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RESEARCH PAPER

Studying foundry resin-bonded sand molds made with the use of variable pressure

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ABSTRACT

It is known that most casting molds are made using a binder. To exhibit its effect, the binder additive must initially be in the liquid state, then form a film on the surface of the solid phase, develop a cuff around the contact points between the grains, and solidify, thereby turning the bulk mixture into a monolithic medium. Sand-resin mixtures meet all these requirements. Casting molds made from such mixtures enable the production of high-quality castings from a wide range of alloys. However, their widespread industrial application is hindered by the relatively high cost of the binder, pulverbakelite. Therefore, research aimed at improving the manufacturing processes of durable sand-resin molds while reducing the content in the mixture, without compromising other parameters, is highly relevant.

Keywords: casting molds, sand-resin mixtures, pressure, pulverbakelite, tensile strength, gas permeability, density.

INTRODUCTION

Sand-resin mixtures exhibit properties of both a viscous liquid and a solid body. Sand-resin mixtures are multiphase dispersed systems with a high concentration of dispersed particles. After preparation, they consist of a solid phase (sand), resin, moisture, and air.

When a load is applied to a sand-resin mixture, the particles of the solid phase (sand) come together due to the removal of the gaseous medium (air). During the heating process, the gaseous phase is filled with molten resin. Interaction of phases under static loading occurs not only during volumetric change of the solid phase but also during its shape change. During shape-changing deformation, a movement of both individual solid particles and some volumes occurs. The gaseous phase and melting resin reduce internal friction, i.e. promote compaction. The density of the mixture can be increased by removing interstitial air.

Many years of experience have shown that the technology of mold manufacturing is based on the physical, chemical, and technological properties of binder compositions and mixtures. It is the study of these properties that leads to the development of fundamentally new technological processes [1]. Physical and chemical processes occurring in dispersed media are considered in works [2-7]. Physical and mechanical properties of molding mixtures that play the key role in compaction include compressive strength, tensile strength, shear strength, density, porosity, mass, bulk density, and humidity. There are also several technological properties, including fluidity, flowability, gas permeability, compactability, and moldability. The mixture strength varies over a wide range, from 0.04 MPa to 0.4 MPa.

In work [8], various compositions of molding mixtures are considered, and methods for improving their physical and mechanical properties are proposed. The relationship between the technological parameters of molding, the composition of the properties, and the properties of the molding mixture is shown.

One of the factors restraining the spread of sand-resin casting is the relatively high cost of the binder. The content of the binder in the mixture can be reduced by applying pressure to the mix during its shaping within the heating process [9]. It is possible to reduce the cost of shell molds and so castings, by decreasing the concentration of the expensive binder in them. This is achieved by using static pressure when heating the mixture and forming the shell mold. Additionally, the operational and mechanical properties of the shell can be enhanced by varying the pressure.

The use of pressing during thermal heating (accompanied by a slight increase in pressure, known as pre-pressing) of the mixture enables a more uniform distribution of the binder on the sand grains, enhances the packing of the grains, and leads to increased compressive, tensile, and bending strength. The density of the mixture also increases due to a denser packing of the sand grains and the removal of interstitial air. This method does not require the use of clad mixtures; therefore, there are no additional costs associated with it. All this ultimately allows reducing the binder content, which leads to cheaper castings.

Several works address the production of solid, durable, and dispersed sand-resin media (molds, cores, briquettes, soils) in both domestic and international scientific contexts. Studies are being conducted to improve the equipment, technology and compositions used in the production of such media. It is known [10, 11] that applying additional load to the sand-resin mixture increases the mold strength.

The casting mold must have sufficient strength to resist external loads (assembly of molds and cores, transportation) without cracking or breaking, as well as internal loads from the static and dynamic pressure of liquid metal during pouring, and from its temperature effect. Although the strength in a sand-resin mould is relatively high due to chemical interaction, it is necessary to provide technological conditions to ensure the required strength with the minimum concentration of the binder. Increasing the mixture strength is possible when using a static load, and its variability during the curing of the shell further contributes to improving the strength.

