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INFLUENCE OF MELTING UNIT TYPE ON THE PROPERTIES OF MIDDLE-CARBON CAST STEEL

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ABSTRACT

Influence of the employed type of the melting unit on the quality of the cast middle-carbon steel has been considered in the article. It has been found out that the electric arc heating of the melt in a direct current furnace allows obtaining a higher level of mechanical and technological properties by contrast with the induction furnace melting. Analysis of the electromagnetic forces acting on melts during electric arc melting has shown that the vibrational pressure produced herewith effectively acts on the melt volume elements and homogenizes it in composition. The results of the work can find application in the production of castings from middle-carbon steels under conditions of the machine-building production.

Keywords: middle-carbon cast steel, induction furnace, electric arc furnace, electromagnetic forces, mechanical properties.

INTRODUCTION

The steel smelting process is always reduced to the processing of raw materials (iron, scrap) in order to obtain a liquid product with the defined temperature and chemical composition. The main task is to achieve the required temperature, since pouring the metal into the mold requires overheating the melt over the melting point by 25 ... 50°C. But the obtainment of a given chemical composition is also not an easy task because its implementation depends on the type of the melting unit where steel is made. In addition, the used melting unit also affects the final quality of the produced steels [1]. The correct selection of a melting unit, the rational management of the smelting and the optimal selection of charge can help reduce costs.

Non-metallic inclusions have a great impact on the quality of produced steel. As a general rule, the main source of non-metallic inclusions in melts during the smelting are the oven gases [2]. Its composition depends on the type of melting unit: in the electric furnaces it is close to the composition of the air atmosphere, in fuel melting furnaces it is determined by the fuel composition, the burning regime and the amount of air supplied for combustion of fuel.

In comparison with gas furnaces, in electric furnaces it is possible to obtain cleaner alloys. Electric furnaces are characterized by higher performance, less metal oxidation, insignificant absorption of gases by the melt, good mixing, etc. In foundry production for steelmaking either induction furnaces (IF) or electric arc furnaces (EAF) are used most often. In recent years direct current electric arc furnaces (DC-EAF) have been widely used.

Another source of non-metallic inclusions is the furnace lining, regardless of the source of heating [3]. The resistance of linings, and consequently the tendency to the melt contamination, is mainly determined by the chemical interaction between them, since the changes resulting from this interaction are so large that they significantly alter the refractory's ability to resist all other impacts [4]. Especially intensive destruction of the lining can occur at thermo-temporal treatment (high-temperature holding) of melts [5], which in recent years has become widespread in foundries at production of many non-ferrous and ferrous metals and alloys [6].

Along with the foregoing regularities of melting processes, the physical principle of charge materials heating and melting realized in the corresponding melting unit also can influence the quality of the obtained alloys [7]. Earlier it has been confirmed that the type of melting unit affects the casting defects formation, which is associated with a change in the gas content of alloys [8]. We assume that the technological and mechanical properties of alloys melted in DC-EAF can differ significantly from those of the alloys melted in IF which may be due to the role of electromagnetic forces in melting processes.

The purpose of this work is to compare the quality of AISI 1035 middle-carbon steel (by mechanical and technological properties) produced in electric furnaces of various types.

MATERIALS AND METHODS

In this work we investigated the properties of AISI 1035 carbon steel (UNS G10350), which was melted in an induction furnace IF-0.06 and in direct current electric arc furnace DC-EAF-0.06. In both cases, the basic lining has been used and the charge weight was 60 kg.

As charge material pig alloy 1035 has been used. The temperature mode of melting in both furnaces has been 1550 ... 1560 °C. The resulting melt has been deoxidized with aluminum to have its content of 0.03 ...

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0.05% at the end of the melting. Aluminum has been fed into the ladle before pouring into the molds. The pouring temperature of the samples (26 mm in diameter, 300 mm in length) in the sand form has been 1530 ± 5 °C.

The chemical composition of the steel samples has been determined using an X-ray fluorescence spectrometer ARL Advant'X (Thermo Scientific, USA). The nitrogen content has been determined by the apparatus METAVAK (Russia).

The alloys fluidity has been determined by a test rod of 5 mm in diameter that has been cast into the steel mold. The mechanical properties of the alloys have been determined on the standard samples with a working diameter of 10 mm on the electronic universal testing machine WDW-100E (China). The hardness has been determined by the Brinell method on an automated universal hardness tester Wolpert 930M (Netherlands). When investigating the properties and characteristics of the experimental alloys in the course of direct measurements, the arithmetical average and confidence span of the obtained values of the measured quantity have been calculated for each series of experiments.

RESULTS AND DISCUSSIONS

Chemical composition and properties of the smelted steels have been given in Tables 1 and 2. The obtained results showed that the content of nitrogen in steel AISI 1035 differs insignificantly depending on the type of the melting unit, but the investigated properties definitely show that steel melted in an arc furnace, compared to the induction furnace, has an increased fluidity value, significantly higher hardness, ultimate tensile strength, but lower plasticity.

This phenomenon can be explained by the following. In induction melting, the electric current and the magnetic field vary sinusoidally with the same circular frequency (ω). Electromagnetic forces act on the molten metal elementary volume

$$P_{\text{em}} = \frac{1}{2} I_{\max} \cdot B_{\max} \cdot \sin \omega t \cdot \sin(\omega t + \varphi), \quad (1)$$

where $I_{\max}$, $B_{\max}$ – the maximum values of the electric current intensity and magnetic induction, respectively; t is the time; φ is the phase angle between $I_{\max}$ and $B_{\max}$. Transforming the products of sines into (1), we obtain

$$P_{\text{em}} = \frac{1}{2} I_{\max} \cdot B_{\max} \cdot \cos \varphi - \frac{1}{2} I_{\max} B_{\max} \cdot \cos(2\omega t + \varphi) \quad (2)$$

The first term in the equation (2) determines the time constant component of the electromagnetic force (P_{em}) creating a hydraulic thrust load and causing the metal forced convection during melting. This force reaches its maximum value $P_{\text{em}\max} = 0{,}5 \cdot I_{\max} B_{\max}$ at $\varphi = 0$ and equals zero at $\varphi = \pi / 2$. The second term determines the alternating force component, causing mechanical vibrations of doubled frequency in metal that are analogous to vibrational oscillations.

