Manufacture of thin-walled steel castings via consumable additive patterns

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The problems of thin-walled steel casting are usually connected with insufficient level of alloy fluidity in the field of operating casting temperatures, as well as with appearing counter-pressure for the alloy which fills the narrow mould sections. These sections correspond to thin walls of the future casting, depending on restricted gas permeability of a mould. To solve these problems, the methods of precise casting via thermodeleting patterns, as well as the methods of external effect on metallic melt which fills the mould. This work analyzes the accumulated experience of casting via lost and consumable patterns, the features of their practical realization in the conditions of a casting mould vacuum treatment; their disadvantages are shown as well. The authors formulated the task to eliminate the revealed disadvantages, to provide stability of the technological process and high quality of manufactured castings (in particular for surface defects, non-metallic inclusions, violations of geometrical shape and dimension accuracy) together with lowering of labour intensity and energy intensity of casting in comparison with Replicast–CS-process as a prototype. The innovative technology of casting via consumable patterns was suggested and successfully tested in the conditions of operating production facilities. This technology differs from the prototype in such way, that the patterns are fabricated via additive technologies providing obtaining of internal cellular adjustable structure from the material which is burnt at the temperature not more than the lower temperature threshold of polymorphic transformations of a filling agent of refractory suspension. This refractory suspension is applied on the pattern block with 1-2 layers, sintering of ceramic shell and burning of a pattern block are carried out after placing the pattern block in a moulding box and its filling by fluid self-hardening mixture. Then mould filling by metallic melt is conducted after solidification and restoration of the required gas permeability of fluid self-hardening mixture, while vacuum treatment of the mould is stopped after reaching the solidus temperature by metal. The authors believe that the suggested technology can be used for manufacture of castings of special duty from low-carbon steels and other alloys, which are sensitive to destruction of consumable patterns manufactured via additive technologies (additive patterns).
Key words: thin-walled steel castings, casting via lost patterns, casting via consumable patterns, additive technologies, liquid self-hardening mixtures, casting mould, vacuum treatment
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Introduction

Specific problems of thin-walled steel casting are usually connected with insufficient level of alloy fluidity in the field of casting operating temperatures, as well as with appearing counter-pressure to alloy which fills narrow section of a mould. These sections correspond to thin walls of the future casting, depending on restricted gas permeability of a mould and alloy susceptibility to cracking [1]. Searching of the variants for solving these problems is still actual at present time. Overlapping of external effects on metallic melt which fills the casting mould (overheating, gas pressure, vacuum treatment) as well as adaptation to concrete castings of sych technological procedures for precise casting as casting via investment patterns (CIP), casting via lost patterns (CLP) and casting via consumable patterns (CCP), which are classified as casting methods via thermodeleting patterns, can be considered as the main directions of this search. Casting via investment patterns is the most labour-, energy- and material-intensive method from all above-mentioned technologies. The main disadvantage of CIP is emission of toxic products of thermal destruction of patterns, what requires corresponding protection measures [2]. E.g., CIP variant with mould vacuum treatment during its pouring is characterized by transfer of products of a pattern thermal destruction from the mould to the unit for their catalyst additional burning with obtaining of carbon dioxide and water vapours [3].

Absence of direct contact between metallic melt which is pouring in a casting mould and this mould itself is considered as the main advantage of CCP method in comparison with CIP method. In the case of burning, the pattern is removed from the mould during its heating before mould filling with metal. It makes possible to decrease gas emissions during mould filling by metal and, as a result, to improve labour conditions for technological employees and to lower the hazard of carbonization and gas penetration inside future casting [4].

Foaming polystyrene is most often used at the Russian enterprises as a material for fabrication via CLP and CCP technologies; it is presented as synthetic polymer product of suspension styrene polymerization in the presence of emulsifier, stabilizer and pore agent [3]. Plasticity during forming is its main disadvantage, because it has negative effect of dimension accuracy of castings.

