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Castability of Aluminum- and Sulfur-bearing Free-cutting Steel

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Abstract: Submerged entry nozzle (SEN) blockage is one of the main problems during continuous casting of Al and S-containing steel, which has a negative effect on the smooth production and product quality. The blockage deposits mainly consisted of $MgO\cdot Al_2O_3$ spinel, calcium sulfide, or (and) high-melting-point calcium aluminate. To understand completely the formation behavior of non-metallic inclusions and provide an optimization direction for improving castability, thermodynamic discussions on the generation characteristic of non-metallic inclusions before liquid steel flow through SEN were conducted. In addition, an industrial trial comprising of 10 heats made on five casting sequences was performed, including not only Al- and S-containing free-cutting steel, but also a medium-carbon Al-killed steel and a high-carbon Al-deoxidized steel. It was found that inclusions transferred into the $MgO\cdot Al_2O_3$ spinel from pure Al_2O_3 and complex inclusions during vacuum degassing (VD) treatment. Two kinds of $MgO\cdot Al_2O_3$ spinel inclusions were observed in the VD-treated steel. One is fine homogeneous inclusion of 1–2 μm in diameter, and the other is 10 μm-sized heterogeneous inclusions, which consisted of an Al_2O_3 core surrounded by a spinel coating. It was suggested that the former was generated from the mutual combination of fine MgO and Al_2O_3 particles produced from the erosion of the refractory materials during the VD process, and the latter was considered to be generated from the local reduction of large residual Al_2O_3 particles by soluble [Mg] provided by the decomposition of MgO in the ladle line during VD treatment. It was also discovered that CaS mainly results from steel-slag desulfurization during soft stirring.

Key words: free-cutting steel; nozzle clogging; thermodynamics; inclusion; castability; CaS; spinel

The requirements of the machining industry promoted the development of free-cutting steel[1-3], especially Al- and S-bearing structural steel. Al is usually used as a deoxidizer for high-quality structural steel. Soluble Al remaining in liquid steel can restrict the growth of the grain during rolling and heat-treatment, enhancing the toughness index of steel products[4-6]. Meanwhile, for improving machinability, S is often added into liquid steel[3,7,8]. Because liquid steel contains Al and S, non-metallic inclusions like Al_2O_3 and CaS are easily formed in steel. $MgO\cdot Al_2O_3$ spinel is also usually formed if the refractory is heavily corroded[9,10], and has a negative effect on castability and product quality. For low sulfur and Al-killed steel, Ca treatment is an effective and widely used method to transform Al_2O_3 and sulfide particles to less harmful inclusions[11,12]. However, for sulfur-containing and Al-killed steel, inclusion control is very difficult because of the shrink and even disappearance of the inclusion “liquid window” after Ca treatment[13]. Therefore, Al- and S-bearing steel always have poor castability. To improve castability, a suitable refining slag with a high absorption ability for Al_2O_3 was designed, and a soft stirring operation was optimized by the authors[14]. The number of continuous casting heats of a single tundish was increased successfully from 1–2 to 4. However, deposition of high-melting-point inclusions on the submerged entry nozzle (SEN) inner wall is always observed if refining operations fluctuates lightly.

The main purpose of this study is to determine the essential reason for the poor castability of Al and S bearing steel, and to provide guidance on how to enhance the continuous casting stability. In this study, a theoretical analysis using the thermodynamic software FactSage and plant experiments were conducted.

1 Plant Experiment

1.1 Description of industrial trials

Al- and S-bearing steel (AS Steel), a medium-carbon Al-killed steel (MCA Steel), and a high-carbon Al-deoxidized steel (HCA Steel) were selected as the experimental steel grades. The nominal chemical compositions of these steels are given in Table 1. The [S] (square bracket denotes an element dissolved in the steel melt throughout the article) content of the AS steel was controlled to 0.05–0.15 mass% and the [Al] content of the three steels was controlled to 0.02–0.05 mass%. Both had an analogous refining process: tapping with Al-deoxidation and slag washing→ladle refining (LF)→vacuum degassing (VD) treatment→sulfur injection (only for AS Steel) and soft stirring→continuous casting. A detailed description of the refining procedure is given elsewhere[14]. An industrial trial comprising of 10 heats

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performed on five casting sequences was conducted. The trials were called T1, T2, …, T5, according to the different casting sequences. T1, T2, and T3 were trials for AS steel, and T4 and T5 were for MCA and HCA steel, respectively. A drastic writhing of the slag surface and even exposure of liquid steel were observed during the soft stirring process of T1, T2, T4, and T5, but was not be observed in T3.

