Effect of External Integrated Treatment on the Structure and Properties of the Castings from Steel Grade 35L

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Abstract. The methods of influence of external physical and thermophysical factors on the cast steel structure formation are considered in the paper. High-temperature processing of the melt is an effective method of heat treatment. It improves a wide range of mechanical and operational properties of finished castings. The parameters of high-temperature treatment were established experimentally in the course of this study. Its influence on the structure and properties of 35L steel castings has been shown. The usage of a nanosecond electromagnetic pulse during the crystallization of a casting in the mold is a method of dynamic action on the metal liquid phase. The parameters of nanosecond electromagnetic pulse processing during crystallization were determined by the technical capabilities of the electromagnetic pulse generator.

The study of the properties and structure of samples cast from a melt processed by electromagnetic pulses confirms the improvement of the mechanical and operational properties of castings by improving the primary cast metal structure. The influence of metal overheating, nanosecond electromagnetic pulse, and temperature-time holding on the structure and mechanical properties of castings is revealed. The modes of thermal holding (final technological heat treatment of the metal) were determined experimentally using the method of differential scanning calorimetry. The paper presents the results of changes in improving the properties of cast products due to the use of optimal modes of external complex influences.

1. Introduction

Current development of the machine building industry is attributed to a higher quality of finished products and lower production costs. In current foundries an original structure of steel rarely satisfies the set requirements without additional treatment or any additional effects on manufacturing processes.

Presently, little attention is paid to improving the quality of steel by applying external treatment without using additional alloys or modifying elements.

Now, steelmakers use a variety of methods to improve the quality of steel by treating it at the solidification stage. Properties of finished steel may be early controlled at initial stages by external treatment of molten steel. By varying molten steel treatment schedules and methods, the structure and properties of steel may be changed within a broad range. Conventionally, researchers pay more attention particularly to the second stage, namely a search for optimum solidification conditions. Attempts of treating steel at the melting stage are limited to additional alloying, modifying and refining processes only to optimize the composition, while little attention is paid to applying additional external treatment without using additional elements. Alloying and modifying elements introduced into molten steel often entail not
only positive, but also negative side effects: many elements adversely affect steel, while increasing the cost. External physical and thermophysical treatment of molten steel contributes to a significant increase in properties of steel, avoiding impurities, characteristic of alloying and modifying. At this stage external treatment is very efficient, but less often used. It does not contain the elements producing detrimental effect and has low cost.

A method of dynamic effect on a liquid phase of molten steel at the solidification stage was applied in practice to produce castings. One of the treatment methods of solidifying molten steel is electromagnetic pulse. The application of high voltage nano- and subnanosecond pulses constantly expands due to development of, and reduction of prices for tools for their generation [1–6].

Many processing methods applied on cast steel in a solidification process are widely used to control and prevent defects in a steelmaking process. Dynamic methods are based on a principle of the forced physical effect on a liquid phase during solidification. Usually these methods not only actively effect heat and mass transfer in a liquid phase, but also considerably change the nature of processes in a two-phase zone [2, 3–9].

As for the well-known methods of external heat, physical and thermophysical treatment, steelmakers use high temperature treatment of molten steel, treatment with electromagnetic pulse and thermal effect on solid steel [4].

2. Research procedure

High temperature treatment (HTT) includes heating steel up to the specified temperature, soaking at such temperature within a definite period and cooling down to casting temperature. The structure of molten steel is homogenized entailing an increase in a range of various parameters and quality of castings [5, 6].

In this paper, HTT is used as preliminary treatment of steel to prepare it for solidification driven by nanosecond electromagnetic pulse (NEMP).

Molten steel heating temperature is determined by studying the ways of changing physical properties of liquid alloys under heat effect and the relations between the structure formation and a liquid state of molten steel. Critical temperature is the temperature when molten steel is in a homogeneous state. The homogeneous state is responsible for the lack of hysteresis in molten steel, when measuring structure-sensitive properties, and the lack of large cluster groups. Such high temperature structure of molten steel is well overcooled. We manage to decrease concentrations of impurities, such as oxygen and nitrogen, directly in molten steel. Consequently, the amount of added reducing agents and non-metallic inclusions decrease due to favorable conditions for their removal. Critical temperature for steel grade 35L, when molten steel is in a disordered state, is calculated by applying a rule of mixtures and determining relative shares of structural components of molten steel [7, 8].

A share of a disordered zone is calculated by the equation:

\[
\psi_{\text{dis}} = A \cdot \exp \left[ \frac{\Delta H_{\text{dis}}}{RT} \right] = 0.5, \tag{1}
\]

where \(\psi_{\text{dis}}\) is a share of a disordered zone in molten steel; \(A\) is an empirical coefficient, which is individual for every molten steel; \(\Delta H_{\text{dis}}\) is thermal effect of complete thermal disorder of clusters in liquid, kJ/mol; \(R\) is absolute gas constant, J/(mol·K); \(T\) is actual temperature, K.

Critical heating temperature, when a disorder level is 0.5 is calculated by the equation:

\[
T_{\text{dis}} = \frac{\Delta H_{\text{dis}}}{R \ln A - \ln 0.5} = 1870, ^{\circ}\text{C}. \tag{2}
\]

Critical heating temperature of steel grade 35L is 1870°C. An alloy melting process was adjusted in the Foundry Laboratory of the NMSTU Department of Casting Processes and Materials Science, applying a 60 kg medium-frequency induction crucible furnace with a basic magnesite lining. This furnace was used to melt steel grade 35L, having a chemical
composition under GOST 977–88, wt. %: C is 0.32 – 0.4; Si is 0.2 – 0.52; Mn is 0.45 – 0.9; S is up to 0.06; P is up to 0.06.