Additive technologies for 3D printing of CLP and CCP allow to replace foaming polystyrene by other thermoplastic materials which are more suitable for building the patterns with complicated configuration and with high precise dimensions, and to avoid necessity of strict keeping the gas dynamic balance in a casting mould during manufacture of thin-walled special duty castings from low-carbon steels and other alloys which are sensitive to destruction products of consumable patterns [5]. Exception of necessity of use of technological accessories for manufacture of these additive patterns via 3D printing is one of their substantial advantages [6].

CLP and CCP technologies with natural or forced ventilation of a mould cavity via its vacuum treatment are characterized by lowered effect of products of patterns thermal destruction on casting process and provide their oxidation without shop atmosphere contamination [7-9].

However, irrational choice of material for patterns and vacuum treatment procedure often has negative effect on mechanical properties of a casting mould, what leads to porosity, forming of non-metallic inclusions and violation of dimension accuracy in obtained castings.

Any researchers use the manufacturing methods of castings with increased complication via additive patterns, which are burnt (lost) directly in cavities of casting moulds during their contact with metallic melt [10-13]. However, they have the main disadvantages that are usual for CLP: intensive gas emission during mould filling by metal and, consequently, deterioration of labour conditions for workers and increase of hazards of carbonization and gas penetration inside the future castings.

Especial interest on this background is presented by such technologies of precise casting via thermodeleting models where advantages of well-known methods are combined and possibilities for adjusting external effect on a forming casting can be used [14-15].

Such is the CCP method Replicast–CS, when ceramic shell having 4-5 layers is applied on the pattern of foaming polystyrene with increased density (40-50 kg/m^3), while shell thickness makes 3.2-4.7 mm. Then obtained ceramic mould is placed in the furnace, where sintering of shell and burning of pattern occur at the temperature 930 °C; obtained ceramic shell is placed in the moulding box and filled with quartzite sand which is compacting there by vibration. Then the mould is covered by polyethylene film and vacuum appr. 0.04-0.05 MPa is created there before metal pouring in this mould [16]. This method was selected by the article authors as a prototype.

The following disadvantages can be mentioned for this method: use of burning patterns from foaming polystyrene, which increases the hazard of quality lowering of castings for their surface defects, gas permeability, non-metallic inclusions and violation of their dimension accuracy, promoting the process destabilization; necessity of application of 4-5 ceramic layers with increased thickness, which enlarges the process labour intensity; conduction of ceramic shell sintering and pattern block burning without placing this block in a moulding box with supporting filling agent, what rises possibility of ceramic shell destruction; increased shell sintering temperature and pattern block burning as well as necessity of quartzite sand compacting via vibration (this sand is used as a supporting filling agent) and keeping of exhausting in a mould during the whole casting process, because they increase the process energy intensity. Additionally, the hazards of cracks origination and propagation in a hot ceramic shell, which is located in a moulding box and filled with cold quartzite sand; these cracks are causes of mould destruction during their pouring by metallic melt and forming of excessive roughness as well as “crests” on castings surface.

Goal setting

The following task was formulated in this work: to develop and test in industrial conditions the casting technology based on consumable patterns, which provides stability of the technological process and improved quality of obtained castings by non-metallic inclusions, violation of geometrical shape and dimension accuracy, together with lowering of labour and energy intensity in comparison with a prototypes.

Selection of the variant for solving the problem

The new method of casting based on consumable patterns was suggested; it includes manufacture of patterns, assembling of a pattern block, layer-by-layer application of refractory suspension on its surface, step-by-step drying of each layer, placing a pattern block into moulding box, simultaneous sintering of ceramic shall and burning of a pattern block, consequent filling the mould by metallic melt in the conditions of its vacuum treatment, knock-out and other finishing operations. This method differs from a prototype in such way that the patterns are manufactured via additive technologies, which provide obtaining of internal cellular adjusting structure in these patterns from the material which is burning at the temperature not exceeding the lower temperature threshold of polymorphic transformations of a filling agent of refractory suspension. This refractory suspension is applied on a pattern block by 1-2 layers, sintering of ceramic shell and burning of a pattern block are carried out after placing this pattern block into the moulding box and its filling with fluid self-hardening mixture. Pouring of the mould with metallic melt is conducted after solidification and restoration of the required gas permeability of fluid self-hardening mixture, while vacuum treatment of the mould is stopped after reaching of the solidus temperature by metal.

