Manufacture of Ceramic Molds and Cores from Inorganic Materials Using Permanent

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Abstract. The paper describes the technology for the manufacture of ceramic molds and cores from inorganic materials using permanent masters. A technique for reinforcing molds and cores using ceramic tubes is proposed. The effect of pulse currents of different power on the slurry has been studied. In the experimental part, the performed experiments and the data obtained are described. In contrast to the conventional Show-process based on ethyl silicate binder (basic option), the technology developed for the manufacture of ceramic molds from inorganic materials ensures improving the quality and economic and environmental efficiency of investment castings. The quality improvement is determined by improved physical and mechanical characteristics of ceramic molds and the stable ceramic cracking. The improvement in environmental indicators is ensured by using safe inorganic molding materials and eliminating the solvent burning. Improving economic indicators is determined by reducing power consumption for calcining ceramic molds, casting defects, and molding material costs. Thus, the technology developed allows improving the quality of investment castings manufactured for the country’s oil and gas complex.

1. Introduction
The development of heavy engineering industries such as oil and gas, power engineering, shipbuilding, and aerospace engineering leads to the year-by-year growing demand for high-quality and high-precision castings. Conventional casting does not allow satisfying the customers’ demand due to the limitations of these techniques.

One of the promising areas is the manufacture of castings in ceramic molds [1, 2, 3]. Well-known techniques for casting in fixed-volume ceramic molds have a lot of advantages:

- lack of limitations on the cast alloy, high chemical resistance,
- lack of limitations on the casting weight,
- high casting surface quality,
- short mold and core manufacture time as compared to shell ceramic molds in investment casting,
- low gas content in the molding sand.

However, the conventional technology for the production of ceramic molds and cores has some shortcomings:

- the high cost of source materials for the preparation of molding sands,
- the high consumption of expensive binder,
- the high toxicity of the materials used,
- the mold tendency to forming large cracks,
the need for precise execution of process; any minimum violations cause irreversible defects in the mold elements and often even their destruction [4, 5, 6].

The main research objective is to develop the optimal composition and technology for the manufacture of ceramic molds and cores using permanent masters with improved properties. The technique should ensure the below technical advantages:

- low molding duration,
- high physical and mechanical characteristics of ceramic molds and cores,
- increased gas permeability,
- replacement of large cracks with small ones,
- environmental safety at the binder and gelling agent preparation and the solvent removal stages.

2. Theoretical

The technology for the manufacture of ceramic molds and cores using permanent masters comprises the below stages:

- preparing a ceramic slurry based on a refractory filler and a silica binder [7, 8, 9],
- preparing a gelling agent,
- introducing the gelling agent into the slurry while continuously stirring,
- pouring the finished slurry into the forming tools,
- curing molds and cores in the tooling,
- removing masters or cores from the molds or tooling,
- calcining mold halves and cores,
- assembling molds,
- pouring metal [10].

In each specific case, choosing the optimal slurry composition requires a comprehensive analysis to ensure the required process properties [11, 12, 13]. The manufacture of castings with thin walls and complex relief requires a high content of fine fractions in the filler; the manufacture of large thick-walled castings requires using a large amount of medium and coarse filler fractions to prevent mold buckling.

The proper distribution of the solid and liquid phases in the slurry ensures the required strength of the mold elements at a sufficiently dense filler grain packing, the minimum slurry shrinkage when curing, and a low tendency to large cracking [10].

Currently, the most widespread molds are those based on a hydrolyzed ethyl silicate binder solution. Ethyl silicate (ETS) is the product of the reaction between ethyl alcohol and silicon tetrachloride. To use ethyl silicate as a binder, it should be hydrolyzed, i.e. ethoxy groups С2Н5О in ethers should be replaced with hydroxyl ОН ones. In the course of hydrolysis, silicic acid is converted to a silica sol. Fused quartz, corundum, chamotte sand, and mullite are most often used as fillers [10].

As part of the study, the manufacture of a slurry based on a colloidal silica sol binder instead of a hydrolyzed ethyl silicate solution has been proposed, which improves the environmental situation, eliminates the fire hazard of the production process, and ensures high physical and mechanical characteristics of ceramic molds and cores based on permanent masters [14].

