Original Article

Cleanliness improvement and microstructure refinement of ingot processed by vacuum electroslag remelting

Yu Liu, Xijie Wang, Guangqiang Li, Xuechi Huang, Qiang Wang, Baokuan Li

The composition analysis, inclusion and microstructure characterizations for two ingots processed by Ar gas protective electroslag remelting (ESR) and vacuum ESR as well as thermodynamic calculation were carried out to explore mechanisms of cleanliness improvement and microstructure refinement of ingot processed by vacuum ESR. The results show that compared with the ingot processed by Ar gas protective ESR, the Al pickup in ingot processed by vacuum ESR is less due to the lower $\text{Al}_2\text{O}_3$ activity in molten slag resulted by fluoride vaporization from molten slag. During Ar gas protective ESR, only Al deoxidation occurs in molten steel. But, the new equilibriums among liquid steel, inclusions and gas phase are established, and C deoxidation could occur upon $1635^\circ\text{C}$ during vacuum ESR. The inclusions size in vacuum ESR ingot is finer because the time for $\text{Al}_2\text{O}_3$ inclusion growth is shorter. The C deoxidation and less steel reoxidation resulted by slag-steel interaction during vacuum ESR contributes to the lower oxygen content in vacuum ESR ingot. Furthermore, because of more uniform temperature distribution in molten slag pool, the smaller SDAS is acquired in vacuum ESR ingot. The higher cleanliness, microstructure refinement and smaller size of carbides contribute to the performance improvement in vacuum ESR ingot.

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1. Introduction

The inclusion has a harmful effect on the performance of steel, especially the large size inclusion, which dramatically degrades the toughness and strength of steel [1–3]. In order to
ensure running reliability, the cleanliness is highly demanded for the high-end alloy steel serving in harsh environment for a long time, namely, the total oxygen content and inclusion size in the steel should be strictly controlled. To reduce the total oxygen content of steel, vacuum carbon deoxidation treatment is adopted for the high-quality alloy steels [4]. The drawback of vacuum carbon deoxidation is that accidental large-size inclusions could not be eliminated.

Electroslag remelting (ESR) has the absolute advantages in the removal of large-size inclusions, thus, which is widely applied in the production of high-end alloy steels [5]. However, the oxygen content of ingot processed by conventional ESR may increase due to the surface oxidation of electrode [6]. During the inert atmosphere protective ESR process, the increase of oxygen content in ingot caused by the surface oxidation of electrode can be avoided [1]. Nevertheless, it is still very difficult to reduce the oxygen content in steel to the relatively low level [7–9], because the components in the slag that are stable at 1600 °C become unstable at the slag pool temperature of ESR, such as Al2O3 [9], which is commonly used in the ESR slag. It is possible to reduce the oxygen content in ESR ingot by adding the deoxidizer to slag under inert atmosphere [10], but this method bring in new brittle inclusions and also increases the deoxidizing element content in steel. It has been reported that vacuum is beneficial to deoxidation by the interaction between molten slag and liquid steel [11,12]. Combining the vacuum condition and ESR process, the vacuum ESR process is expected to give full play to the advantages of the vacuum carbon deoxidization without formation of inclusions and ESR that can effectively remove large inclusions. Furthermore, from the view of thermodynamics, the C-O reaction under vacuum will be promoted at higher temperatures. The slag pool temperature of ESR is higher than conventional steelmaking temperature, which provides better thermodynamic condition for the C-O reaction under vacuum. In addition to cleanliness, the microstructure of ingot also has a fatal influence on the performance of steel [13–15], such as the secondary dendrite arm spacing, has a great influence on microsegregation [16]. The fluoride vaporization from fluoride containing slag will become severer, which is a great challenge for realizing vacuum ESR. To ensure the smooth operation of vacuum ESR, the vaporization behavior of slag used for ESR has been studied in our previous study, providing a reference for the selection of slag for vacuum ESR [17]. However, the mechanisms of deoxidation and inclusion removal from liquid steel, and the evolution of microstructure characteristics during vacuum ESR process have not been clarified and the relevant reports are very scarce.

