High Temperature Treatment of Castings from Steel Grade 150KhNM

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Abstract. High-temperature processing of steel cast is an effective way to obtain a high range of properties of finish product. The main purpose of the study was to determine the critical temperatures and modes of processing of molten steel 150KhNM. The thermal calculation was carried out according to the additivity rule. The holding time of the melt was determined experimentally. Laboratory melts were performed with varying temperatures of maximum heating of the melt above and below tcr. The optimal modes of high-temperature processing of the melt were determined by analyzing the structure of solid samples. The influence of high-temperature treatment on the structure and properties of castings from steel grade 150KhNM has been studied. The main processing parameters of this alloy have been determined. The dependences of the metal overheating influence on the castings mechanical properties improvement are obtained. Examples of improving the quality of products with using optimal modes of high-temperature processing are given. The investigated modes have showed that holding at a critical temperature leads to change in the type of casting-box (raw sand, dry sand, chill mold) and uniformity of distribution. This fact leads to a change in properties and a more homogeneous structure is formed.

1. Introduction

High temperature treatment (HTT) is a highly efficient and successfully developed method of treating molten steel. This is one of the methods of thermal effect on steel. It includes heating steel up to a set temperature, soaking at such temperature within a definite period and cooling down to casting temperature or soaking steel near casting temperature. Molten steel is refined and homogenized, resulting in an increase in a broad range of various performance properties and the quality of the castings [1–3].

The current machine industry, metallurgy and other industries of the metalworking industry are characterized by high requirements for properties of materials. This is attributed to an increasing rate of loading machines, including a trend in decreasing their weight. In many cases, weight is a decisive factor.

Quality and operational reliability of industrial products – machines, pieces of machinery and devices – directly depend on relevant properties of their elements – parts, joints and assemblies. In their turn, structural properties of the latter depend on the properties of materials. Static and dynamic strength, brittle fracture resistance, scuff and wear resistance, resistance to fatigue fracture, physical, corrosion, heat-resisting and other properties of materials are attributed to main factors determining reliability and lifetime of machines.
Main structural materials are metals and alloys. Production of metals and alloys in the countries with a high technical production level significantly increases, especially with an increase in melting steel that undergoes heat treatment. A main objective of steelmaking is production of molten steel with a set chemical composition, definite physical, chemical and casting properties with minimum power consumption, burden materials and melting time. Production of high-purity steels is widely spread. Development of heat treatment operations includes names and parameters of such operations. This includes setting the heating temperature, heating time, soaking time, cooling time, heating and cooling media.

When producing ingots, billets and castings, to control and prevent defects, manufacturers apply many techniques that can be divided by a method of treatment to the specified degree of convention. Dynamic methods are based on a principle of the forced physical effect on a liquid phase during solidification. Such methods usually ensure an active influence not only on heat–and mass transfer in a liquid phase, but also significantly change the nature of the processes in a two-phase zone [2, 3].

Transfer of the system to the equilibrium state or the state near to equilibrium is resulted from heating up to such high critical temperatures. The higher degree of equilibrium and uniformity of alloying component atoms distributed in molten steel, the weaker inherited influence of burden materials and the higher quality of the castings. By heating up to a set temperature, liquid eliminates some burden inheritance according to a trend in a phase transfer, not by a chemical reaction; therefore, molecular formations cannot be a main basis for this process [1, 4–6].

2. Objective
This medium-carbon steel grade for rolls undergoes very complex and power-consuming heat treatment. Hypereutectoid steel grade 150KhNM is used for manufacturing forged and cast rolls for hot rolling and rolls for cold rolling. Despite complexity and power consumption of relevant operations, steel that underwent these types of treatment often did not show significant improvement of mechanical properties.

One of main disadvantages of this steel grade is its tendency to crack. This steel grade also has lower wear and thermal resistance. This paper is aimed at studying the structural factors influencing impact strength and structural homogeneity of the castings from steel grade 150KhNM [7, 8].

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3. Materials and methods of studies
To determine main parameters of high temperature treatment, such as critical temperature, we applied a calculation method depending on a chemical composition of the alloy according to the rule of mixtures. Critical temperature is the temperature when molten steel is homogeneous. A homogeneous state contributes to the lack of hysteresis in molten steel and cluster groups. Such high temperature structure of molten steel is well overcooled; we managed to decrease concentrations of detrimental impurities, such as oxygen and nitrogen, directly in molten steel. Thus, the amount of added reducing constituents and non-metallic inclusions decreases due to favorable conditions for their removal [1, 8–10].