MATERIAL AND METHODS

The main components of the mixture are quartz sand and a binder: pulverized bakelite. The most common is pulverized bakelite grade SF-011A, which is a mixture of phenol-formaldehyde resin powder and urotropine [12]. Additionally, the mixture contains kerosene and an industrial solvent (alcohol). The study was carried out on molding mixtures based on quartz sand grades 1K0315 and 1K02, where pulverized bakelite SF-011A was used as a binder, as well as additives: kerosene, white spirit.

The process of forming a hard shell from the SRM was studied using an experimental setup and devices of an original design. Industrial studies were carried out at the Parkhomenko KMZ LLP (Karaganda, Republic of Kazakhstan).

The moulding machine for manufacturing shell moulds using the tested technology has been modernised based on the semi-automatic moulding machine model 51713. The diagram of the molding machine model 51713 is shown in **Fig. 1**.

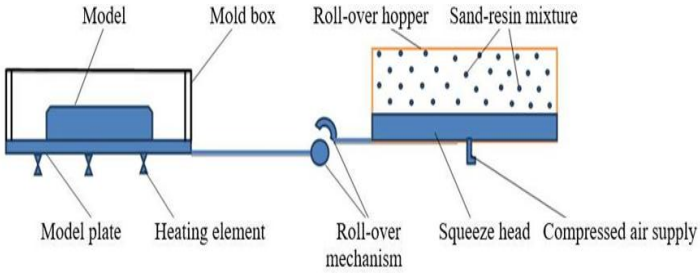


Fig. 1 Diagram of the molding machine of the 51713 type

The molding machine consists of a hopper into which the sand-resin mixture is poured, a furnace, a plate for additional static application of the load, and a table on which an electrically heated model plate with a model is mounted. A mold box is mounted on the model plate [13, 14].

On one side of the model plate there are casting models, on the opposite side of the plate there are spring pushers (for removing the finished shell half-mold from the model) and electric heating devices. A temperature sensor was also present, which helped control the heating of the plate to the set temperature. Casting models were mounted on the model plate, on the back of which there were spring pushers (to separate the finished shell half-mold from the model) and electric heating devices. There was also a temperature sensor there, with the help of which the heating of the plate to 240-260ºC was controlled. A 100 mm high mold box coinciding with the hopper with the mixture along the perimeter, was mounted on the model plate with the casting models. In the initial position, the model plate with the models was covered with the body of the drying oven. A bunker was located nearby, into which the mechanical mixture of quartz sand and pulverised bakelite was poured. Before the machine started working, the model plate was covered with a release agent that consisted of a mixture of water (100%, dimethylpolysiloxane (8%, and laundry soap (3%. When applied to the model heated to 250°C, the release agent formed a hard, thin, yet heat-resistant film that was preserved after several removals of the shells from the model. When the molding machine was turned on, the furnace rose upward, and the mixture was poured from the bunker onto the model plate. At the same time, the support plate of the bunker as a result of rotation ended up in the upper position, was movable and could exert a static load on the mixture. Then the bunker returned to its original position. The pressure on the press plate is applied by compressed air from the pneumatic pipeline.

Under the effect of the heat of the model equipment, the pulverized bakelite in the layer of the mixture directly adjacent to the model plate melts and wets the sand grains. After the shell is formed, the model plate returns to its original position, and the model plate with the formed shell is covered with a furnace, inside which the temperature reaches 350ºC. The thickness of the shell is 10-15 mm [13]. The tensile strength of sand-resin mixtures was determined on standard samples (**Fig. 2**).

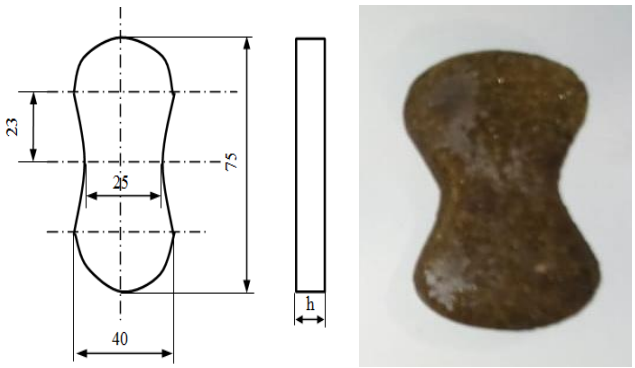


Fig. 2 Form and sizes of samples for tensile testing

The samples were manufactured in accordance with the technology of manufacturing shell molds. Samples for compressive strength testing (**Fig. 3**) were manufactured using a process similar to the method for manufacturing shell molds 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 preliminary backfill of the sand-resin mixture. The arithmetic mean of the obtained results was considered the indicator of strength. If the data for one sample differed from the arithmetic mean by more than 10%, the tests were repeated [13, 15].

