The object of this study is the structure of hollow steel modules filled with various types of functional materials, as well as the technology of their production using lost foam casting.

Computer simulation of hydrodynamic and heat-mass exchange processes and solidification was carried out to establish the laws and prerequisites for designing state-of-the-art hollow cast structures and to devise their production technology. The study investigated the influence of reinforced steel elements and reinforcement directly from the liquid alloy of the shell on the peculiarities of hydrodynamic, heat-mass transfer processes, and solidification during the production of hollow steel structures with functional fillers.

It has been determined that the presence of polystyrene membranes in the functional filler for subsequent reinforcement from the liquid phase of the shell metal affects the hydrodynamics of filling the casting. In the thin channels formed in the filler, the metal flow rate increases from 2 m/s to 8 m/s in the upper channels, and from 3 m/s to 12 m/s in the lower channels, which is associated with an increase in metallostatic pressure.

The presence of metal reinforcement in the functional filler and the reinforcement of the functional material from the liquid phase of the shell metal accelerates the heating of the non-metallic filler by 1.2–1.4 and 1.4–1.8 times, respectively. Reinforcement also helps increase the maximum heating temperature of the functional filler by 200–300 °C, which creates better conditions for its sintering.

The grades of steels for their use as a matrix alloy in the production of hollow cast castings were determined; their structure and physical-mechanical properties were studied. The recommended modes of heat treatment of low-alloy steel to obtain the required properties have been determined.

The study reported here is a theoretical prerequisite for verification in the manufacture of experimental cast hollow structures with metallic and non-metallic reinforcing phase

Keywords: reinforced steel casting, computer simulation, lost foam casting

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DEVISING A TECHNOLOGY FOR MANUFACTURING HOLLOW CAST STEEL STRUCTURES WITH COMPOSITE AND REINFORCED NON-METALLIC FUNCTIONAL FILLER

Oleg Shinsky
Doctor of Technical Sciences*
Iuliia Kvasnytska
Doctor of Technical Sciences
Department of Special Steels and Alloys**
Inna Shalevska
Corresponding author
Doctor of Technical Sciences*
E-mail: innashalevska@gmail.com
Pavlo Kaliuzhnyi
PhD*
Oleksandr Neima
Junior Researcher*
*Department of Physics and
Chemistry of Foundry Processes**
**Physico-Technological Institute of Metals and Alloys of
the National Academy of Sciences of Ukraine
Acad. Vernadskyi blvd., 34/1, Kyiv, Ukraine, 03142

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1. Introduction

At present, there is a need for cast structures that have special high operational properties. Therefore, devising state-of-the-art scientifically based technologies for the production of shell binary cast structures with high functional properties is an urgent task that requires additional research into the processes of heat and mass transfer and gas-hydrodynamics. Such structures are made by lost foam casting, using reinforcing metallic and non-metallic materials. At the same time, it is necessary to determine the effect of metal and non-metal materials, the presence of solid and porous polystyrene foam models in the mold on the flow of metal, the speed of filling the mold, and the speed of casting solidification. Internal reinforcement with combined non-metallic and metallic fillers of shell cast structures makes it possible to reduce the weight of the article and give it special properties, which enables its application in protective structures and devices.

The development of the technological foundations of such processes corresponds to the modern trends in the evolution of foundry production to obtain competitive metal products. Therefore, research into designing steel shell reinforced structures, as well as devising state-of-the-art technologies for their production based on lost foam casting, is a relevant task.

2. Literature review and problem statement

Design requirements for modular cast structures, including the level of physical-mechanical properties of steels and the possibility of manufacturing modules with non-metallic and metallic reinforcing phases, necessitate the development of new high-strength low-alloy cast steels. These steels should not contain expensive and rare alloying elements and also require highly efficient technologies for the production of cast elements of a cellular structure and optimal modes of their heat treatment.

For such cast structures, the required level of physical-mechanical properties of steels of the C-Si-Mn system is usually achieved through complex alloying with chromium, molybdenum, nickel, vanadium, and the use of sophisticated heat treatment regimes. The authors of works [1, 2] conducted a systematic review to study the influence of various alloying elements, in particular boron, carbon, chromium, manganese, molybdenum, niobium, rare earth elements, silicon, titanium, and vanadium, on the wear resistance characteristics of iron-based alloys. It should be noted that alloying with a large number of elements is not always economically justified, so it became necessary to research low-alloyed steel and choose modes of its heat treatment. The results of studies on improving mechanical properties, in particular tensile strength (1580 MPa) and plasticity (~20 %), by increasing the carbon content in highly alloyed iron-chromium-nickel alloys are reported in [3]. Work [4] determined the effect of alloying on the corrosion resistance of iron-nickel alloys, and study [5] found that the iron-based alloy Fe-20Mn-15Cr-10 V-10Al-2.5C (in at%) has increased hardness. Also, the authors of work [6] consider state-of-the-art advancements regarding the improvement of mechanical and special properties by strain hardening and additional alloying of low-alloyed manganese steels. These studies confirm the possibility of increasing the mechanical and special properties of alloy steels with various elements and additional effects, but this leads to an increase in material consumption, energy intensity of the process and, as a result, to an increase in the price of the finished articles.