Fabrication of patterns via additive technologies, providing obtaining of internal cellular adjusting structure in these patterns (additive Quick-Cast technologies based on the masking method) allows to decrease substantially mass of a pattern material without risk of losing its strength properties and buckling during forming. It also allows to decrease gas emission during pattern block burning as well as possibility of introduction of gas and non-metallic inclusions in a casting body and its surface carburization during mould pouring by metallic melt.

Use of the material which is burning at the temperature not exceeding the lower temperature threshold of polymorphic transformations of a filling agent of refractory suspension (lower temperature in comparison with a prototype) in the process of material patterns manufacture allows to remove a pattern block out of the mould quickly and efficiently via its burning. It occurs during heating to the temperature which is lower than that of a prototype and minimizes possibility of crack forming in a ceramic shell, what, in its turn, prevents defects of a "crest" type on the surface of obtained castings. Additionally, lowering of energy intensity of this process (compared with a prototype) is provided.

Applying of refractory suspension on a pattern block by 1-2 layers (lower number of layers in comparison with a prototype) provides high dimension accuracy and quality of the front mould surface; it also decreases labour intensity of this process. Increase of number of layers is inexpedient owing to inevitable lowering of gas permeability of ceramic shell which is connected with such increase.

Filling of a moulding box by fluid self-hardening mixture after pattern block placing inside this moulding box promotes forming of a powerful support around a pattern block; this support prevents violation of a working cavity shape and counteracts to thermomechanical loads during consequent sintering of a ceramic shell and burning of a pattern block, as well as mould filling by metallic melt.

Conduction of metallic melt pouring in the mould after solidification and restoration of the required gas permeability of fluid self-hardening mixture leads to lowering of the hazards of mould erosion and destruction as well as more complete elimination of gases out of the mould through perforating holes of the moulding box and porous volumetric ceramic mould during vacuum treatment.