The height of the samples depends on the pressure, the temperature of the model plate, and the duration of exposure to the temperature.

Fig. 3 Model for determining compressive strength

To determine the surface roughness of the castings, after cooling, samples measuring 30 × 30 × 15 mm were cut out of them using a disk cutter. The plane of the samples was cleaned of easily separable burnt-on molding sand [16].

Standardized methods and modern equipment of accredited (SS ISO 17025-2009 "General requirements for the competence of testing and calibration laboratories") laboratories of the

International Center for Materials Science and the Engineering Testing Laboratory "KORMS" of Karaganda Technical University were used to study the samples [13].

The following parameters of the mold were determined: compressive strength, tensile strength, porosity, gas permeability, roughness, as well as the amount of burn-on and roughness of the casting.

To determine compressive and bending strength, a floor-standing setup for determining mechanical properties INSRON-100 (United Kingdom) was used.

The roughness of the samples and cast blanks was determined after their cleaning using a TR-220 roughness measuring device [13, 17].
The dependence of the mold gas permeability on the value of pressure applied during the hardening of the casting mold was determined. To test gas permeability of the sand-resin mixture (SRM), a well-known method of testing sand-clay mixtures was used [18]. Samples with the diameter of 10 mm that were made using a pile driver in a sleeve were tested. Different fractional compositions of sand were also used in the mixture [13]. The sand-resin mold was determined using a well-known method on a device for deciding gas permeability of the 04315M brand. The samples were sintered in a Nobertherm furnace (Germany).

RESULTS AND DISCUSSION

In a series of experiments, the most appropriate application of the mixture composition formula was determined (**Table 1**).

Table 1 – Mixtures that were used in the studies

Component	Limits of used concentrations of components in the mixture, %
Quartz sand grade 1K0315	0-100
Quartz sand grade 1K02	0-100
Pulverbakelite SF-011A	1-8 (over 100%)
Kerosene	0-1 (over 100%)
White spirit	1-5 (over 100%)

The microstructure of the mixture was studied under two conditions: cured without variable pressure (constant pressure of 0.25 MPa) and using variable pressure (base pressure of 0.25 MPa, with an initial increase to 0.35 MPa and subsequent decrease to 0.2 MPa) (**Fig. 4**).

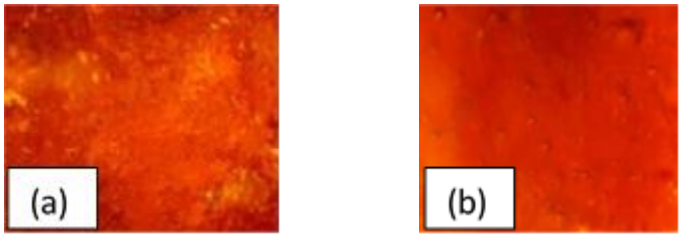


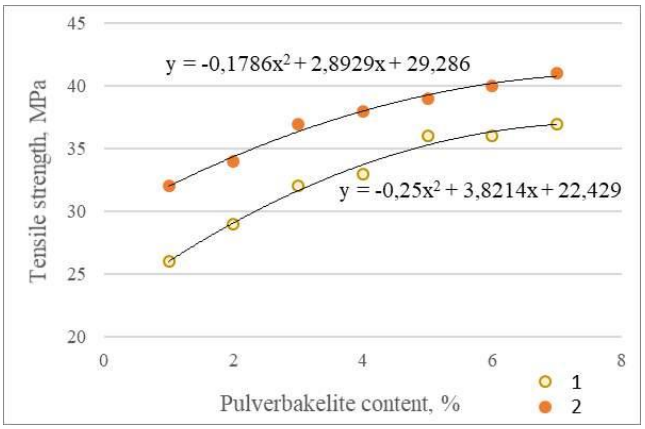
Fig. 4 Structure of the mixture: a – constant pressure; b – variable pressure (×500)

