Effect of Directional Solidification in Electroslag Remelting on the Microstructure and Cleanliness of an Austenitic Hot-work Die Steel

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The current study focuses on the effect of directional solidification in electroslag remelting (ESR) on the removal efficiency of inclusion and the shape of molten metal pool during this refining process as well as on solidification structure of remelted ingot. Two ingots were remelted through traditional ESR process and continuous directional solidification in electroslag remelting (ESR-CDS) process for comparison, respectively. Moreover, a two-dimensional (2D) coupled mathematical model was employed to simulate the temperature field, solidification and velocity fields as well as inclusion motion to reveal the refinement mechanism of inclusion removal, microstructure and carbides during remelting process. The results showed that the macro-segregation of carbon was reduced and the microstructure of columnar grains paralleled to axis of ingot was obtained through ESR-CDS process, together with the refinement of carbides distribution. Moreover, the number and size of inclusions in ingot were much more reduced remelting through ESR-CDS process compared to ESR process. The total number and average diameter of MnS particles are obviously reduced from 689 and 2.28 μm in S1 ingot to 78 and 1.78 μm in S2 ingot respectively, remelting through ESR-CDS process. Meanwhile, the number of MnS particles with size >3 μm is reduced from 15.67% in S1 ingot to 1.28% in S2 ingot, and that with size 1–2 μm is increased from 49.93% in S1 ingot to 67.95% in S2 ingot. It was found that ESR-CDS technology was beneficial for refinement of microstructure and carbides as well as removal of inclusions, thus achieving considerable improvement in mechanical properties of austenitic hot-work die steel.

KEY WORDS: electroslag remelting; numerical simulation; solidification; segregation; inclusion.

1. Introduction

Hot-work die steels with martensitic matrix, such as 3Cr2W8V, H13, THG2000 and QRO90, are widely applied in such fields as hot forging, hot extrusion and die-casting. The working temperature at the surface of these dies could reach up to 550°C, which is close to the tempering temperature. Operating at an elevated temperature inevitably leads to continuous evolution of the microstructure and certainly affect various properties of dies related to hot hardness, wear resistance and high-temperature fatigue strength.1) In recent years, demands for the specifications and performance requirements of die steels with higher temperature strength are enhanced unceasingly with the rapid development of large-scale equipment manufacturing industry. In order to improve the strength of die steel at the temperatures higher than 600°C, austenitic hot-work die steel, which has no matrix phase transformation during the thermal cycle services, has attracted much more attentions.2–6)

Austenitic hot-work die steels always have longer service life and better thermal stability at higher working temperature than 600°C, but lower hardness. These steels are strengthened by solid solution strengthening and precipitation strengthening with intermetallic, carbides and carbonitrides phases. During solidification, alloying elements such as chromium, molybdenum, vanadium and carbon generally segregated seriously due to highly alloying and correspondingly primary carbides often formed a network along dendrite boundaries in as-cast microstructure. The type, shape, amount and distribution of primary carbides have great influence on the mechanical properties, exceptional for fracture toughness.1) It is very important to control the size and distribution of primary carbides in steel used as die-casting molds and extrusion molds. The defects caused by large primary carbides are difficult to eliminate during forging and heat treatment stages. A well-known way for controlling primary carbides is to reduce element segregation during solidification. Several methods have been explored, including adding nucleating agent or alloying elements,7,8) mechanical or electromagnetic stirring,9–11) etc. However, the electroslag remelting (ESR) process is considered as a widely used secondary refining technology for producing high-quality special steel ingots. The ESR method can not only refine microstructure and homogenize component, but also greatly remove the non-metallic inclusions of elec-
trode. However, the refinement of microstructure and effective removal of inclusions during the ESR process must be combined with reasonable remelting technology; otherwise, mixed crystal dendrites with coarse carbides formed along cell boundaries and large inclusions may form in the ingots. Therefore, the effect of operating condition of ESR on microstructure, segregation and inclusions in ingots is worthy to be studied.

The characteristic of ESR process is gradually crystalized almost parallel to the axis centerline of ingots from bottom to top. The solidification microstructure of ESR ingots is closely related to the depth of the metal pool. Some research showed that shallow and flat molten pool can shorten the local solidification time and restrict the carbide segregation. In respect to the traditional fixed-mould ESR process, the depth of metal pool was generally modified by these measures as follows: decreasing the remelting speed of electrodes; increasing the fill ratio of the electrode cross-sectional area to the mold cross-sectional area; increasing the appropriate weight of slag. However, the shape of the molten-metal pool changes gradually in the traditional fixed-mould ESR process, so it is difficult to achieve the critical balance between surface quality and internal quality. Moreover, remelting rate is not a linear relationship with the local solidification time. Therefore, the traditional fixed-mould ESR limits the ability to control carbide segregation in ingot. Shi et al. and Chumanov et al. reported that the rotation of a mold and consumable electrode respectively in ESR process can not only alleviate the segregation of carbides and reduce the size of carbides in the high speed steel, but also reduce inclusions and improve the surface quality of ingots. However, these measures above are feasible to achieve the shallow and flat molten pool of ESR in small section ingots, but exhibit some limitations in large cross section ingots.