Melting heat, as well as other properties, follows the rule of mixtures. Liquidus and solidus temperatures were calculated according to the equation:

\[ \frac{T_L}{S} = T_0 - \Delta_{L/S}, \]  

where \( T_0 \) is melting temperature of the solubilizing agent (iron); \( \Delta_{L/S} \) is a decrease in liquidus/(solidus) temperature resulting from various chemical elements contained in steel.
where Δlt / sl(a) + Δtl / sl(b) + Δtl / sl(c)… is liquidus/(solidus) temperature of molten steel with the concentrations of a, b, c… elements according to the binary phase diagrams.

Melting temperatures are given in Table 1.

Table 1. Melting temperature of steel grade 150KhNM.

| Elements | Percentage, % | \( T_{\text{liq}} \) | \( \Delta T_{\text{liq}} \), °C | \( T_{\text{sol}} \) | \( \Delta T_{\text{sol}} \), °C |
|----------|---------------|-----------------|------------------|-----------------|------------------|
| Fe-C     | 1.45          | \( t_1 = 1470 \) | \( \Delta t_1 = 69 \) | \( t_s = 1240 \) | \( \Delta t_s = 319 \) |
| Fe-Si    | 0.29          | \( t_1 = 1537 \) | \( \Delta t_1 = 2 \) | \( t_s = 1535 \) | \( \Delta t_s = 4 \) |
| Fe-Mn    | 0.65          | \( t_1 = 1534 \) | \( \Delta t_1 = 5 \) | \( t_s = 1532 \) | \( \Delta t_s = 7 \) |
| Fe-Cr    | 0.995         | \( t_1 = 1538 \) | \( \Delta t_1 = 1 \) | \( t_s = 1538 \) | \( \Delta t_s = 1 \) |
| Fe-Ni    | 1.05          | \( t_1 = 1530 \) | \( \Delta t_1 = 9 \) | \( t_s = 1528 \) | \( \Delta t_s = 11 \) |

\( \sum \Delta T_{\text{liq}} = 86 \quad \sum \Delta T_{\text{sol}} = 332 \)

Mole fractions were used to determine molar melting heat. To calculate a mole fraction of every component, we determined a number of moles of every component (Table 2).

\[
n_i = \frac{C_i}{M_i},
\]

where \( n_i \) is a number of moles of the component in 100 g of the alloy; \( C_i \) is a concentration of the component in the alloy, % (g/100 g); \( M_i \) is molar mass of the component.

The sum of moles:

\[
\sum n_i = n_1 + n_2 + n_3 + \ldots + n_n.
\]

A mole fraction is calculated as a ratio of the number of moles of the component to a total number of moles:

\[
m_i = \frac{n_i}{\sum n_i}.
\]

Melting heat for every chemical element is taken from reference data. By summing all the components, we calculate a mole fraction of melting heat in kJ/mol (Table 3).

A share of a disordered zone at melting temperature is calculated by the relation:

\[
\psi_{\text{melt}} = \frac{\Delta H_{\text{melt}}}{\Delta H_{\text{dis}}},
\]

where \( \psi_{\text{melt}} \) is a share of the disordered zone at melting temperature; \( \Delta H_{\text{melt}} \) is melting heat, kJ/mol; \( \Delta H_{\text{dis}} \) is thermal effect of full thermal disorder of clusters in liquid, kJ/mol.

In our case, liquidus temperature is taken as melting temperature. Thermal effect (Table 1) of full thermal disorder is calculated by the below empirical dependence:

\[
\Delta H_{\text{dis}} = -1.26 + 2.95 \cdot 10^{-2} \cdot T_{\text{melt}}.
\]
Temperature dependence of the share of the disordered zone is expressed by the equation:

\[ \psi_{\text{dis}} = A \exp \left( \frac{-\Delta H_{\text{dis}}}{RT} \right). \]  (8)

Knowing the share of the disordered zone at liquidus temperature, we calculate coefficient \( A \):

\[ A = \frac{\psi_{\text{melt}}}{\exp \left( \frac{-\Delta H_{\text{dis}}}{RT} \right)}. \]  (9)

