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# Effects of Mould Rotation on Element Segregation and Compact Density of Electroslag Ingots during Electroslag Remelting Process

**Abstract:** Steel solidification process control, especially in the solidification process of high-alloy steel, and improving the solidification structure have been increasingly gaining interest among metallurgists, particularly the electroslag workers. To further develop the electroslag remelting (ESR) process and to improve the ingot solidification structure, the effects of mould rotation on chemical element distribution and the compact density were investigated in this study. The experimental results showed that chemical element distribution would become more uniform when the mould keeps the reasonable rotation rate. However, the excessive rotation rate would deteriorate the solidification structure of steel. When mould rotation rate was between 0 and 28 r/min, maximum segregation of carbon could decrease from 3.19 to 1.084, and statistical segregation decreased from 0.2636 to 0.0554. Maximum segregation of chromium could decrease from 1.316 to 1.131, and statistical segregation decreased from 0.2753 to 0.0657. The compact density increased from 0.7693 to 0.94. But element segregation would become bigger and compact density would become smaller if rotation rate further increased. The improvement in the solidification structure could be attributed to reasonable mould rotation rate which could initiate movement in the slag pool and further increase the uniformity of the temperature in the slag pool. At the same time, the movement in the slag pool could also affect the metal molten droplet, scattering the liquid drop randomly in the metal pool. But the excessive rotation rate made the slag pool violent motion, so as to drive the molten metal pool to rotate which would carry off enriched steel surrounding the dendrites in the mushy zone and reduce the solute content in the region. As a result, the element segregation would occur.

**Keywords:** electroslag remelting, solidification, segregation, compact density, mould rotation

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## 1 Introduction

Metal manufacturing techniques aim to improve metal purity and to control solidification quality. Electroslag remelting is a smelting process that can satisfy the above requirements. By integrating refining and solidification, ESR can efficiently remove nonmetallic inclusions in steel and decrease the sulfur content. Moreover, the crystallization direction can be controlled and a crystalline structure that tends to conform along the axes can be obtained [1–3].

Along with the progress of modern steel-making processes, the sulfur content in metal consumable electrodes can be decreased to less than 0.001%, the oxygen content (for example, ball bearing steel) can be decreased to less than 0.0005%, and inclusions can also be greatly decreased [4–6]. Thus, controlling sulfur and inclusions has not been the major limitation in ESR production. Continuous casting greatly improves metal yield and production efficiency, but the billet solidification structure has not seen great improvement, even with the application of various advanced technologies, such as tundish heating, electromagnetic stirring, and soft reduction [7]. Therefore, the steel solidification process, especially the solidification process of high-alloy steel, and improving the solidification structure have increasingly attracted the attention of metallurgists, particularly the electroslag workers [8–9].

The solidification structure of electroslag ingots is closely related to the depth of the metal pool. In an ideal case, the metal pool keeps a shallow shape during the

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ESR process. An extremely deep pool will result in loose arrangement, porosity, and other solidification defects, which will decrease the uniformity of the alloying element in the steel. However, keeping a shallow metal pool during the ESR process is difficult. For example, along with the remelting, the heat conduction conditions of ESR ingots would deteriorate and the metal pool would gradually deepen. Thus, the remelting rate must be decreased. This approach is especially applicable for large ingots with extremely poor heat conduction conditions. Low power and low remelting speed are necessary to obtain a shallow metal pool. However, any decrease in remelting speed also brought about a series of problems, such as increased power consumption and poor surface quality. Therefore, producing electroslag ingots with good solidification quality at low cost (or with unchanged technological parameters) has been a challenge in electroslag production.

Based on the above reasons, a new electroslag furnace with mould rotation was designed and the effects of mould rotation on element segregation and compact density of electroslag ingots were studied in this paper.

## 2 Experimental

### 2.1 Experimental equipment

A schematic of the ESR furnace is shown in Figure 1.