In addition, traditional ESR technology has some other disadvantages, including high costs, high-energy consumption and poor production efficiency, which greatly impedes its widely application. To tackle these drawbacks, electroslag continuous casting (ESCC) technique was developed by combining traditional ESR and continuous casting technology. In fact, ESCC also has some shortcomings. During the ESCC process, heat transfer mainly through the mold wall due to the molten metal pool is far from the water-cooled baseplate. This radial heat transfer easily leads to apparent radial crystallization phenomenon, which is detrimental to the mechanical properties of high-quality remelting ingots. Therefore, more effective measures should be attempted to improve the ESCC technology.

Base on cooling excitation theory, continuous directional solidification in electroslag remelting (ESR-CDS) was introduced in this investigation by applying secondary aerosol cooling water at 160 mm below water-cooled copper mold in the electroslag remelting withdrawal process. Fu et al. and Li et al. demonstrates that ESR-CDS could effectively eliminate macro-segregation in as-cast ingot through the shallow molten metal pool controlled by directional solidification, as well as the removal of inclusions. To understand the solidification features of the processes in ESR and ESR-CDS, numerical simulation can be used to analyze the differences. The commercial software Melt-Flow ™ appropriately predicted the several thermal physical fields and flow fields, including liquid metal pool shape, primary dendritic arm orientation, secondary dendritic arm spacing and extent of chemical segregation etc. in ingots.

In this work, the effect of ESR-CDS process on microstructure including solidification structure, segregation degree of alloys, distribution of carbides and inclusions were investigated. In addition, the effect of secondary aerosol cooling on the shape of the molten metal pool and solidification features were studies by commercial soft Melt-Flow ™.

2. Experimental

2.1. Experimental Materials

The austenitic hot-work die steel was obtained by melting industrial pure iron and some other alloying elements in a 200 kg vacuum induction furnace at 800 Pa under an argon atmosphere. After fully deoxidizing the molten steel by infusing Al, the resulting molten steel was further modified by rare earth yttrium. The molten steel was cast into a rod at 1 853 K, and then forged into two rods of 120 mm in diameter. Then the electrodes were remelted using traditional ESR and ESR-CDS technology for comparison, and electrodes sampled as S0. The remelting process were conducted in the argon gas atmosphere. The produced as-cast ingots of 160 mm in diameter remelted by ESR and ESR-CDS were sampled as S1 and S2, respectively. The pre-melted slag (60 mass pct. CaF₂, 20 mass pct. CaO, 20 mass pct. Al₂O₃) was roasted at 500°C in a dry box for at least 5 hours to remove the moisture in slag before the remelting experiment. The chemical compositions of electrode and remelted ingots S1 and S2 were determined by inductively coupled plasma optical emission spectrometer, at the top position of 1/4 of longitudinal length, and the results are shown in Table 1.

The schematic diagram of the traditional ESR and ESR-CDS apparatus were illustrated in Figs. 1(a) and 1(b), respectively. In contrast with traditional ESR process, the improved measures in ESR-CDS process include these methods as follow: applying electric conductively water-cooler mold with water-cooled baseplate continuously downward; spraying secondary aerosol cooling water at 160 mm below mold when ingot drawing out of the hot zone. The similar remelting speed of the two ingots were taken by adjusting the input voltage, current and other process parameters, and the process parameters were listed in Table 2.

2.2. Microscopic Observation

Carbon segregation with the size of 80 mm×80 mm in the transverse section of both ingots from center to boundary was analyzed using an original position analyzer (OPA 200, NCS, China). OPA is a technology based on continuous excitation spark spectroscopy with two-dimensional scanning of specimens, high-speed signal acquisition of single spark discharge, and data analysis. The OPA instrument can scan large-sized specimen and generate signals reflecting both the concentra-

| Ingot | C   | Si  | Mn  | Cr  | Mo  | V   | Al  | P  | S   | Y   | T[O] | Fe  |
|-------|-----|-----|-----|-----|-----|-----|-----|----|-----|-----|------|-----|
| S0    | 0.74| 0.59| 15.38| 3.55| 1.61| 1.78| 0.017| 0.0090| 0.0064| 0.0030| 0.0032| Bal. |
| S1    | 0.70| 0.55| 14.95| 3.45| 1.57| 1.723| 0.012| 0.0085| 0.0023| 0.0005| 0.0021| Bal. |
| S2    | 0.698| 0.544| 14.90| 3.53| 1.55| 1.726| 0.011| 0.0088| 0.0021| 0.0007| 0.0016| Bal. |

Table 1. Chemical composition of steel (wt.%).
3. Numerical Simulation

To illuminate the condition of solidification and the motion of inclusion removal during remelting process, a two-dimensional commercial software (Melt-Flow™) was employed to simulate the velocity fields and temperature fields for ESR and ESR-CDS process, respectively. The simulated conditions containing the shape of molten metal pool, the temperature gradient of mushy zone, the motion of inclusion removal, primary dendrite arm orientation, secondary dendrite arm spacing, and extent of chemical segregation could be simulated by Melt-Flow™, and the related results has been described elsewhere.\(^{27}\)

The data used for the simulation were mainly the thermo-physical properties of slag and metal, the geometry of the furnace (i.e., slag, ingot, electrode and mold) and the operating conditions (i.e., the electric current profiles and power input). The properties for both the metal and slag are presented in Table 3. These thermo-physical properties were compared and performed with information reported in the literature and adjusted by comparison of the experiment and calculated by Thermo-Calc™ software.

