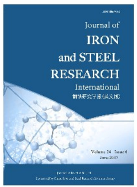
Journal of Iron and Steel Research, International 24 (2017) 579−585

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn



Effect of slag composition on steel cleanliness in interstitial-free steel

Rui Wang[1], Yan-ping Bao[1,*], Yi-hong Li[2], Tai-quan Li[3], Di Chen[3]

[1] State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China
[2] School of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, Shanxi, China
[3] Handan Iron & Steel Group Co., Ltd. of HBIS, Handan 056000, Hebei, China

ARTICLE INFO

Key words:
IF steel
Ladle slag
Reoxidation
Inclusion
Holding process

ABSTRACT

Ladle slag affects steel cleanliness at the end of the Ruhrstahl-Hereaeus (RH) and holding process. The relationship between composition of ladle slag, total oxygen (TO) and inclusions was investigated using X-ray fluorescence (XRF), infrared absorption, and SEM+EDS methods. The results indicate that TO in steel at the end of RH increases linearly with increasing FeO content in slag. TO is lower when $w_{\mathrm{CaO}}/w_{\mathrm{Al_2O_3}}$ (C/A)=1.5−2.0 than that of C/A=1.0−1.4 under an approximate content of FeO. During the holding process, irregular Al_2O_3 inclusions are newly generated due to slag reoxidation. Additionally, Al_2O_3-Ti_xO inclusions are newly generated in the steel when the content of FeO is higher. By combining experimental and thermodynamic calculation results, it is determined that the slag has a good melting property within the zone of C/A=1.2−1.8 and adsorption capacity of Al_2O_3 when the content of SiO_2 in slag is controlled at 4%−6%. The increase in the C/A ratio and the decrease of FeO content in slag can slow down the reoxidation rate.

Symbol List

R_d—Absorption capacity of slag;
K—Mass transfer coefficient related to melting point, $\mu m\cdot s^{-1}$;
C_s—Saturation fraction of Al_2O_3 in slag, wt.%;
C_b—Real mass fraction of Al_2O_3 in slag, wt.%;
J_S—Diffusion flux of FeO in slag, $mol\cdot cm^{-2}\cdot s^{-1}$;
J_M—Diffusion flux of FeO in steel, $mol\cdot cm^{-2}\cdot s^{-1}$;
k_S—Mass transfer coefficient of FeO in slag, $cm\cdot s^{-1}$;
k_M—Mass transfer coefficient of FeO in steel, $cm\cdot s^{-1}$;
$c(\mathrm{FeO})$—Concentration of FeO in slag, $mol\cdot cm^{-3}$;
$c(\mathrm{FeO})^i$—Concentration of FeO at steel/slag interface, $mol\cdot cm^{-3}$;
$c[\mathrm{O}]$—Concentration of [O] in steel, $mol\cdot cm^{-3}$;
$c[\mathrm{O}]^i$—Concentration of [O] at steel/slag interface, $mol\cdot cm^{-3}$.

1. Introduction

In recent years, with the development of automobile industry, the growth of market demand for high quality steel for deep drawing is predictable. Due to excellent deep drawability, interstitial-free (IF) steel is widely used in automobile industry[1,2]. However, silver defects in cold sheets often emerge. Several studies[3-5] have shown that large Al_2O_3 inclusions and mold slags entrapped in steel are the main reasons for the formation of defects.

The general process of producing IF steel is as follows: BOF (basic oxygen furnace)→RH (Ruhrstahl-Hereaeus)→Holding process→CC (continuous casting). Thus, some converter slag with a high FeO content enters into the ladle during tapping. This slag accompanies steel in ladle during the RH and holding process, and steel becomes contaminated with oxidizing slag if ladle slag is not modified. In Nippon Steel, the TFe (total Fe) content of ladle slag is reduced below 4% by adding a modifier after tapping in IF steel, and the surface defects of cold-rolled sheets are reduced by 1/6 compared with a conventional process[6]. From the testing results of NKK (Nippon Kokan), the index of surface defects is decreased by 80% after deoxidizing of ladle slag[7]. The study by Sun and Mori[8] showed that more alumina inclusions were generated in the metal bath for slag with a higher FeO or MnO content and metal with a lower aluminum content and the restrictive step of

---

* Corresponding author. Prof., Ph.D.
E-mail address: *baoyp@ustb.edu.cn* (*Y. P. Bao*).

