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Role of vacuum on cleanliness improvement of steel during electroslag remelting

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ABSTRACT

To clarify the effect of vacuum on cleanliness of steel during electroslag remelting, the interaction between slag and steel under air, Ar and vacuum condition were investigated by laboratory experiments. The results show that the number, size and area fraction of inclusions decreases in the remelted steel. Compared with the steels remelted under air and Ar atmospheres, the inclusion number, size and area fraction of steel remelted under vacuum condition are lower because the steel surface oxidation is inhibited and the reaction of C and O to form CO gas in liquid steel is promoted under vacuum conditions. The removal of inclusions in the remelted steel contributes to the elimination of large carbides. Under vacuum condition, the highest desulphurization rate is acquired because the oxygen content is the lowest and the floating of the CO gas formed by C deoxidization speeds up mass transfer. Reduction of the white speckles resulted by S segregation is attributed to the sharp decrease of the S content. Compared with the steels remelted under air and Ar atmospheres, the steel remelted under vacuum shows the higher cleanliness.

1. Introduction

The harm of inclusions to steel has been widely reported, which can destroy the continuity of steel and become the sources of the cavities that grow with plastic deformation [1]. The formation of non-metallic inclusions is usually due to the slag entrapment, the spalling of the refractory materials, deoxidation and precipitation of sulfides and nitrides. The oxide inclusions adversely affect the fatigability, ductility, and toughness of steel [2–6]. Larger and elongated MnS inclusions have a remarkable influence on hydrogen-induced cracking (HIC) resistance and ductile fractures of steel [6–8]. Thus, it is significant for the quality improvement of steel to reduce the number and size of inclusions, the oxygen and sulfur contents.

Electroslag remelting (ESR) shows strong ability to remove inclusions and harmful element (S), and provides cooling condition for directional solidification [9–11]. Conventional ESR is carried out under air atmosphere, and it is difficult to reduce the oxygen content in the steel because of the severe electrode surface oxidation [12]. Although the inert gas shielding ESR can avoid electrode surface oxidation, it still could not deoxidize. A lot of researches focused on the deoxidizer addition such as Al or Ca have been carried out [13,14]. The lower oxygen content is acquired, but the amount of deoxidizer is difficult to be properly controlled and such deoxidation process also introduces new inclusions. ESR carried out under vacuum is expected to achieve a low oxygen content of ESR ingot. The application of vacuum in steelmaking industry has been studied in the past decades, which plays an important role in the production of high-grade steel [15–18]. The vacuum refining processes can assure the following benefits: hydrogen and nitrogen removal; low oxygen levels; decarburation for manufacture of ultra-low carbon unalloyed and alloyed steel; deep desulphurization by intensive mixing of molten steel and slag; decrease of oxide inclusions [16]. Currently, the application of vacuum in steelmaking process is mainly focused on RH [17,18]. To the authors' best knowledge, the mechanism of interaction between the slag and steel during ESR under vacuum has not been clarified and relevant reports are very scarce. The effect of vacuum on the cleanliness and the sulfur content of steel during ESR also has not been well studied. Because of these factors, in the present study, the inclusions and composition of steels remelted under distinct atmosphere were analyzed to investigate the mechanism of interaction between the slag and steel during ESR under vacuum.

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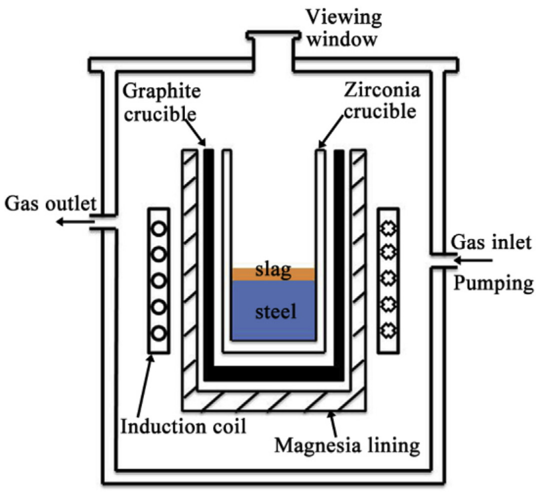

Fig. 1. Schematic diagram of experimental apparatus.

Table 1
Chemical composition of the steel used in present experiment (wt. %).