### 3.1. Model Description

#### 3.1.1. Equations of Electromagnetic Field

(1) Governing Equations

The electromagnetic field is the basic physical phenomenon in ESR due to the current that runs through the circuit. Thus, the electromagnetic field can be described by Maxwell’s equations:

\[
\mathbf{J} = \nabla \times \mathbf{H} \ \text{or} \ \nabla \times \mathbf{E} = \mathbf{J}
\]

However, for the electromagnetic field, we have:

\[
\nabla \times \left( \nabla \times \mathbf{H} \right) = \nabla \times \mathbf{J} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}
\]

\[
\nabla \times \left( \nabla \times \mathbf{H} \right) = \nabla \times \mathbf{J}
\]

\[
\nabla \times \left( \nabla \times \mathbf{E} \right) = \nabla \times \mathbf{J} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}
\]

(2) Boundary Conditions

The radial current is assumed to be zero at the electrode-slag interface and at the base of the ingot. This results in the following boundary condition on the magnetic flux density.

\[
\frac{\partial \mathbf{H}}{\partial r} = 0 \ \ \text{at} \ \ r = R
\]

### Table 3. Thermo-physical properties for the metal and slag.

| Physical properties | Metal | Slag |
|---------------------|-------|------|
| Liquid density, kg/m\(^3\) | 7 500 | 2 626 |
| Solid density, kg/m\(^3\) | 8 146 | 2 790 |
| Liquidus temperature, K | 1 653 | 1 723 |
| Solidus temperature, K | 1 503 | 1 618 |
| Liquid vol. thermal exp. Coeff., K\(^{-1}\) | 1.5×10\(^{-4}\) | 9.0×10\(^{-5}\) |
| Liquid thermal conductivity, W/(mK) | 30.52 | 0.5 |
| Solid thermal conductivity, W/(mK) | (773 K) 16.72 | (773 K) 7.8 |
| Electrical conductivity, Ω\(^{-1}\) | 7.6×10\(^3\) | 239 |

3.1.2. Equations of Fluid Flow

(1) Governing Equations

The fluid flow in the slag and the molten steel pool is driven by the combined action of Lorentz and buoyancy forces. The flow field is represented by the time-averaged form of the mass and momentum conservation equations.

\[
\nabla \cdot (\rho \mathbf{v}) = 0
\]

\[
\nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \tau + \mathbf{f}
\]

where \(\rho\) is the density, \(\mathbf{v}\) is the velocity, \(p\) is the pressure, \(\tau\) is the shear stress, and \(\mathbf{f}\) is the body force per unit volume.
Momentum conservation:
\[ \nabla \cdot (\rho \mu \mathbf{u}) = -\nabla P + \nabla \cdot ((\mu + \mu_f)(\nabla \mu + \nabla \mu^T)) \]  
\[ - \rho \mathbf{g}(T - T_{\text{ref}}) + \mathbf{F}_L \]  
\[ (9) \]

(2) Boundary Conditions
The no-slip boundary condition is imposed on the region of the mold boundary where the liquid phase (slag and molten metal) is in contact with the mold. The slag is subject to a zero shear stress at the electrode-slag interface and the exposed surface of the slag. In the ingot region, the macro-level flow is assumed to be absent below the immobilization liquid fraction \( f_{\text{immob}} \) and it corresponds to the solid-liquid interface in the flow calculation.

Top surface: \[ \frac{\partial \mu}{\partial x} = 0 \]  
(10)

Mold surface: \[ \mu = 0, f \geq f_{\text{immob}} \]  
(11)

Solidified ingot: \[ \mu = \mu_{\text{cast}}, f \leq f_{\text{immob}} \]  
(12)

3.1.3. Equations of Energy Conservation
(1) Governing Equations
Joule heating created by the current flow appears as the source term in the above equation and it is predominant in the slag region. In the metal region, the release of latent heat, as the liquid metal solidifies, appears as a source term. The temperature distribution in the slag and metal phases in governed by the energy conservation equation.

Energy conservation:
\[ \rho C_p \mu \cdot \nabla T = \nabla \cdot (k \nabla T) + S_i - \rho \mu L \nabla \cdot \lambda \]  
(13)

Liquid fraction:
\[ \lambda = f\left(\frac{T - T_{\text{Solidus}}}{T_{\text{Liquidus}} - T_{\text{Solidus}}}\right) \]  
(14)

(2) Boundary Conditions
The present study performs analysis of the remelting process for a specified melt rate. Thus, a uniform heat flux is applied below the immobilization interface in the flow calculation.

Electrode - slag interface:
\[ -k \frac{\partial T}{\partial x} = \frac{m}{A_{\text{electrode}}} \left( L + \tau_{\text{ slagmic}} \right) \]  
(15)

Exposed slag surface:
\[ -k \frac{\partial T}{\partial x} = \varepsilon \sigma (T^4 - T_{\text{sink}}^4) \]  
(16)

3.1.4. Equations of Turbulent Mixing
(1) Governing Equations
The two-equation \( k-e \) model is used to determine the effect of turbulent mixing on the flow and the temperature fields. The governing equations are listed below.

