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ISSN 0543-5846
METABK 57(1-2) 67-70 (2018)
UDC – UDK 669.15:669.85/.86:669.187:620.18:620.17=111

EFFECT OF Ce ON STAINLESS STEEL PERFORMANCE DURING ELECTROSLAG REMELTING (ESR)

Received – Primljeno: 2017-04-18
Accepted – Prihvaćeno: 2017-08-29
Original Scientific Paper – Izvorni znanstveni rad

Three electroslag remelting heats were carried out by using a 1-ton argon atmosphere ESR furnace under three kinds of slag containing different Ce_2O_3 content. Specimens were taken at electrode and each ingot for analyzing the inclusions by scanning electron microscope - energy dispersive spectrometer (SEM-EDS). After heat treatment, the tensile and impact of each steel product was measured to study the effect of Ce content on steel performance. The results show that the non-metallic inclusions content was largely reduced in each ingot compared with that in electrode, and the ingot containing 0,05 % Ce has the best steel cleanliness and performance, while the ingot containing 0,13 % Ce has the worst steel cleanliness and performance.

Key words: 1Cr17 steel, Ce element, ESR furnace, SEM-EDS, Mechanical property

INTRODUCTION

1Cr17 Ferritic stainless steel is used under the corrosive environment by virtue of its superior performance such as corrosion resistance, fatigue strength and wear resistance. With the increasing demand on toughness performance of 1Cr17 steel product, the Ce element was added into steel as it can improve the steel cleanliness and refine grain [1, 2]. As electroslag remelting (ESR) was the last steel product process of the 1Cr17 steel [3, 4], it is important to investigate the effect of slag and remelting process on Ce content control and steel performance during the ESR process.

Until today, research on the effects of rare earth element on steel performance is still continuing [5, 6]. Liu studied the effect of rare earth element on inclusions, and found the Re can promote the precipitation and refine the precipitated particles [7]. Song investigated the effect of La on the oxidation resistances of Ni-22Cr-14W-2Mo superalloy, and found that the alloy containing 0,026 % La has the best oxidation resistance at 1 100 °C [8].

As discussed above, there have been few studies to investigate the effect of slag and remelting process on Ce content control and steel performance during the ESR of 1Cr17 steel. The current work focused on steel cleanliness, Ce content control and its effect on performance of 1Cr17 steel during electroslag rememlting. In the present work, a 1-ton ESR furnace has been employed for providing Ce content control technique and finding a suitable way to produce 1Cr17 stainless steel with superior toughness performance.

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EXPERIMENTAL

Three experimental heats were carried out using a 1-ton argon atmosphere ESR furnace with 360 mm inner diameter of water cooled copper mold under 45 kg different slag listed in Table 1 (Exp.No.E1, E2 and E3). The consumable electrode material used in each heat was produced by the electrical arc furnace-ladle furnace-vacuum casting (EAF -LF-VD-DC) process, and its chemical composition is given in Table 2. The oxide layer of electrode, with a shape of 240 mm in diameter, was eliminated mechanically before electroslag remelting. In each heat, the voltage and input current were all kept at about 55 V, 7 500 A, respectively. The remelting rate is 300 kg·h^{-1} during the process of each heat. High-purity argon gas was introduced into the electroslag furnace through a gas inlet at a flow rate of 250 NL·min^{-1} for each experiment.

Table 1 **Chemical composition of slag / %**

Exp.	Slag	CaO	CaF_2	Al_2O_3	MgO	Ce_2O_3
E1	S1	8	66	16	10	0
E2	S2	8	60	12	5	15
E3	S3	8	48	12	5	27

Table 2 **Chemical composition of electrode used in experiments / %**

C	Si	Cr	Al	S	O	Ce
0,02	0,47	16,51	0,04	0,0014	0,0042	0,26

Table 3 **Element contents in each ingot**

Exp.No.	S/ ppm	O/ ppm	Ce/ %	Al_{Sol}/ %
E1	10	42	0	0,02
E2	8	39	0,05	0,04
E3	6	47	0,13	0,05

After the ESR experiment, the S, O, soluble Al (Al_{Sol}) and Ce contents at the top of each ingot were analyzed, and the results are listed in Table 3.

