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The Role of the Slag Phase in the Regulation of Thermal Processes During Steel Processing in a Ladle Furnace

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Abstract

The development of out-of-furnace steelmaking technologies opens up new opportunities for improving the energy efficiency of steelmaking. This paper discusses the impact of the slag regime during ladle furnace steelmaking on the process energy consumption and heat balance of the system. The thermodynamic and kinetic aspects of the slag-metal interaction, the heat transfer characteristics, and the influence of energy resources on the refining process are reviewed. The role of slag in the processes of electric arc combustion and heat loss, as well as its influence on the final quality of the steel are analyzed. Optimal parameters of the slag regime are proposed to minimize energy consumption and improve metal refining. Ensuring an optimal slag regime during the steelmaking and finishing process helps to reduce the content of non-metallic inclusions, which is critical to improving the durability and reliability of railway wheels and rails. This, in turn, helps to reduce the cost of maintaining railway infrastructure and improve the safety of rolling stock
KEY WORDS: *out-of-furnace steel treatment; ladle-furnace unit; slag mode; steel desulphurization; energy efficiency; heat exchange; heat loss*

1. Introduction

The development of out-of-furnace steel finishing equipment began in the 1960s and has evolved significantly since then, opening up new opportunities for energy savings and efficiency improvements in steelmaking. In modern metallurgical production, steel finishing offers unique opportunities to combine individual elements of the steelmaking and casting process into a single energy- and resource-saving complex.

An important task in creating an energy-saving cycle is to integrate the steelmaking and casting processes in the face of a decrease in the metal's enthalpy due to heat losses during transport and processing of the steel in the ladle furnace. One of the possible ways forward is the use of new materials and technologies that can reduce energy costs by reducing heat losses and improving the overall energy efficiency of production.

In addition, research into the automation and intellectualization of steel processing units outside the furnace can significantly improve processes and reduce the number of deviations in the quality of final products. Thus, the development of new technologies, improvement of automation and intellectualization of processes can provide a significant improvement in the quality and efficiency of out-of-furnace steel treatment, particularly in terms of energy saving and thermal characteristics and the overall efficiency of out-of-furnace steel treatment [1, 2].

2. Influence of Slag Cover Thickness on Process Energy Efficiency

The rate of formation of liquid refining slag from solid slag forming materials is an important parameter of the ladle furnace unit that directly affects the efficiency of the steel desulfurization process [3]. The faster the formation of a liquid slag with an optimal composition, the more efficient the metal purification processes. Studies [4] show that steelmaking slags synthesized in the reactor can maintain their liquid state for 2-4 hours, making them suitable for effective use in out-of-furnace metal treatment processes. A truncated steel ladle lined with chamotte was used as an experimental slag reactor.

Paper [5] presents the results of studies of the rate of refining slag formation in a 120-ton ladle during the processing of silicon deoxidized steel. The amount of slag in the ladle was determined from the actual weight of slag forming additives, and the amount of furnace slag entering the ladle was calculated from changes in the chemical composition of the ladle slag before and after the addition of additives and deoxidizers. It was found that the desulfurization efficiency depends not only on the chemical composition of the slag, but also on its quantity (multiplicity), which is determined by the mass of slag forming additives. However, according to [3], the dissolution of slag forming materials is accompanied by heat consumption, which reduces the technical and economic performance of the ladle furnace unit. In practice, the slag multiplicity is usually 2.0-3.5, and its further increase is impractical due to significant heat losses.

According to the literature [3, 6], the optimum amount of liquid synthetic slag for deep desulfurization of steel should be 3-5 % by weight of the metal. Such a regime allows achieving a desulfurization rate of 30-70% in the process of melt release. In addition, during electric arc heating in a ladle furnace installation, it is important to ensure the optimal slag layer thickness, which affects the stability of the arc burning and reduces heat losses to the environment.