Turbulent kinetic energy:
\[ \nabla \cdot (\rho \mu_k) = \nabla \cdot \left( \frac{\mu}{\sigma_k} \nabla k \right) + \mu_G - \rho e \]  
(17)

Turbulent dissipation:
\[ \nabla \cdot (\rho \mu_e) = \nabla \cdot \left( \frac{\mu}{\sigma_k} \nabla e \right) + (c_1 \mu_G - c_2 \rho e) \frac{e}{k} \]  
(18)

Turbulent viscosity and conductivity:
\[ \mu_t = c_\mu \rho k^2 \frac{k_t}{\varepsilon} \]  
\[ k_t = \frac{\mu_t}{\varepsilon} \]  
(19)

(2) Boundary Conditions
Since the fully turbulent version of the \( k-e \) model is used, wall functions are employed for specifying boundary conditions for turbulent kinetic energy, turbulent dissipation, shear stress, and heat flux on all the solid surfaces and on the pool boundary corresponding to the immobilization liquid fraction.

Mold surface and molten metal pool boundary:
\[ \frac{\partial k}{\partial y} = 0, \quad \frac{\partial e}{\partial y} = 0 \]  
(20)

Slag top surface:
\[ \frac{\partial k}{\partial y} = 0, \quad \frac{\partial e}{\partial y} = 0 \]  
(21)

Molten metal pool top surface:
\[ k = c u_0^2, \quad e = \frac{k^{3/2}}{l_f R_0} \]  
(22)

3.1.5. Description of Inclusion Motion
The equation of motion of an inclusion is solved using a time-stepping technique that advances the inclusion along its trajectory. It involves an adaptive determination of the size of the time step to account for large differences in buoyancy and drag forces within the slag and metal pools experienced by the inclusion. This enables tracking the behavior of inclusions of a wide range of densities and sizes in an efficient manner. Hence, the instantaneous flow and temperature fields in the ESR system at the time an inclusion enters the molten pool are used in calculating its behavior.

4. Results and Discussion

4.1. Macrosegregation Analysis
The concentrations and distribution of alloying elements in the transverse section of the ingots could be obtained directly by original position analysis (OPA). The 2D contour maps of carbon distribution scanned by OPA in the same transverse section of ingots produced through ESR and ESR-CDS process respectively were shown in Fig. 2. The different colors of label in the Fig. 2 indicate the concentration of the element qualitatively. The degree of the carbon contents in ingots was represented by different colors, which increases with the transition of colors change from cold to warm. Therefore, the red and pink regions in Fig. 2 indicate the areas of maximum carbon content, whereas the yellow and purple parts indicate the areas of minimum carbon content. Thus, the color contrast could stand for degree of carbon segregation. It can be seen by comparing Figs. 2(a) and 2(b) that more uniform distribution of carbon and less segregation were achieved in the case of the ingot subjected to the ESR-CDS process.

The segregation of carbon is beneficial to the formation of carbides and alloying elements during solidification should be reduced through ESR-CDS process. The prediction was verified later in this paper.
4.2. Microstructure and Carbide Segregation

The microstructure morphology of cross section and longitudinal section of the ingot produced through ESR and ESR-CDS process are presented in Figs. 3 and 4, respectively. Among them, Figs. 3(a) and 4(a) shows that the morphology of dendrite in ingot remelted through traditional ESR process. Figures 3(b) and 4(b) exhibit fine microstructure of as-cast ingot produced by ESR-CDS process. The comparison of microstructures in cross section (Fig. 3) reveals that dendritic grains (Fig. 3(a)) in the central region of ingot are well-developed, but obviously refined (Fig. 3(b)) with the effect of directional solidification. Meanwhile, along the longitudinal section, the contrast of Figs. 4(a) and 4(b) illustrates that coarse dendrites (Fig. 4(a)) grows with different directions and tends to translate from columnar to equiaxed grain in the center of ingot, but those (Fig. 4(b)) are prone to develop in a relatively organized way and grow with columnar grain parallel to the axis of ingot under the effect of directional solidification.

Compared to traditional ESR process, the directional solidification of ESR-CDS process has following advantages: (1) shorter local solidification time caused by shallow molten pool; (2) larger cooling rate controlled by external conditions; (3) larger temperature gradient in metal molten pool; (4) larger concentration gradient at the solid/liquid interface. The four factors above could result in the finer microstructure in ingot S2 produced by ESR-CDS process in comparison with ingot S1 produced by ESR process. The difference of these characteristic (i.e. the direction of thermal flow, the temperature gradient of solidification front and the solidification rate) between ESR and ESR-CDS process were detail discussed in section 4.4. It is obviously seen that the dendrites morphology and dendrite spacing all could be refined through directional solidification in ESR-CDS process.

