Resource Saving Design of High Resistible Lining of a Teeming Ladle

L S Molchanov¹, B M Boichenko² and Ye V Synehin²

¹Department of Steel Metallurgy, Institute of Ferrous Metallurgy named after Z. I. Nekrasov National Academy of Science of Ukraine, 1, Akademika Starodubova Square, Dnipro, 49050, Ukraine
²Department of Steel Metallurgy, National Metallurgical Academy of Ukraine, 4, Gagarina Ave., Dnipro, 49600, Ukraine

E-mail: Sinegin.ev@gmail.com

Abstract. It is described in the article a process of erosive destruction of teeming ladle lining. Special attention is paid to erosion by metal jet during tapping from melting furnace, for example BOF or EAF. This phenomena lead to steel contamination by non-metallic inclusions (NI). In case the steelmaking plant does not have any opportunity to remove NI from steel, for example argon blowing or electromagnetic stirring, a significant part of them remains in steel. Authors have proposed a lining design of teeming ladle, which alter a flow pattern in a way to move NI up. To confirm this hypothesis authors have developed a methodology of “water” modelling and high-temperature modelling with use of fusible metal. As a result of experiment topography of lining destruction for traditional and developed lining design has been achieved. An efficiency of developed lining design has been confirmed.

1. Introduction

Modern metallurgical production provides for the proceeding of complex technological operations to obtain the necessary properties of metal products. Refining of liquid steel proceeds under various physical and chemical conditions, that significantly increases the role of teeming ladle. The most significant design of metallurgical ladles affect the quality of metal melt directly after smelting, especially if operations of blowing with neutral gas in the ladle are excluded from the production cycle. That worsens significantly the conditions for NI removing from the melt, especially at the finishing stages of steel production [1–5].

The interaction of the metal melt with the lining in the casting ladle is based on two physical processes: hydrodynamic destruction of the lining by fluid flows and the ascent of NI in a liquid medium.

It is well known that NI significantly affect the quality of metal products. The removal of NI from steel occurs due to the action of Archimedes force and the convective metal flows. For NI of small size, the influence of convection prevails, and for large ones – Archimedes force [6]. This process can be intensified by increasing the speed of the upward flows of the melt using blowing or electromagnetic stirring. However, the use of these technological operations for ladles of small capacity is practical because of the significant heat losses and the risk of drawing slag inclusions from the coating slag back into the metal when argon is blown [7–9]. Electromagnetic processing requires significant capital
expenditures for its implementation [10, 11]. Therefore, an alternative technologically expedient method of refining steel from NI is the exposure of the molten metal in the ladle.

The floating of a single NI in a liquid metal melt is described by the Stokes law. However, for a number of reasons, including the intensive movement of flows caused by the tapping of steel from a furnace, the Stokes law is violated [12, 13]. The study of the floating of a NI ensemble in the melt by computer and mathematical modeling is extremely difficult. The best option for this purpose is physical modeling. The aim of the study is to carry out a physical simulation to determine the characteristics of the floating of an ensemble of NI in liquid steel and define the design of lining to intensify removal of NI.

2. Goals of research
At previous stages of research, it was defined that a shape change of the working space of the ladle significantly affects the removal efficiency of NI [14]. At the same time, the influence of the defined rational parameters of the working space of the teeming ladle on the hydrodynamic destruction are not established. Thus, the goal of this study is to determine the influence of geometrical parameters of the teeming ladles lining on the hydrodynamic features of the interaction of refractory materials with high-temperature metallurgical melts (slags and metals).

3. Methodology of research
The study of the hydrodynamic features of the interaction of the teeming ladle lining with metallurgical melts was based on the use of the π-theorem [15–19] and included two stages: cold modeling and high-temperature modeling using liquid tin (99.5 % Sn).