As shown in Figure 1, a single-phase and bifilar ESR furnace was used. Upper and lower mould were bolted together, and were driven by an adjustable-speed motor. The rotation rate of the adjustable-speed motor was between 0 and 45 r/min, which could be adjusted during ESR. Other technical parameters of the electroslag furnace were as follows: a 10 kg to 20 kg ingot could be refined in a water-cooled mould, which had a 110 mm bottom

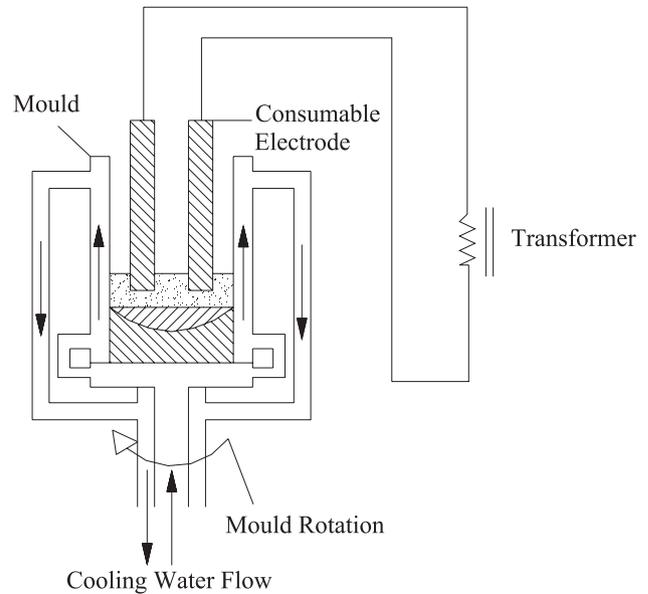


Fig. 1: Schematic of mould rotation ESR furnace.

diameter, a 100 mm top diameter, and a 28 mm electrode diameter. A 100 KVA AC supply was available for ESR ingot production, with a high-voltage terminal of 380 V, a low-voltage terminal ranging from 28 V to 40 V, and a maximum current of 2,500 A. Based on pre-established electrical parameters, the consumable electrode could be driven up and down at a certain speed. The speed was controlled manually.

### 2.2 Experimental schemes

To clarify the effect of mould rotation rate on the distribution of chemical elements and compact density of ESR ingots, experiments showed in Table 1 were carried out.

Table 1: Experimental schemes.

Schemes	Slag	Steel	Electrical parameters		Mould rotation rate, $\omega$ (r/min)
			Current (A)	Voltage (V)	
1	70%CaF <sub>2</sub> +30Al <sub>2</sub> O <sub>3</sub>	GCr15*	1000	34	0
2	70%CaF <sub>2</sub> +30Al <sub>2</sub> O <sub>3</sub>	GCr15	1000	34	6
3	70%CaF <sub>2</sub> +30Al <sub>2</sub> O <sub>3</sub>	GCr15	1000	34	19
4	70%CaF <sub>2</sub> +30Al <sub>2</sub> O <sub>3</sub>	GCr15	1000	34	28
5	70%CaF <sub>2</sub> +30Al <sub>2</sub> O <sub>3</sub>	GCr15	1000	34	35

\* GCr15, containing 0.96% to 1.0% C, 0.35% to 0.4% Mn, 0.2% to 0.3% Si, and 1.4% to 1.5% Cr

## 2.3 Experimental process

The remelting process began with a solid slag, which had a slag weight of 1.2 kg. The arcing agent was composed of 50% CaF<sub>2</sub> and 50% TiO<sub>2</sub>. The arc had a starting voltage of 31 V and a current of 700 A. The scale of the electrode surface was removed by grinding prior to ESR, and no deoxidizer was added to the slag bath during the ESR process.

The finished ingots were transversally split, and subsequently polished. The distribution of chemical elements and compact density were observed using an original position analysis (OPA) apparatus (NCS Testing Technology Co., Ltd.). OPA can determine various parameters, such as segregation, quantity and distribution of inclusion, porosity, and chemical composition, for elements in a sample. The analyzer is widely used in the metallurgical industry because of its advantages of simple sample preparation, accurate quantization, and high-speed analysis over conventional analytical methods.

The following technical parameters were used for OPA: (1) discharge parameters (continuous excitation system): frequency, 500 Hz; inductance, 120 H; capacitance, 5 F; voltage, 400 V; (2) spectrophotometric system: focal length, 750 mm; spectrum range, 120 nm to 800 nm; distinguishability surpass, 0.01 nm; (3) sample size: length 500 mm × width 245 mm; and (4) load bearing: 20 kg.

## 3 Experimental results

### 3.1 In situ scannogram

The in situ scannogram spot of the cross section of the ESR ingot is shown in Figure 2.

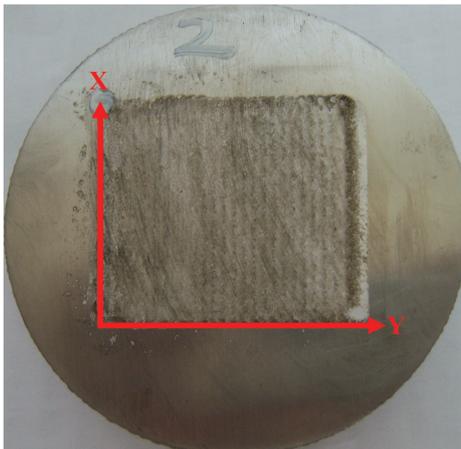


Fig. 2: In situ scannogram spot of the cross section of the ESR ingot.