The primary dendrite arm spacing, secondary dendrite arm spacing as well as growth direction of columnar grain are important parameters to characterize the quality of electroslag remelting process. Moreover, dendrite spacing could be used to characterize micro-segregation in the ingot. Thus, the primary dendrite arm spacings (d_I) and secondary dendrite arm spacing (d_{II}) in longitudinal section of ingot...
were used to evaluate the microstructure in this study. The dendrite spacings were conducted in a statistical averaging way to prevent randomness. The schematic diagram of dendrite arm spacing measuring method and correspondingly statistical results are shown in Fig. 5. It is obvious seen that dendrite arm spacing were refined remelted through ESR-CDS process. As known, there was a quantitative relationship between dendrite arm spacing and local solidification time, which indicated that the ingots had similar local solidification time except the edge chill zone during ESR-CDS process. This indicated that the molten pool was shallow, and subsequent segregation of alloying element could be effectively reduced in ESR-CDS process.

During solidification, the segregation degree of alloying elements and dendrite spacing were refined by the higher cooling rate during ESR-CDS process. Therefore, precipitation of carbides in the solute atom-rich region logically should be alleviated. To confirm this opinion, the precipitated carbides in ingots were characterized by image analysis software. The statistic results were listed in Table 4 and the distribution of carbides were shown in Fig. 6. The type of carbides in ingots S1 and S2 could be divided into two categories: the first type (designated as “I”) was MC-type carbides which were vanadium-rich containing a certain amount of Cr and Mo elements; the other type (designated as “II”) was M2C-type carbides which were molybdenum-rich containing a certain amount of Mn, Cr and V elements.

The characteristic parameters included in Table 4 are as follows: volume fraction \( V_v \); the number of carbides per unit volume \( V_N \); the average diameter of carbides \( D \); length \( l \) and width \( w \) of the carbides; length \( L \) and width \( W \) of the metallography; the number \( N \) of carbides; the area \( A \) of carbides; the average diameter \( D \). Comparing characteristic parameters of carbides in Table 4, it could be found not only the amount but also the size of carbides decreased when using ESR-CDS process. The dendritic arm spacing in ESR-CDS is smaller than that in ESR, resulting in the interdendritic segregation of solute atom in ESR-CDS is lighter than that in ESR. The precipitation of carbides is related to the degree of local solubility, and the uniform distribution of the solute atoms change the thermodynamic condition of carbides precipitation, which results in decreasing of the amount of precipitate carbides in ESR-CDS. The cooling rate in ESR-CDS is larger than that in ESR, resulting in the solidification time in ESR-CDS is much shorter than that in ESR. The short solidification time is insufficient for the diffusion of atom, which would lead to the size of the carbides became small. This illustrated that the microstructure with small size and dispersed distribution of carbides can be obtained by ESR-CDS process.

### 4.3. Number and Size Distribution of Inclusions

The key factor to obtain high-quality steel is not only the refinement of composition and solidified structure, but also the highly removal efficiency of inclusion. As known, inclusion easily initiates micro-voids and cracks at interface between inclusions and steel, which might be the origins of fatigue fractures or other defects, and it is not the exception for the ESR ingot. Thus, the size and distribution of inclusion...
The contents of sulfur and oxygen in S2 ingot listed in Table 1 are partly decreased in ESR-CDS process. Meanwhile, the contents of all other elements are almost constant. To illustrate the removal efficiency of inclusions in ESR and ESR-CDS process, the inclusions in ingots were counted. The morphology and distribution of inclusions was shown in Fig. 7 and the element mappings of typical inclusions were presented in Fig. 8. The characteristics of particles and correspondingly calculated results were listed in Table 5. Where, \( N_A \), the total number of particles per unit area; \( \bar{d} \), average diameter of particles in cross section; \( f_A \), the area fraction of particles. The particles in ingots were MnS inclusion and Oxide inclusion containing alumina oxide and rare earth oxide. It can be clearly seen from Table 5, the total number and average diameter of MnS particles are obviously reduced from 689 and 2.28 \( \mu \)m in S1 ingot to 78 and 1.78 \( \mu \)m in S2 ingot, respectively. Meanwhile, the number of MnS particles with size > 3 \( \mu \)m is reduced from 15.67% in S1 ingot to 1.28% in S2 ingot, and that with size 1–2 \( \mu \)m is increased from 49.93% in S1 ingot to 67.95% in S2 ingot. Therefore, these variation in inclusions indicated that the removal efficiency of inclusion can be promoted through ESR-CDS process compared to traditional ESR process.

4.4. Numerical Simulation of Solidification in Mushy Zone

Within the remelting process, the metal pool is solidified directionally that results in uniform and relatively fine dendritic structure. The dendritic structure is mostly influenced by the cooling rate, temperature gradient ahead of the crystallization front, and the intensity of interdendritic flow in the process. With the increasing of cooling rate, the local solidification time decreases and the mushy zone becomes thinner. To investigate the solidified conditions in ESR and ESR-CDS process, the numerical simulation calculated by Melt-Flow ™ software was applied to analyze the temperature fields and velocity fields.

The pool profiles in different remelting process are shown in Fig. 9. The mushy zone and solidified ingots could be clearly recognized. The liquidus and solidus maximum depth are 67 mm and 250 mm individually in ESR process. However, the maximum depth of solidified pool in ESR-CDS process are 50 mm and 180 mm, which decreases by 25.4% and 28.0% compared with same conditions in ESR process, respectively. Thus, the two-phase zone crystallized from liquid to solid becomes narrower in ESR-CDS process. It is obviously that the shape of metal pool profile would be shallow and flat remelting through ESR-CDS process. In conclusion, shallow and flat molten pool could be obtained during the ESR-CDS process by controlling the direction of thermal flow, the temperature gradient of solidification front and the rate of solidification.

