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THE INFLUENCE OF SAND-RESIN MOLD FORMATION MODES ON THE QUALITY OF THE CAST

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ABSTRACT
When heating pulverbakelite in sand-resin mixtures during the manufacturing of shell molds, its state of aggregation changes into solid–liquid–solid form. In the process of forming a sand-resin mold, to reduce the amount of binder (pulverbakelite) in the mixture and to increase strength, along with the thermal effect, static pressure was applied that varied in accordance with changing the aggregate state of the resin. The initial pressure was 0.25 MPa, and the mixture was fed from the hopper into a model plate heated to 230 °C. After 10 seconds, pressure increased to 0.35 MPa, and after another 10 seconds it decreased to 0.2 MPa. It was experimentally established that the internal stresses of castings obtained in sand-resin molds made with the use of variable pressure were minimal and uniform. Studies also showed that such castings had a high surface purity (Rz 70-80) and no internal defects.

INTRODUCTION

Sand-resin mixtures exhibit properties characteristic of both viscous fluids and solid bodies. These mixtures constitute multiphase dispersed systems characterized by a high concentration of dispersed particles. Immediately following preparation, they consist of a solid phase (sand), resin, moisture, and air.

When a load is applied to a sand-resin mixture, the solid-phase particles (sand) coalesce as a result of the gaseous medium (air) expulsion. During the heating process, the gaseous phase becomes filled with molten resin. Under static loading, phase interaction occurs not only in response to changes in the volume of the solid phase but also in response to changes in its shape. During shape deformation, both individual solid particles and certain volumes of material undergo displacement. The gaseous phase and the molten resin serve to reduce internal friction, thereby enhancing the compaction process. The density of the mixture can be increased through the elimination of intergranular air.

As demonstrated by years of practical experience, the technology of producing molds is fundamentally based on the physicochemical and technological properties of the binders and mixtures employed. Studying these properties leads to the development of fundamentally new technological processes (Kowalczyk et al., 1995). The physicochemical processes occurring within such a dispersed medium are examined in works (Beeley, 2001; Issagulov et al., 2008; Issagulov et al., 2015; Koreniugin & Rovin, 2023; Kovaleva et al., 2017; Kulikov et al., 2025). The physical and mechanical properties that play the crucial role in the compaction of molding mixtures include compressive strength, tensile strength, shear strength, density, porosity, mass, bulk density, and moisture content. Additionally, there exists a range of significant technological properties, such as flowability, pourability, gas permeability, compactability, and moldability. The mixture strength varies over a wide range, typically spanning from 0.04 MPa to 0.4 MPa.

Work (Dostayeva et al., 2025) examines various compositions of molding mixtures and proposes methods of enhancing their physical and mechanical properties. The interrelationship between the parameters of the molding process, the properties of the composition, and the properties of the molding mixture is demonstrated.

One of the factors that hinder the widespread adoption of resin-bonded sand casting is a relatively high cost of the binder material. The amount of binder in the mixture can be reduced by applying pressure during the heating phase of the molding process (Issagulov et al., 2008). The cost of shell molds and castings can be lowered by reducing the concentration of the expensive binder within them. This is achieved by applying static pressure while heating the mixture and forming the shell mold. Furthermore, by varying the applied pressure, it is possible to enhance the operational and mechanical properties of the shell.

The application of compression during the thermal heating of the mixture accompanied by a slight increase in pressure, the process known as "pre-pressing", facilitates the uniform distribution of the binder among the sand grains, improves grain compaction, and results in increased compressive, tensile, and flexural strength. The density of the mixture also increases due to the compaction of the sand grains and the elimination of interstitial air. This method does not require the use of coated sand mixtures, so, it entails no additional costs. Ultimately, all these factors enable reducing the binder content, thereby leading to lower casting costs.

Within both domestic and international scientific contexts, numerous studies have focused on the production of rigid, high-strength, and granular sand-resin materials (including molds, cores, briquettes, and foundations). Studies are currently underway to refine the equipment, technologies, and material compositions utilized in the manufacturing of such materials. It is well established that applying an additional load to a sand-resin mixture enhances the resulting mold strength [8].