The authors of [7] used modeling processes to predict the chemical composition of carbides but their studies were concerned with the construction of appropriate regression models and did not take into account the influence of the mold and heat and mass exchange processes on the result.

According to the international standards for cast steels [8] A352...A732 are intended for the manufacture of cast parts, which are used as elements of protective structures, economically alloyed steels of the C-Si-Mn system. This makes it possible, after the appropriate heat treatment regimes, to ensure the mechanical properties required by the technical task (strength limit – 550...900 MPa, yield strength – 450...750 MPa, relative elongation – 15...30 %, impact strength – 55...75 J/cm^2).

On the other hand, increasing the functional properties of steel elements in protective structures could be achieved by using composites whose types and technologies are available in large numbers. For example, there are data on the design of Al/Al_2O_3 hybrid composite metal foam reinforced with SS316L stainless steel (SHS) hollow steel spheres for applications with high energy absorption and enhanced mechanical properties [9]. But such structures have disadvantages in terms of high price and manufacturing complexity.

In work [10], the effect of a technique for obtaining reinforced castings by lost foam casting on the formation of adhesion of a matrix alloy of gray cast iron with reinforcing inserts of carbon and stainless steel was determined. The results of the work show the promising application of this casting method for the production of reinforced iron castings; however, in the case of using steel as a matrix alloy, they cannot be used.

Work [11] shows that interpenetrating metal/ceramic composites are able to combine attributes and improve properties, which is not possible in composite materials with conventional reinforcement architecture. The work confirms the relevance of devising technologies for the production of metal-ceramics, but its results do not make it possible to predict the final properties of such composites since the nature of the metal and ceramic material would determine the nature of their interaction.

Techniques for obtaining composite materials based on foundry iron-carbon alloys are becoming widespread. For example, in work [12], a metal composite made of gray cast iron and chrome cast iron with an insert made of foam ceramics was made by casting method, due to which it was possible to increase the wear resistance of the material. In works [13, 14], space frames made of titanium printed on a 3D printer were used as inserts. Pouring molds with inserts with gray iron melt led to the local formation of titanium carbides, due to which the wear resistance of the casting was increased. The cited works confirm the prospect of the idea of using ceramic inserts in cast iron castings, but they do not cover composites based on cast steels.

The results of studies on the kinetics of solidification and cooling of the casting depending on the volume weight of the reinforcing elements on the surface of the steel 40–steel 20 joint showed that macro reinforcing elements affect the mechanism and rate of formation of the solid phase [15]. Therefore, it is possible to use a metal reinforcing phase to intensify the crystallization process in massive steel castings [16]. When using combined reinforcement with metallic and non-metallic materials, new distribution and heat exchange surfaces arise, which requires additional research.

It should be noted that in the above studies [10–12, 15, 16] there are no data on heat and mass exchange and hydraulic processes in hollow metallic binary structures that are reinforced with a combination of metallic and non-metallic materials.

Our review of paper [17] revealed that for the manufacture of hollow cast structures with a functional filler, lost foam casting is the most suitable, which makes it possible to control the quality parameters of the casting. Therefore, the lost foam casting method was used in this work.

All this gives reason to assert that it is expedient to conduct a study aimed at devising a technology for manufacturing hollow cast structures with a functional filler using lost foam casting. As the initial matrix alloy, it is advisable to use 45L steel or low-alloy medium carbon steels, which provide the required minimum level of physical-mechanical characteristics of the article and have good casting properties [18].

3. The aim and objectives of the study

The purpose of our work is to devise a technology for manufacturing varieties of steel shell modules, which are reinforced with metallic and non-metallic materials, with special operational properties. This will make it possible to fabricate experimental hollow thin-walled structures, in particular for protective structures, using lost foam casting.

To achieve the goal, the following tasks must be solved:

– to analyze temperature fields of the module cell and determine the influence of reinforcement on the hydrodynamics of filling the mold and thermal processes in the functional filler;

– to test the physical-mechanical properties of experimental cast steels and to devise technologies for their heat treatment.

4. The study materials and methods

The object of our research is the structures of hollow steel modules filled with various types of functional materials, as well as the technology of their production using lost foam casting.

Preliminary, it was accepted that hollow steel modules consist of cylindrical cells, which are subsequently reinforced. The simulation process was carried out for single cells.

Computer simulation of the processes of pouring and solidification of the lost foam casting was performed using the Procast software. The 3D drawings of the model, gating system, reinforcement, and core, built in the CAD system (Fig. 1), were saved in the IGES format, and uploaded into the simulation program. The size of the element when applying the mesh to the model, core, and reinforcement was set to 2 mm. The total number of calculated elements was 739 thousand. The following materials were specified from the database: Steel AISI 1040 – for the alloy, Sand LFC – for the mold, Foam 30 kg/m^3 – for the model, Resin bonded sand permeable – for the core, Chill Carbon steel – for the reinforcement. The steel pouring temperature was set at 1580 °C, the initial temperature of the mold, core, model, and reinforcement, as well as the environment – 20 °C. The heat transfer coefficients were set as follows W/(m^2·°C): between liquid metal and foam – FOAMHTC 840, FOAMHTCMAX 10460, between liquid metal and mold/core – 500, between metal and reinforcement – 3000, between mold and core– 400. Boundary conditions – inlet pressure on the upper surface of the riser is 1.05 atm, temperature 1580 °C, the pressure around the mold is 1 atm.