The slurry fluidity is a very important property since it ensures the composition mobility, it's spreading over the tooling, and the ability to qualitatively fill the entire cavity and reproduce the tool contour [15, 16].

The slurry is prepared by stirring the ingredients in a mixer at an impeller speed of 1,500 ... 1,800 rpm for 30 ... 40 minutes.

The gelling agent is introduced into the slurry just before it is molded. Thorough mixing of the slurry while feeding the gelling agent is a very important factor for its uniform distribution and subsequent high-quality curing throughout the entire mold or core volume [17].

The slurry to gel conversion time is one of the most important parameters of the entire ceramic mold manufacture process. The gelling time depends on the binder quality and the type and amount of gelling agent. On the one hand, the gelling time should be minimum, and on the other hand, it should ensure
the possibility to perform the required operations, i.e. preparing the slurry for molding, processing it (if necessary), and directly, pouring into the mold-core tooling; a time reserve (about 20 sec) should also be provided. Too short gelling does not allow performing high-quality preparatory operations, and too long one leads to stratification of the slurry in the mold, which may cause the mold defects (buckling, macrocracking, etc.) [18].

Alkalis (NaOH), urotropine ((CH₂)₆N₄), ferrochrome slag, etc. are conventionally widely used as gelling agents. In the technology developed, an aluminoborophosphate concentrate is proposed to gelatinate the slurry. To ensure uniform distribution of the gelling agent throughout the ceramic slurry, the ABPC requires preliminary preparation. To do this, water is poured into the initial aqueous aluminoborophosphate concentrate solution to a density of 1150 ... 1300 kg/m³.

The aqueous aluminoborophosphate concentrate solution density of less than 1150 kg/m³ does not allow ensuring stable and uniform slurry curing in the mold. The gelling agent density of more than 1300 kg/m³ causes premature gel precipitation in separate slurry microvolumes. This significantly reduces the ceramic strength.

Fast and uniform gelling agent distribution leads to accelerated molding and eliminates large cracking of the ceramics. In this case, small cracking occurs, which is required to ensure the gas permeability of the ceramics.

Immediately after the gelling agent preparation, it is introduced into the previously prepared slurry while continuously stirring. Then, the finished molding sand is molded into the tooling.

To avoid defects in ceramic molds, before pouring the metal, the liquid composition should be almost completely removed. To improve this process, ceramic tubes are installed in the mold immediately after it is filled with the slurry; they contribute to the complete and stable solvent removal under the effect of pulse currents. In this case, solvent removal is a volumetric process rather than a superficial one, like in most electric furnaces. As a result, the manufacture of ceramic molds and cores using permanent masters is accelerated, and their high crack resistance is ensured, as well as conditions are created to reduce the temperature and duration of subsequent calcination [10].

Depending on the gelling agent amount, the slurry is cured in the molds for 5 ... 15 minutes. The mold or core is placed in a microwave oven to remove the solvent under the effect of pulse current at a frequency of 2,450 MHz and a power of 600 ... 2,000 W, depending on the mold or core weight. A power of less than 600 W does not ensure high-quality solvent removal, which causes defects in ceramic molds, cores, and investment castings. The pulse electric current power of more than 2000 W is impractical due to unjustified energy consumption.

The next process stage is mold calcination. Thermal treatment of molds depends on several factors:
- type of alloy poured into a ceramic mold,
- overall mold dimensions,
- configuration of the casting,
- the prevailing wall thickness of the casting,
- the weight of the molded metal.

Depending on the combination of the above factors, three calcination modes are conventionally used:
- for large castings - calcination at 900 °C for 2 hours,
- for medium castings with a wall thickness of up to 20 mm, the mold is calcined at 500 °C, or the surface is simply dried using gas burners,
- for small castings with a wall thickness of up to 4 mm, molding is performed without calcining immediately after the solvent burns out.