Four 15×15×15 mm metal samples cut from the consumable electrode (E0) and each ESR ingot were analyzed by metallographic microscope and SEM-EDS. In quantitative metallography, fifty view fields selected randomly and continuously in each metal sample were analyzed by an image analyzer (Image Plus 6.0). SEM-EDS was employed to determine the size, morphology and chemical composition of ten inclusions randomly selected in each metal sample, respectively.

In order to investigate the effect of Ce content in each ingot on 1Cr17 stainless steel product performance, the tensile and impact tests were employed after rolling and heat treatment of each ESR ingot. The process of heat treatment is normalizing at 800 °C for 60 min and then cooled in air.

RESULT AND DISCUSSION

Cleanliness and inclusion of ingot

As shown in Table 3, the slag has a large effect on sulfur, oxygen and Ce content in ESR ingot. It is clear that: (i) in the case of ESR under No.E1, the (S) in ingot would be reduced to 10 ppm compared with the 14 ppm sulfur content in the consumable electrode, the (O) in ingot is 42 ppm, and no rare earth element was analyzed in ingot; (ii) in the case of slag S2 containing 15 % Ce_2O_3 (No.E2), the (S) in ingot would be reduced to 8 ppm, the (O) in ingot is 39 ppm, and the Ce content is 0,05 %; (iii) in the case of slag S3 containing 27 % Ce_2O_3 (No.E3), the (S) in ingot would be reduced to 6 ppm, the (O) in ingot is 47 ppm, and the Ce content is 0,13 %. It can be concluded that the ingot remelting with slag S3 has the higher (O) content than others, and the slag containing high Ce_2O_3 content helps to desulphurization according to Equation (1).

$$(2Ce^{3+}+3O^{2-})+3(S)=(2Ce^{3+}+3S^{2-})+3(O) \qquad (1)$$

Table 4 shows the inclusion content analyzed by quantitative metallography in the electrode and each ESR ingot. It can be seen from Table 4 that S_a, the ratio of the area sum of all the inclusions to the total observed area, was significantly reduced after ESR compared with the electrode. The value of S_a is 0,25 % in consume electrode, 0,074 % in Exp.E1 ingot, 0,072 % in Exp.E2 and 0,079 % in Exp.E3 ingot, respectively. The maximum equivalent diameters of non-metallic inclusions analyzed in samples E0, E1, E2 and E3 are 18,5, 10,1, 9,3 and 10,2 μm, while the average equivalent diameters are 4,0, 2,9, 2,8 and 2,9 μm, respectively. It can be concluded that ingot containing 0,05 % Ce has the best steel cleanliness, and excessive Ce in ingot (0,13 % Ce in Exp.E3) can increase the inclusion content and lower the steel cleanliness.

Figure 1 is the distribution of non-metallic inclusions in electrode and each ESR ingot. It can be seen

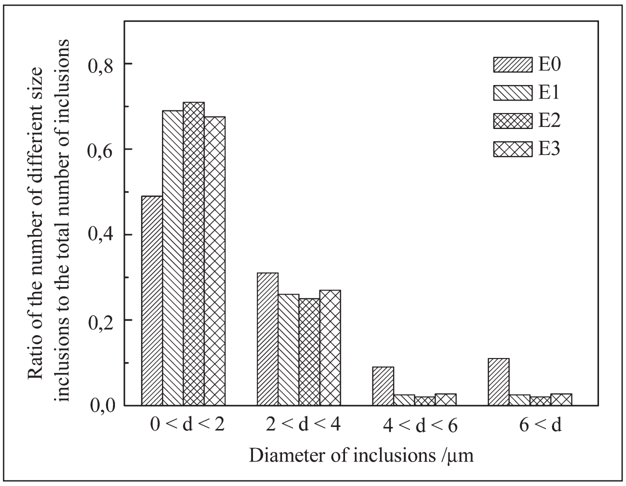

Figure 1 Distributions of inclusions in steel

that the small inclusions (< 2 μm) take up about 50 %, the inclusions of 2 - 4 μm take up about 30 % and the inclusions of larger than 4 μm take up about 20 % in the electrode. After electroslag remelting, in spite of different kinds of slag were employed, more than 65 % of non-metallic inclusions in each remelting ingot were smaller than 2 μm in size, and more than 95 % of non-metallic inclusions in ingot were smaller than 4 μm in size. Results from comparing the inclusions distribution reveal that appropriate Ce content in ingot can improve the distribution of inclusions.