The distribution of temperature field in ESR and ESR-CDS process are displayed in Fig. 10. The temperature gradient of ingot in ESR-CDS process is evidently larger than that in ESR process.
than that in ESR process. This difference indicated that spraying secondary aerosol cooling water in ESR-CDS process could improve intensity and change direction of heat transformation, thus controlling the growth direction of columnar grains to parallel to the axis of ingot and refining the microstructure (Fig. 4). Moreover, carbides precipitated along grain boundaries could be always reduced by smaller segregation degree of solute atoms in inter-dendrites (Fig. 6). In conclusion, microstructure in terms of columnar grains and precipitated carbides could be refined remelting through ESR-CDS process.

Directional solidification of remelting could not only refine the microstructure and carbides in ingot, but also improve the removal of inclusions and harmful elements in electrode. The velocity fields and inclusion motion in liquid fraction fields in ESR and ESR-CDS process are presented in Fig. 11, respectively. Information about the behavior of inclusions and the trajectories of all inclusions at the time instant are noticed in the slag pool and metal pool. Colors related to red, green, blue, yellow, and cyan are used for trajectories of different particle density ratios that inclusion compared to metal. The flow in the middle of the slag pool during ESR-CDS process becomes stronger than that during ESR process. This stronger flow would improve the interaction between inclusion and slag. It can be seen that a large proportion of the inclusion with relative density of 0.5 could be improved remelting through ESR-CDS process. The renewal rate of the metal film surface would be higher due to the washing by stronger slag flow with the increasing of temperature gradient in metal pool controlled by ESR-CDS. The migration speed of inclusions from the inside of liquid metal to the steel-slag interface is determined by the renewal rate of the metal film surface. Consequently, the interaction frequency between slag and inclusion in liquid metal film (i.e., the opportunity for inclusions to directly contact with molten slag) in ESR-CDS process is much higher than that in ESR process, which is beneficial to inclusion removal.

It has been widely confirmed that most of original inclusions in the consumable electrode could be removed during the formation and the falling of the metal droplets. Inclusions in the final ingot are the newly precipitated inclusions due to the partial segregation of elements at solidifying front during the solidification of liquid steel in the water-cooled mold. During the solidification of liquid metal, the number and size distribution of inclusion would be different in ingots controlled by different cooling rates. The newly inclusions formed in residual liquid during solidification can be removed by floating up, and thereafter absorbed by the slag at slag-metal pool interface. As known, density ratios of particles MnS and Al₂O₃ compared to molten metal are similar to 0.5. It can be concluded combining the results in Table 5 and Fig. 11 that removal of inclusions reacting between slag and metal in ESR-CDS process is larger than that in ESR process.

Compared to ESR process, the microstructure of ingot controlled by the ESR-CDS process were summarized as follows: the dendrites with compact columnar grain parallel to axis of ingot; carbides precipitated with smaller size and distributed more uniform and dispersed; ingot with less non-metallic inclusions. These results can be attributed to the different solidification path and the schematic diagrams of the solidification path in ESR and ESR-CDS process are shown in Fig. 12. The mechanism for refinement of structure and removal of inclusions can be concluded as follows.

Firstly, as shown in Fig. 12, the size of formed metal droplet on the consumable electrode tip becomes smaller when remelting through ESR-CDS process. The shape of electrode tip remelting in industrial experiment were presented in Fig. 13. According to the Stokes equation:

\[ v = \frac{2gr^2 (\rho_{\text{metal}} - \rho_{\text{slag}})}{9\eta} \] 

Where, \( v \), the falling velocity of metal droplet in slag pool; \( g \), the gravitational acceleration; \( r \), the radius of metal drop; \( \rho_{\text{metal}} \), the metal liquid density; \( \rho_{\text{slag}} \), slag liquid density respectively; \( \eta \), dynamic viscosity of slag liquid.

It is known that the density difference between liquid metal and slag (\( \rho_{\text{metal}} - \rho_{\text{slag}} \)) could be considered as a physical constant value, then the falling velocity of metal droplet.
Based on Eq. (23) the smaller radius of metal droplet is, the lower the velocity falls in slag pool and the larger the specific surface area is. This indicated that the small metal droplet has more time to travel through the molten slag pool. Thus, the metallurgical reactions time between metal droplets and molten slag increases with the decrease of the droplet radius. Moreover, impurity elements as well as non-metallic inclusions are easier to wipe out due to its large ratio surface area. Analysis above are conducive to the removal of inclusions.