Studies [7, 8] show that for an arc length of 160 mm, the maximum slag layer thickness should not exceed 195 mm. If heating is short term and desulfurization is not required, the slag thickness should be approximately 1.5 arc lengths. If the slag thickness exceeds 1.6-1.8 arc lengths, some of the current will flow through the slag rather than through the arcs and molten metal, resulting in excessive overheating of the slag and additional heat loss.

In 2011, the Central Energy Laboratory of PJSC DMZ developed recommendations for the arc length and operating voltage level for the VAI Fuchs ladle furnace, which are shown in Table. These recommendations also define the calculated values of the optimal thickness of the slag cover to ensure effective thermal interaction between the arc and the molten metal. Due to the fact that heating takes place mainly in the first voltage stage of the furnace transformer, the optimum slag thickness in the ladle under CCM conditions should be 140 mm [7]

Table

The recommended ratio of slag cover thickness to arc length

Operating voltage level	Arc length, mm	Slag layer thickness, mm		
		min.	optimal	max.
1	114	90	140	180
2	104	80	125	170
3	96	77	115	150
4	89	70	107	140
5	75	60	90	120
6	62	50	75	100

According to research by VAI Fuchs, the thickness of the slag layer should be 20% greater than the arc length to ensure optimal arc burning conditions. The main factor in this requirement is the uneven distribution of the slag layer thickness on the surface of the molten metal [9].

The authors also determined the required flux mass for different conditions of actual slag formation during metal processing in a ladle furnace (LF). The chemical composition of the slag during the period of metal finishing in the ladle furnace and the influence of its individual components on the thermal stability of the ladle slag coating were studied. It was found that the MgO content in the slag during melting under industrial conditions does not fall below 8.0%. Such a content provides a sufficient level of protection of the ladle lining against wear and makes it possible to dispense with the use of magnesium powder in the application of refining slag [7].

Intensive ionization and dissociation of oxides contained in slag, metal or in the melting process takes place in the arc burning zone. The high temperature and energy of the arc contribute to the decomposition of oxides into their constituent elements. For example, iron monoxide (FeO) can dissociate into iron (Fe) and molecular oxygen (O2) [10].

Several authors have already analyzed the equilibrium of some two- and multi-component systems [11-14]. The authors of [12, 13] analyzed the thermodynamic probability of the formation of complex oxide compounds with the participation of silica using the selected system CaO-MgO-Al2O3-SiO2. The data analysis showed that during the out-of-furnace treatment of steel in the CCM, at a slag temperature of 1800-1900 K, only monosilicates and orthosilicates of calcium (CaO-SiO2, 2CaO-SiO2), silicate (3CaO-SiO2), forsterite (2MgO-SiO2), mullite (3Al2O3-2SiO2), dioxide (CaO-MgO-SiO2), anorthite (CaO-Al2O3-2SiO2), and gelenite (2CaO-Al2O3-SiO2). The formation of mullite and anorthite was found to be thermodynamically preferable.

In order to control the slag composition and to slow down the transition of silicon to metal during the out-of-furnace treatment in the CCM of OJSC AMK, when its content in steel increases rapidly, magnesite powder is added to the refining slag. In the arc furnace zone, at temperatures above 2200°C, silicon can act as a magnesium reducing agent. Thus, when magnesite is introduced into the arc furnace, silicon dissolved in metal or reduced from silica is consumed to reduce magnesium from MgO [10, 15-17].

It is known [3] that basic slags have a high electrical conductivity, with CaO increasing it, while SiO2 and Al2O3 decrease it. As the thickness of the slag layer increases, part of the electric current is conducted through the slag rather than through the arc and molten metal. This results in intense heating of the slag. At a certain layer thickness, its temperature can reach 1800-1900 °C, which slows down the heating of the metal, even if electricity is constantly supplied. In this case, the rate of heating of the metal is greatly reduced despite the continuous supply of electricity, and is carried out only by mixing with the slag.