It is evident that in the second case, the filler particles are more closely packed together, resulting in a higher density and strength of the mixture.
In a series of experiments, the effect of the pulverbakelite content on the mechanical and technological properties of the mixture was determined [19]. The technological process previously determined looks like this: after the process of mixing the components of the molding sand-resin mixture, it is poured into the hopper of the molding machine. After that, the hopper filled with the
mixture is turned over onto a model plate with casting models preheated to 230 ^{0}C. At the same time, pressure of 0.25 MPa is simultaneously applied to the mixture by means of a plate mounted in the hopper. After 10 seconds, pressure increased to 0.35 MPa. After another 10 seconds, pressure is reduced to 0.2 MPa. As a result of such technological modes, a shell with the thickness of 15-17 mm is formed. After removal from the model plate, the shell is sintered at the temperature of 330- 350 ^{0}C within 2 minutes.
The results of studying the effect of pulverbakelite content on the strength and gas permeability of the sand-resin mold are presented in **Table 2**.

Table 2 – Pulverbakelite content effect on compressive strength and gas permeability

Pulverbakelite content, %	Compressive strength, MPa	Gas permeability, un.
4	13.9	144
7	14.3	133
10	14.7	126
13	14.9	119

From **Table 2** [19] it is evident that according to this technology the content over 4-7 percent has little effect on increasing strength. Gas permeability remains within the technologically necessary limits at all the resin concentrations used.
The dependence of tensile strength on the binder content is shown in **Fig. 6**. In the experiments carried out, the binder (pulverbakelite) content in the mixture varied from 1 to 7%. The formation of the shell mold was accompanied by pressure of 0.25 MPa applied to the mixture within the entire time of shell formation and the initial 0.25 MPa increase to 0.32 MPa and decrease at the end of molding to 0.2 MPa.
It is evident (**Fig. 5**) that to achieve the necessary technological indicators of the mixture using the employed technology, it is sufficient to use 4-7% of the binder. With the use of a lower binder content in the mixture, the adhesion and cohesion of its components are not great enough to withstand the pouring of the melt into the mold. A higher content is not advisable, since the technological parameters of the mold do not increase, and the cost of such a mold will increase. The content of pulverbakelite above 7-8% will lead to the formation of an excess liquid phase and the system strength will decrease.



1 – using variable pressure in the molding process;
2 – using constant pressure in the molding process

Fig. 5 Dependence of the tensile strength of the mixture on the resin content

The use of quartz sands of different fractions on the strength of the mixture and its gas permeability was studied (**Table 3**).

Table 3 – The ratio of sand fractions (1K0315 and 1K02) effect on strength and gas permeability

Ratio of fractions K0315 and 1K02 in the mixture	Compressive strength, MPa	Gas permeability, un.
100:0	12.5	148
30:70	11.9	111
70:30	14.6	129
0:100	10.7	102

The most appropriate is to use quartz sand of two fractions: a large fraction 70%, and a small fraction 30%. The ratio of sand fractions (1K0315 and 1K02) in the mixture was investigated for its effect on strength and gas permeability. The content of pulverbakelite was 7%.

The optimal ratio is obviously associated with the densest packing of sand particles and the largest number of contacts in this arrangement. At the same time, gas permeability remains within the technologically necessary indicators (about 100 units). This is generally due to the fact that the compacted sand-resin mixture is sufficiently well and uniformly able to pass gases.

The quantitative content of kerosene in the mixture was also studied (**Fig. 6-8**). Kerosene is added to the mixture to reduce its adhesion to the walls of the model and the model plate. The composition of the mixture in this series of experiments is as follows: quartz sand 1K315 70%; quartz sand 1K02 30%; pulverized bakelite 7% (over 100%), kerosene 0-6%
(over 100%).

The graphs show that the most positive dynamics are demonstrated by the kerosene content of 0.2-0.4%. A higher content leads to increased gas formation, a lower content leads to increased adhesion, and the surface of the mold when removed from the model plate becomes significantly more uneven and has a greater number of surface defects (**Fig. 9**). At the same time, kerosene does not have a significant effect on strength and gas permeability.

