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Improvement Of The Technology For Producing High-Quality Castings Through Out-Of-Furnace Treatment Of Molten Metal

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Abstract

The present study is devoted to improving the technology for producing high-quality castings from carbon structural steels through the out-of-furnace modification of molten metal. Experimental investigations were carried out under laboratory conditions using an IST-0.001 induction furnace. During the melting process, the molten metal was treated with different types of nickel-based modifiers, particularly ПН-ХН80С3Р3 (ПГ-СР3). The modifier was introduced into the melt in various proportions relative to the weight of the molten metal in order to influence the crystallization process and refine the microstructure of the casting. The chemical composition of the obtained samples was analyzed using SPECTROLAB-10M spectrometric equipment. Microstructural studies were performed at different magnifications to evaluate the phase composition and structural features of the cast steel. The results showed that the modification of molten metal increased the number of crystallization nuclei, leading to grain refinement and the formation of a more uniform structure. The microstructural analysis revealed a pearlite–ferrite structure with a predominance of pearlite, which contributes to improved mechanical properties. The presence of small amounts of sulfides, oxides, and silicates was also detected in the structure. The obtained results confirm that out-of-furnace modification of molten metal using nickel-based modifiers is an effective technological method for improving the structural quality and performance characteristics of cast carbon steels

Keywords: out-of-furnace treatment, molten metal modification, carbon structural steel, casting technology, microstructure, ferrite–pearlite structure, induction furnace, crystallization nuclei, nickel-based modifier, grain refinement

INTRODUCTION

High-quality castings from carbon structural steels are widely used in various engineering applications, including machinery, automotive, and construction industries. The performance of these castings largely depends on their chemical composition, microstructure, and mechanical properties [1]. One of the key challenges in casting technology is achieving a refined grain structure and uniform distribution of phases in the alloy, which directly affects its strength, toughness, and wear resistance.

Recent studies have shown that the microstructure of cast steel can be significantly improved by introducing modifiers into the molten metal under controlled conditions. Out-of-furnace treatment, which involves modifying the molten steel in a ladle before casting, is an effective method for increasing the number of crystallization nuclei, refining grain size, and reducing casting defects. Nickel-based modifiers [2-6], in particular, have been demonstrated to enhance mechanical properties by promoting the formation of a pearlite–ferrite structure and controlling non-metallic inclusions.

Despite the widespread use of carbon structural steels, there is still a need to optimize the modification process to achieve consistent microstructural characteristics and high-quality cast products. This study aims to investigate the effect of nickel-based modifiers, specifically ПН-ХН80С3Р3 (ПГ-СР3), on the microstructure and mechanical properties of 20Л grade steel. The research focuses on the out-of-furnace modification technique, examining its influence on chemical composition, phase distribution, and the formation of non-metallic inclusions in the castings [7-11, 12]. The findings of this work contribute to improving casting technology and provide practical guidelines for producing structurally sound and high-performance cast steel components.

MATERIALS AND METHODS

To improve the quality and mechanical properties of cast products obtained from carbon structural steels, the molten metal was modified in the ladle under out-of-furnace conditions using different amounts of modifiers. As a result, it was possible to increase the number of crystallization nuclei in the casting and refine the grain structure [13, 14]. The chemical composition of the melted carbon structural alloy was prepared in accordance with the ГОСТ 977–88 standard. The melting of the charge materials was carried out in the IST-0.001 furnace in the laboratory of the Department of Mechanical Engineering of Namangan State Technical University. The melting process is shown in Figure 1.