Because of these factors, the authors were motivated to experimentally explore the underlying mechanism of the cleanliness improvement and evolution of microstructure characteristics of ingot processed by vacuum electroslag remelting. The subtle differences on compositions, inclusions characteristics and microstructure characteristics of two ingots processed by Ar atmosphere protective ESR and vacuum ESR were compared. This work was designed to provide the fundamental knowledge for preparation of ultra clean ingots by vacuum ESR.

![Fig. 1 – Schematic drawing of vacuum ESR furnace.](image)

### Table 1 – Chemical composition of the consumable electrode (wt.%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
<th>T.O</th>
<th>T.N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.603</td>
<td>0.96</td>
<td>0.35</td>
<td>5.11</td>
<td>0.12</td>
<td>0.81</td>
<td>0.21</td>
<td>0.016</td>
<td>0.0022</td>
<td>0.0089</td>
</tr>
</tbody>
</table>

### 2. Experiment

#### 2.1. Experimental apparatus and method

A 200-kg scale vacuum ESR furnace (Zhuoxing Metallurgical Technology, China) was employed to remelt the alloy steel under different atmosphere conditions. The schematic diagram of experimental apparatus is shown in Fig. 1. The inner diameter of the copper mold is 200 mm. The diameter and length of consumable used in each heat is 120 mm and 1000 mm, respectively. The chemical composition of consumable electrode is listed in Table 1. The oxide scale on the electrode surface was basically removed mechanically before ESR experiments.

To decrease the effect of fluoride vaporization from slag on the vacuum ESR process, the vacuum pressure was set to 20 kPa. Two heats were carried out under Ar atmosphere with a flow of 10 l/min and vacuum condition of 20 kPa, respectively. The composition of slag determined by X-ray fluorescence (XRF; model: ARL9900; Thermo Fisher, USA) and carbon sulfur analyzer (model: CS844; LECO, USA) is 42.9 wt% CaF2, 28.8 wt% CaO, 27.1 wt% Al2O3, 0.4 wt% SiO2 and 0.5 wt% FeO and 0.3 wt% C, which was roasted at 300 °C for 10 h before each heat. Approximately 8 kg slag was added into the furnace in each heat. To prevent the damage to the water-cooled baseplate during arc initiation, a round steel sheet with the diameter of 190 mm and thickness of 20 mm was placed on the water-cooled baseplate. In each heat, the AC current and voltage were kept at approximately 3100 A and 38 V, respectively.
2.2. Specimen preparation and analyzing methods

After remelting, the thickness of two slag caps were measured for assessing the fluoride vaporization during Ar protective ESR and vacuum ESR, which are about 80 mm and 75 mm, respectively. Two ingots were obtained, and equally split into two parts along the longitudinal by using wire-electrode cutting, as shown in Fig. 2. The slice was taken near the upper third of the ingot, because in general, the upper part possesses the relatively poor metallurgical quality. Then the specimens for analysis were sampled at the center of the slices taken from the ingots processed by Ar gas protective ESR and vacuum ESR, and indicated as Ar-ESR ingot and vacuum-ESR ingot, respectively. The carbon, soluble aluminum, soluble silicon and oxygen contents of the steel specimens were determined by the carbon sulfur analyzer, ICP-AES (model: DGS-III; Tailun, China) and the oxygen nitrogen analyzer (model: TC500; LECO, USA). The size, morphology and composition of inclusions and carbides in the specimens were analyzed by a field emission scanning electron microscope (FE-SEM; Model: Nova 400 Nano; FEI, USA) equipped with energy dispersive spectrometer (EDS; Model: Le350 PetaFETx-3; Oxford Instruments, UK). To observe the three-dimensional morphology of carbides, the steel specimen was dissolved in the HCl solution (volume ratio of water with concentrated hydrochloric acid = 1:1) for extraction of carbides. To study the differences on the microstructures of two ingots, the specimens were etched at 80 °C in 4 vol.% nital solution for metallographic observation by optical microscope (OM; model: DSX510; Olympus, Japan). The micro-tensile tests were carried out for the measurement of tensile properties of samples.