A casting mold must possess sufficient strength to withstand external loads, such as the assembly and transport of molds and cores without cracking or fracturing, as well as internal loads resulting from the static and dynamic pressure of the molten metal during casting, along with its thermal effects. Although the sand-resin mold strength is relatively high due to chemical interactions, it is essential to establish specific processing conditions to achieve the requisite strength while minimizing the binder concentration. The mixture strength can be enhanced through the application of static loads, and the variability of this strength during the shell-curing process contributes to the overall increase in durability.

In contrast to previously published studies on resin-bonded sand molds produced under constant or variable pressure conditions, the present work focuses on the optimization of pressure variation during shell mold formation in accordance with the thermally induced phase transformation of the resin binder. The scientific contribution of the study consists in establishing a pressure–temperature processing mode that improves particle packing, enhances binder distribution uniformity, reduces binder consumption, and improves casting surface quality. Furthermore, the relationships between molding pressure, binder concentration, sand grain size distribution, strength, gas permeability, and surface roughness were quantitatively analyzed, providing a comprehensive technological basis for the production of high-quality shell molds and castings.

The scientific novelty of this study lies in the development and experimental validation of a variable-pressure shell mold formation method synchronized with the thermally induced solid–liquid–solid transformation of the resin binder. Unlike previous studies that considered the general application of pressure during shell mold production, the present work establishes an optimized pressure schedule (0.25–0.35–0.20 MPa) and evaluates its influence on mold structure, mechanical strength, gas permeability, and casting surface quality. Furthermore, the combined effects of binder content and quartz sand fraction distribution under variable-pressure conditions were systematically investigated. The obtained results provide practical recommendations for reducing binder consumption while maintaining the required technological and mechanical properties of shell molds and ensuring the production of defect-free castings.

MATERIALS AND RESEARCH METHODS

One method of producing precision castings is casting in sand-resin molds. This method enables the production of castings with precise geometric dimensions and low surface roughness (Kowalczyk et al., 1995). Furthermore, one approach to enhancing the quality of castings produced via the shell molding method involves forming the molds under variable pressure (Koreniugin & Rovin, 2023).

When a sand-resin mixture is heated, resin liquefies at the temperature of approximately 130 °C; however, at temperatures exceeding 200 °C it undergoes irreversible solidification, that is, the resin undergoes changing its physical state. The use of shell molds significantly improves both the surface quality and the geometric accuracy of the resulting castings (Kovaleva et al., 2017).

This study utilized a device designed and manufactured based on a patented technology for the production of sand-resin molds. The device design and operating principle are predicated on the precise control of the key technological molding parameters, specifically temperature and pressure, thereby enabling the regulation of the density, strength, and thermal stability of the resulting molds.

A distinctive feature of the device design is its compatibility with interchangeable pattern plates. This capability allows for the fabrication of sand-resin molds in a wide variety of shapes and geometric dimensions, thereby ensuring the device broad applicability in experimental and laboratory research.

Despite the widespread adoption of 3D-printed plastic molds in modern manufacturing, sand-resin molds remain technologically relevant in traditional metallurgy, particularly for high-temperature casting applications and the processing of heat-resistant alloys. In this context, the proposed device serves as an effective tool for studying and optimizing metallurgical casting processes.

Prior to the commissioning of this unit, sand-resin molds were produced under laboratory conditions using manual compaction (ramming); this increased the labor intensity of the process and limited reproducibility of the resulting molds properties. The proposed unit eliminated these drawbacks, enabling the automation and stabilization of the mold-making process.

Strict safety protocols are observed during the operation of the unit. The sand-resin mixture is loaded into a dedicated hopper in the specific ratio prescribed by the proprietary technology. The control system sets the required temperature and pressure parameters, and the unit automatically forms the mixture against the pattern plate. Upon completion of the process, the upper mold lifts, and the finished sand-resin mold is extracted.

The average production time for a single mold is 3–5 minutes; this demonstrates the device high throughput and enables the production of a large volume of molds within a short timeframe under laboratory conditions. The finished molds emerge at high temperatures and emit a distinct odor resulting from the thermal decomposition of resin; therefore, additional safety precautions are observed during their extraction.