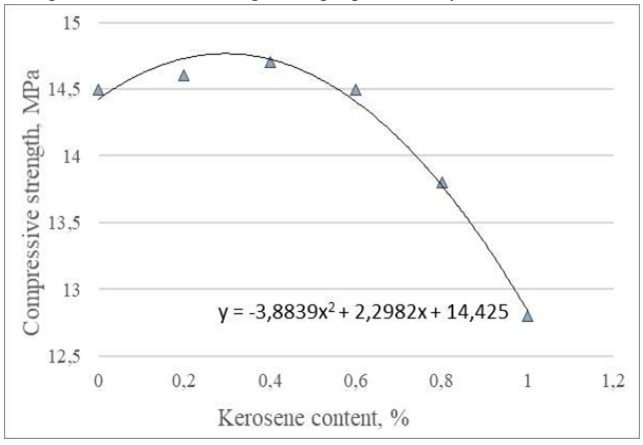


Fig. 6 – The kerosene content effect on the compressive strength of a sand-resin mold

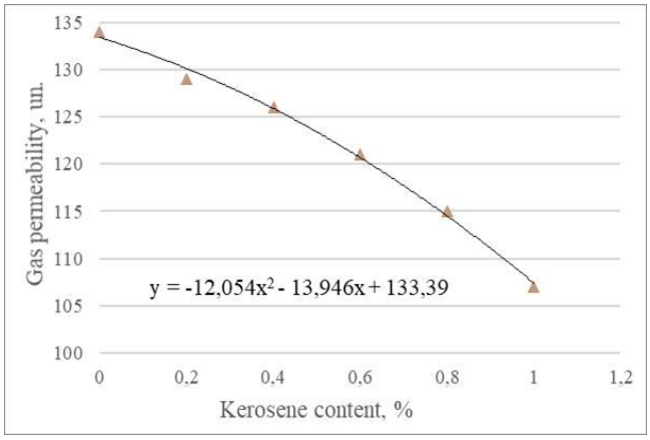


Fig. 7 – The kerosene content effect on gas permeability of a sand-resin mold

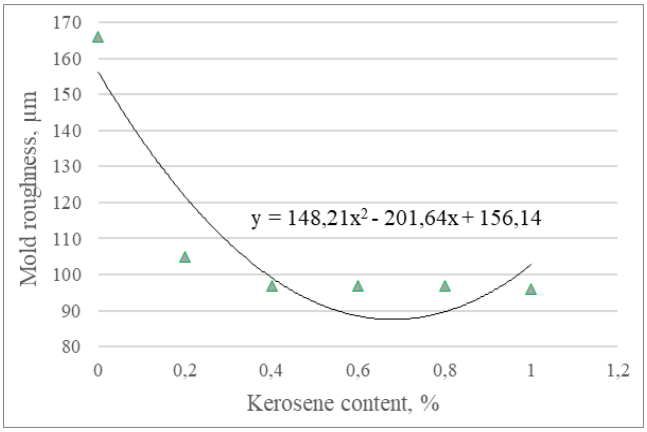


Fig. 8 The kerosene content effect on the roughness of a sand-resin mold

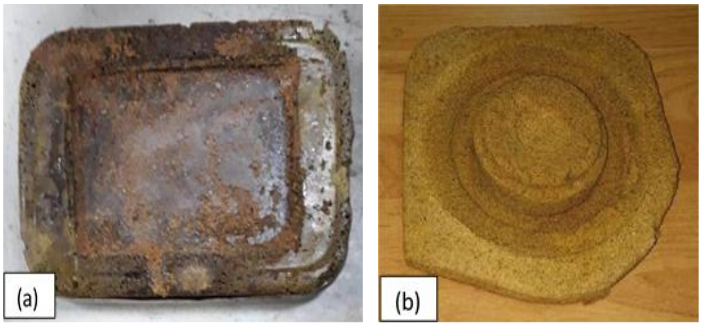


Fig. 9 – Shell mold: a – in the absence of kerosene in the composition; b – with addition of 0.6% kerosene

Another additive used in the mixture is white spirit, also known as industrial alcohol. They act as a humectant. The effect of humectant concentration on the technological parameters of the finished shell mold was studied (**Fig. 10-12**).