The line-by-line scan mode was adopted during sample scanning. The X-axis was the continuous scan. The Y-axis was the stepping scan. Scanning area was 50 mm × 50 mm.

### 3.2 Effects of mould rotation on carbon segregation in the electroslag ingots

Figure 3 shows a two dimensional contour diagram of carbon distribution at different mould rotation rates.

In the two dimensional contour diagram, the horizontal coordinate represented the X direction and the longitudinal coordinate represented the Y direction (seen in Figure 2). Different colors represented the carbon contents in the ESR ingot. Maximum carbon content was indicated in red and minimum carbon content was indicated in purple. A large variation in colors indicated increased element segregation and vice versa.

Figure 3 shows that when the mould was stationary, the carbon content at the center of the cross section obviously increased; whereas when the mould rotated, the carbon segregation obviously decreased. But when the rotation rate increased to 35 r/min, the carbon segregation, on the contrary, increased which showed there is an optimum mould rotation rate range. The carbon segregation was improved within this range and deteriorated beyond this range.

Figure 4(a) shows relation between maximum carbon segregation ( $C_{\max}/C_0$ ) and mould rotation rate.

It could be seen from Figure 4(a) that the maximum carbon segregation was 3.19 when the mould keeps stationary. With increase of mould rotation rate, the maximum carbon segregation decreased gradually. When the rotation rate increased to 35 r/min, the maximum carbon segregation increased to 1.236.

To further analyze carbon segregation, carbon statistical segregation was calculated according to the formula below:

$$S = \sigma / C_0 \quad \sigma = \sqrt{(\sum(C - C_0)^2 / N)} \quad (1)$$

where  $C_0$  represents the average carbon content,  $C$  represents the carbon contents at different positions, and  $N$  represents the collected spot number;  $\sigma$  represents confidence expansion range of  $C_0$  at 95% confidence level and 95% confidence interval is between  $(C_0 - \sigma)$  and  $(C_0 + \sigma)$ .

Relatively higher statistical segregation was indicative of higher element segregation. Conversely, lower statistical segregation was indicative of a more uniform