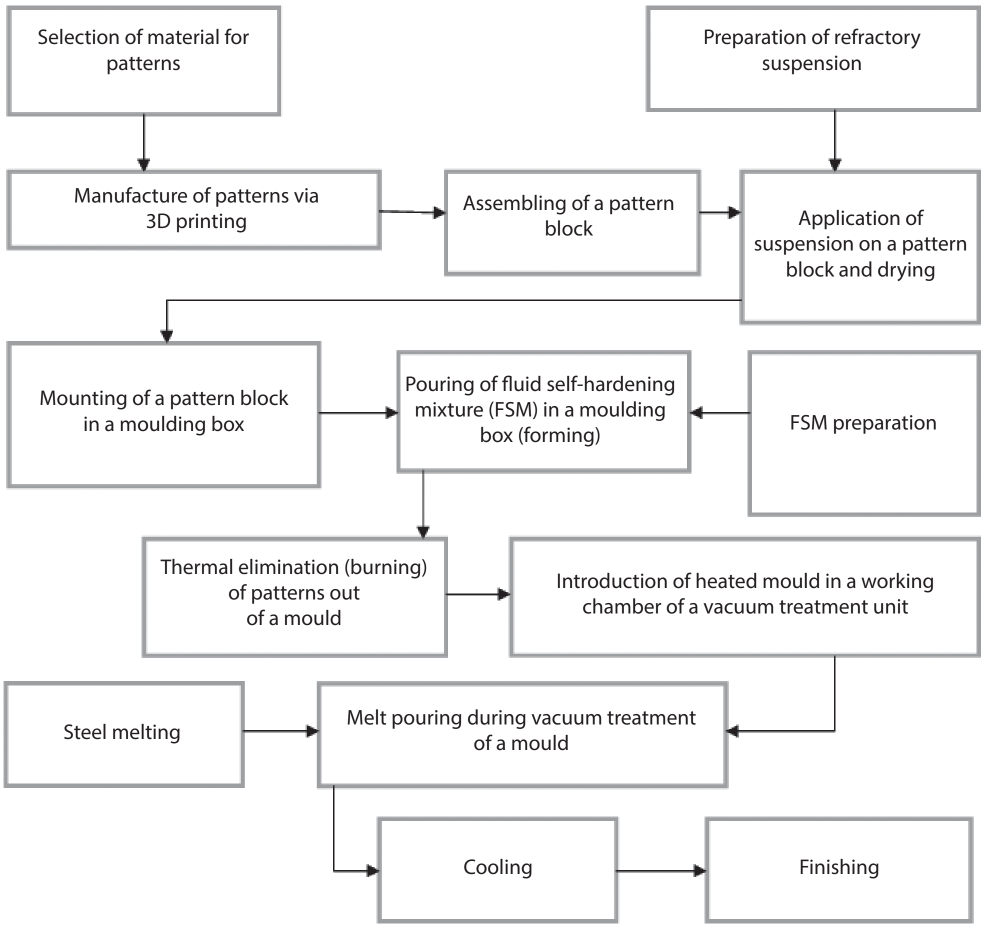

Fig. 1. The block-scheme of the suggested technology for manufacture of thin-walled steel castings via consumable additive patterns

When metallic melt reaches the solidus temperature, any liquid phase disappears in it and it completely loses fluidity properties. In this connection, continuation of vacuum treatment use to provide the conditions of melt penetration in thin-walled mould parts becomes inexpedient economically, because it leads to unjustified increase of energy intensity of the process.

Suggested technology

The block-scheme illustrating the suggested technology is presented on the **Fig. 1**.

At first the patterns of castings and elements of the gating and feeding system were fabricated from material which was burning at the temperature not exceeding the lower temperature threshold of polymorphic transformations of the filling agent of refractory suspension. This process uses additive technologies, providing obtaining internal cellular adjusting structure, and includes finishing treatment, such as mechanical removal of supports and surface processing by solvent for lowering of the "waving" effect which is inevitable during 3D printing by polymeric thread. Then the pattern block is assembled, 1-2 layers of refractory suspension are applied on its surface and drying is carried out after application of each layer. Then the pattern block is placed into perforated moulding box, filled (poured) it by fluid self-hardening mixture, charged the moulding box in the heating furnace and simultaneous sintering of the ceramic shell and burning of the pattern block out of moulding cavity are conducted at the temperature not exceeding the lower temperature threshold of polymorphic transformations of the filling agent of refractory suspension. After solidification and restoration of the required gas permeability of fluid self-hardening mixture, the mould is placed in the working chamber of the unit of "vacuum-metal" type and filled by metallic melt in the conditions of vacuum treatment, which is stopped after reaching the solidus temperature by metal. When cooling of castings in the mould was carried out, they were subjected to knock-out, fettling, scarfing and other required finishing operations.

Pilot-experimental worksand discussion on the results

The pilot-experimental research in the conditions of operating production facilities was conducted for assessment of casting quality obtaining via the suggested technical solution in comparison with a prototype.

Testing castings of "Barrel" type, with mass 7.5 kg and variable wall thickness from 2.0 to 15.0 mm were fabricated from 20L steel (according to the GOST 977) via suggested method (pilot batch) and prototype (control batch) – five castings in each batch.

The patterns of castings and elements of the gating and feeding system were fabricated for pilot party from CAST plastic - the material on the base of polymethyl methacrylate (PMMA) with addition of special plasticizers (thermoplastic polymeric material with burning temperature 405 °C), via 3D printing using additive FDM technology (the method of layer-by-layer melting of polymeric thread). Obtaining of internal cellular adjusting structure of patterns was provided by use of the corresponding printer function. "Waviness" was partly eliminated during finishing treatment via surface processing of patterns by acetone.