The thickness of the slag layer also affects the carburization of the metal. With a thin slag layer, the metal absorbs carbon from the electrodes at a rate of about 2.0-2.5 ppm/min. However, if the slag thickness increases significantly beyond the arc length, negative effects can occur that affect the thermal regime of the melt [6]. In addition, the thickness of the slag layer determines the degree of gas saturation of the steel. Fig. 1 shows the dependence of nitrogen absorption by metal on the thickness of the slag layer [7]. The data show that when the slag layer thickness is less than 40 mm, nitrogen absorption increases sharply, which can have a negative effect on steel quality.

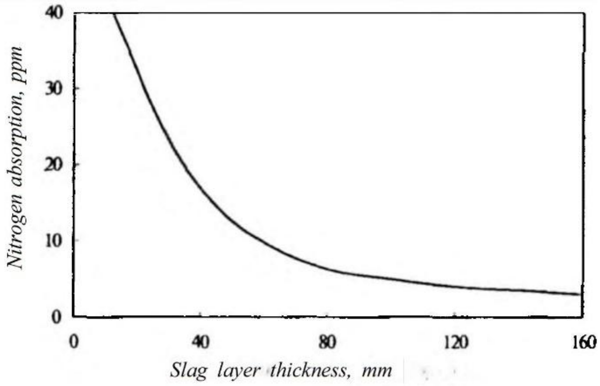

Fig. 1 Dependence of nitrogen absorption by metal on slag layer thickness [3]

According to the authors' research [7, 8], to ensure process efficiency with a thin slag layer, it is recommended to operate at reduced heating levels. This will optimize energy consumption and prevent excessive overheating of the system. Fig. 2 shows the dependence of slag layer thickness and arc length on the active power supplied to the ladle furnace.

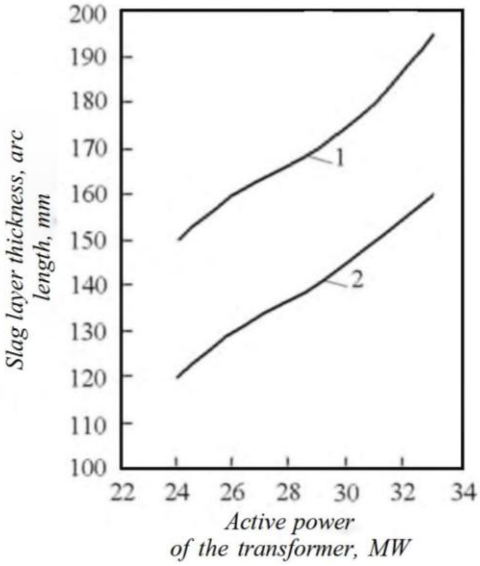

Fig. 2 Dependence of the electric arc length and slag layer thickness on the active power of the ladle-furnace transformer: *1* – slag layer thickness; *2* – arc length [6]

It should be noted from the above data that for the efficient operation of the unit, the thickness of the slag layer should be 20-25% greater than the arc length, which is also confirmed by the authors of [18].

Therefore, when treating steel in a ladle furnace using electrodes, the thickness of the slag layer depends not only on the desulphurization requirements of the steel, but also on the arc length.

3. Conclusions

The study analyzed the effect of the slag regime on steel quality during ladle furnace treatment. It was found that controlling the composition and properties of the slag phase is a key factor in reducing non-metallic inclusions and ensuring the required physical and chemical parameters of the steel.

The results of numerical modeling and experimental studies have shown that optimization of slag basicity and refining additives helps to reduce sulfur and oxygen content in the metal. The dynamics of changes in the oxidation potential of the slag, which directly affects the carbon balance and degassing processes, has been studied.

The proposed recommendations for the management of the slag regime make it possible to increase the efficiency of the metallurgical process, reduce the consumption of alloying materials and improve the quality characteristics of the steel. Application of the obtained results in industrial conditions will help to improve energy efficiency and environmental safety of production. Therefore, optimization of the out-of-furnace steel treatment technology is an important area for ensuring the reliability and durability of railway infrastructure, which is of strategic importance for transport and the economy as a whole.

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