Under laboratory conditions, a non-standard induction furnace with a main lining with a crucible capacity of 3 kg was used for smelting the studied steels. The melt from the furnace is released directly into dry, heated molds.

Samples for determining the physical-mechanical properties and metallographic studies of steels were made from test bars-clubs in line with [19].

Metallographic studies were carried out on a Neofot 2 optical microscope (Germany). Metal contamination with non-metallic inclusions was determined using three samples of each grade of steel. The size of inclusions was determined using the eyepiece scale of a Neofot 2 optical microscope at a magnification of 200. The contamination index of steel samples with non-metallic inclusions was determined using the linear method. According to this method, a micro section is moved along the line with the help of micrometric screws of the microscope. The total length of this line is 100 mm. With the help of an eyepiece scale, the maximum sizes of the inclusions falling into the crosshairs of the eyepiece were measured; they were registered according to certain size groups. Contamination was assessed collectively by all types of inclusions; the Contamination Index, I, was calculated from the well-known formula:

$$I = \frac{B \times \sum A \cdot M}{L},$$

where B is the unit of the eyepiece scale division at a given magnification, µm;

A is the average value of the size of inclusions in the divisions of the ocular scale, the number of divisions, units (pieces);

M is the number of inclusions;

L is the length of the counting line, µm

The morphology of non-metallic inclusions was determined according to reference scales for evaluating oxide and nitride inclusions using a Neofot 2 microscope [20].

The austenite grain size was determined on samples in a normalized state by comparison with reference scales according to [19, 21].

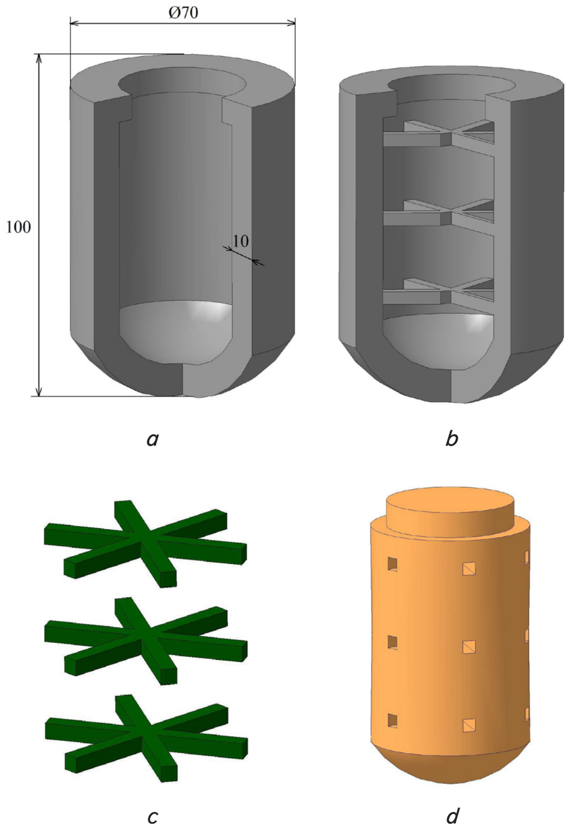

Fig. 1. General view of 3D models: *a* — cell; *b* — cell with partitions; *c* — reinforcement, *d* — core with channels

5. Results of investigating the hydrodynamic and heat-mass exchange processes in the mold and verifying steel properties

5. 1. Results of simulating the metal pouring and solidification processes in the production of steel hollow structures

The processes of production of hollow reinforced castings by the method of casting in molds in which metallic and non-metallic reinforcing materials are placed are accompanied by complex gas-hydrodynamic and heat-mass exchange processes.

According to the tasks related to the implementation of technologies for obtaining lightweight high-strength steel hollow structures with non-metallic and metallic functional fillers, which have varieties:

1 – a steel shell filled with non-metallic functional material;

2 – a steel shell with a non-metallic functional material, which is reinforced with metal elements that combine the shell and the functional material at the same time;

3 – a steel shell with a non-metallic functional material, which is reinforced by solidification in its channels a liquid alloy of the shell, which at the same time combines the shell and the functional material.

Thus, it became necessary to investigate the influence of reinforced steel elements and reinforcement directly from the liquid alloy of the shell on the features of hydrodynamic, heat-mass exchange processes, and solidification when producing hollow steel structures with functional filler.

The design and geometric dimensions of the structure cell are shown in Fig. 1.

As a result of the implementation of multi-level computer simulation, hydrodynamic and heat-mass exchange processes and solidification of various types of hollow structures were investigated.

Thus, Fig. 2 shows the process of filling the experimental cell with a functional filler without reinforcement. Under these conditions, the metal front moves from top to bottom with gradual spreading to the sides and closing of the two streams in the part opposite to the feed point.