Received 21 September 2016; Received in revised form 11 December 2016; Accepted 15 December 2016
Available online 15 June 2017

reoxidation of $[\mathrm{Al}]_s$ is the diffusion of $[\mathrm{Al}]_s$ in steel or diffusion of (FeO) in slag. Lee et al.[9] found that the reoxidation rate increased linearly with increasing TFe content in the case of TFe content higher than 1.5 wt.%, and it decreased with increasing the $w_{\mathrm{CaO}}/w_{\mathrm{Al_2O_3}}$ (C/A) ratio of the slag for a given TFe content.

The modification of ladle slag was performed not only to decrease the content of FeO but also to control the proper ratio of C/A to ensure the absorption capacity of Al_2O_3. Yoon et al.[10] found that controlling the C/A ratio is the most efficient method for removing inclusions from bearing steels, and its value was most effective at 1.7—1.8. The total oxygen (TO) can be reduced from $(10-12)\times10^{-6}$ to $(5-8)\times10^{-6}$. However, the content of FeO was very low in refining slag during bearing steel production. In Kawasaki Steel[11], through the modification of slag in ultra-low carbon steel production, it was found that slag had good absorption capacity of Al_2O_3 by controlling the C/A ratio from 1.2 to 1.8.

All above-mentioned studies showed that the control over the content of FeO and C/A ratio is the key during the production. However, there is a lack of theoretical description to explain why the steel cleanliness is improved by controlling slag composition. Additionally, the content of SiO_2 is not mentioned in any of the above-mentioned studies, but it affects the melting property and absorption capacity of Al_2O_3. In this paper, the effect of the content of SiO_2 and FeO as well as C/A ratio on steel cleanliness and steel reoxidation was investigated.

2. Production Process and Experimental Method

2.1. Production process

The process adopted to produce IF steel is as follows: 280 t BOF → RH → Holding process → CC. During tapping, an amount of lime is added into the ladle, and slag deoxidant is added onto the slag. The RH vacuum treatment includes decarburization, followed by aluminum deoxidation, then Ti-Fe alloying and keeping the RH circulation time for 8 min. After the RH treatment, molten steel remains unstirred in the ladle for 30—40 min before casting.

2.2. Experimental method

In total, 10 experimental heats were carried out. The difference between the two processes was the amount of deoxidant addition. In Process A, the added amount was more than that in Process B. The addition of lime during tapping of different heats is shown in Table 1. Slag and steel samples were collected at the end of the RH process of each heat. For Heat 2, Heat 3, Heat 4, and Heat 6, steel samples were collected at 5, 10, and 15 min of holding time.

Table 1

Addition of lime for each experiment

Process	Heat No.	CaO/kg
A	1	800
	2	800
	3	500
	4	500
	5	500
B	6	800
	7	800
	8	800
	9	500
	10	500

The initial oxygen activities before deoxidation of ten experimental heats were measured.

The total oxygen content of steel samples was analyzed using the infrared absorption method. Steel composition was analyzed via the ICP-AES method. Slag composition was analyzed using an X-ray fluorescence spectrometer. The characterization of inclusions was observed and analyzed using scanning electron microscopy (SEM) and an energy-dispersive X-ray spectrometer (EDS). The samples from two heats were observed at 100 locations with 3000 times magnification using SEM to obtain the inclusion type, quantity, and size.

3. Results and Discussion

3.1. Steel and slag compositions

Table 2 shows the slag composition of 10 heats. The content of FeO in Process A is lower than that in Process B, and the ratio of C/A varies due to different amouts of lime addition. TFe (Fe^{2+} and Fe^{3+}) and SiO_2 are main reducible oxides, and TFe can be treated as FeO[12].

The content of MgO is steadily controlled at approximately 5%. However, the content of SiO_2 fluctuates from 2% to 9%, and the effect of SiO_2 content on slag property will be discussed in the following section.

Table 3 provides steel composition at the end of RH

Table 2

Slag composition in each heat (wt.%)

Heat No.	CaO	FeO	SiO_2	MgO	MnO	Al_2O_3	C/A
1	40.0	15.9	4.1	5.1	2.1	26.3	1.5
2	42.3	13.5	7.2	5.0	2.4	27.6	1.5
3	34.7	13.5	3.1	4.9	2.9	35.9	1.0
4	38.2	13.5	6.1	4.6	2.5	32.1	1.2
5	39.3	14.8	6.3	4.6	2.6	32.1	1.2
6	37.9	24.9	2.7	5.7	2.4	21.9	1.7
7	41.1	20.1	4.9	4.1	2.2	19.6	2.0
8	39.8	21.1	8.6	4.6	2.0	21.1	1.9
9	36.3	19.8	3.4	5.0	2.2	28.9	1.3
10	36.4	18.1	4.9	4.2	2.8	29.1	1.3