In arc melting, the pulsating forces acting on the elements of the liquid metal volume have a different nature. It has been established that heteronymous atoms have positive or negative charges in solid and liquid solutions and are converted into ions. So, in iron-carbon alloys, carbon has a positive charge of +3 or +4. All the impurities forming interstitial solutions in γ- and α-modifications (P, H, B, N) in steels and cast iron have the same charge. The impurities forming the substitution solutions (Cr, Mn, Si, V, Ni, etc.) also carry a positive or a negative charge, depending on the value of their electro negativity with respect to the iron atom.

The resultant axial force acts on the metal during melting in the DC-EAF at the base of the arc

$$F = k \cdot I_{a\max}^2, \quad (3)$$

where $I_{a\max}$ is the maximum electric arc current, k is the proportionality coefficient. The electric current of the arc (I_a) makes forced oscillations:

$$I_a = I_{a\max} \sin(\omega t + \varphi), \quad (4)$$

where φ is the angle of phase shift between the current and the voltage.

The alternating force $F_{\omega} = kI_{a\max}^2 \cdot \sin^2(\omega t + \varphi)$, which leads to a periodic displacement of the ions, acts on the charged ions of all impurities from the side of the alternating current (4)

$$X = X_{\max} \sin(\omega t + \varphi + \alpha), \quad (5)$$

where $X_{\max}$ is the maximum displacement of the ion; α is the phase shift between the displacement of the particle and the force acting on it from the side of the electric current.

Table-1. Chemical composition of steel AISI 1035 depending on the used melting unit.

Type of the furnace	Composition, wt. %								
	C	Mn	Si	S	P	Cr	Ni	[N]	Fe
IF	0,37	0,68	0,35	0,021	0,020	0,04	0,06	$4{,}4 \cdot 10^{-3}$	bal.
DC-EAF	0,32	0,71	0,39	0,029	0,15	0,06	0,06	$4{,}8 \cdot 10^{-3}$	bal.

Table-2. Mechanical properties and fluidity of steel AISI 1035 depending on the used melting unit.

Type of the furnace	Λ, mm	UTS, MPa	Yield strength, MPa	δ, %	ψ, %	HB
IF	180 ± 5	530 ± 8	300 ± 7	8 ± 0.4	15 ± 0.8	183 ± 2
DC-EAF	200 ± 6	630 ± 12	340 ± 9	5 ± 0.3	13 ± 1.2	245 ± 3

In addition, the vibrational force (F_v) arising through the interruption of the arch or a sudden change of the electrical parameters acts on the metal in the region of the arc. This vibrational force doesn't possess periodic nature, but it can be expanded in a Fourier series

$$F_v = \frac{\alpha_0}{2} + \sum_{n=1}^{\infty} A_n \sin(n\omega t + \varphi_n), \quad (6)$$

where $A_n = (a_n{}^2 + b_n{}^2)^{1/2}$ is the amplitude in the of the metal volume oscillations; $\varphi_n = \text{arctg}(a_n / b_n)$.

The coefficients a_n and b_n are determined by Euler's formulas:

$$a_n = \left(\frac{2}{T}\right)\int_{-T/2}^{T/2} F_в(t)\cdot \cos n\omega t dt,$$

(n = 0, 1, 2,…);

$$b_n = \left(\frac{2}{T}\right)\int_{-T/2}^{T/2} F_в(t)\cdot \sin n\omega t dt,$$

(n = 0, 1, 2,…);

where T is the period of the fundamental oscillation.

Expanding $F_v(t)$ on the harmonic components, we can find the vibrational pressure from each harmonic component per element of the liquid metal volume

$$P_i = (A_n{}^2 \cdot \omega^2)\cdot \rho_m / 2, \quad (7)$$

where ρ_m is the metal density.

The periodic displacement of impurity ions (5) and the vibrational pressure (7) lead to the destruction of clusters or the liquid steel microscopic in homogeneities at a usual melting temperature. The arc melting metal is almost completely homogenized in composition. The powerful forces (3) and (6) do not act on the metal in the induction furnace during the smelting period, the cluster nature of the liquid is transferred to the ingot or casting during the crystallization that leads to the difference of the technological and mechanical properties of the arc and induction melting alloys with the same chemical composition.

Carrying out the melt temperature treatment in the arc furnace according to the optimum processing modes will further promote the intensification of homogenization process, and it will significantly reduce the bad heredity of the low-grade charge materials in the induction furnace and also obtain a more homogeneous melt.

CONCLUSIONS

a) It has been shown that the type of the used melting unit influences the quality of the produced steels.
b) The property level of castings from the steel AISI 1035 melted in the arc furnace is higher than from the steel obtained in the induction furnace.
c) The theoretical substantiation of the observed effect of increasing steel properties during arc melting, related to the emergence of the vibration pressure on the elements of the melt volume under the influence of electromagnetic forces has been proposed.
d) Carrying out melting in the arc furnace promotes more intensive melt homogenization that makes it possible to improve the quality of steels obtained from low-grade charging materials.

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