Effect of Transverse Static Magnetic Field on Droplets Transient and Inclusions Evolution During the Electroslag Remelting Process of GCr15 Ingots

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Abstract

The voltage was recorded to investigate the influence of the static magnetic field on droplet evolution during the magnetically controlled electroslag remelting (MC-ESR) process. MC-ESR experiments were carried out under different remelting current, and transverse static magnetic fields (TSMF) of 85 mT, 130 mT and 160 mT were superimposed. Statistical work was performed to obtain the quantitative data of the droplets. The ASPEX Explorer was utilized to investigate the inclusions evolution of GCr15 ingots. The number of the droplets was 31 in 20 s during the traditional ESR process and reached 50 and 51 under the MC-ESR process with the TSMF of 85 mT and 130 mT, respectively. When compared the traditional ESR process with the MC-ESR process, the inclusions amount reduced 67%.

Keywords Electroslag remelting · Static magnetic field · Droplet transient · Inclusions evolution · Electromagnetic vibration effect

1 Introduction

Nonmetallic inclusions remained in the alloy steel ingots or high-temperature alloy ingots will destroy the matrix's continuity and increase the risk of inducing microcracks under stress, which will reduce the mechanical properties and the service life of the products [1]. Gutman et al. [2, 3] studied that the nonmetallic inclusions can be removed efficiently by electroslag remelting (ESR) process. The sounder structure can be obtained during the fabrication of ingots [4, 5]. The ESR process has been widely used in many aspects such as functionally graded steel [6], high-speed steel [7] and metals with high reaction activity [8]. However, with the demands for huge ESR ingots, the ESR process still faces severe challenges. Low inclusion removal efficiency, oversized dendrites and macrosegregation are the three main factors have to be solved. These

flaws are mainly attributed to the low solidification rate [9]. Therefore, ideal alternative technologies are emergently required to produce huge steel ingots with high performance.

The application of an alternative magnetic field has attracted much attention during the last decades. It efficiently refines the solidified structure of alloy with the help of the induced Lorentz force in the molten alloy [10, 11]. Electromagnetic field has been considered as the most promising dominant method to control the heat, mass transfer and solidification process [12, 13]. Langenberg [14] described that an alternating magnetic field would influence the solidification process and refine the microstructure in the continuous casting production of alloy. Moreover, the rotating magnetic field has acted as an important way to promote the dendrite to turn to equiaxed grain during the solidification process of alloys, especially, during the casting of steel or aluminum alloys [15, 16]. Due to the strong shielding effect in the thick copper pipe which is used in the ESR furnace, it is not easy to introduce an alternative magnetic field into the ESR process. Traditionally, in the ESR process, 50 Hz alternating current is often used to melt the consumable electrode and slag; then, Lorentz force could be induced if a TSMF was introduced.

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Of importance here, there is no shielding effect generated in the copper pipe for the TSMF.

In the present paper, a novel concept named magnetically controlled electroslag remelting (MC-ESR) process has been proposed (Fig. 1a). Compared to the traditional ESR process, an alternating current with 50 Hz and a transverse static magnetic field (TSMF) have been applied during the ESR process. The induced Lorenz force in the molten slag pool, the metallic melting pool and the droplets influence the droplets transient and inclusions evolution remarkably. A physical mechanism is established to describe this process.

2 Experimental

The GCr15 Φ 25 mm $\times$ 700 mm consumable electrodes (the chemical compositions are listed in Table 1) were remelted by using a micro-ESR system with a TSMF as shown in Fig. 1a. The TSMF was provided by two groups of the NdFeB magnets. Each block of the NdFeB magnet had the size of 80 mm $\times$ 40 mm $\times$ 10 mm. By changing the number of the NdFeB magnets, the magnetic flux density in the air gap between the two grouped magnets could be tuned from 0 mT to 160 mT. The mold was made of copper and stainless steel. The inner diameter and height of the mold were 50 mm and 130 mm, respectively. The voltage between the consumable electrode and the bottom electrode was recorded by the device of ADVANTECH USB-4711A with a collection frequency of 1×10^6 Hz.