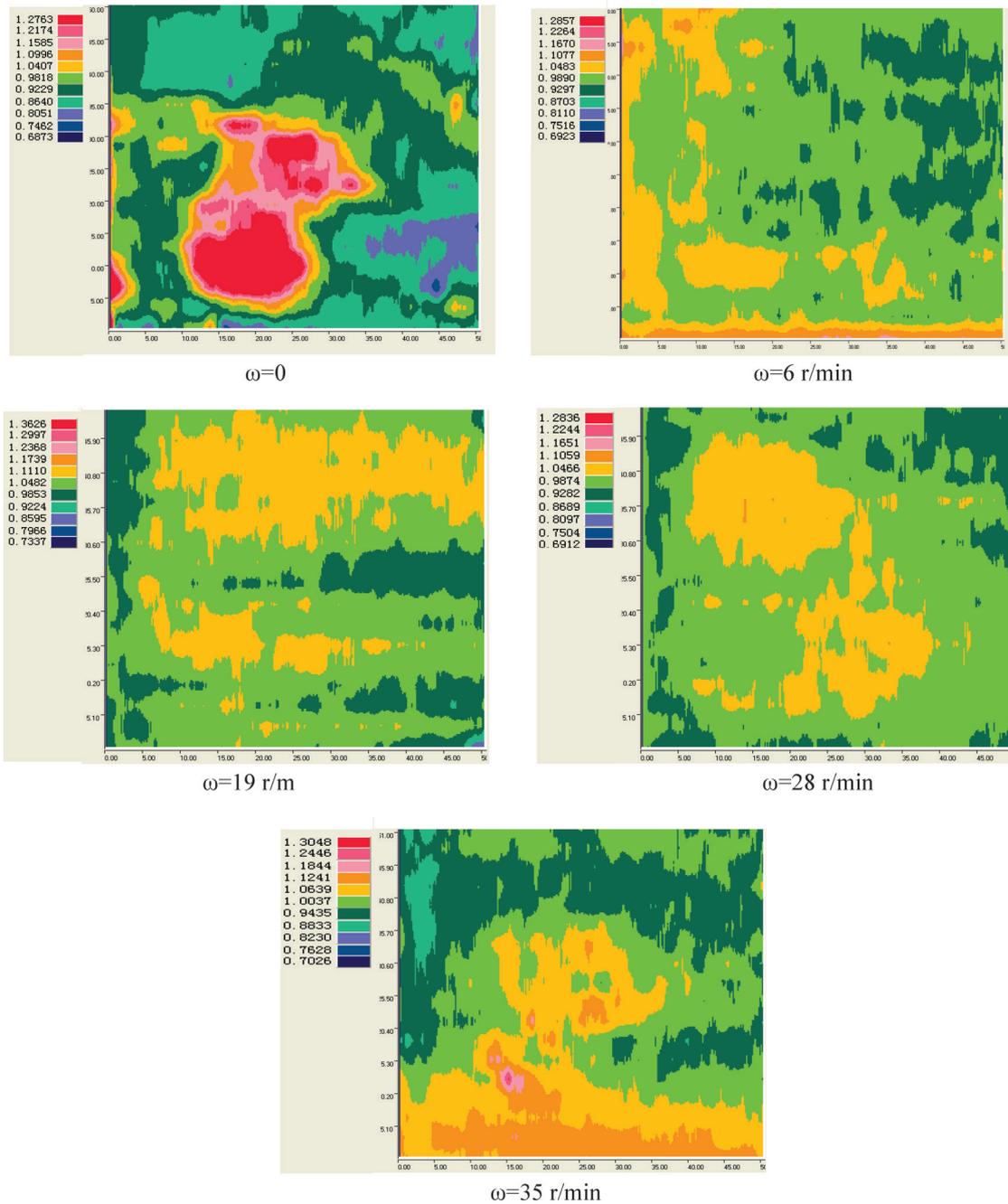


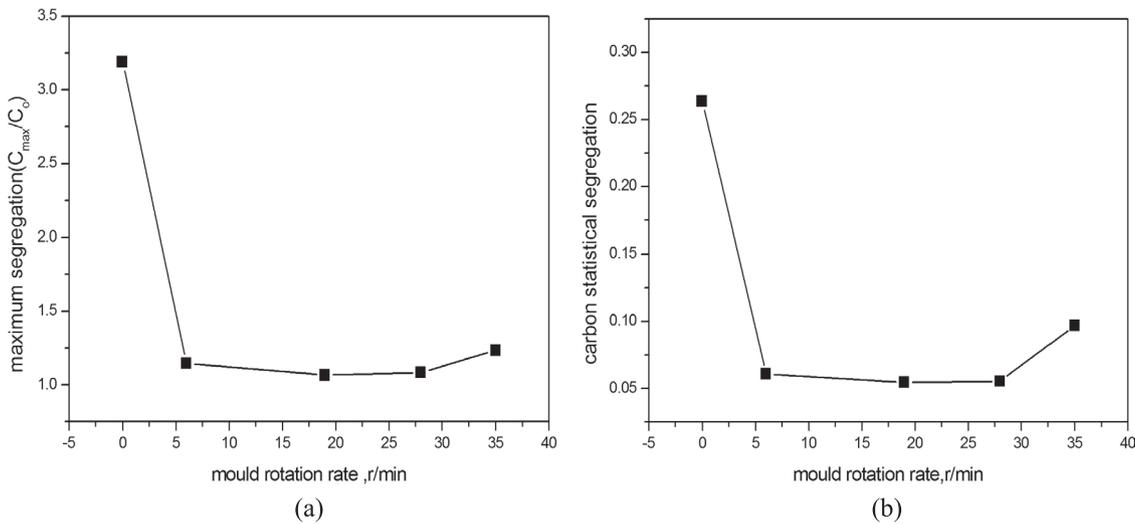
Fig. 3: Effects of mould rotation on carbon segregation.

element distribution. According to Eq. (1), the carbon statistical segregation was calculated with the variation of the mould rotation rate, as shown in Figure 4(b).

Similarly with the variation of the maximum carbon segregation, carbon statistical segregation decreased with rotation of mould. However, when the rotation rate increased to 35 r/min, the statistical segregation increased to 0.097 from 0.0554 when the rotation rate was 28 r/min.