Table 2 – Carbon, aluminum, silicon and oxygen contents in samples (wt.%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Al</th>
<th>Si</th>
<th>TO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td>0.603</td>
<td>0.016</td>
<td>0.96</td>
<td>0.0022</td>
</tr>
<tr>
<td>Ar-ESR ingot</td>
<td>0.621</td>
<td>0.051</td>
<td>0.85</td>
<td>0.0038</td>
</tr>
<tr>
<td>Vacuum-ESR ingot</td>
<td>0.607</td>
<td>0.027</td>
<td>0.93</td>
<td>0.0016</td>
</tr>
</tbody>
</table>

consumable electrode, the Al contents in both ingots increase, but the Si content shows the opposite trend, decreases in two ESR ingots, which agrees well with the previous results [7,8]. In the present study, the Al content in the consumable electrode and the activity of SiO$_2$ in molten slag are relatively low, which leads to the Al pickup in both ingots by reaction (1) as follows [7,8]:

$$3\text{[Si]} + 2\text{(Al}_2\text{O}_3)_{\text{slag}} = 4\text{[Al]} + 3\text{(SiO}_2)_{\text{slag}}$$

The Gibbs free energy change for reaction (1) regarding the present ESR trials can be calculated by following Eq. (2):

$$\Delta G = \Delta G^0 + RT \ln \frac{a^4_{\text{Al}} \cdot a^2_{\text{SiO}_2}}{a^3_{\text{Si}} \cdot a^2_{\text{Al}_2\text{O}_3}} = \Delta G^0 + RT \ln \frac{(f_{\text{Al}} \cdot %\text{Al})^4 \cdot a^2_{\text{SiO}_2}}{(f_{\text{Si}} \cdot %\text{Si})^3 \cdot a^2_{\text{Al}_2\text{O}_3}}$$

where $\Delta G$ is the Gibbs free energy change (J mol$^{-1}$), $\Delta G^0$ is the standard Gibbs free energy change (J mol$^{-1}$), $R$ is ideal gas constant (8.314 J mol$^{-1}$ K$^{-1}$), $a_{\text{SiO}_2}$ and $a_{\text{Al}_2\text{O}_3}$ are the activities of SiO$_2$ and Al$_2$O$_3$ in slag, respectively. $f_{\text{Al}}$ and $f_{\text{Si}}$ are the activity coefficients of dissolved alumina and silicon in liquid steel, respectively, and can be expressed by the following Eq. (3) [18]:

$$\lg f_{\text{Al}} = \sum \varepsilon^i_j [\%]$$

where $\varepsilon^i_j$ is the interaction parameters between element $i$ and $j$ in liquid steel, and the corresponding values at 1600 °C is listed in Table 3 [18,19].
Table 3 – The activity interaction parameters of elements in liquid steel at 1600 °C.

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.14</td>
<td>0.08</td>
<td>−0.012</td>
<td>−0.024</td>
<td>0.12</td>
<td>−0.0083</td>
<td>−0.077</td>
<td>0.043</td>
</tr>
<tr>
<td>Si</td>
<td>0.18</td>
<td>0.11</td>
<td>0.002</td>
<td>−0.0003</td>
<td>0.005</td>
<td>0.025</td>
<td>0.058</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0.091</td>
<td>0.056</td>
<td>−0.035</td>
<td>0.012</td>
<td></td>
<td>−0.0173</td>
<td>0.043</td>
<td></td>
</tr>
</tbody>
</table>

The activities of oxide components in molten slag can be calculated using the reported activity model (for details of the modeling and solution produce, see Ref. [20,21]) based on the ion and molecule coexistence theory (IMCT) [20–23]. The calculated activity of SiO2 in the slag used in present tests is less than 0.0001, and the Al2O3 activity is 0.0146 at 1600 °C. Combining Eqs (2,3), the value of standard Gibbs free energy change [24] and interaction parameters listed in Table 3, the Gibbs free energy change for reaction (1) was calculated to be less than -96.9 kJ/mol at 1600 °C, which is much less than 0 kJ/mol. It indicates that the reaction (1) can occur. It should be noted the current calculated Gibbs free energy change is only the value at 1600 °C, and the value at higher temperature cannot be obtained due to the limitation of thermodynamic data. Al2O3 is relatively stable at conventional steelmaking temperature, while the slag pool temperature of ESR is above 1750 °C [5], at which temperature the stability of Al2O3 would decrease [9]. It implies that the reaction (1) is more likely to occur at the slag pool temperature of ESR.