A circular iron base plate was fixed on the bottom electrode to protect the bottom copper electrode plate. The slag was made of 20% CaO, 20% Al₂O₃ and 60% CaF₂. The AC intensities in a range from 400 A to 800 A with a frequency of 50 Hz were introduced into the MC-ESR

Table 1 Chemical composition of the consumable electrode used in experiments (wt%)

C	Si	Mn	S	P	Cr	Al
0.980	0.025	0.367	0.011	0.032	1.39	0.023

process according to the previous research [17]. Two grouped magnets were located at the outside of the mold. Combined with the four different magnetic flux densities and 400 A remelting current, the MC-ESR experiments were carried out in the groups as listed in Table 2. Powder slag was melt by the Joule heat. Then, the liquid slag was used for melting the consumable electrode and offered a controlled molten metal pool. Finally, the ESR ingots with the diameter of 50 mm and height of 100 mm could be obtained.

ESR ingots were cut into two parts along the axial direction, and one of them was cut along the radial direction as shown in Fig. 1b. For the cross section profile analysis, the 10-mm-thick one was sampled and each sample was carefully grinded and polished. In detection analysis, ASPEX Explorer (manufactured by FEI) was used to observe and obtain the quantitative data of the non-metallic inclusions. The amounts of phosphorus element were measured by PMI-MASTER PRO portable spectrometer.

3 Results and Discussion

3.1 Droplets Transient Under Different Current Intensities

In order to understand how the TSMF influences the droplet transient during the MC-ESR process, it is necessary to do experiments without the TSMF for comparison. The experiments were carried out under the different remelting current intensities (400 A, 500 A, 600 A, 700 A and 800 A) without an external magnetic field. The continuous data of the voltage were recorded during the ESR process. The results showed a difference between the ESR process and the power current, which is shown in Fig. 2. Lots of peak values can be found. The peak value appeared at the moment when the droplet was separated from the tip of the consumable electrode.

To better explain the peak value, visualization of the droplet transient process was conducted as shown in Fig. 3a. The resistance between the consumable electrode tip and the melting pool was changed as the droplet appeared, reached its critical size and fell from the consumable electrode tip. The voltage data would change with

Fig. 1 **a** Schematic view of the ESR process under a static magnetic field (1—consumable electrode, 2—water-cool mold, 3—permanent magnets, 4—slag pool, 5—droplet, 6—metal pool, 7—ingot, 8—bottom copper electrode), **b** MC-ESR GCr15 ingot

Table 2 Remelting current and intensities of the TSMF conditions in experiments

Remelting current intensities (A)	Intensities of the external TSMF (mT)
400, 500, 600, 700 and 800	0, 85, 130 and 160

Fig. 2 Peak value of the voltage data during the ESR process **Fig. 3** **a** Visualization of the droplet transient, **b** peak value of the voltage during the ESR process

the change in resistance (Fig. 3b). Statistical work has been done by analyzing the voltage data to evaluate the amount of the droplets under different remelting current intensities as shown in Fig. 4. With the increase in the current intensity, the Joule heat produced by the molten slag increases. As a result, the number of the droplets increases.

3.2 Droplets Transient Under Different TSMF Intensities

The experiments were carried out under different intensities (0 mT, 85 mT, 130 mT and 160 mT) of the external TSMF when the remelting current was 400 A. Voltage data in 20 s were collected during the MC-ESR process, which is shown in Fig. 5.

For the traditional ESR process (Fig. 5a), the main feature is the high superheat of metal due to the high

Fig. 4 Number of the droplets under different remelting current intensities

Fig. 6 Number of droplets under different intensities of TSMF

Fig. 5 Voltage data in 20 s during the MC-ESR process: **a** 0 mT, **b** 85 mT, **c** 130 mT, **d** 160 mT

temperature of the molten slag. The temperature of the molten slag is usually 423–473 K higher than that in metallic melting pool [18], which resulting in a relatively low cooling speed during the solidification process [19]. The application of a TSMF caused significant positive changes to the droplets transient during the ESR process (Fig. 5b–d). After the application of 85 mT and 130 mT TSMF, the counts of the voltage peak are obviously increased (Fig. 5b, c). When the intensities of TSMF reached 160 mT, the frequency of the occurrence of voltage peak did not increase.