### 3.3 Effects of mould rotation on chromium segregation in the electroslag ingots

Figure 5 shows that the chromium distribution in the electroslag ingot was obviously more uniform when mould rotation rate was between 6 r/min and 28 r/min. When the rotation rate increased to 35 r/min, the segregation increased instead. Figure 6 shows the relation between



**Fig. 4:** (a) Relation between maximum carbon segregation ( $C_{\max}/C_0$ ) and mould rotation rate. (b) Relation between carbon statistical segregation and mould rotation rate.

chromium segregation and mould rotation rate which had similar variation with carbon segregation.

### 3.4 Influences of mould rotation on compact density of electroslag ingots

One important function of OPA is to detect the compact density of the sample surface as well as the defects and micropores on the metal surface. Information on the location of defects and micropores as well as the distribution of element contents at the micropores and defects can also be obtained.

The compact density distribution of the ESR ingot casting is shown in Figure 7. In the two dimensional contour diagram of compact density, different colors represent the variation in compact density, with a maximum of 1 and a minimum of 0. A higher compact density was desired. The maximum compact density for the electroslag ingot was indicated in red, whereas the minimum compact density was indicated in violet blue. Conversely, less variation in color difference was indicative of a more uniform compact density distribution.

Statistical compact density was calculated as follows:

$$D = \sum D_j / N \quad D_j = \sum C_i \quad (2)$$

where  $D$  represents the statistical compact density,  $D_j$  represent the compact density at the different position of ESR ingot,  $C_i$  represents the content of element  $i$  at the position of spark spectrometric single discharge at the  $j$  time

and  $N$  represents the sum of spark spectrometric single discharge.

According to Eq. (2), the statistical compact density was calculated with the variation of the mould rotation rate, as shown in Figure 8.

As can be seen from Figs. 7 and 8, ESR ingot became more compact when the mould rotation rate increased to 28 r/min from 0. But the compact density of the electroslag ingot would decrease when the mould rotation rate increased to 35 r/min.

## 4 Discussion

To achieve uniformly distributed chemical elements in an electroslag ingot, the solidification structure of the ingot casting must be improved. One key measurement index of solidification structure was to obtain a shallow metal pool during electroslag remelting progress. In the traditional ESR process (single-phase and single-electrode ESR furnace), the current flowed in the following direction: metal consumable electrode  $\rightarrow$  slag pool  $\rightarrow$  metal pool  $\rightarrow$  solidified ingot casting. The calorific value at the electrode tip was maximum, and its temperature was highest. Moreover, this position was found at the center of the metal pool. Meanwhile, because of the slow motion in the slag pool, the high-temperature metal molten droplet directly fell on the center of the metal pool. This condition caused a deep metal pool and further decrease the solidification quality of the electroslag ingot, as shown in