In the case of the presence of polystyrene foam elements in the functional material (Fig. 3), the nature of pouring is similar to the previous one. The presence of processes of filling the thin channels of the partitions (4×4 mm) is different. Since the metal fills the cylindrical part of the cell, the metal enters each “ray” of the partition from the main wall and moves to the place of their intersection.

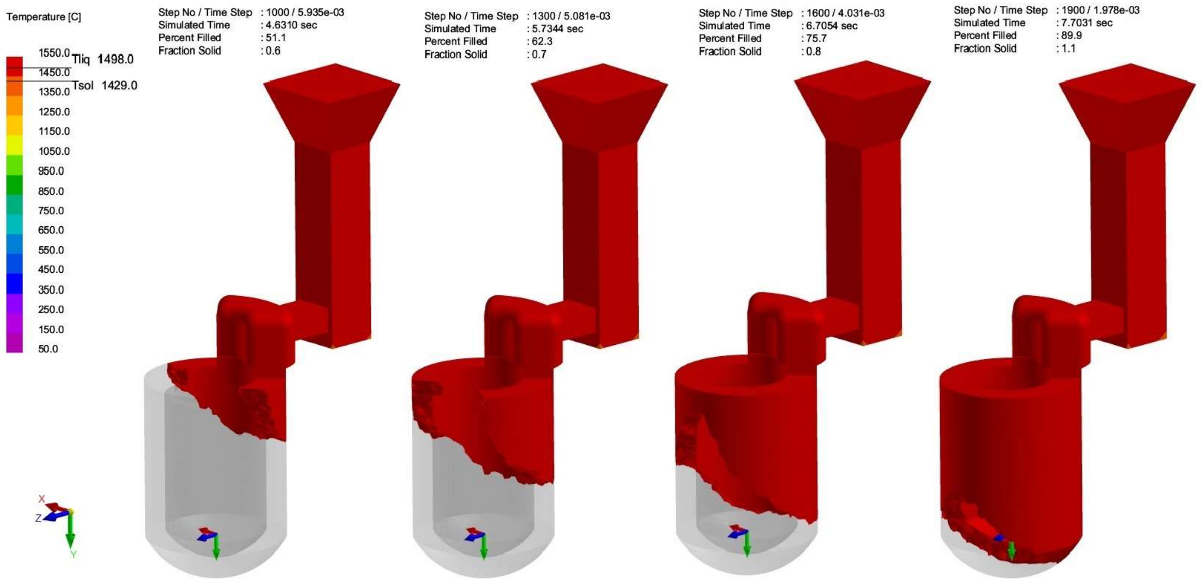

Fig. 2. The process of filling the experimental cell (without reinforcement)

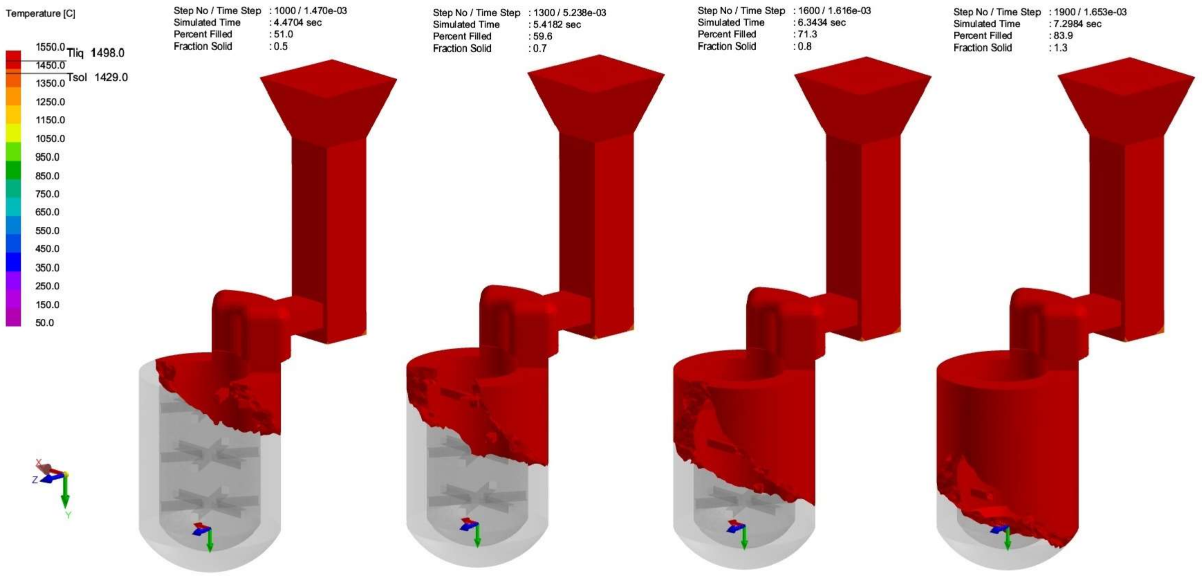

Fig. 3. The process of pouring an experimental cell with thin channels for reinforcement

The flow rate of liquid metal in channels for reinforcement is shown in Fig. 4. At the beginning of filling the upper channel, the flow rate is about 2 cm/s. Then the speed increases to 4 cm/s, and at the end of filling – to 8 cm/s. According to a similar law, the speed of the metal flow is distributed in two channels, but at the beginning it is 2–3 cm/s, then the speed increases to 6 cm/s and, for a short time at the end, to 10–12 cm/s. The increase in the metal flow rate in the lower tiers is related to their location and the increase in metallostatic pressure directly in the shell. It is believed that the optimal speed is 3–4 cm/s. During the movement of metal through thin channels, a high speed contributes to their filling since at a low speed the flow may stop due to its cooling.