C	Si	Mn	Cr	Ni	V	Mo	S	T.O
0.379	0.838	0.346	3.96	0.146	0.80	1.17	0.0094	0.0057

2. Experiment

Three laboratory experiments were carried out at 1600 °C in high frequency vacuum induction furnace under air atmosphere, Ar atmosphere and vacuum condition, respectively. The experimental apparatus is shown as Fig. 1. The chemical composition of the steel used in present experiment was consistent with the composition of H13 die steel, which was sampled from a steel plant after the die casting, but before the ESR process. The chemical composition of steel is listed in Table 1, indicated as T0. The slag was pre-melted before the experiments and the composition determined by XRF was 33.4 wt% CaF_2-33.3 wt% CaO-33.3 wt% Al_2O_3. The zirconia crucible with an inner diameter of 40 mm and a height of 70 mm was used for the slag-steel interaction because of a comparatively slow dissolution rate in the fluoride based slag [19]. A layer of 0.3 mm thick molybdenum film was

Table 2
Statistical results of inclusions in steel samples.

Sample	Number of observed inclusions/mm^{-2}	Inclusion size/μm		Area fraction of inclusions to total area of observed view fields/%
		Max. Dia.	Ave. Dia.	
T0	324	13.51	2.11	0.179
T1	148	5.28	1.61	0.043
T2	146	4.72	1.59	0.036
T3	127	3.93	1.26	0.023

Table 3
Carbon, silicon, sulfur and oxygen contents in steel samples (wt.%).

Sample	C	Si	S	T.O
T0	0.379	0.838	0.0094	0.0057
T1	0.369	0.630	0.0012	0.0040
T2	0.371	0.689	0.0010	0.0032
T3	0.358	0.777	0.0007	0.0024

Table 4
The activity interaction parameters of elements in liquid steel at 1600 °C.

e_i^j i	C	Si	Mn	Cr	Ni	V	Mo	S
Si	0.18	0.11	0.002	−0.0003	0.005	0.025	–	0.056
C	0.14	0.08	−0.012	−0.024	0.012	−0.077	−0.0083	0.046

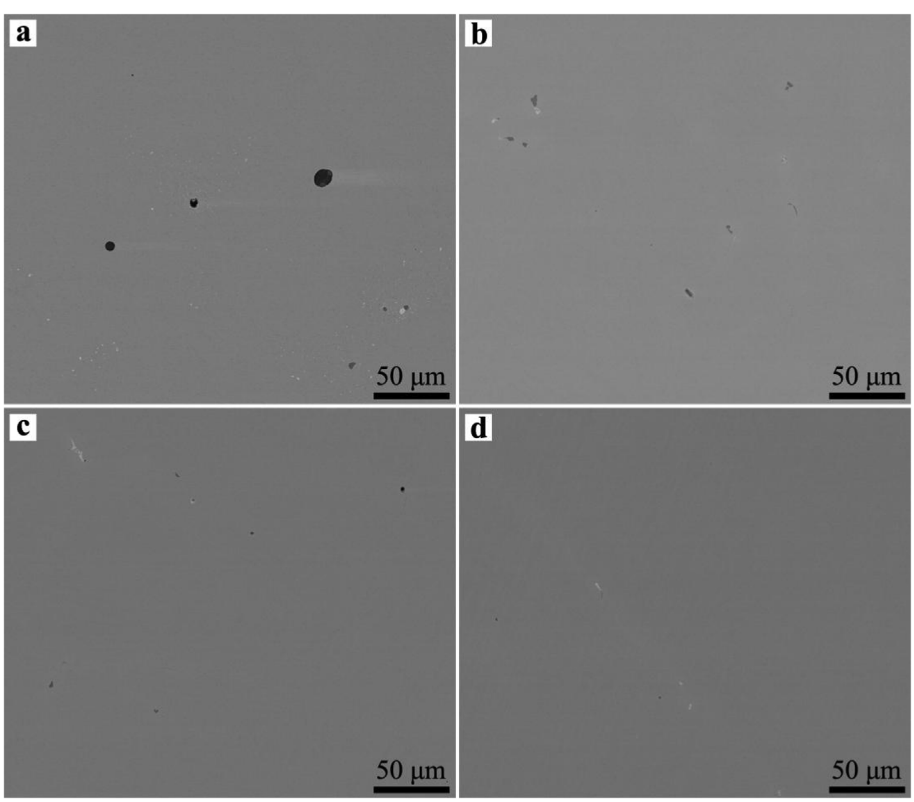

Fig. 2. SEM images of inclusions in four steel samples: (a) specimen T0-original steel, (b) specimen T1-air, (c) specimen T2-Ar, (d) specimen T3-vacuum.