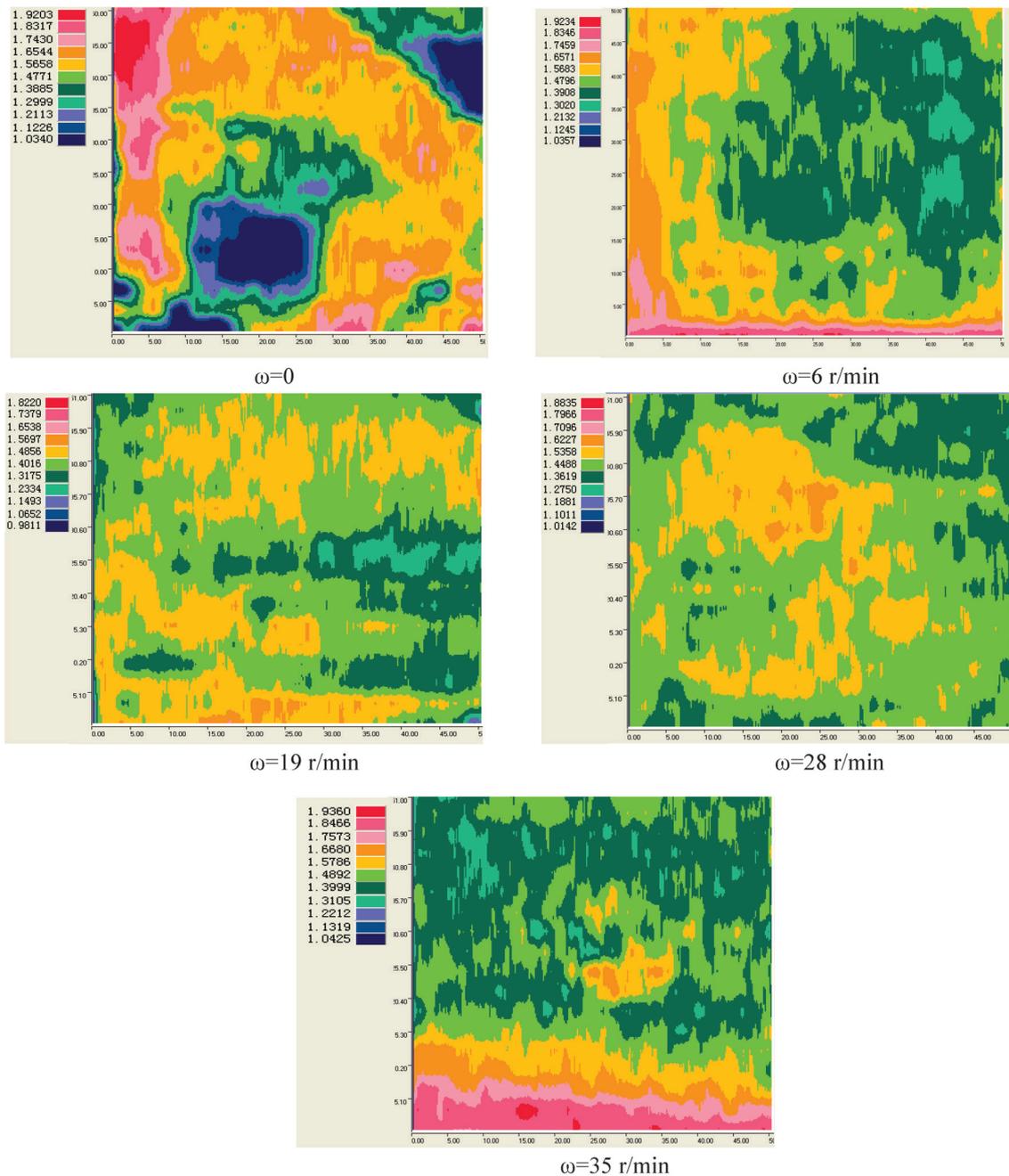


Fig. 5: Effects of mould rotation on chromium segregation.

Figure 9(a). Furthermore, in the traditional bifilar ESR furnace process, the current flowed in the following direction: metal consumable electrode1  $\rightarrow$  slag pool  $\rightarrow$  metal consumable electrode 2, as shown as Figure 9(b). The high-temperature areas remained focused between the two electrodes, namely, the center of metal pool. Compared with the single-phase and single-electrode ESR furnace, the high-temperature areas were scattered, but a deep metal pool can still being generated.

Nevertheless, the application of the mould rotation during the ESR process triggered the slag motion, which further increased the uniformity of the slag pool temperature [10–11], as shown in Figure 9(c). Uniform temperature distribution could lead to the generation of a shallow pool and movement in the slag pool could also cause movement of the metal molten droplet, thereby scattering the liquid droplet randomly in the metal pool. This effect also contributed to the uniform distribution of the tem-

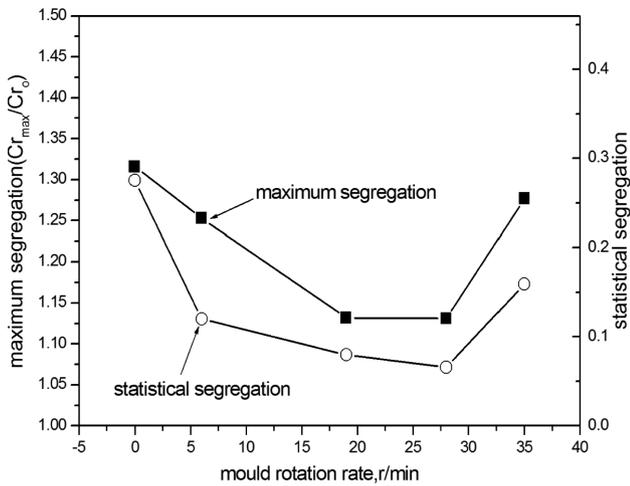


Fig. 6: Relation between chromium segregation and mould rotation rate.

perature. Therefore, mould rotation was beneficial for the reduction of metal pool depth, the improvement of solidification structure, and the uniform distribution of chemical elements in the ESR ingot.

However, as shown by the experimental results, there must be an optimum mould rotation rate range. The excessive rotation rate made the slag pool violent motion, so as to drive the molten metal pool to rotate which will carry off enriched steel surrounding the dendrites in the mushy zone and reduce the solute content in the region. As a result, the severe element segregation would occur.