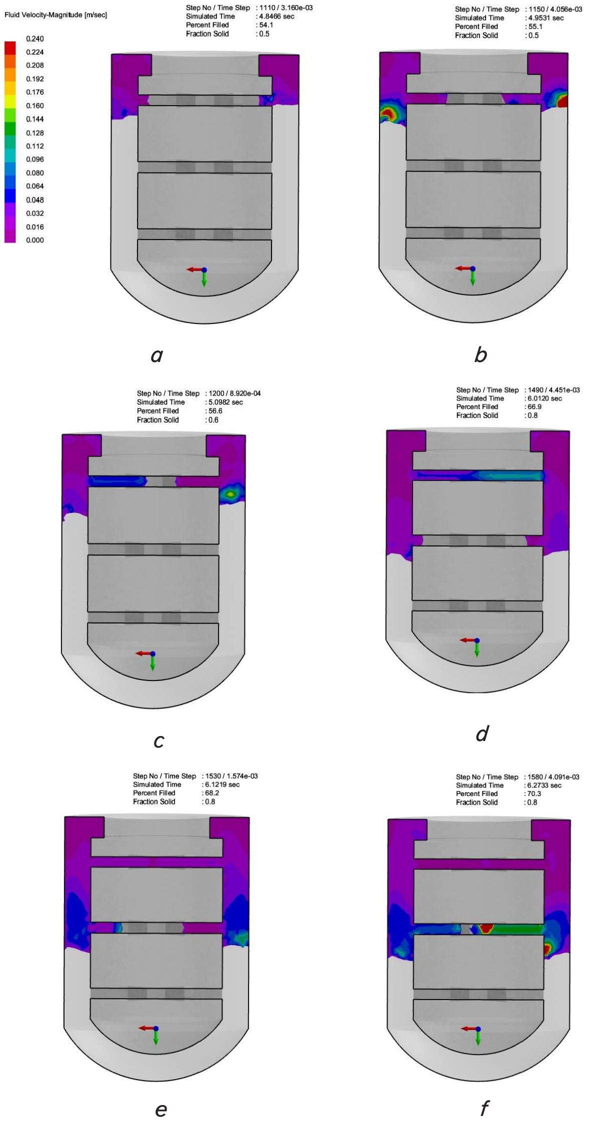

Fig. 4. Flow rate of liquid metal in the channels of the functional filler: *a* — 4.8 s; *b* — 5.0 s; *c* — 5.1 s; *d* — 6.0 s; *d* — 6.1 s; *f* — 6.3 s

Fig. 5, *a* shows temperature fields of the longitudinal cross section of a casting with a functional filler; a casting with a reinforced functional filler (Fig. 5, *b*); and a casting with a functional filler reinforced from the liquid phase of the shell metal (Fig. 5, *c*). The nature of filling the casting cavity for the first two cases is the same. In the third variant, the character of the filling is slightly different, which is connected with the presence of partitions. During pouring, the functional material is heated only in the contact zone to approximately 400 °C. At the end of pouring, the upper part of the functional filler is heated to a depth of up to 2 mm to a temperature of 700 °C.

Fig. 6 shows temperature fields of the longitudinal cross section of the casting during solidification and cooling of the metal. Fig. 7 shows the time of solidification of the cross section of the castings. 30 seconds after filling the casting, heating of the functional filler to a depth of up to 7 mm is observed. Full heating of the functional filler in the first version occurs in 180 s, in the version with reinforcement – in 130 s, in the version with reinforcement from the liquid phase of the shell metal – in 100 s.

The highest temperature to which the functional filler is fully heated is 850 °C in the first case, 1050 °C in the case of reinforcement, and 1150 °C in the case of casting with partitions. Thus, the best conditions for the sintering of the functional filler are created in the second two options.