Mechanical or erosive destruction of the lining by a jet of liquid metal is the most intensive in the bottom area of the ladle at the beginning of steel tapping from a furnace. It is obvious that the jet impulse plays a significant role in the destruction, the value of which depends on the acceleration of gravity $g$, the volumetric flow rate $q$, the fluid density $\rho$ and the length of the jet $h$. As the parameter that characterizes the resistance of the refractory to erosion destruction, its strength $\sigma$ was assumed. Destruction rate of the refractory is described by the mass flow $m$, which indicates the weight of the refractory material separated from the lining surface during its contact with the jet. Generalized formula is follow:

$$m = f (g, q, \rho, h, \sigma).$$

The similarity numbers obtained by the Markov method [15] are given in Table 1. Magnitude of most of them is close to zero, which testifies of their adequacy.

| Parameter | Magnitude | Unit | Base unit | Similarity number | Magnitude |
|-----------|-----------|------|-----------|------------------|-----------|
| $m$       | $10^{-2}$ | [kg·m$^2$·sec$^{-1}$] | -         | $\pi_1 = \frac{m}{\rho \cdot \sqrt{g \cdot h}}$ | $10^{-7}$ |
| $\sigma$  | $10^4$    | [kg·m$^{-1}$·sec$^{-2}$] | -         | $\pi_2 = \frac{\sigma}{\rho \cdot g \cdot h}$ | $10^{-1}$ |
| $\rho$    | $10^3$    | [kg·m$^{-3}$] | [kg]      | -                | -         |
| $g$       | $10^1$    | [m·sec$^{-1}$] | [sec]     | -                | -         |
| $h$       | $10^0$    | [m]           | [m]       | -                | -         |
| $q$       | $10^{-1}$ | [m$^3$·sec$^{-1}$] | -         | $\pi_3 = \frac{q}{\sqrt{g \cdot h}}$ | $10^{-3}$ |

Table 1. Similarity numbers for describing erosive wear of refractories.
In Table 2 the calculated scales of the selected parameters were shown. The experiment included a series of 5 consecutive fillings for a ladle model with a traditional lining and a developed one. These designs of ladle lining design are presented in Figure 1.

The operating the lining of teeming ladles during the experiment was as close as possible to industrial conditions (according to the research conditions, the drop height of the metal jet and the duration of the liquid flow were controlled).

**Table 2.** The values of the parameters for the model and nature, their scale and the domain of selected similarity numbers.

| Parameters and similarity numbers | Original | Model     | Scale |
|----------------------------------|----------|-----------|-------|
| Mass flow \(m\) [kg·m\(^{-2}\)·sec\(^{-1}\)] | 1,5·10\(^{-2}\) | 4,15·10\(^{-4}\) | 1:36   |
| Strength of refractory \(\sigma\) [kg·m\(^{-1}\)·sec\(^{-2}\)] | 40000 | 221 | 1:181 |
| Fluid density \(\rho\) [kg·m\(^{-3}\)] | 7200 | 1000 | 1:7,2 |
| Length of the jet \(h\) [m] | 3…4 | 0,12…0,16 | 1:25   |
| Volumetric flow rate \(q\) [m\(^3\)·sec\(^{-1}\)] | 58…77 | 0,018…0,024 | 1:3182 |
| \(\pi\) \(_1\) | 3,3·10\(^{-7}\)…3,8·10\(^{-7}\) | - |
| \(\pi\) \(_2\) | 0,1…0,2 | - |
| \(\pi\) \(_3\) | 5,8·10\(^{-4}\)…1,2·10\(^{-3}\) | - |

In order to simulate the lining of teeming ladle with calculated strength (see Table 2), a sandy-clay mixture was used for low-temperature modeling in a ratio of 21:5 (at high temperature, mortar MMK-72 [20] after drying and thermal strengthening and heating to 400 °C), which was formed into a ladle in a wet state. Lining drying was carried out naturally by holding for 10 days at a temperature of 28…30 °C.

**Figure 1.** Sketch of teeming ladles lining: a – traditional design; b – developed design; without brackets, the values for “water” modeling are given, and in brackets for high-temperature modeling.