Secondly, the shape of the molten metal pool changes from a deep V-shape to shallow and flat shape controlled by spraying secondary cooling water in ESR-CDS process. Meanwhile, the single vertical falling path of droplets in ESR could be changed to the multiple routing paths in ESR-CDS. This uniform heat source is beneficial to form the shallow and flat molten pool. This pool tends to grew primary dendritic axis in the axial direction because of the growth in other directions was restrained. The columnar grain parallel to axis of ingot could avoid the formation of closed mushy zone shown in Fig. 12(a), and present better hot forging performance. Furthermore, a deep V-shape molten pool generally leads the local crystal growth direction of liquid steel to grow radially. Thus, the inclusions would be wrapped into the molten pool by dendrites in converging columnar grains at the solidification front, which is adverse to the flotation removal of inclusions. Whereas, the compact and paralleled columnar obtained through ESR-CDS process is beneficial to the flotation removal of inclusions.

In addition, uniform and finer microstructure as well as carbides with small size and dispersed distribution could always be obtained through ESR-CDS process. As known, secondary dendritic arm spacing (SDAS) is an important parameter to evaluate the as-cast ingot microstructure, which related to composition segregation and the size, quantity and distribution of the precipitates in the interdendritic region of ingot. Flemings revealed that the local solidification time (LST), mushy zone withy and dendritic axial spacing can be calculated as follows:

$$LST = \frac{X_r}{v_r} \quad (24)$$

$$v_r = \frac{v_M \times \cos \theta}{X_r} \quad (25)$$

$$\log d = k_1 + k_2 \log LST \quad (26)$$

(LST, the local solidification time, min; \(X_r\), the width of the mush zone, mm; \(v_r\), the local solidification velocity, mm/min; \(d\), the dendritic axial spacing, \(\mu\)m; \(k_1\) and \(k_2\), the alloy componential parameters). The geometric relation is explained in Fig. 14. Shi et al. revealed that the precipitation of newly inclusions depends on the segregation degree of elements at solidifying front of the solid-liquid interface during solidification. The segregation degree of elements is related to the rate of solidification at the bottom of shallow liquid metal pool during remelting process. LST can be reduced by these methods such as: reducing the width of mushy zone, increasing the local solidification rate and improving temperature gradient. Combining experimental results and numerical simulation, spraying secondary cooling water in ESR-CDS process could reduce the width of mushy zone and improve the local solidification rate of molten steel. The number of newly precipitated inclusions in the solidified process was reduced, which indicated direc-
tional solidification in remelting could effectively improve the removal efficiency of inclusions. In conclusion, the ESR-CDS process can not only refine the microstructure and reduce the segregation of elements, but also inhibit the precipitation of carbides and newly inclusions in ingot.

5. Conclusions

In this paper, the effect operating conditions (i.e., ESR and ESR-CDS) on the steel cleanliness, segregation of alloying elements, motion of inclusions and solidified microstructure as well as precipitated carbides, especially the removal efficiency of inclusions were investigated. The following conclusions can be drawn from the present study:

1. Compared to traditional ESR process, ESR-CDS process is more favorable to eliminate macrosegregation of alloying elements, obtain a more uniform and refined microstructure as well as carbides. Meanwhile, the growing direction of columnar grains with smaller dendritic spacing is almost parallel to the axis of ingot produced by ESR-CDS.

2. The finer primary carbides and more uniform distribution of carbides can be obtained when remelting using ESR-CDS process. The average secondary dendritic spacings controlled through ESR-CDS process are 36 μm, while those in ESR ingot are about 80 μm.

3. Removal efficiency of inclusions in ESR-CDS process is higher than that in ESR process, especially the removal of MnS particles. The total number and the average diameter of MnS particles are obviously reduced from 689 and 2.28 μm in S1 ingot to 78 and 1.78 μm in S2 ingot, respectively. Meanwhile, the number of MnS particles with size >3 μm is reduced from 15.67% in S1 ingot to 1.28% in S2 ingot, and that with size 1–2 μm is increased from 49.93% in S1 ingot to 67.95% in S2 ingot.

4. Combining with the numerical simulation and experimental results, the shape of molten metal pool in ESR-CDS process becomes shallow and flat, and temperature gradient in ESR-CDS ingot is remarkable larger than that in ESR ingot. It is favorable to reduce the segregation, refine microstructure and carbides. Meanwhile, the removal efficiency of inclusions in ESR-CDS process is larger than that in ESR process.

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List of symbols:

- \( B \): Magnetic flux density (T)
- \( H \): Magnetic field intensity (A m\(^{-1}\))
- \( J \): Current density (A m\(^{-2}\))
- \( F \): Lorentz force (N/m\(^2\))
- \( S \): Source term
- \( C_0 \): Initial concentration (wt.%)
- \( \rho_c \): Liquid fraction
- \( H_0 \): Complex amplitude (A/m)
- \( \bar{I} \): Root mean square of the current (A)
- \( \bar{J} \): Current density (A/m\(^2\))
- \( L \): Latent heat (J/Kg)
- \( P \): Pressure (Pa)
- \( T \): Temperature (K)
- \( T_{ref} \): Reference temperature (K)
- \( \mu \): Turbulent viscosity (Pa s)
- \( \mu_l \): Laminar viscosity (Pa s)
- \( \phi \): density (Kg/m\(^3\))
- \( \bar{v} \): Velocity (m/s)
- \( k \): Turbulent kinetic energy (m\(^2\) s\(^{-2}\))
- \( \varepsilon \): Dissipation rate of turbulent kinetic energy (m\(^2\) s\(^{-3}\))
- \( \sigma_t \): Turbulent Prandtl numbers for \( k \) (1.0)
- \( \sigma_e \): Turbulent Prandtl numbers for \( \varepsilon \) (2.0)
- \( G \): Generation of turbulence kinetic energy due to the mean velocity gradients (Pa s)
- \( C_p \): Specific heat of slag (J kg\(^{-1}\) K\(^{-1}\))
- \( g \): Gravity (m/s\(^2\))
- \( r \): Radius (m)