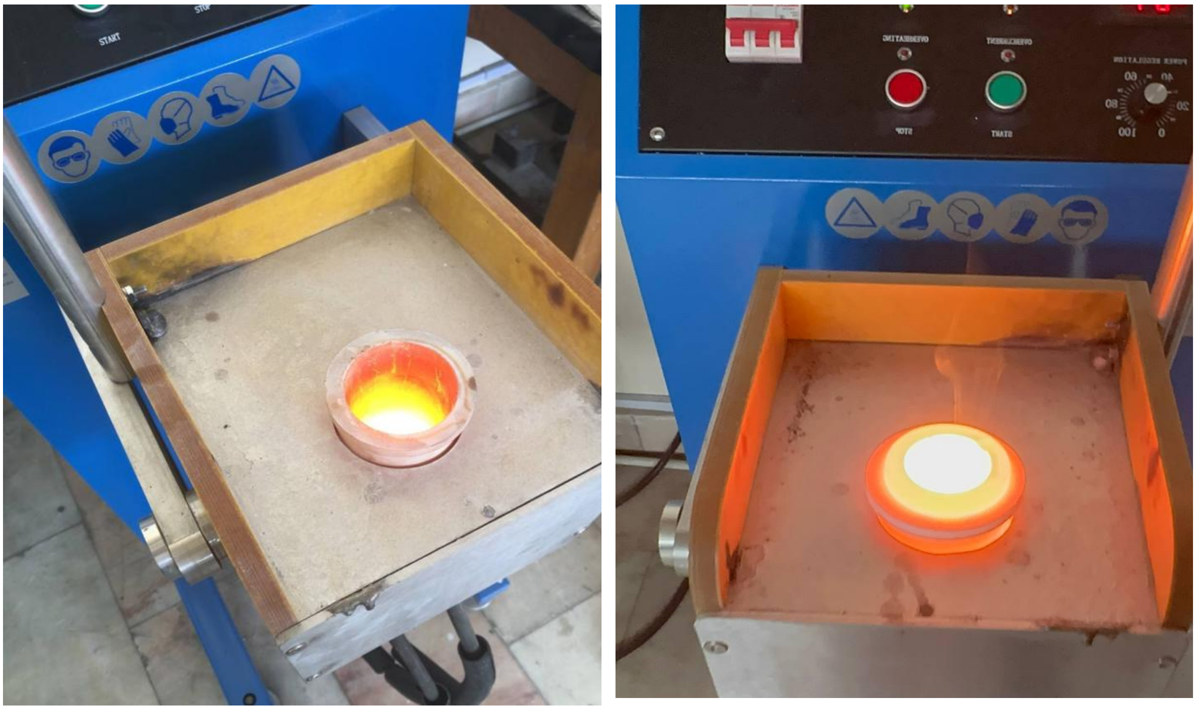

Fig 1. The process of melting charge materials in the IST-0.001 induction furnace

First, before charging the furnace with the charge materials, the serviceability of the induction furnace was carefully inspected. The crucible used in the experiment was made of aluminum corundum, whose chemical composition mainly consists of α-aluminum oxide (Al_2O_3) – 95÷99.9%, with small amounts of additional impurities such as SiO_2 (silicon dioxide), Fe_2O_3 (iron (III) oxide), Na_2O and K_2O (sodium and potassium oxides), and TiO_2 (titanium dioxide). The melting temperature of the crucible is 2050÷2072 °C [15]. Such a crucible was selected because during the melting of the carbon structural steel alloy, the temperature may increase during alloying, flux treatment, and modification processes. Therefore, it was necessary to use a crucible capable of withstanding these temperature changes without any negative effects. After checking the reliability of the crucible, the primary and secondary charge materials were prepared. Since an induction furnace was used, larger charge materials with sizes of 45÷55 mm were first loaded into the crucible. The main reason for this is that melting in an induction furnace occurs due to the electromagnetic field, which first heats the charge materials placed in the furnace. Gradually, the melting process begins, which takes approximately 3÷4 minutes. If fine charge materials are loaded into the furnace at this stage, the burning loss increases due to their small size. Since the capacity of the furnace used for melting was 1 kg, the use of small-sized initial charge materials could lead to weight losses due to oxidation and burning. Moreover, part of the oxidation products released from fine charge materials may enter the molten metal and pass into the slag, while another part may negatively affect the quality of the casting. Such processes hinder obtaining high-quality cast products with the required properties. Therefore, large-sized charge materials were initially loaded into the induction furnace under laboratory conditions [16, 17]. After 3÷4 minutes, these large charge materials melted in the crucible, and smaller charge materials were then added onto the molten metal. This approach reduced both the melting time and the burning losses of the fine charge materials. The fine charge materials placed on the molten metal melted quickly. After that, FeMn-85 and FeSi-45 ferroalloys were introduced into the furnace. To form slag, fluxes were added, namely $CaCO_3$ and CaF_2. After the slag separated from the molten metal, it was removed from the melt. Once the ferroalloys were completely melted and the molten metal was fully purified from slag, the following modifiers were introduced into the furnace in different percentages for modification purposes during each melting process: ПН-ХН80С3Р3 (ПГ-СР3), ПГ-С27, ПГ-СР2, ПГ-ФБХ6-2, and ПГ-СР2.7. In the first melting experiment, the ПН-ХН80С3Р3 (ПГ-СР3) modifier was added to the molten metal in an amount of 2.5 % of the molten metal weight [18-20]. To ensure proper mixing, the melt was held in the crucible for 2÷3 minutes. After that, the molten metal was poured into a pre-prepared sand–clay mold. The modifier used was nickel-based, and its chemical composition is presented in Table 1.