The HZ-450-B is a four-column machine featuring an open-and-closed frame design intended for the production of resin-coated sand cores (Figure 1).

The machine is capable of operating in fully automatic, single-cycle, and manual control modes. It is designed for the production of sand molds weighing no more than 6 kg.

This equipment is utilized for manufacturing cores and thin-walled sand molds using sand coated with phenolic resin.

This method proves highly effective in foundry operations where high precision, surface finish quality, and dimensional stability are critical requirements.

Figure 1. General view of sand shell molding machine HZ-450-B
Note – compiled by the authors

For each experimental condition, three specimens were prepared and tested to ensure the repeatability of the results. The values presented in the tables and figures correspond to the arithmetic mean of the measurements obtained from the tested specimens. Tensile strength and gas permeability were determined using standard laboratory methods employed in foundry practice. Surface roughness of the castings was evaluated using profilometric measurements and expressed as the roughness parameter Rz. The resulting castings were additionally subjected to visual inspection and metallographic examination to assess the presence of surface and internal defects. The repeatability of the obtained results confirmed the reliability of the experimental methodology and the observed process trends.

RESULTS AND DISCUSSION

When the sand-resin mixture is discharged from the hopper onto the pattern plate, specific initial pressure (0.25 MPa) is applied. This helps to expel excess air from the mixture and to increase the contact area between the sand grains and the powdered bakelite particles, which in turn enhances heat transfer. During formation of the powdered bakelite layer around the pattern, it is advisable to increase pressure to 0.35 MPa. As demonstrated by experiments, this ensures the establishment of strong bonds between the sand grains; resin is distributed uniformly throughout the entire mold shell and completely coats the sand particles.

Once the shell layer has cured in the region immediately adjacent to the pattern, pressure must be reduced again to prevent the sand from being forced out of the formed shell and to avoid the overall structural failure of the shell. Previously (Dostayeva et al., 2025), the optimal composition for the sand-resin mixture intended for molding using variable pressure was determined (Table 1).

The technological process was carried out as follows: after mixing, the sand-resin mixture was loaded into the machine hopper. Subsequently, the pattern plate heated to 230 °C and fitted with the casting patterns was moved into position beneath the hopper containing the mixture. At this moment, pressure of 0.25 MPa was simultaneously applied through the plate. After 10 seconds, pressure was increased to 0.35 MPa, and after further 10 seconds, it was reduced to 0.2 MPa. As a result, a shell mold with the thickness of 10–12 mm was formed. The molds were then heated at the temperature of 320–340 °C witin 2 minutes.

Table 1. The sand-resin mixture composition

No.	Parameter	Additive content, %
1	Quartz sand, fraction 0.1–0.5 mm	70
2	Quartz sand, fraction 0.4–0.9 mm	30
3	Powdered Bakelite SFP-011A	4,5 (100% and higher)
4	TS Kerosene	0,2-0,4
5	Oil thinner (white spirit)	2-3
6	Boric acid	0-0.2
Note – compiled by the authors		

To select correctly the technological parameters of the shell, it is advisable to determine their impact on stress concentration in the resulting casting, as an excessively dense and rigid mold will impede the solidification of the metal. Figure 2 illustrates a mold fabricated of a mixture of sand and resin.