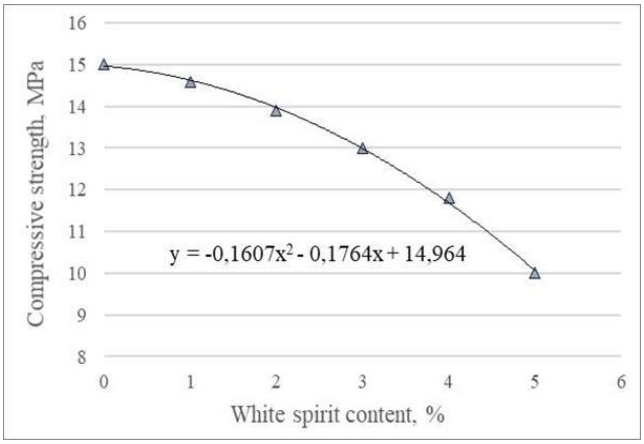


Fig. 10 – The white spirit content effect on compressive strength of the sand-resin mold

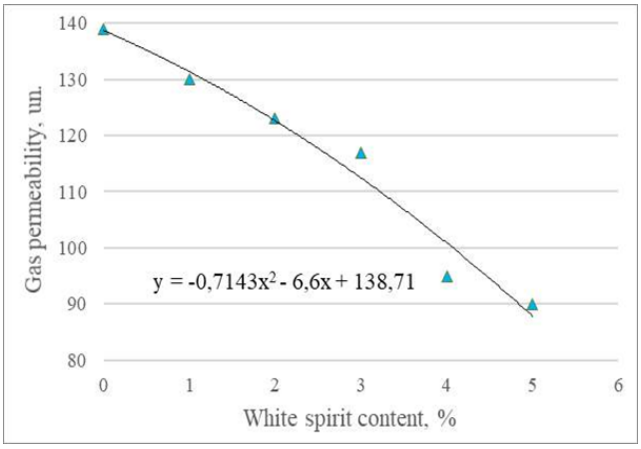


Fig. 11 – The white spirit content effect on gas permeability of the sand-resin mold

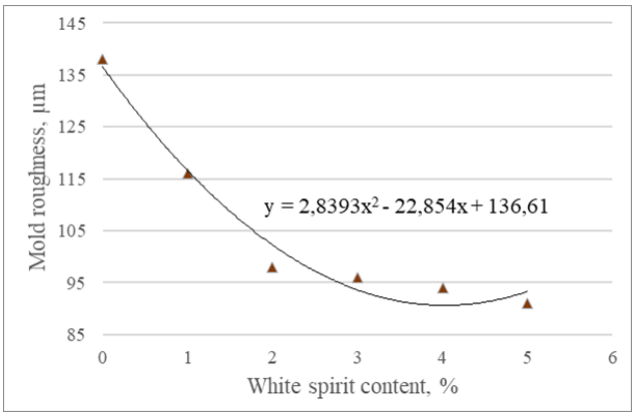


Fig. 12 – The white spirit content effect on the roughness of the sand-resin mold

Studies have shown that it is advisable to use 2-4% of the humectant (**Fig. 13**). Exceeding this indicator leads to weakening and increased gas formation when pouring, and a lower content contributes to the filling of the dusty fraction of sand in the space between the particles of sand and resin and therefore, significantly worsens gas permeability, which ultimately also leads to gas porosity in castings. Roughness is also improved within the specified limits of the humectant content. A smaller amount of white spirit leads to the presence of an increased content of finely dispersed sand fraction on the layer of the mold bordering the casting, while a large amount leads to increased gas formation and the appearance of irregularities on the surface of the casting as a result.

Fig. 13 – Shell mold: with 4% white spirit content

The residual moisture in the sand after drying effect on the mechanical properties of the shells was also assessed (**Table 4**).