The use of the technique developed allows a significant decrease in the calcination temperature and duration. The temperature regime is 350 ... 600 °C; the duration is limited to 30 ... 90 minutes, depending on the mold and core dimensions. Reducing the thermal treatment temperature and duration makes the technology more energy-efficient, especially when manufacturing large complex-shaped castings.
3. Experimental
The ceramic slurry is made of silica sol base (20 % wt.) and refractory filler (80 % wt.). A mix of flint and granular fused quartz at a ratio by weight of 1:1 is used as a refractory filler. The slurry is prepared by stirring the ingredients in a mixer at an impeller speed of 1,500 rpm for 30 minutes. Then, the gelling agent is prepared. Water is poured into the initial solution of aluminoborophosphate concentrate to obtain three solutions of different densities: 1,150; 1,250; 1,300 kg/m³. These three gelling agents with different densities are introduced, respectively, into three containers with prepared ceramic slurry at a rate of 10 % wt. of the gelling agent in the slurry while continuously stirring. Then, three slurries obtained are poured into the tooling (three master molds). Ceramic tubes with a diameter of 5...8 mm and a thickness of 2...3 mm are installed in the curing slurry in the mold with an interval of 3...5 cm. They reinforce the ceramics, increase its strength and crack resistance, and ensure stable accelerated removal of the solvent under subsequent exposure to pulse currents. The slurry is cured in the mold, after which the permanent masters are removed. The molds are placed in a microwave oven, where the solvent is removed at a frequency of 2,450 MHz and a power of 800 W for 2 minutes. The final stage is calcining the molds and pouring molten metal into them to obtain 20GL steel castings. The characteristics of the molds and castings obtained are given in table 1.

Table 1. Characteristics of Molds and Castings.

| Indicator                           | The Technique Claimed at a Gelling Agent Density, kg/m³ |
|-------------------------------------|--------------------------------------------------------|
|                                     | 1,150        | 1,200        | 1,300        |
| 1. Molding duration, min.           | 60           | 50           | 45           |
| 2. Bending strength of samples, MPa:|                                          |                                          |                                          |
| a) after curing                     | 3.5          | 3.8          | 2.5          |
| b) after calcination                | 6.0          | 6.3          | 5.5          |
| 3. Large cracks                     | no           | no           | no           |
| 4. Gas permeability, units          | 6.0          | 5.0          | 9.0          |
| 5. Calcination temperature, °C      | 450          | 500          | 600          |
| 6. Calcination duration, min        | 70           | 60           | 90           |
| 7. Flashes on 20GL steel castings   | no           | no           | no           |

In the next experiment, the microwave oven current power to remove the solvent from ceramics has been varied: 600; 1,200; 2,000 watts.
Ceramic cores are made according to the above technique. The gelling agent is diluted to a density of 1,250 kg/m³. Removing the solvent from ceramic cores by exposure to pulse currents allows improving the ceramics strength and reducing the calcination temperature and duration. This improves the quality of manufacturing investment castings, especially the complex-shaped ones made of alloy steels.
The effect of the current power on the ceramic core properties is given in table 2.

Table 2. Effect of the Current Power on the Ceramic Core Properties.

| Property                          | Current Power, W |
|-----------------------------------|------------------|
|                                   | 600              | 1,200           | 2,000           |
| 1. Bending strength of samples, MPa:|                  |                  |                  |
| a) after removing the solvent     | 3.6              | 4.8              | 5.3              |
| b) after calcination              | 6.5              | 7.4              | 7.0              |
| 2. Calcination temperature, °C    | 500              | 400              | 350              |
| 3. Calcination duration, min      | 45               | 40               | 30               |
4. Conclusion
Analysis of the data obtained has shown that the technology and composition developed allow shortening the mold manufacture cycle and improving the physical and mechanical characteristics of ceramic molds while reducing the power consumption. This ensures reducing defects in the investment castings and improving their quality.

The use of cheaper materials significantly reduces the product costs, and the elimination of toxic and harmful conventional ceramic mix components leads to improving the environmental situation and working conditions in the workshop.

The further research area will be testing the technology on a pilot batch of complex-shaped castings for the oil and gas industry and adjusting the process parameters to obtain consistently high results.

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