Morphology and types of inclusions

As indispensable indicators of assessing steel cleanliness, the morphology, types, sizes and chemical compositions of inclusions were analyzed to investigate the effect of remelting conditions on steel cleanliness.

Figure 2 represents the SEM-EDS analysis results of typical non-metallic inclusions in the electrode and each ESR ingot. The typical inclusions observed in the consume electrode was $CeAlO_3$ inclusion, as shown in Figure 2a. The typical non-metallic inclusions observed in Exp.E1 ingot was Al_2O_3-MgO inclusion, as shown in Figure 2b. The typical non-metallic inclusions observed in Exp.E2 and E3 ingot were $CeAlO_3$ inclusion.

Thermodynamic analysis was employed to study the formation [9-10] of $CeAlO_3$ inclusion according to the Equation (2).

$$(Ce) + (Al_2O_3) = (CeAlO_3) + (Al) \qquad (2)$$

$$\Delta G_m^\Theta = 476009 - 274.50\ T \qquad (3)$$

$$-\Delta G_m^\Theta / RT = \ln \frac{a_{(CeAlO_3)} \cdot a_{(Al)}}{a_{(Al_2O_3)} \cdot a_{(Ce)}} = \ln \frac{w_{(Al)} \cdot f_{(Al)}}{w_{(Ce)} \cdot f_{(Ce)}} \qquad (4)$$

$$\lg f_i = \sum e_i^j w_j \qquad (5)$$

Where: f_i is the activity coefficients of i element in metal; e_i^j is the interaction parameters and can be obtained according to the reference [11].

If assuming the temperature of metal pool during ESR process ranges from 1 477 °C to 1 727 °C [12],

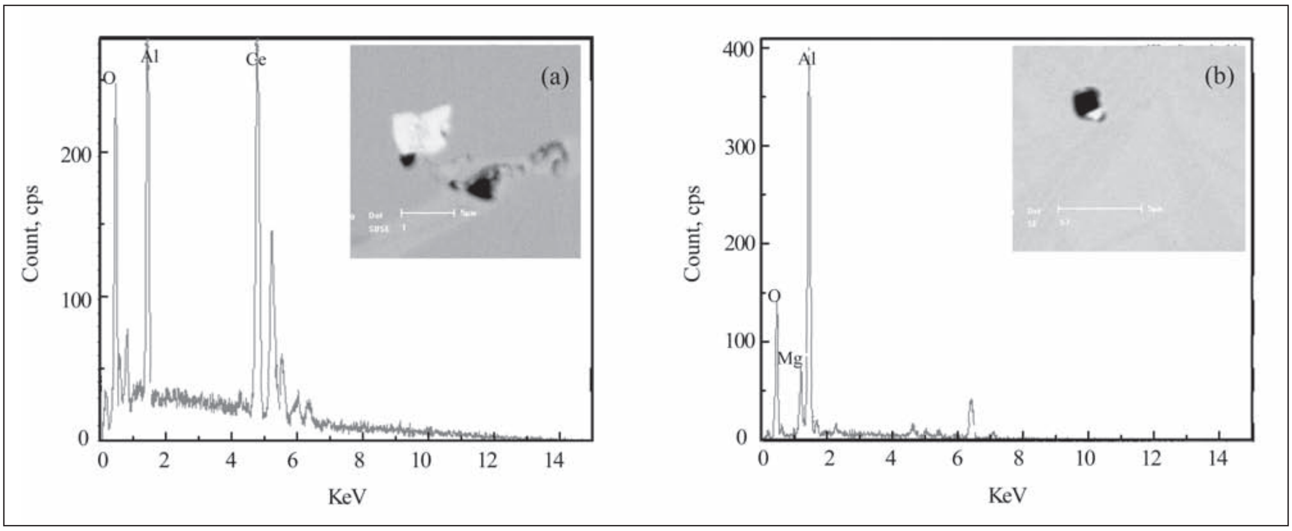

Figure 2 SEM images and EDS analysis results of typical inclusions

Table 4 **Quantitative metallography results of inclusions in the electrode and each ingot**