When melting steel, after adding and melting of all burden components, molten steel was heated up to 1870–1880 °C. Soaking time at such temperatures during all the experiments was 10 minutes, then molten steel was cooled down to pouring temperature. Soaking time at maximum temperature was calculated based on the results of previous tests. Steel was poured into dry green sand molds.

Molten steel was treated with NEMP directly in green sand molds. Having cast molten steel into the mold, we supplied NEMP through graphite electrodes contacting molten steel. Electromagnetic pulse effected until complete solidification of steel in the mold. The diagram of the unit is given in Figure 1. Then the castings underwent temperature-time treatment.

NEMP parameters: pulse time is 0.5 ns; amplitude is 10 kV; pulse frequency is 1000 Hz.

Temperature-time soaking (TTS) of steel is heat treatment, when short thermal effect is produced on steel in a solid state. Steel was heated up to a set temperature, when structural phase transformations began. To avoid complete phase transformation processes and to fix a definite modified structure after TTS, we applied multiple repeated short cycles of thermal effect under equal conditions. A number of repeated similar operations of thermal effect on the alloy and cooling conditions were determined by experiment.

Temperature-time soaking is based on the pearlite-austenite phase transformation. Pearlite grain sizes depend on the sizes of inherited austenite grains. The larger austenite grains, the larger pearlite grains, as a rule (Figure 2). Austenite grains grow during heating only (they do not become smaller during subsequent cooling); therefore, maximum heating temperature of steel in an austenite state and its inherited grain size determines a final grain size. TTS is aimed at forming a highly dispersed structure due to grain refinement in an austenite area [9, 10–17].
To determine and fix temperatures of beginning phase transitions, we applied a thermal analysis representing a differential scanning calorimetry (DSC) method.

![Figure 3. DSC curve of steel 35L.](image)

Within a temperature range of 747 °C–776 °C there is an area characterized by a nucleation period of a new phase. The existing carbides are dissolved and crystallization centers of a new phase (austenite) nucleate. Minimum peak at 760 °C is attributed to maximum formation speed of new crystallization centers.

Steel samples were placed in the furnace preliminary treated up to 760 °C. Casting heating temperature was calculated according to the method suggested by A. P. Gulyaev to determine heating time for a total volume of various products in various media subject to their location in the furnace. Heating time for all the samples is 20 minutes. The samples were cooled in water. The number of treatment cycles, being three under equal conditions, is determined by experiment [10–11, 18–23].

3. Effect of integrated treatment on steel 35L
Medium-carbon cast steel 35L, which did not undergo heat treatment, has a ferrite-pearlite structure, including a Widmanstätten (oriented) distribution of ferrite and a ferrite network along boundaries of former austenite grains. A pearlite to ferrite ratio is 35/65 %. There are minor (insignificant) dendritic areas. The structure has 4–5 points of the Widmanstätten pattern under GOST 5640–68. Minimum and maximum sizes of structural components for the casting samples are from 0.1 µm to 130 µm. Pearlite points is 8–10 (Figure 4).

A structure of sample b that underwent NEMP and HTT also has a ferrite and pearlite structure. It is characterized by the near absence of the ferrite network. Grain number changed from 6–7 to 4–5. Highly-dispersive lamellar pearlite (3–4 points) changed to granular pearlite (1 point). Minimum and maximum sizes of structural components for the steel samples that underwent HTT are from 0.1 µm to 9 µm. (Table 1).

| Sample       | Pearlite points | Pearlite to ferrite ratio | Grain number | Interlamellar spacing | Structural inclusion sizes, µm |
|--------------|-----------------|----------------------------|--------------|-----------------------|-------------------------------|
| Cast         | 6–7             | 75/25–85/15                | over 1       | 1.0–1.2 µm            | 0.1–30                        |
| Integrated treatment | granular, 1     | 85/15                      | 4–5          | grain diameter is up to 0.25 µm | 0.1–9                         |
Figure 4. a) cast sample; b) sample that underwent integrated treatment.

Table 2 shows mechanical properties of the samples.

| Samples                        | Cast     | Integrated treatment |
|--------------------------------|----------|----------------------|
| Hardness, HB                   | 185      | 285                  |
| Tensile strength $\sigma_{uts}$, MPa | 620      | 950                  |
| Wear resistance, Kw            | 1.32     | 1.68                 |
| Impact strength, KCV           | 11       | 11                   |

4. Findings

The steel structure changes significantly under the integrated effect. We noted a significant recrystallization of the structural components. A new finely dispersed and uniform structure is characterized by a total absence of the Widmanstätten pattern; the ferrite network is almost completely dissolved. Lamellar pearlite was fully transformed to granular pearlite. Consequently, hardness of the castings increases by 54 %. Due to a new uniform, fine-grain structure hardness increases by 53 %.

When applying temperature-time soaking, wear resistance in the castings increases by 27 %, impact strength does not show a significant change (Figures 5, 6).

High temperature treatment applied during melting and nanosecond electromagnetic pulse at the crystallization stage of molten steel and subsequent time and temperature soaking contribute to a better microstructure of the castings in general, resulting in a higher quality of the castings without additional alloying elements and complex high temperature heat treatment in a solid phase.
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5. Conclusion
This paper:
- determines main parameters of molten steel 35L and critical temperature of its heating during HTT, and soaking time,
- describes the effect of high temperature treatment on the structure and properties of the castings from steel grade 35L and the relevant process,
- studies the effect of NEMP on the casting structure and properties; describes the developed process of its application, while molten steel is crystallizing, and
- sets schedules of time and temperature treatment as an option of high temperature tempering of steel.

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