## 5 Conclusions

The main conclusions that could be drawn were as follows:

1. When mould rotation rate was between 6 r/min and 28 r/min, chemical element distribution was more uniform. Compared with the electroslag ingot of con-

ventional ESR, maximum carbon segregation could decrease from 3.19 to 1.084, and statistical segregation decreased from 0.2636 to 0.0554. Maximum chromium segregation could decrease from 1.316 to 1.131, and statistical segregation decreased from 0.2753 to 0.0657. But the element segregation would increase if the rotation rate further increase.

2. When mould rotation rate was between 6 r/min and 28 r/min, ESR ingot became more compact. Compared with the electroslag ingot of conventional ESR, the compact density for the stationary mould increased from 0.7693 to a compact density of 0.94. But the compact density of the electroslag ingot would decrease when the rotation rate further increase.
3. The improvement in the solidification structure of the electroslag ingot could be attributed to appropriate mould motion, which could initiate movement in the slag pool and further increase the uniformity of the temperature in the slag pool. At the same time, movement in the slag pool could also affect the metal molten droplet, scattering the liquid drop randomly in the metal pool. These two reasons contributed to the uniform distribution of the metal pool's temperature, which in turn led to the generation of a shallow pool and the improvement of the solidification structure.
4. Excessive rotation rate would result in element segregation. The main reason was that excessive rotation rate make the slag pool violent motion, so as to drive the molten metal pool to rotate which would carry off enriched steel surrounding the dendrites in the mushy zone and reduce the solute content in the region. As a result, the element segregation would occur.