Compared with the Ar-ESR ingot, the Al content in vacuum-ESR ingot is lower, which is attributed to the changes in composition of molten slag under vacuum. At the elevated temperature, the CaF2 and Al2O3, as the slag components, easily react to form AlF3 and CaO by reaction (4) [17].

\[
3(\text{CaF}_2) + (\text{Al}_2\text{O}_3) = 3(\text{CaO}) + 2\text{AlF}_3 (g)
\] (4)

As the reaction (4) proceeds, the CaO content in molten slag increases, but the Al2O3 content decreases. The activity of Al2O3 in molten slag gradually decreases during ESR process. Under Ar atmosphere, the rate of fluoride vaporization is slow, and composition of slag and the activity of Al2O3 in molten slag changes slightly. Whereas, the fluoride vaporization becomes severer under vacuum, which increases the CaO content and decreases Al2O3 content in molten slag further. The activity of Al2O3 in molten slag is lower in the case of vacuum ESR, and the driving force for reaction (1) decreases. The Al pickup is less in vacuum-ESR ingot due to the lower Al2O3 activity resulted by fluoride vaporization from molten slag.

Meanwhile, it is well known that the total oxygen in steel contains the dissolved oxygen in steel that equilibrated with the deoxidizing elements and the oxygen in the inclusions resulted by deoxidation. The decrease in Si content implies that the steel reoxidation occurs due to the difference in the oxygen potential between liquid steel with ultra low oxygen content and the slag phase [8]. The oxygen supplied by molten slag (O_R) can be roughly estimated by Eq. (5) as follows [2,25]:

\[
O_R = \sum ((M)_{\text{initial}} - (M)_{\text{final}}) \frac{yW_o}{xW_M}
\] (5)

Where M represents dissolved deoxidizing element in molten steel; W_O and W is the atomic weight of oxygen and M, respectively; x and y is the atom numbers of M and O in the stable oxide M_xO_y. According to the changes of Si content in both ingots, the calculated O_R are 1257 ppm and 343 ppm in the test of Ar gas protective ESR and vacuum ESR, respectively. The total oxygen contents in both ingots (Table 2) are much lower than the oxygen supplied by molten slag (O_R), implying that most of the deoxidized products were absorbed by molten slag. Chang et al. confirmed that the steel reoxidation is attributed to the poor stability of Al2O3 in molten slag at the slag pool temperature, and decrease in the Al2O3 activity in molten slag by adding rare earth oxides can reduce the steel reoxidation and the oxygen pickup in ingot [9]. In the test of vacuum ESR, the Al2O3 activity in molten slag is lower, indicating that the steel reoxidation is reduced during vacuum ESR. Thus, the total oxygen content in the vacuum-ESR ingot (16 ppm) is lower than that in the Ar-ESR ingot (38 ppm) (Table 2). Besides the less steel reoxidation resulted by slag-steel interaction under vacuum, the vacuum C deoxidation also contributes to the lower total oxygen in vacuum-ESR ingot, which will be discussed in detail later.

The C contents in both ingots are also higher than the consumable electrode due to the carbon originating from the slag and macrosegregation [26,27] (Table 2), because the slags used in the present experiments were pre-melted by graphite electrode and the pre-melted slag contains a certain amount of carbon. Compared with the Ar-ESR ingot, the C pickup in vacuum-ESR ingot is less due to the consumption of carbon resulted by the C-O reaction under vacuum, which will be discussed in detail in Section 3.2.

3.2. Effect of steel-inclusion-gas phase interaction on oxygen content and inclusion characteristics of ingot during vacuum ESR

Fig. 3 shows the size distribution of inclusions observed in the consumable electrode and ingots processed by Ar gas protective ESR and vacuum ESR. It indicates that the frequency of large-size inclusions (>9 μm), the maximum diameter and average diameter of inclusions in ingots dramatically decrease after ESR. Compared with the Ar-ESR ingot, maximum diameter and average diameter of inclusions in the vacuum-ESR ingot decrease further (Fig. 3b and c). Size of inclusions in ingots processed by vacuum ESR is smaller and more uniform (Fig. 3), and total oxygen content is also lower (Table 2), implying that the higher cleanliness is obtained in the ingot processed by vacuum ESR.