RESULT

Table 1

Chemical composition of the ПН-ХН80С3Р3 (ПГ-СР3) modifier

Brand	Element content, %				
	Ni	Cr	Si	B	Fe
ПН-ХН80С3Р3 (ПГ-СР3)	70-80	13.5-16.5	2.5-3.5	2.0-2.8	≤ 5

The elements contained in the modifier introduced into the molten metal affected the process as follows:

Boron (B): The boron (B) element contained in the modifier ensured the strengthening of the alloy due to the formation of high-hardness borides such as CrB, NiB, and FeB. In addition, the formed borides improved the mechanical properties and wear resistance of the alloy. These borides are very hard and resistant to abrasion, and their accumulation within the internal structure of the alloy contributed to enhancing its wear resistance. At the same time, boron has a positive effect on the solidification process of steel even at very low concentrations (at the ppm level).

Silicon (Si): Silicon is a strong deoxidizer, removing oxides from the molten metal, which leads to the formation of non-metallic inclusions of silicate type. During the alloying process, silicon partially strengthens the ferrite phase of the molten metal and alters the morphology of the non-metallic inclusions. These changes positively affect the cleanliness of the steel and its wear resistance.

Chromium (Cr) and Nickel (Ni): As part of the alloy phases, these elements increased high-temperature and corrosion resistance. Chromium reacts with boron to form Cr-borides or Cr-carbides, which are highly resistant to wear and oxidation. Nickel, in turn, enhances the cohesion of the coating or molten metal phase, ensuring strong metallurgical bonding while partially maintaining the ductility of the alloy.

1. Reactions related to Silicon (Si):

In the molten metal, silicon acted as a deoxidizer:

$$Si + O_2 \rightarrow SiO_2$$

$$Si + 2FeO \rightarrow 2Fe + SiO_2$$

$$SiO_2 + CaO \rightarrow CaSiO_3 \text{ (passed into the slag).}$$

2. Reactions related to Chromium (Cr):

Chromium reaction with oxygen and interaction with slag:

$$2Cr + 1½O_2 \rightarrow Cr_2O_3$$

$$Cr_2O_3 + 3CaO \rightarrow 3CaO{\cdot}Cr_2O_3 \text{ (slag compound)}$$

$$Cr_2O_3 + Si \rightarrow 2Cr + SiO_2 \text{ (reduction occurred).}$$

3. Reactions related to Boron (B):

Boron oxidation and slag compounds:

$$4B + 3O_2 \rightarrow 2B_2O_3$$

$$B_2O_3 + CaO \rightarrow CaO{\cdot}B_2O_3 \text{ (slag)}$$

$$B_2O_3 + 2Al \rightarrow 2B + Al_2O_3 \text{ (aluminothermic reduction occurred).}$$