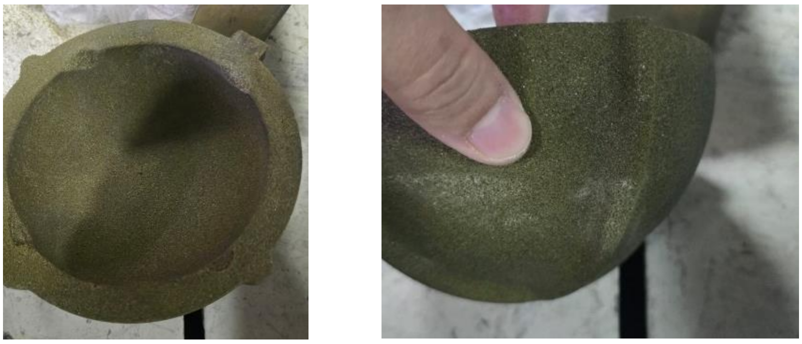
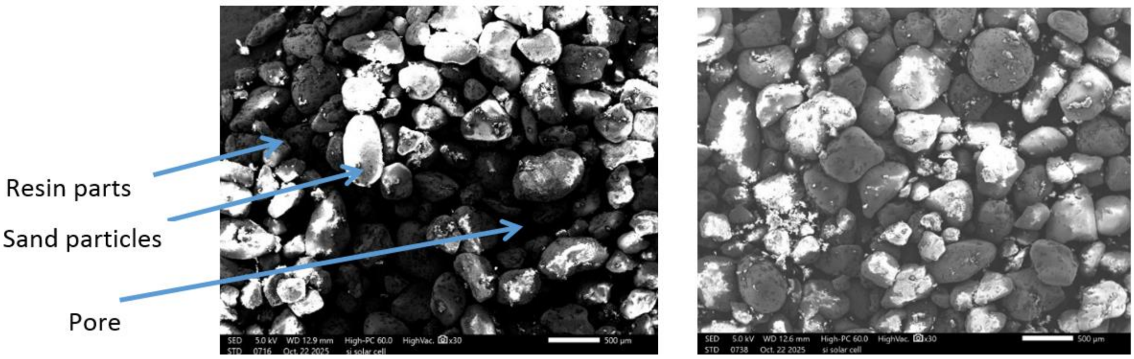


Figure 2. Molds made at the factory with the use of variable pressure
Note – compiled by the authors

It is well known that stresses are particularly dangerous during the initial stage of cooling, as the high-temperature strength of alloys is very low at this time. Furthermore, if low-melting phases form within the alloy, its strength can decrease even further. These stresses lead to the formation of hot cracks in castings.

Figure 3 (magnification ×30) illustrates the structures of a mixture of quartz sand and powdered bakelite obtained under constant pressure (a) and variable pressure (b), respectively.



a) – with constant pressure; b) – with variable pressure
Figure 3. Compound structure, (×30) 500 μm
Note – compiled by the authors

Figure 3a reveals that the sand particles are not sufficiently densely packed, resulting in the formation of pores; moreover, the bakelite particles are distributed unevenly, which leads to insufficient strength in the mixture.

Figure 3b shows that the sand particles are packed more densely, and the frequency of contact points is significantly higher than that observed under constant pressure. Additionally, a relatively uniform distribution of the powdered bakelite particles is visually apparent. Such a structure contributes to an increase in the mechanical strength of the shell.

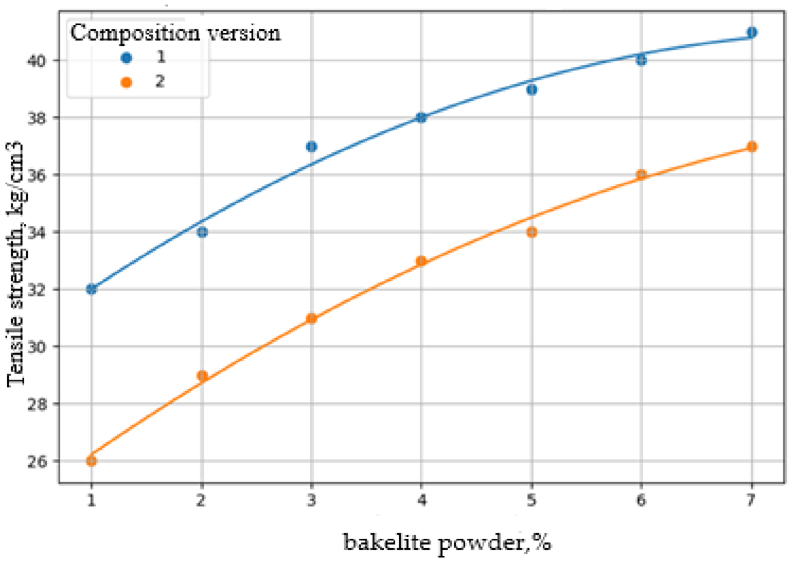
Table 2 presents the results of studying the powdered bakelite content effect on strength and gas permeability of sand-resin molds.