Statistical results of the number of droplets under different intensities of TSMF are shown in Fig. 6. During the traditional ESR process, 31 droplets were recorded in 20 s. The number reached 50 and 51 when the TSMF were 85 mT and 130 mT, respectively, under the MC-ESR process. When the intensities of TSMF reached 160 mT, 36 droplets were recorded in 20 s. The result showed that the number of droplets increased 66.7% when the

suitable TSMF was applied, and the remelting current kept the same.

The effort that increased the number of the droplets was stimulated by the effectiveness of the electromagnetic vibration caused by the interaction between the alternating current and the TSMF. The above phenomenon guides us a bright direction that it is possible to produce the ESR ingots quickly by a static magnetic field and reduce the power supply.

3.3 Element and Inclusion Analysis

Figure 7 summarizes the influence of TSMF on the phosphorus (P) content in the remelted ingot under different intensities. This indicates that, in the absence of TSMF and with the increase in the current, the dephosphorization effect was inhibited because of the exothermic reaction which leads to the rising of the temperature in the slag pool. In the case of 85 mT TSMF, the phosphorus content is further reduced by 10%. When the intensity of TSMF

Fig. 7 Influence of TSMF on phosphorus (P) content of MC-ESR ingot with different intensities of AC

increases to 130 mT, the phosphorus content reaches the minimum value 72.6 ppm with the current of 400 A.

The influences of TSMF on the number of inclusions of remelted ingots under different intensities of the TSMF are summarized in Fig. 8. It is found that the number of inclusions is 733 in a collected area of 8.405 mm² on the traditional ESR ingot. When it comes to the cases of 130 mT and 160 mT TSMFs, the numbers of inclusions are further reduced to 241 and 301, respectively. Therefore, it can be concluded that the TSMF is in favor of the elimination of the phosphorus element and the decrease in the number of inclusions.

During the original ESR process, consumable electrode was melted by the Joule heat. Melted metal droplets fell into the metallic melting pool vertically (Fig. 9a). As a result, a deep melted pool was formed. By using MC-ESR process, the alternating Lorentz force was induced when imposing a TSMF. The alternating Lorentz force will change its direction frequently as the 50 Hz alternating current. In the first half cycle of the alternating current, the Lorentz force points left. When the current changes to the other half cycle, the Lorentz force points right (Fig. 9b); consequently, the electromagnetic oscillation affects the direction of initial velocity and the volume of melting

Fig. 8 Influence of TSMF on inclusion count of MC-ESR ingot

Fig. 9 Schematic view of MC-ESR

droplets. The droplets would fall into the melted pool in a smaller shape dispersively. Thus, a shallower melt pool was formed, and the metallic liquid–solid interface was much more flat. As a result, the temperature field in the melted pool became more uniform. A smaller shape of the melting droplets and a shallower melt pool could make it easier for the inclusions to move to the melting slag pool and be removed by the slag. In the ordinary ESR process, the dephosphorization effect was inhibited because of the exothermic reaction which leads to the rising of the temperature in the slag pool. By using MC-ESR process, the temperature field in the melted pool became more uniform and caused significant positive changes to the elimination of the phosphorus element.

4 Conclusions

1. A process of the MC-ESR is proposed. Recording the voltage data is a credible method to study the droplets transient during the MC-ESR process.
2. The number of droplets increases without adding the power supply with TSMF of 130 mT in the MC-ESR process. The phosphorus content and number of inclusions decrease under the effect of TSMF.
3. The electromagnetic vibration effect improves the refinement capacity of ESR process.

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