4. Reactions related to Nickel (Ni):

Nickel is generally inert, but at high temperatures it can react as follows:

$$Ni + O_2 \rightarrow NiO$$

$$NiO + Si \rightarrow Ni + SiO_2$$

$$Ni + S \rightarrow NiS \text{ (it contributed to the reduction of sulfur (S) to a certain extent).}$$

After the molten metal was prepared, it was poured into a pre-prepared sand–clay mold. The prepared sand–clay mold mixture consisted of 90÷91 % quartz sand, 4÷5% bentonite clay, and 3÷4% water, which were mixed in a mixer for 5÷6 minutes. After mixing, the molding mixture was compacted thoroughly into the flask using a rammer. The main reason for selecting quartz sand was that it does not contain soil impurities and contains certain amounts of montmorillonite, muscovite, and kaolinite clays. Due to these characteristics, the use of this sand during the mold preparation process provides good bonding properties between the components of the molding mixture and ensures that the mold does not collapse. Because of these favorable properties, quartz sand was selected as the primary molding material. Bentonite clay was added additionally to improve the binding properties of the molding mixture. Another advantage of bentonite clay compared to other clays is that when it is added to the molding mixture, it does not significantly reduce the gas permeability of the mold. However, after exposure to temperatures above 400 °C, bentonite clay loses its binding properties. Therefore, this clay has both advantages and disadvantages. The main purpose of adding water to the molding mixture is, first, to increase the plasticity of the mixture due to moisture, and second, to improve its fluidity and cohesiveness. Improved fluidity of the molding mixture ensures that sharp edges and thin-walled sections of the pattern are accurately reproduced when producing castings with complex shapes. However, if the moisture content of the molding mixture exceeds 3÷4%, it may lead to casting defects. Excess moisture can cause the mold to boil during pouring, which ultimately results in defective castings. Therefore, excessive moisture in the molding mixture must be avoided. Under laboratory conditions, the process of pouring the prepared molten metal from the crucible into the sand–clay mold at a temperature of 1530 °C in the IST-0.001 induction furnace is shown in Figure 2.

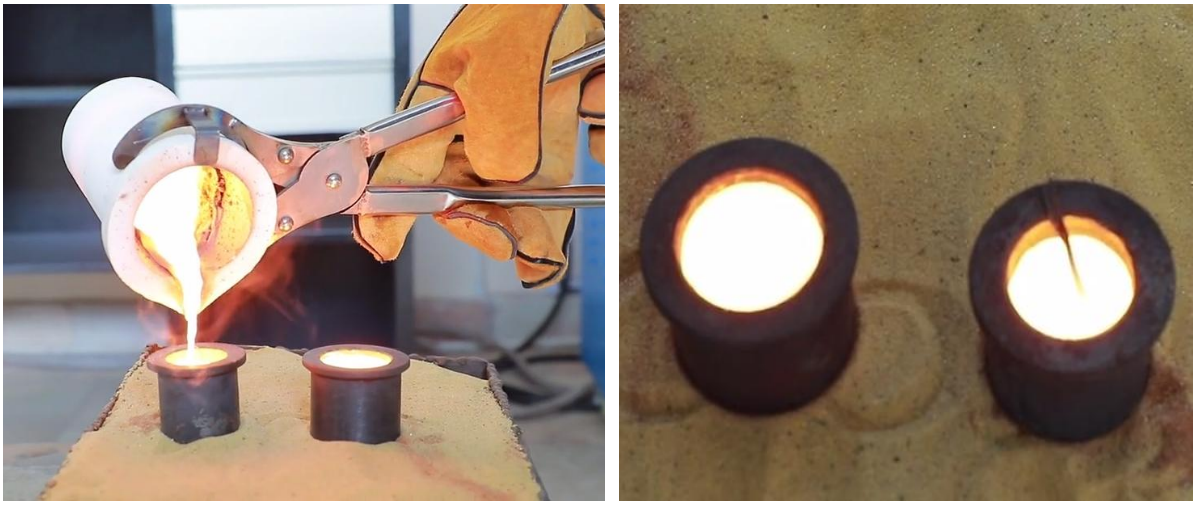

Fig 2. The process of pouring molten metal into a sand–clay mold

After the cast samples had completely cooled, they were thoroughly cleaned from the sand. The appearance of the samples after cleaning from the sand can be seen in Figure 3.