Table 2. The amount of powdered bakelite in the mixture effect on tensile strength values and gas permeability

Bakelite content in the mixture, %	Tensile strength limit, MPa	Gas permeability, un.
4	13.9	144
7	14.3	133
10	14.7	126
13	14.9	119
Note – compiled by the authors		

Table 2 demonstrates that, when utilizing this technology, the binder content exceeding 4–7% has a negligible effect on increasing strength. However, gas permeability remains within the technologically required limits across all the binder concentrations employed.

The dependence of tensile strength on the binder content is illustrated in Figure 4. In the experiments, the amount of binder (bakelite powder) in the mixture varied from 1% to 7%. The formation of the shell mold was carried out under pressure of 0.25 MPa applied to the mixture throughout the entire molding period; initial pressure was 0.25 MPa and was increased to 0.32 MPa and subsequently decreased to 0.2 MPa by the end of the molding process.



1 – composition obtained under variable pressure during the molding process;
2 – constant pressure during the molding process

Figure 4. Tensile strength dependence on bakelite powder content

Note – compiled by the authors

It is evident that, with the technology employed here, the a binder content of 4–7% is sufficient to achieve the required technological properties of the mixture. Naturally, using the minimal amount of binder in the mixture does not result in sufficient adhesion and homogeneity among its components to withstand the pouring of molten metal into the mold. Conversely, a higher binder content is inadvisable, as it yields no improvement in the mold performance characteristics while simultaneously increases its production cost. The bakelite powder content exceeding 7–8% leads to the formation of an excessive liquid phase, which ultimately compromises the structural integrity of the system.

A study was conducted on the effect of quartz sand of different fractions on the strength and gas permeability of the mixture (Table 3).

Table 3. Strength and gas permeability of the quartz sand and fraction 0.1–0.5 mm and 0.4–0.9 mm mixture in different proportions

Quartz sand and fraction 0.1–0.5 mm and 0.4–0.9 mm mixture in different proportions	Tensile 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
Note – compiled by the authors		

The most optimal solution proved to be the use of quartz sand composed of two fractions: 70% coarse sand and 30% fine sand. The ratio of sand fractions in the mixture (0.1–0.5 mm and 0.4–0.9 mm) was assessed based on strength and gas permeability. The content of Bakelite powder was maintained constant at 7%.

The optimal ratio of sand fractions is characterized by the densest arrangement of particles and the greatest number of contact points. In this case, the mixture gas permeability is maintained at the level that meets technological requirements (approximately 100 units). This result is explained by the uniform compaction of the sand-resin mixture and its effective gas permeability.