Fig. 5. Temperature fields (cross-section of the cell) during pouring: *a* — casting with functional material, *b* — casting with reinforced filler, *c* — casting with functional filler, which is reinforced from the liquid phase of the shell metal

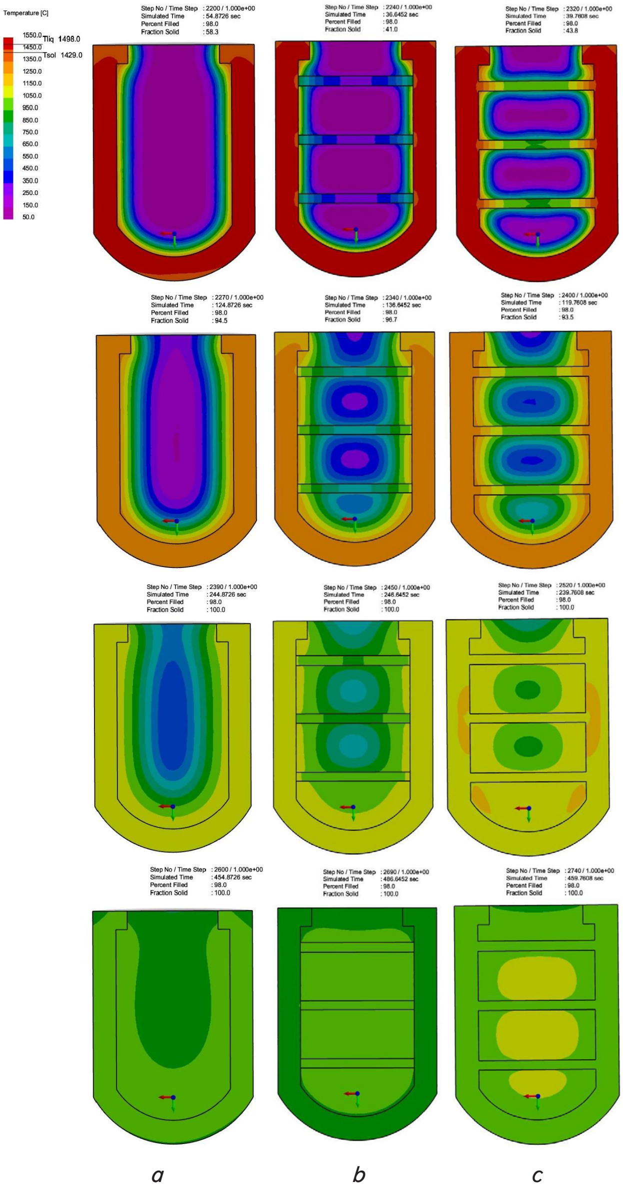

Fig. 6. Temperature fields (cross-section of the cell) during solidification and cooling: *a* – casting with functional material; *b* – casting with reinforced functional material; *c* – a casting with a functional filler, which is reinforced from the liquid phase of the shell metal

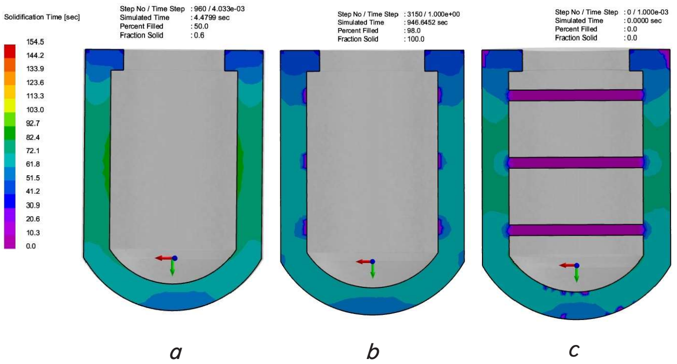

Fig. 7. Casting solidification time: *a* – casting with functional material; *b* – casting with reinforced functional material; *c* – casting with a functional filler, which is reinforced from the liquid phase of the shell metal

The presence of reinforced functional material with various types of metal, or from the liquid phase of the shell metal, affects the processes of solidification of the casting. In this case, the reinforcement in the functional filler acts as a refrigerator and reduces the solidification time of the casting shell by 11 seconds. Under the conditions of reinforcement of the functional material from the liquid phase of the shell metal, which solidifies quite quickly (12 s) and partially cools the casting, the casting solidification time is reduced by only 6 s.

5. 2. Verifying the physical-mechanical properties of experimental cast steels and devising their heat treatment technology

According to the results of previous comprehensive studies on the influence of microalloying and modification processes on the structure and mechanical properties of steels, in particular, as a material for the production of protective modules, 45L and 35CrMnNVL steels were preliminary proposed for further research [22].

Contamination with non-metallic inclusions of samples No. 1 (steel 45L) and No. 2 (steel 35CrMnNVL) in the as-cast state was investigated at a magnification of ×200. The general appearance of non-metallic inclusions on non-etched micro sections is shown in Fig. 8.

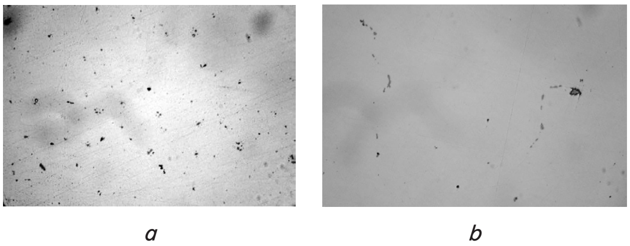

Fig. 8. Contamination with non-metallic metal inclusions of steels for the manufacture of hollow cast structures ×200: *a* – sample No. 1 (steel 45L); *b* – sample No. 2 (steel 35CrMnNVL)

Studies of the metal of 45L steel micro sections have established that the index of metal contamination by non-metallic inclusions ranges from 0.009 to 0.017. For steel 35CrMnNVL, the index of contamination by non-metallic inclusions ranges from 0.008 to 0.014. The index of contamination of steel with oxides is somewhat lower compared to steel 45L due to additional alloying. However, relatively large non-metallic inclusions of oxides are found in the metal (Fig. 8, *b*). It is evident that such inclusions are slag particles since the samples were cut from the upper part.

