pressure increase
1	0	97	4,4	the whole process
2	0,01	88	4,6	after 15 seconds
3	0,03	75	4,7	0.01 MPa each after 5, 10, 20 seconds
4	0,05	67	4,9	0.01 MPa each every 5 seconds
5	0,075	68	5,2	0.025 MPa each every 5 seconds
6	0,09	69	5,3	0.025 MPa each every 5 seconds

The initial pressure in all cases was 0.25 MPa. The holding time of the shell on the plate is 30 seconds at a temperature of 250 °C. Sintering of the shell took place in an electric furnace at a temperature of 350 °C for 180 seconds. The filler is sand fractions in the ratio of 1K0315–70% and 1K02–30%. The binder is pulverbakelite – 4.5% [14, 17]. The dependences of the tensile and bending strength on the applied static pressure on the mixture during shell formation were experimentally investigated. Compressed air from a pneumatic pipe carried the pressure through the press plate. A graph of the dependence of the tensile and bending strength on the applied static pressure on the mixture is shown in **Fig. 9, 10** [14]. It has been experimentally determined that applying pressure to the mixture increases the strength. With an increase in pressure after 0.2–0.25 MPa, the strength increases, but the intensity of the rise in strength decreases as the pressure increases. Thus, the optimal pressure for forming shells for castings of heating equipment should be recognized as 0.18–0.25 MPa [17].

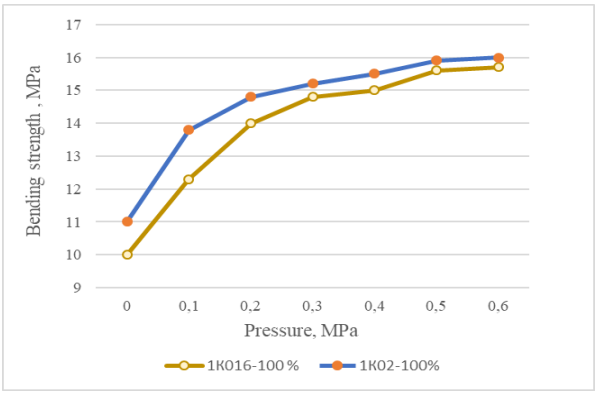

Fig. 9 The dependence of the bending strength on the applied static pressure on the mixture

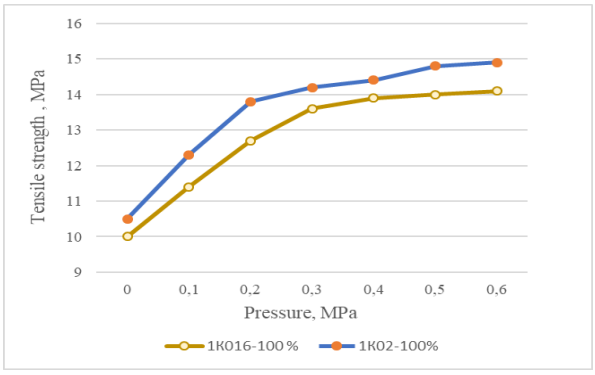

Fig. 10 The dependence of the tensile strength on the applied static pressure on the mixture

In another series of experiments, the effect of the applied static pressure on the mixture during the formation of the shell on the tensile and bending strength was determined. Pressure was exerted by means of compressed air using a press plate [17]. The effect of the dependence of the applied static pressure on the mixture on its tensile and bending strength is shown in **Fig. 11, 12**. Thus, the optimal initial pressure during shell formation should be recognized in the range of 0.2-0.25 MPa.

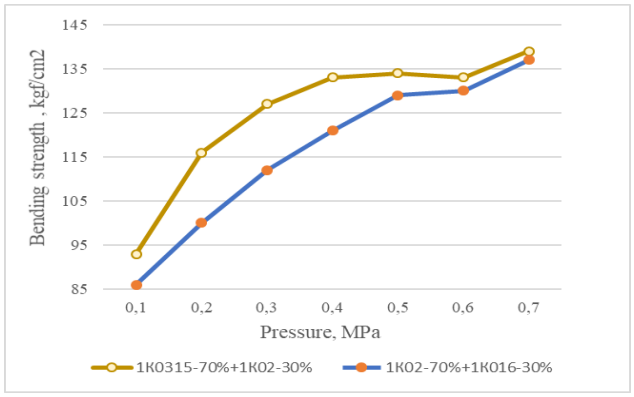

Fig. 11 The effect of static pressure on the mixture during the formation of the shell on its bending strength