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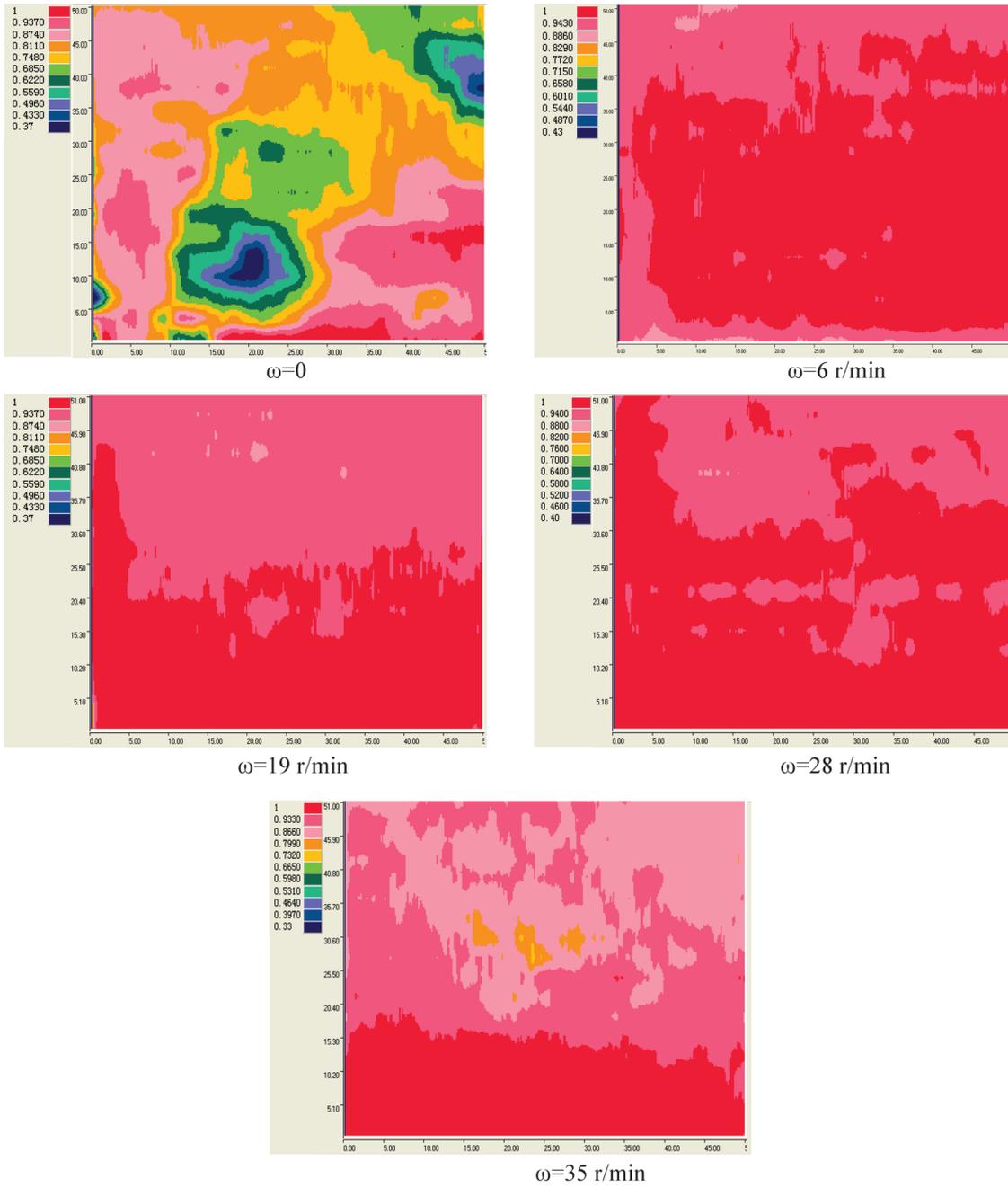
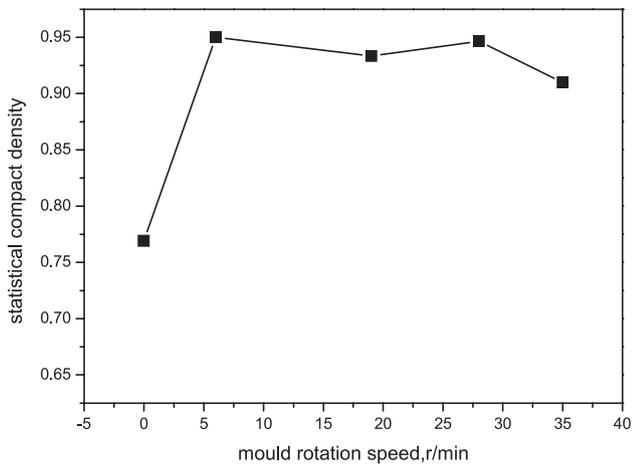
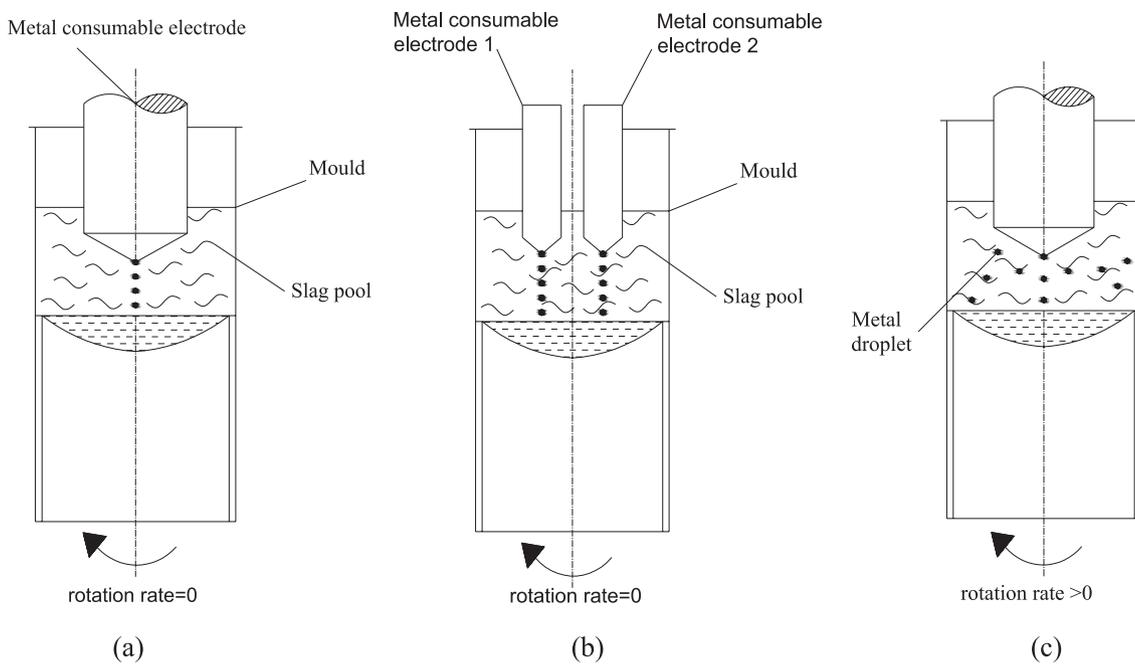


Fig. 7: Effects of mould rotation on compact density of electroslag ingot.



**Fig. 8:** Relation between the statistical compact density and mould rotation rate.



**Fig. 9:** Schematic of traditional ESR (a, b) and mould rotation ESR (c).

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