Fig 3. Appearance of cast samples made of 20Л grade steel after sand removal

The obtained samples were first analyzed for chemical composition at the “Central Laboratory” of Andijan Mechanical Plant JSC using the

SPECTROLAB-10M equipment. The chemical composition of the alloys is presented in Table 2.

Table 2

Chemical composition of samples obtained from 20Л grade steel

Samples	C	Si	Mn	P	S	Fe
№1	0,20	0,35	0,45	< 0,06	< 0,06	Bal.
№2	0,14	0,41	0,64	< 0,05	< 0,07	Bal.
№3	0,13	0,50	0,72	< 0,06	< 0,062	Bal.
№4	0,15	0,42	0,81	< 0,04	< 0,054	Bal.
№5	0,19	0,51	0,65	< 0,035	< 0,056	Bal.

After determining the chemical composition of the samples, the other mechanical properties of the alloy were examined.

The microstructures of the samples obtained by adding 0.5% of the modifier ПН-ХН80С3Р3 (ПГ-СР3), based on the weight of the molten metal, are shown in Fig. 4 (a, b, c).

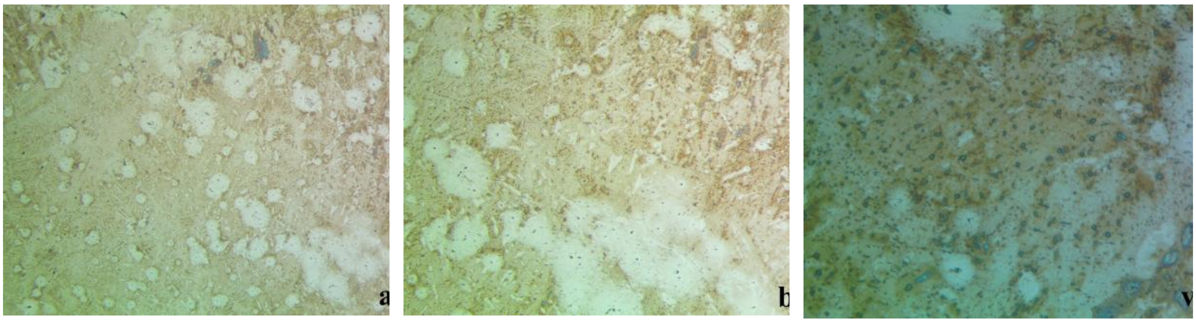

Fig. 4. Microstructure of the sample cast from 20L grade steel after out-of-furnace treatment with a modifier: a) ×50, b) ×100, c) ×500 magnification.

In Fig. 4, the light white regions correspond to the ferrite phase. This phase, typical for low-carbon steels, is distinguished by its relatively high softness and plasticity compared with other phases. The dark, fine fibrous-like areas correspond to pearlite, which is harder than the ferrite phase. From the microstructure it can be observed that the amount of pearlite is higher than that of ferrite. Therefore, the microstructure of this sample can be characterized as a pearlite–ferrite microstructure. In addition, the small black spots observed in the sample indicate the presence of sulfides, oxides, and a small amount of silicates.

CONCLUSION

The conducted experimental studies demonstrated that the modification of molten metal under out-of-furnace conditions significantly influences the structural formation and quality of cast carbon structural steels. The introduction of the ПН-ХН80С3Р3 (ПГ-СР3) modifier into the molten metal promoted the formation of additional crystallization centers, which resulted in grain refinement and improved structural homogeneity of the casting. Microstructural analysis of the samples showed a ferrite–pearlite structure with a predominance of pearlite phase, indicating favorable conditions for enhancing the strength and wear resistance of the alloy. Additionally, the formation of small non-metallic inclusions such as sulfides, oxides, and silicates was observed. Overall, the results indicate that the application of nickel-based modifiers during out-of-furnace treatment is an effective approach to improving the technological process and ensuring higher quality cast products from carbon structural steels.

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