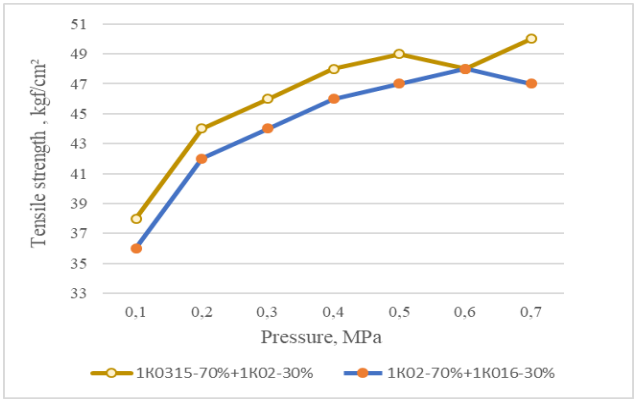

Fig. 12 The effect of static pressure on the mixture during shell formation on its tensile strength

Fig. 13 and **Fig. 14** show that the moulds strength and roughness depend on the change in pressure during the forming process.

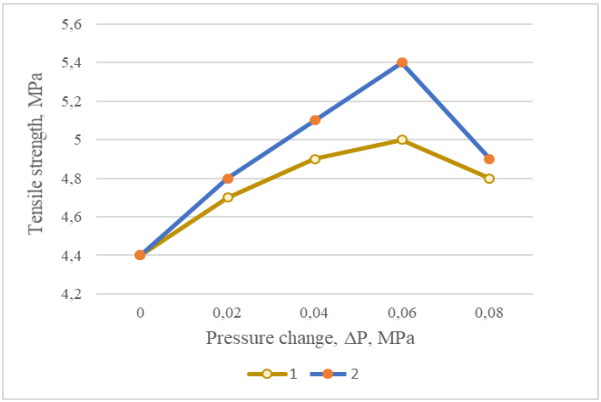

Fig. 13 The dependence of the strength of the mould on the change in the applied pressure during the formation of the shell

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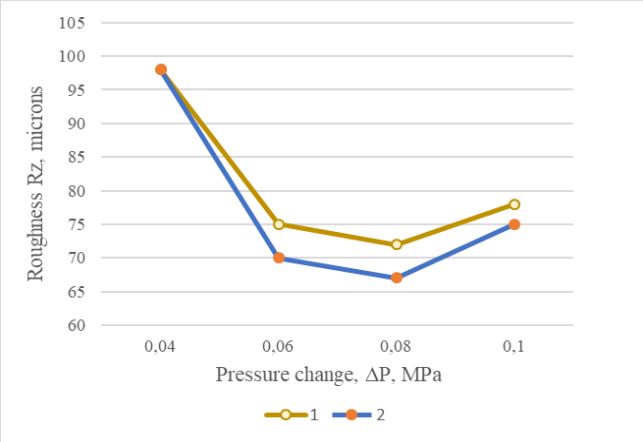

1 – roughness without pressure reduction at the end of shaping;
2 – roughness with pressure reduction at the end of shaping

Fig. 14 The dependence of the roughness on the change in the applied pressure during the formation of the shell

Changes in pressure relative to the initial one during the forming process increase the mould's strength. This is associated with increased filler grains (sand) packing and a change in the resin's adhesive properties due to a more uniform enveloping of the sand grains. At the same time, the remaining technological parameters of the shape (gas permeability, roughness) remain stable.

CONCLUSION

It was found that when using 4.5% pulverbakelite in a mixture, variable pressure allows obtaining the technologically necessary compressive strength (11-12 MPa) and hardness (90-95 units) of the shell shape, whereas using only a constant load requires a 6-7% binder to achieve these indicators.

The proposed application of variable pressure (0.2-0.25 MPa) during shell formation generally contributes to obtaining a durable shell shape.

It has been experimentally proved that a change in the pressure on the mixture during the forming process (an increase during the melting period of the resin to 0.35 MPa and a decrease during solidification to 0.2 MPa) increases the purity of the surface of the mould cavity (up to Rz 60-70), increases its compressive strength (up to 11-12 MPa), hardness (up to 105 units), reduces the amount of on castings. At the same time, the technologically necessary gas permeability (90-100 units) will not decrease.

It was determined that the temperature regime of shell forming at 240-250 0C and sintering at 320-340 °C, in combination with variable pressure, increases the compressive strength (up to 12-13 MPa) and provides a proportion of pores, the average size of which is in the range of 60-1000 nm to 61%.

The dependence of the mould pressing pressure on its dimensions, the model's mass, and the amount of heat going to heat the sand-resin mixture on the time of thermal action on this mixture are determined. These formulas allow us to calculate the pressure and temperature values necessary for the formation of the shell.

For the formation of a shell mould using variable pressure, the composition of a sand-resin mixture was experimentally determined, which ensures the formation of a high-quality casting in it: quartz sand of the 1K0315 brand-70%, quartz sand of the 1K02 brand-30%, pulverbakelite SF-011A 4.5 (over 100%), kerosene 0.2-0.4 (over 100%), white spirit 2-3 (over 100%), boric acid 0-0.2 (over 100%).

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