Taking into account that cast shell structures work under static load conditions, with the aim of minimal energy consumption for their production, the influence of heat treatment regimes on the physical-mechanical properties of steels was investigated.

Based on thermodynamic calculations of the equilibrium temperature of dissolution, the formation of the VN phase in a solid solution, heat treatment regimes for 35CrMnNVL steel have been developed. It was established that the temperature of austenizing heating for normalization and tempering is 920–940 °C; the time of aging the samples in the furnace at these temperatures is one hour.

After normalization, the samples for metallographic studies are cooled in air, the samples are quenched in water. The release of samples after normalization and tempering is carried out at temperatures of 510 °C, 550 °C, and 600 °C. After aging for 2 hours – cooling in the air.

It was determined that the microstructure of the steel in the normalized state is pearlitic-ferritic. According to the morphology of non-metallic inclusions of 35CrMnNVL steel samples, oxides take first place with a contamination index of 0.0024, and nitrides – 0.0011. This confirms the expediency of modifying steels with nitrogen for nitride strengthening of the metal and improving the physical-mechanical properties of steels.

The studied steels have a fine-grained structure – 6...7 points – in 45L steel and 7...8 points in 35CrMnNVL steel. In addition, it was established that the modes of heat treatment of steels have little effect on the change in the morphology of non-metallic inclusions and their number, with the exception of normalization. Long-term cooling of the metal in air contributes to a certain redistribution of the morphology of non-metallic inclusions – an increase in the number of sulfides since they are formed due to a decrease in the solubility of sulfur in iron with a decrease in the temperature of the metal.

The results of testing the experimental samples for strength characteristics are given in Table 1.

Table 1

Mechanical properties of the investigated steel samples

Steel grade	Tensile strength, σ_u, MPa	Yield limit, σ_y, MPa	Relative elongation, δ, %	Impact strength, J/cm^2
45L	650	360	16	59
35CrMnNVL	980	795	27	84
Requirements for the technical assignment	550–900	450–750	15–30	55–75

We have studied the influence of the microalloying process of structural C-Si-Mn steels of the ferritic-pearlite class on their microstructures and the level of physical-mechanical properties. It was established that the dispersion separation in the solid solution of the secondary phases – VN and AlN during tempering provides a comprehensive increase in physical-mechanical properties. The conditions for the optimal result of a comprehensive increase in strength, plastic properties, and impact toughness have been determined. Such conditions are created at the temperature of austenitic heating for normalization or tempering by 100...150 °C less than the equilibrium temperature of dissolution (formation) of the VN phase and the amount of residual Al not more than 0.02 %.

6. Discussion of results of investigating the hydrodynamic and heat-mass exchange processes in the mold and verification of the properties of steels

The task to design lightweight, high-strength steel hollow structures with a non-metallic functional filler, which is a binary part of a single structure and resists impact dynamic loads when in contact with high-speed bodies, has been solved. Additional reinforcement was carried out in the systems "metal shell – functional filler – solid reinforcing phase or reinforcing phase formed from the liquid metal of the shell", which has not yet been studied in the theory of foundry production, and therefore there are no analogs.

The peculiarities of the hydrodynamics of metal flow in the mold cavity with a monolithic filler (Fig. 2) and with channels formed in the filler (Fig. 3) during the upper supply of metal according to the specified thermo-time parameters of lost foam casting were studied. In this case, it was established that the filling time of the mold cavity in both cases corresponds to the specified time and is 7.3...7.5 (Fig. 2, 3, *c*), because the volume of the channels in the filler is 3.5 % of the total volume cells and does not significantly affect the mass velocity.

Also important were the studies of the flow of liquid metal of the shell in thin channels formed in the filler with a cross-sectional area of 0.16 cm^2 against a cross-section of the mold cavity of 17 cm^2, that is, the latter exceeds the area of the thin channel by 100 times. It was established that the flow rate of liquid metal in the channels of the filler (Fig. 4) depends on the gas pressure in the channels, which is formed from the thermal destruction of polystyrene foam and acts in the cavity of the mold on each of the horizons of the placement of the channels.

Thus, at the beginning of the cycle of filling the upper horizon of the channels, the flow speed is about 2 cm/s (Fig. 4, *a*). Then the speed increases to 4 cm/s (Fig. 4, *b*), and at the end of filling – to 8 cm/s (Fig. 4, *c*), it depends on the change in the value of the metallostatic pressure in the channel (kPa):

$$P_m = P_s - P_g,$$

where P_m – metal head in the channel; P_s – metal pressure in the gating system; P_g – gas pressure in the channel. At the initial stage of metal flow in a thin channel, conditions are created to create the maximum P_g, which is associated with the maximum mass of polystyrene foam and the absence of a filtering area for its gaseous products of thermal destruction. In the subsequent stages of filling the channel, the mass of polystyrene decreases and a "metal-model" gap is formed, which contributes to a decrease in the P_g value and, accordingly, an increase in the value P_m, which tends to approach the P_s value.