No.	S_a /%	Number of inclusions per mm[2]	Max equivalent diameter /μm	Average equivalent diameter /μm
E0	0,25	201	18,5	4,0
E1	0,074	115	10,1	2,9
E2	0,072	114	9,3	2,8
E3	0,079	118	10,2	2,9

stable diagram of $CeAlO_3/Al_2O_3$ can be obtained, as shown in Figure 3. With the increase of temperature, the $CeAlO_3$ inclusion becomes more stable. Thus, large numbers of $CeAlO_3$ inclusions can be observed in Exp. E2 and E3 ingot.

Mechanical properties of remelting ingot

As indispensable indexes of assessing 1Cr17 stainless steel product performance, the tensile and impact experiments were employed to analyze the effect of Ce content in steel product on steel performance.

As shown in Table 5, tensile strength (R_m), non-proportional extension strength ($R_{p0.2}$) and elongation (A%), impact energy (A_{KV}) were measured to assess the steel

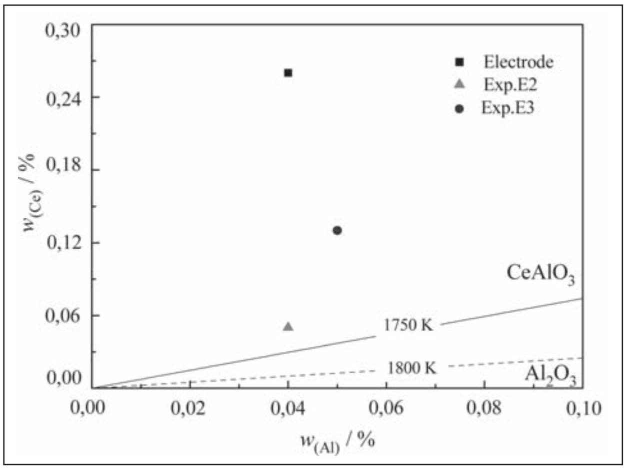

Figure 3 Diagrams of $CeAlO_3/Al_2O_3$ inclusions

Table 5 **Steel properties after heat treatment**

Exp. No.	R_m, MPa	$R_{p0.2}$, MPa	Elongation, A/%	Impact, A_{KV}/J
E1	482	294	36	38,7
E2	510	305	40	57,7
E3	470	288	33	24

performance. The results show that steel product containing 0,05 % Ce has the best steel performance of tensile and impact, and the steel product containing 0,13 % Ce has the worst steel performance of tensile and impact. It is clear that the ingot remelting with slag S2 not only has the lowest oxygen and inclusion content, but also has the best steel performance. Appropriate Ce content in steel can improve the steel cleanliness and performance, while excessive Ce content in steel would decrease the steel cleanliness and performance.

CONCLUSION

In order to improve the toughness performance of 1Cr17 stainless steel, the effects of slag on Ce content control, non-metallic inclusions and steel performance during ESR of 1Cr17 steel were studied. The results were as follows.

Large numbers of inclusions in electrode were eliminated after the ESR process, and the sulfur content in ingot decreases with the increase of Ce_2O_3 content in slag.

The Exp.E2 ingot containing 0,05 % Ce content has the lowest oxygen and inclusion content. The inclusions in Exp.E1 ingot was Al_2O_3-MgO, while in Exp.E2 and Exp.E3 ingot were $CeAlO_3$. Excessive Ce content in ingot can increase the oxygen and inclusion content, and lower the steel cleanliness.

1Cr17 stainless steel containing 0,05 % Ce content has the best steel performance of tensile and impact, while excessive Ce content in steel product can lower the steel performance.

Acknowledgments

This work is supported by the Young Teachers Educational Foundation of Fujian Province (No. JAT160488).

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Note: Responsible person for English translation Tao Yan, Da Tong Normal College, China