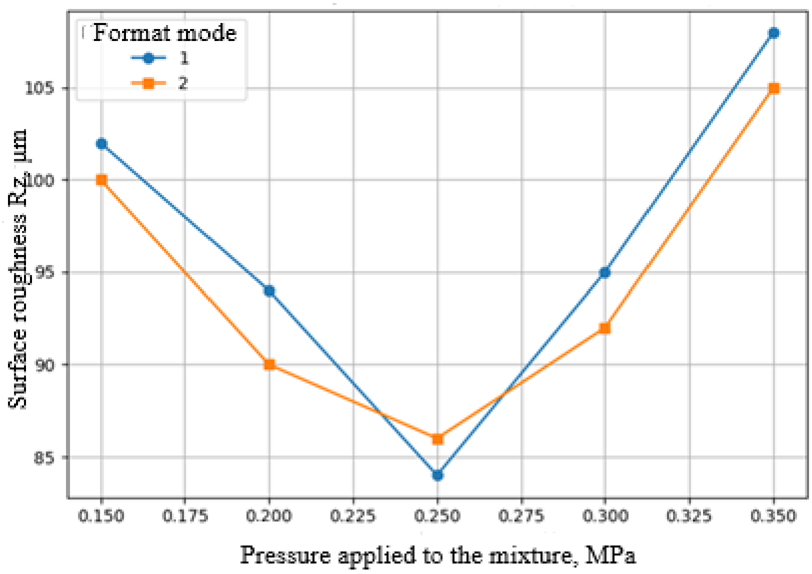


Figure 5. Pressure impact in the film surface roughness

Note – compiled by the authors

The dependence of casting surface roughness on the pressure acting on the mixture is shown in Figure 5. Experimental data indicate that the optimal value is reference pressure of 0.25 MPa. Pressures below this value lead to decreasing the mold strength due to insufficient compaction, while higher pressures cause thermal combustion of the bakelite powder and extrusion of sand particles. As a result, the mechanical strength of the mold decreases and the surface roughness increases, which contributes to crack formation in the hardened mixture.

The effect of alternating pressure on the surface quality of the mixture was also studied. Reference pressure was maintained at 0.25 MPa, with pressure changes occurring every 10–12 seconds, and the total molding time was 35 seconds. Experiments showed that using alternating pressure significantly improved the surface quality of the casting. In this case, the mold surface is formed as smooth as possible, since the surface sand layer is compacted to the boundary of the molten resin which ensures the formation of uniform and smooth zones.

Thus, it can be concluded that the use of variable static pressure in the molding process improves the adhesion between components, increases strength, homogeneity and stability of the resulting mold, which improves the physical and mechanical properties of the entire molding mixture.

The assessment of casting quality was based on a combination of visual inspection, metallographic examination, and comparative analysis of defect formation tendencies in castings produced under different molding conditions. Particular attention was paid to the occurrence of surface cracks, internal discontinuities, and other casting defects associated with excessive mold rigidity and non-uniform cooling conditions. Castings produced in molds formed under variable-pressure conditions demonstrated a lower tendency toward defect formation and exhibited a more uniform microstructural appearance. Therefore, the term “minimal and uniform internal stresses” used in this study refers to the reduced likelihood of stress-related casting defects observed during experimental evaluation.

CONCLUSION

This study substantiated the effectiveness of using static pressure that varied depending on the resin state of aggregation, taking into account the characteristics of the solid-liquid-solid transition of the bakelite powder upon heating during the formation of film sand-resin molds. A pressure curve was chosen as the process mode, in which the model plate temperature was 230 °C, Initial pressure: 0.25 MPa; after 10 s increased to 0.35 MPa; after another 10 s reduced to 0.20 MPa. This mode resulted in the stable formation of a film mold 10–12 mm thick, which then completely hardened upon additional heating at 320–340 °C within 2 minutes.

Structural analysis showed that when applying variable pressure, the mechanical properties of the mold were improved due to the dense arrangement of sand grains, the increased frequency of contact points, and the uniform distribution of bakelite particles. This in turn helps maintain internal stresses in the castings at the minimal and uniform level, reducing the risk of hot cracking. Furthermore, the surface quality of the resulting castings was high, characterized by the roughness of Rz 70–80 and the absence of internal defects.

As a result of assessing the effect of the amount of bakelite powder on the properties of the mixture, it was found that the range of 4–7% was optimal from the technological standpoint: within that range, strength indicators were maintained at a sufficient level, and gas permeability met technological requirements with all the concentrations. It was shown that with bakelite powder amounts greater than 7–8%, there was a high probability of excess liquid phase formation, which reduced strength of the system and led to economic inefficiency.

Experiments to optimize the particle size distribution of sand grains confirmed the advantages of combining the two fractions. The most effective result was observed with the ratio of 0.1–0.5 mm:0.4–0.9 mm = 70:30. In this case, the sand particles were packed most densely, the number of contacts increased, and gas permeability remained within technological limits. Overall, the use of variable pressure improves strength, uniformity, and mold stability by reducing the amount of binder and is recommended as an effective technological method of producing high-quality, defect-free castings in shell molds.

CONFLICT OF INTEREST. The authors declare no conflict of interest.

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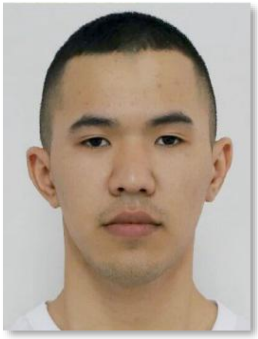

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