Table 4 –The residual moisture of sand after drying effect on the mechanical properties of shells

Sand residual moisture, %	Gas permeability, un.	Shell compressive strength, MPa
1	99	11.0
0.8	107	12.2
0.6	122	13.1
0.4	140	13.9
0.2	138	14.6
0	126	14.5

Thus, the most optimal composition for making molds with the use of variable pressure is recognised as the following (**Table 5**) [20]:

Table 5 – The optimal composition of the sand-resin mixture

Component name	Percent content in the mixture, %
Quartz sand grade 1K0315	70
Quartz sand grade 1K02	30
Pulverbakelite SF-011A	7 (over 100%)
Kerosene	0.2-0.5 (over 100%)
White spirit	2-5 (over 100%)

Thus, it was determined that the optimal time for obtaining a sand-resin shell of technological thickness (8-12 mm) was 25-30 s. Further heating time is impractical, since the intensity of heat release for heating the mold decreases; in addition, the resin burns out, which weakens the mold.

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The optimal composition for molding using variable pressure was determined as follows: quartz sand grade 1K0315 – 65.4%, quartz sand grade 1K02 – 23%; pulverized bakelite SF-011A – 7.2%; kerosene – 0.4%; white spirit – 4%.

It was determined that the technologically needed value of gas permeability was ensured if the pressure on the mixture was initially used amounting 0.27-0.36 MPa, which should then be adjusted using the above-described technology. If pressure continues to increase (above 0.35 MPa), the gas permeability of the shell mold drops below 90 units. The deterioration in gas permeability occurs due to the extrusion of filler grains and “clogging” the pores in the hardened shell.

The effect of shell formation time on the plate under heating conditions (250°C) and pressure changes, as described above, was also studied (**Fig. 14**).

It is obvious (**Fig. 14**) that when the shell is kept on the plate for more than 100 seconds, its gas permeability deteriorates due to the burning out of the resin in the layers adjacent to the plate, which leads to the shedding of sand particles and contamination of the pores with them.

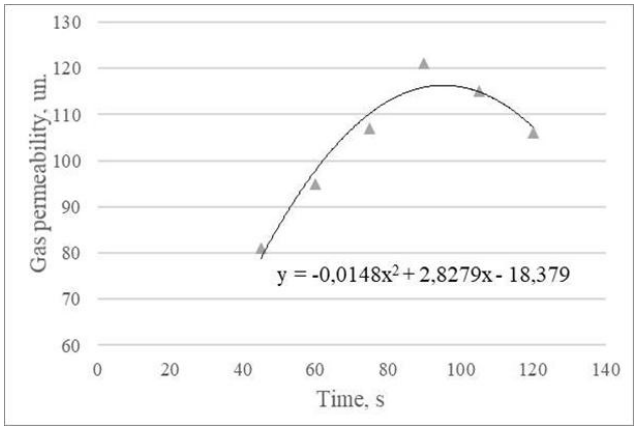

Fig. 14 – Gas permeability of the sand-resin shell depending on the duration of molding

In another series of experiments, the effect of the advisability of increasing the pressure on the mixture during the molding process was studied. It was determined that with increasing pressure during the molding process by 0.03-0.05 MPa relative to the initial pressure (0.25 MPa), the roughness of the shells decreases, while its gas permeability remains within 90-100 units. With further increasing pressure, a decrease in gas permeability of less than 100 units and a slight increase in roughness are observed, which is due to the extrusion of grains in the already forming shell. Table 5 presents experimental data on determining the optimal pressure on the mixture. The graph of the dependence of the mold roughness on changing pressure during the shell formation is shown in **Fig. 15**, the dependence of the mold strength on changing pressure during the shell formation is shown in **Fig. 16**. The initial pressure in all the cases was 0.25 MPa. The shell was held on the plate within 30 s at the temperature of 250 °C. The shell was sintered in an electric furnace at the temperature of 350 °C within 180 s. The filler was sand of fractions in the ratio of 1K0315–70% and 1K02–30%. The binder was pulverized bakelite – 7% [13, 16].

The dependences of tensile and bending strength on the applied static pressure on the mixture during shell forming were experimentally studied. The pressure through the pressing plate was carried out by compressed air from the pneumatic pipeline. It was experimentally determined that applying pressure to the mixture increases strength. With an increase in pressure after 0.2-0.25 MPa, the strength increases, but the intensity of the increase in strength decreases as the pressure increases. Thus, the optimal pressure during shell forming for heating equipment castings should be recognized as 0.20-0.30 MPa [16].