Temperature of disorder (Table 2) is expressed by the share of disorder:

\[ T_{\text{dis}} = \frac{-\Delta H_{\text{dis}}}{(R \ln A)}. \]  (10)

### Table 2. Mole fractions.

| Elements | C | Si | Mn | S  | P  | Cr | Ni | V  | W  | Fe | Total |
|----------|---|----|----|----|----|----|----|----|----|----|--------|
| Moleweight | 12 | 28 | 55 | 32 | 31 | 52 | 59 | 61 | 184| 56 | 100    |
| Steel grade | % | 1.45 | 0.29 | 0.65 | 0.018 | 0.015 | 0.995 | 1.05 | 0 | 0 | 95.53 |
| 150KhNM | wt | 0.064 | 0.0053 | 0.006 | 0.0003 | 0.0003 | 0.01 | 0.0095 | 0 | 0 | 0.904 |
| \( \Delta H_{\text{web}} \) | 103.2 | 47600 | 14630 | 393.6 | 25960 | 21008 | 17523 | 23050 | 46000 | 14120 |
| Share of \( \Delta H_{\text{web}} \) | 6.605 | 252.3 | 175.6 | 0.118 | 7.788 | 210.1 | 166.5 | 0 | 0 | 12764 | 15583 |

### Table 3. Temperature of disorder.

| Steel grade | \( \Delta H_{\text{dis}}, \text{kJ/mol} \) | \( \phi_{\text{dis}} \) | \( A \), coefficient | \( T_{\text{dis}} \) at \( \phi_{\text{dis}} = 0.5 \) |
|-------------|-----------------|-----------------|-----------------|------------------|
| 150KhNM     | 49717           | 0.273214        | 8.7476          | 1817 0°C         |

During steel melting, after adding and melting all burden components, molten steel is heated up to 1800–1820 °C. Soaking time at these temperatures for all molten steels was 10 minutes, then they were cooled down to steel pouring temperatures. Steel was poured into dry green sand molds. The HTT parameters are based on previous studies on the selection and evaluation of HTT schedules for molten steel to improve its structure and properties.

To analyze the chemical composition of steel, we applied a spectral method.

### 4. Effect of high temperature treatment on the structure and properties of the castings

The structure of cast steel 150KhNM (Figure 1) consists of granular pearlite and thin cementite network, as well as carbide inclusions. It consists of a pearlite matrix and secondary cementite precipitated on boundaries of dendritic branches and primary grains of austenite as a network and coarse laminae growing from a boundary network inside dendritic branches. Eutectic carbide areas are formed between branches of dendrites. A ferrite skin is formed along the network and laminae of secondary carbide. Depending on the cooling rate below point A1, eutectoid austenite is transformed into lamellar pearlite or partially into lamellar pearlite and partially into granular pearlite. Steel is hypereutectoid [5, 11–21].

At overheating a volume of cementite decreases (Figure 2). A cementite network was almost completely dissolved (the matrix was broken) and became thin and broken. Grains became
significantly coarser. Granular pearlite transformed to lamellar pearlite. Overheating with nanosecond electromagnetic pulses: the structure consists of eutectic (a mechanical mixture of pearlite and carbides). Pearlite is ordinary. Dendrites grew in the direction to the anode, when treated with nanosecond electromagnetic pulses; therefore, solidification is directed to the anode. Alloyed carbides of a regular square type were formed due to the direction of crystallization.

Figure 1. Structure of cast steel 150KhNM that did not undergo HTT.

Figure 2. Structure of cast steel 150KhNM that underwent HTT.

Steel that underwent HTT has higher ductile properties, hardness decreased from 45 HRC to 31 HRC, by 1.4 times. Impact resistance increased by 1.4 times, from 4 J/cm² to 5.6 J/cm². Overheating contributes to the increase in ductile properties of steel.

5. Conclusion
This paper describes how high temperature treatment influences the structure and properties of the castings from steel grade 150KhNM. Optimum treatment schedules were developed to improve steel properties. It was found that the changed structure had influenced the mechanical properties of the castings under such treatment.

High temperature treatment contributes to the significant improvement of physical, chemical and casting properties of steel, as well as mechanical and strength parameters. It promotes lower inhomogeneity and better ordering of the structure in the castings.

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