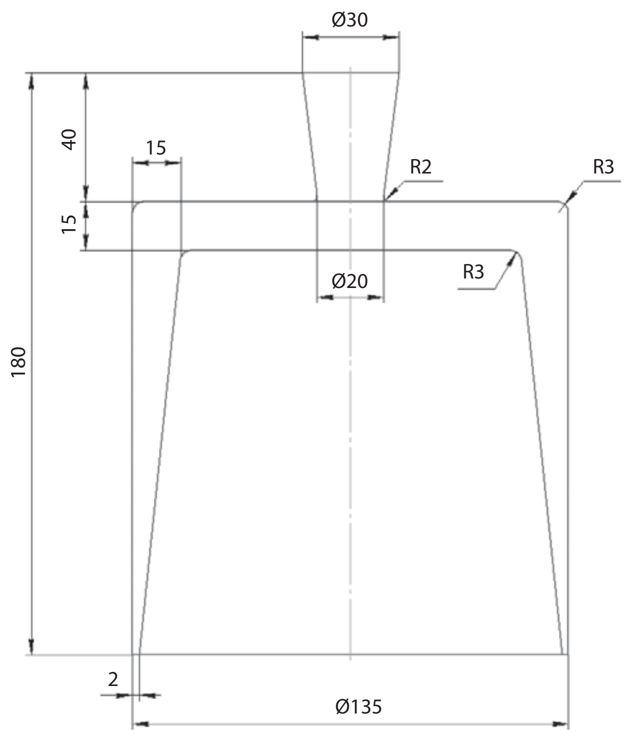

Fig. 2. Pattern block: casting of «Barrel» type with gating and feeding system

Assembled pattern block included the pattern of one casting with the elements of the gating and feeding system (**Fig. 2**). Two layers of quartzite-based refractory suspension were applied on the surface of this block. Quartzite has the lower temperature threshold of polymorphic transformations equal to 573 °C, and application of each layer was accompanied by air flow drying during 20 min using a ventilator.

The pattern block was placed in the perforated moulding box and then poured with fluid self-hardening mixture, including refractory filling agent (quartzite sand), binder (liquid glass), hardening compound (ethylene glycol acetate), foam generating agent, foam stabilizer and water.

The moulding box was charged in the heating furnace SNO 8.5.17.5/12, where it was heated according to the following procedure: heating up to 500 °C with speed not more than 150 °C per hour and holding during 3 hours at the maximal temperature. Gas products of thermal destruction of the pattern block material, which were obtained during its burning, were removed through ventilation system. Experimental tests displayed that this heating procedure provides sintering of the ceramic shell, complete burning of the pattern block as well as solidification and restoration of the required gas permeability of fluid self-hardening mixture (not less than 250 units).

The mould was placed in the working chamber of the vacuum unit, which was equipped with skidding vane rotary pump 2NVR-5DM with production capacity 19.8 m^3/h and providing vacuum treatment at the level 0.003-0.005 MPa.

Mould pouring by metallic melt was carried out in the conditions of vacuum treatment, while pouring temperature of vacuum treated mould made 1530-1550 °C. Vacuum treatment was stopped after reaching the solidus temperature (equal to 1480 °C) by metal after 4 min since pouring finishing. Duration of cooling to the solidus temperature was preliminarily determined based on the results of computer-aided simulation of casting solidification using the program LVMFlow for modeling of casting processes. Melt cooling time during pilot and experimental research was measured by timing device.

Quality of the control batch (prototype) and pilot batch (suggested solution) was assessed after knock-out and fettling via the techniques using at the enterprise. Quality assessment included control on the following casting defects: shrinkage holes, porosity, looseness; surface roughness, "crests", surface carburization; gas holes, porosity, non-metallic inclusions; violation of geometry, dimension accuracy, buckling. Additionally, minimal wall thickness creating by metal pouring was controlled for castings.

As a result, increased surface roughness, "crests", traces of surface carburization and violation of geometry and dimension accuracy were revealed in 2 from 5 castings of the control batch (40 % of total amount). At the same time, no defects were found out in the castings of the pilot party. At the same time, minimal wall thickness creating by metal pouring was 5.0 mm and 2.5 mm for the castings of the control and pilot batches respectively. The obtained results were the base for taking the solution about putting this development into practice at the basic industrial enterprise.

Conclusion

The new technology of thin-walled steel casting via consumable additive patterns was successfully developed and tested experimentally in the conditions of operating production facilities. This technology is characterized by lower labour and energy intensity in comparison with the Replicast–CS process which was chosen as a prototype. The authors believe that this suggested technology can be used for manufacture of special-duty castings from low-carbon steels and other alloys; these castings are susceptible to destruction products of consumable patterns obtained via additive technologies (additive patterns).

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