REFERENCES

1. J. Y. Li, Y. L. Chen and J. H. Huo: Mater. Sci. Eng. A, 640 (2015), 16.
2. C. S. Xie, P. Z. Sun and J. S. Zhao: Mater. Sci. Eng. A, 124 (1990), 203.
3. G. A. Baglyuk, V. N. Terekhov and Y. F. Ternovoi: Powder Metall. Met. Ceram., 45 (2006), 317.
4. X. C. Wu, H. Jiang and L. P. Wang: Iron Steel Res. B, 23 (2011), 25.
5. Z. S. Wang, X. Chen, Y. X. Li, H. W. Zhang and Y. Liu: Acta Metall. Sin., 51 (2015), 519.
6. X. Chen, Z. S. Wang, Y. X. Li, H. W. Zhang and Y. Liu: China Foundry, 13 (2016), 1.
7. D. W. Hetzner: Mater. Charact., 46 (2001), 175.
8. J. Lan, J. J. He, W. J. Ding, Q. D. Wang and Y. P. Zhu: ISIJ Int., 40 (2000), 1275.
9. Y. K. Luan, N. N. Song, Y. L. Bai, X. H. Kang and D. Z. Li: J. Mater. Process. Technol., 210 (2010), 536.
10. Q. Wang, H. G. Yan, F. Wang and B. K. Li: JOM, 67 (2015), 1821.
11. Y. W. Dong, Z. H. Jiang, Z. X. Xiao and Z. B. Li: J. Northeast. Univ., 30 (2009), 1598.
12. B. Podgornik, V. Leskoviček, M. Godec and B. Senčič: Mater. Sci. Eng. A, 599 (2014), 81.
13. W. M. Li, Z. H. Jiang, X. M. Zang, X. Deng, H. Y. Qi and G. Wang: Proc. 2017 Int. Symp. on Liquid Metal Processing and Casting, TMS, Pittsburgh, PA, (2017), 85.
14. Q. T. Zhu, J. Li, C. B. Shi, W. T. Yu, C. M. Shi and J. H. Li: Int. J. Mat. Res., 108 (2017), 20.
15. S. H. Suh and J. Choi: ISIJ Int., 26 (1986), 305.
16. X. Chen, Z. H. Jiang, F. B. Liu, J. Yu and K. Chen: Steel Res. Int., 88 (2017), 188.
17. Q. Wang and B. K. Li: Appl. Therm. Eng., 91 (2015), 116.
18. A. Kharicha, A. Ludwig and M. Wu: Mater. Sci. Eng. A, 413 – 414 (2005), 129.
19. Q. Wang, H. Cai, L. P. Pan, Z. He, S. Liu and B. K. Li: JOM, 68 (2016), 1343.
20. X. F. Shi, L. Z. Chang and J. J. Wang: Int. J. Min. Metall. Mater., 22 (2015), 1033.
21. V. I. Chumanov and I. V. Chumanov: Russ. Metall., 66 (2010), 499.
22. X. M. Zang, Z. H. Jiang and T. Y. Pan: J. Univ. Sci. Technol. Beijing, 14 (2007), 302.
23. D. Alghisi, M. Milano and L. Piazzena: Metall. Ital., 1 (2005), 21.
24. R. Fu, F. L. Li, F. J. Yin, D. Feng, Z. L. Tian and L. T. Chang: Mater. Sci. Eng. A, 638 (2015), 152.
25. F. L. Li, R. Fu, D. Feng, F. J. Yin and Z. L. Tian: Rare Met. Mater. Eng., 45 (2016), 1437.
26. C. J. O’Connell, J. J. deBarradillo, D. G. Evans, R. S. Minisandram, R. H. Smith, J. M. Yanke, E. M. Taleff, T. A. Ivanoff, K. M. Kelkar, W. Hutchison and M. Benedict: Proc. 2017 Int. Symp. on Liquid Metal Processing and Casting, TMS, Pittsburgh, PA, (2017), 93.
27. K. M. Kelkar, S. V. Patankar, S. K. Srivatsa, R. S. Minisandram, D. G. Evans, J. J. deBarradillo, R. H. Smith, R. C. Helmink, A. Mitchell and H. A. Sizkic: Proc. 2013 Int. Symp. on Liquid Metal Processing and Casting, TMS, Pittsburgh, PA, (2013), 3.
28. E. Karimi Sibaki, A. Kharicha, J. Korp, M. Wu and A. Ludwig: Mater. Sci. Forum, 790–791 (2014), 396.
29. M. C. Flemings: Solidification Process, Metallurgical Industry Press, Beijing, (1981), 104 (in Chinese).
30. C. B. Shi, X. C. Chen, H. J. Guo, Z. J. Zhu and H. Ren: Steel Res. Int., 83 (2012), 472.