According to a similar law, the speed of the metal flow is established in the two lower horizons of the channels, but, accordingly, 3 cm/s, increases to 6 cm/s and, for a short time at the end, to 10...12 cm/s. The increase in the metal flow rate in the channels below the horizon is associated with an increase in the value P_s (Fig. 4, *d–f*).

Computer simulation of heat and mass transfer during cooling and solidification of steel shells in contact with non-metallic and metallic bodies and fillers has established distinctive features from the conditions of similar processes of casting in conventional sand molds.

During pouring and solidification of metal, if the functional filler contains solid reinforcement or reinforcement from the liquid phase of the shell metal, the rate of heating of the functional filler increases. In accordance with the temperature field of the functional layer with solid-state reinforcement, its heating time to the maximum temperature of 1050 °C is 130 s. The heating of the functional interlayer, reinforced from the liquid phase of the shell material, to the maximum temperature of 1150 °C takes place in 100 seconds. However, the heating of the unreinforced functional material to the maximum temperature of 850 °C takes 180 seconds. That is, the latter indicators are 1.2...1.4 times and 1.4...1.8 times lower in comparison with reinforced functional materials. Such significant changes in the heating rates and heating temperature of the functional layer are associated with a high heat exchange coefficient of reinforced materials (3000 W/(m^2·°C)) compared to a low heat exchange coefficient of a non-metallic functional material (500 W/(m^2·°C)). Under such conditions, reinforced elements are heated to a temperature of 850...950 °C (solid reinforcement) and to a temperature of 1400...950 °C (shell metal). At the same time, they form secondary thermal fields within two adjacent reinforcing elements, and the heating parameters of the functional layer in the thermal field formed by the reinforcement from the liquid phase of the metal are 1.1 and 1.3 times higher in comparison with the use of solid reinforcement.

The research data make it possible to predict options for obtaining high-quality hollow castings depending on the presence of types of reinforcement in the functional filler and to determine the necessary technological parameters. At the same time, it is necessary to check these indicators during the production of experimental castings and, if necessary, adjust the technology.

In view of the given features of steels and requirements for them, based on studies of their physical-mechanical properties, it was established that it is advisable to use 45L and 35CrMnNVL steels for the manufacture of cast hollow structures.

It was determined that normalization and tempering at a temperature of 920–940 °C with a holding time in the furnace of one hour ensures the level of mechanical properties for steel 35CrMnNVL in accordance with the technical task.

This study is a theoretical prerequisite for verification in the manufacture of experimental cast hollow structures with metallic and non-metallic reinforcing phase.

In this study, only two grades of steel were tested. Therefore, for the possibility of using a wider range of steels when implementing technologies, there is a need to systematize and expand the recommended alloys.

7. Conclusions

1. The presence of polystyrene partitions in the functional filler affects the hydrodynamics of filling the casting. The speed of the flow of liquid metal in the channels of the filler depends on the gas pressure in the channels, which is formed from the thermal destruction of polystyrene foam, and the growth of the metallostatic pressure. At the same time, in the thin channels formed in the filler, the speed of metal flow increases from 2 m/s to 8 m/s in the upper horizon of the channels and from 3 m/s to 12 m/s in the lower horizon of the channels. Steel reinforcement or reinforcement of the functional material from the liquid phase of the shell metal accelerates the heating of the non-metallic filler by 1.2–1.8 times and increases its maximum heating temperature by 200–300 °C, creating better conditions for its sintering. The use of reinforcing metal elements and reinforcement directly from the shell's liquid alloy will improve the characteristics of hollow cast structures with functional fillers, which are made by lost foam casting.

2. Based on the results of our research, steel 35CrMnNVL of chemical composition, wt. %: C=0.30...0.40; Mn=0.60...0.90; Si=0.55...0.65; Cr=0.20...0.70; N=0.012...0.015; V=0.08...0.11; S and P≤0.025 of each element; Al=0.015...0.025, is recommended for the manufacture of hollow thin-walled structures, in particular, for protective structures. It was determined that the index of contamination of steel 35CrMnNVL with oxides is somewhat lower compared to steel 45L due to additional alloying. In particular, it was established that modification of steels with nitrogen helps reduce the contamination index and increase the physical-mechanical properties. It was established that the best set of mechanical properties for 35CrMnNVL steel could be achieved after quenching at a temperature of 930 °C in water and tempering at a temperature of 510 °C: σ_u=1150 MPa, σ_y=1010 MPa, δ=16 %, ψ=20 %, KCU=70 J/cm^2, hardness – 31 HRC. Thus, steel recommended for the manufacture of hollow thin-walled structures, in particular for protective structures, by lost foam casting, exceeds the required indicators of physical-mechanical properties set in the technical task.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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