Table 1 Nominal chemical composition of AS, MCA and HCA steel mass%

Steel	C	Si	Mn	P	S	Cr	Al
AS	0.30−0.45	0.30−0.70	1.40−1.60	<0.015	0.05−0.15	<0.20	0.02−0.05
MCA	0.42−0.50	0.17−0.37	0.50−0.80	<0.025	<0.025	<0.25	0.02−0.05
HCA	0.95−1.05	0.15−0.35	0.25−0.45	<0.025	<0.025	1.40−1.65	0.02−0.05

Note: Fe is in balance.

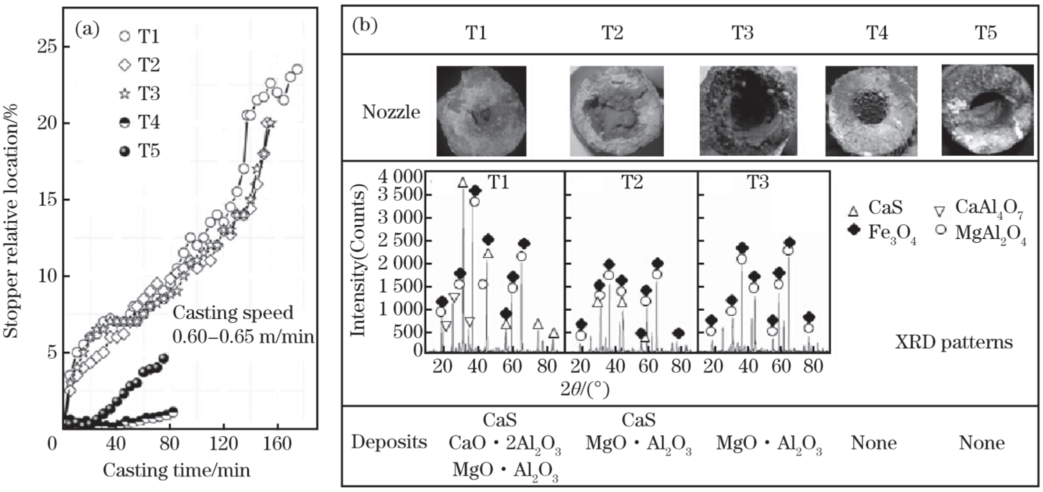
1.2 Sample schedule and analysis methodology

Molten steel and top slag samples were obtained before and after VD (before sulfur injection). The deposits on the inner wall of the SEN were detected by X-ray diffraction (XRD). A detailed description of the chemical analysis for steel and slag samples is given elsewhere[14]. Observation of non-metallic inclusions on the polished cross-sectional and fractured surface of the steel samples was accomplished using SEM coupled with EDS. In this work, the SEM working magnification was set as 1 000 and the minimum detectable inclusion was 1.0 μm in diameter.

2 Results

2.1 Castability

The change in the relative location of the stopper when the casting speed was kept constant can be treated as an index of the castability of steel. The larger the change, the poorer is the castability of steel[9]. Fig. 1(a) shows the curves of the relative stopper location, from which it is concluded that AS Steel has a much poorer castability compared to MCA and HCA Steel. Fig. 1(b) presents the corresponding photographs of the casted SEN. Nozzles for AS Steel were totally blocked by deposits, which were detected by XRD, and the results are shown in Fig. 1(b). It was believed that the blockage deposits mainly consisted of $MgO \cdot Al_2O_3$ spinel, CaS, or (and) $CaO \cdot 2Al_2O_3$. It is worth noting that blockage deposits excluded Fe_3O_4, which originated from the oxidization of leftover molten steel on the rough inner wall of SEN in the presence of air.



(a) Stopper relative location curves; (b) Nozzle photographs and detected result of deposits by XRD.

Fig. 1 Castability of the five casting sequences

2.2 Non-metallic inclusions

Fig. 2 exhibits the evolution of inclusions with respect to composition during VD treatment. Before VD, almost half of the inclusions were pure Al_2O_3 and the others were a high-melting-point complex Al_2O_3- SiO_2-CaO-(MnO). Both had a relatively large size of 10–20 μm in