The study of the process of erosion destruction of the teeming ladle lining was carried out according to the following methodology. After filling the ladle with liquid, it was held for 2…3 minutes, after which the water was drained through the upper edge of the ladle. Each campaign of the lining of the teeming ladle model assumed a consistent acceptance of 5 heats. In order to eliminate errors in the implementation of the experiment, each experiment was repeated 5 times.

At the end of each experiment in the series, a mechanical scanning of the surface of the lining of the teeming ladle model was performed. The measurement accuracy was 0.1 mm.

In order to obtain the detailed map of lining wear during the operation of teeming ladle, its surface was cut by four planes (Figure 2) passing through the vertical axis of the ladle model (planes...
I-I, II-II; III-III; IV-IV). There were also 5 points in the bottom part of the bucket along the line of intersection of each of the planes: 0 is a center of the bottom part (a place where the jet falls) 1 is 25% of the bottom part radius; 2 is 50% of the bottom part radius; 3 is 75% of the radius of the bottom part and 4 is 100% of the radius of the bottom part. Along the projection of each of the planes on the side surface of the walls of the lining 5 points were distinguished: 0’ is the junction of the bottom and the walls of the ladle; 1’ is 25% of the height of the working space of the ladle; 2’ is 50% of the height of the working space of the ladle; 3’ is 75% of the height of the ladle working space and 4’ is 100% of the height of the ladle working space.

Figure 2. Scheme of topography of the wear of the teeming ladle lining during the “water” simulation: a) the horizontal projection; b) vertical projection on the half-plane I-0.

The high-temperature modeling of destruction of the teeming ladles lining a contamination level of the metal melt with NI were also determined, for which samples of the melt after melting and filling and holding of tin were taken in each series of experiments. The obtained samples were analyzed by using metallographic methods of analysis. Determining the nature of the origin of NI was carried out by X-ray analysis, which allowed determining their mineralogical compound.

4. Results of studies
The results of studies of the hydrodynamic destruction of the teeming ladle lining during operation and the influence of the lining design on this process are presented in Figure 3. During the research, a detailed topography of the erosional destruction of the steel-teeming ladles in the process of operation for the standard design and optimized was obtained (Figure 3). Thus, in the case of the use of the linings of both structures, considerable wear is observed along the O-II line, due to the peculiarities of the experiment (liquid was drained along this line simulated melt after filling).

It can be seen in the Figure 3 a, c, the significant erosion destruction of traditional design of lining to almost ½ the height of the working space of the ladle, which is caused by considerable turbulization of melt flows. Due to this, the energy of the fluid flow is significantly increased, destroying the lining. The average rate of the bottom destruction when “water” modeling was 0.73 mm per melt, and when high-temperature modeling it was 1.41 mm per melt.

In the case of using the developed lining design (Figure 3b, d), the turbulence of the flows decreases, which leads to a decrease in the destruction rate. On the topography of the destruction, it can be observed as a decrease in the total destruction area of the lining by ¼ of the ladle height. The average destruction rate for “water” modeling was 0.59 mm per melt, and for high-temperature modeling it was 1.14 mm per melt.

As a result of research, it was established that the application developed lining design makes it possible to decrease the destruction rate of the lining by 18.1% (according to “water” modeling) and by 17.2% (according to high-temperature modeling).

A study of samples of tin taken during high-temperature modeling made it possible to determine that contamination of the melt with NI decreases by 35.3% when using the developed design of the ladle lining in comparison with the traditional. The X-ray analysis of the samples let to determine the presence of NI of the Al₂O₃ – SiO₂ system.
Figure 3. Topography of lining wear on the ladle model (legend’s colored markers show the depth of wear in millimeters): a) the traditional design of lining after “water” modeling; b) developed design of lining after “water” modeling; c) the traditional design of lining after high-temperature modeling; d) developed design of lining after high-temperature modeling.
5. Summary
A complex physical modeling of the influence of the geometrical parameters of the working space of the teeming ladle on the destruction of the lining was carried out. The efficiency of the developed lining design for teeming ladles has been confirmed. The use of the proposed lining design allows increasing the life of refractories by 17.2%, and to increase the purity of the metal by 35.3%.

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