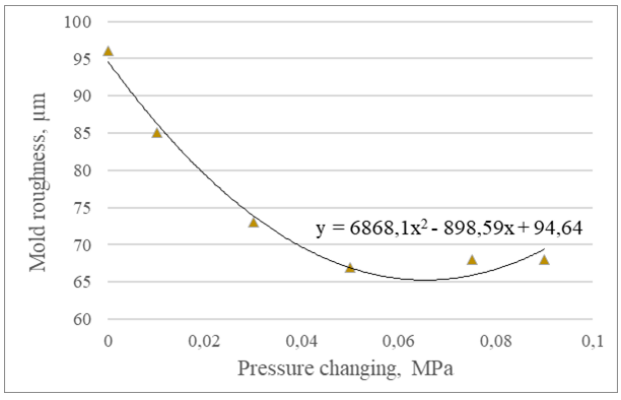

Fig. 15 – The mold roughness dependence on changing pressure during formation of the shell [16]

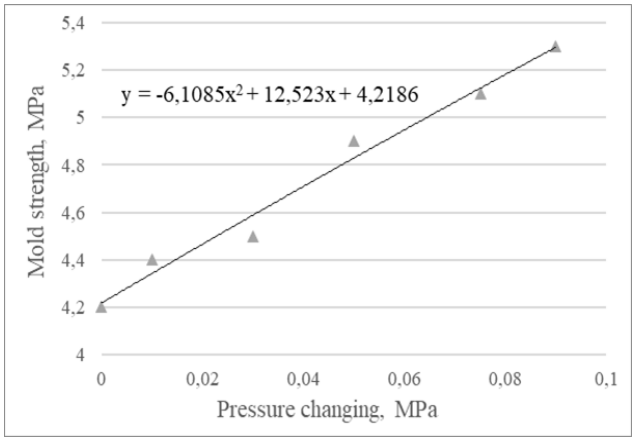

Fig. 16 –The mold strength dependence on changing pressure during formation of the shell [13]

Studies have shown that even initially with the application of pressure, the density of the shell mold increases significantly relative to the bulk one. This is determined by the exclusion under the influence of the applied static pressure. From the lump of the mixture, most of the interstitial air and, as a result, a more compact packing of sand particles and unmelted resin particles.

Subsequently, the density increases less significantly and is determined by the melting and hardening of the resin throughout the volume of the shell, which fills the remaining pores between the sand particles. Long-term thermal exposure to the PSS will lead to the burning of the resin and, consequently, to loosening and a reduction in strength. A similar behaviour of the mixture is observed when measuring its density as a function of heating time. The greater the value of the initial pressure on the mixture, the higher the density of the form at the initial moment of the shell formation due to the complete removal of the interstitial air and the approach of the bulk density of the mixture to the specific gravity.

CONCLUSION

It was experimentally confirmed that non-stationary pressure in combination with thermal heating increases the density of shell molds, which ultimately affects the quality of castings produced in these molds.

The results of studying the effect of molding modes on the properties of a shell mold and castings obtained in it show that changing the pressure on the mixture during the molding process (increasing within the period of resin melting to 0.30 MPa and decreasing during solidification to 0.2 MPa) improves the purity of the mold cavity surface (up to Rz60-70), increases its compressive strength (up to 11-12 MPa), hardness (up to 105 units), and reduces the amount of casting burn-on. At the same time, the technologically required value of gas permeability (90-100 units) remains unchanged.

The temperature mode of forming the shell mold at 240-250 0C and sintering at 330-350 0C in combination with variable pressure increases compressive strength (up to 12-13 MPa) and provides the share of pores, the average size of which is in the range of 60-1000 nm, up to 61%.

When using 7% pulverbakelite in the mixture, the use of variable pressure allows obtaining the technologically needed indicators of compressive strength (11-12 MPa) and hardness (90-95 units) of the shell mold, while the use of only a constant load requires 9-13% of the binder to achieve these indicators.

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