Fig. 4 shows the SEM micrographs of typical inclusions in consumable electrode. It indicates that oxide inclusions are mainly Al-Ca-Mg-Si oxide, Al-Ca-Si oxide and Al-Ca-Mg oxide. The SiO2 in oxide inclusions is trace, and the (Ti,V)N and CaS exist at the edge of inclusions (Fig. 4a–c). The single (Ti,V)N inclusions are also found in the consumable electrode (Fig. 4d).
Fig. 3 – Size distribution of inclusions observed in the consumable electrode (a), Ar-ESR ingot (b) and vacuum-ESR ingot (c).

Fig. 4 – SEM images of typical inclusions observed in consumable electrode.

Fig. 5 shows the SEM image and element mappings of the typical inclusion with two-layer structure observed in the consumable electrode. It indicates that the typical inclusions with two-layer structure are Al-Ca-Mg oxides covered with a layer with CaS.

Fig. 6 shows the SEM images of typical inclusions observed in ingots processed by ESR under Ar and vacuum condition. After remelting, the inclusion types in both ingots are similar. The oxide inclusions are mainly Al-Ca-Mg oxide (Fig. 6c,d,g,h). The (Ti,V)N and the inclusions with two-layer structure also exist in both ingot (Fig. 6a,b,e,f). The EDS mappings indicates that the typical inclusions with two-layer structure are Al-Ca oxides covered with (Ti,V)N (Fig. 7). The SiO$_2$ and CaS are not found in both ingots.

There are two sources for inclusions in the ESR ingot, one is the inclusions that in consumable electrode, which are not removed by molten slag. During ESR, the large-size inclusions in consumable electrode can be almost completely removed by the interaction between liquid steel and molten slag, but a few of inclusions with small size can be still remained in the molten steel due to the lower interfacial energy [2,28,29]. The other is the inclusions that newly formed during ESR, which is dominated by the equilibrium between deoxidizing alloy elements and inclusions in liquid steel [29,30]. To study the absence of SiO$_2$ in oxide inclusions of ESR ingot, the thermodynamic calculation was carried out by reaction (6) as follows [8,24]:

$$3[\text{Si}] + 2(\text{Al}_2\text{O}_3)_{\text{inclusion}} = 4[\text{Al}] + 3(\text{SiO}_2)_{\text{inclusion}}$$

$$\log K = 5.6 - \frac{34400}{T}$$  \hspace{1cm} (6)

Where $(\text{Al}_2\text{O}_3)_{\text{inclusion}}$ represents the Al$_2$O$_3$ in inclusion and $(\text{SiO}_2)_{\text{inclusion}}$ represents the SiO$_2$ in inclusion, the activities
of Al₂O₃ and SiO₂ in inclusions are unity (pure solid as the standard state). The activity interaction parameters for activity calculation at different temperatures can be calculated by Eq. (7) [18]:

$$\tilde{a}_{ij}(T) = \frac{1873}{T} \times \tilde{a}_{ij}(1873K)$$  \hspace{1cm} (7)

The equilibriums of Al-Si reaction in liquid steel at different temperatures were calculated by combining the reaction (6), Eq. (7) and the relevant data in Table 3. Fig. 8 shows the Al-Si equilibrium curves at different temperatures for the Al₂O₃ and SiO₂ phases in liquid steel. It indicates that Al has the stronger affinity with O than Si in liquid steel with the same
compositions as ingots during ESR. The trace SiO\textsubscript{2} in the oxide inclusions of consumable electrode is reduced by the Al in molten steel during ESR, thus the SiO\textsubscript{2} are not found in both ingots.

Furthermore, it is well known that the C deoxidation may occur in the liquid steel with a certain C content under vacuum, and do not bring new oxide inclusions into liquid steel, which can markedly improve the cleanliness of steel [11]. To study the C deoxidation from the view of thermodynamics, the equilibriums of Al-C reaction in liquid steel were also calculated. The relevant reactions are as follows [18,19):

\[
[C] + [O] = \text{CO(g)}, \log K = \frac{1168}{T} + 2.07 \tag{8}
\]

\[
3[\text{Al}] + 3[O] = (\text{Al}_2\text{O}_3)_{\text{inclusion}}, \log K = 11.62 + \frac{45300}{T} \tag{9}
\]

The Al-C equilibrium curves at different temperatures for the Al\textsubscript{2}O\textsubscript{3} and CO phases under Ar atmosphere and vacuum were calculated by combining the Eq. (7), reactions (8,9) and the relevant data in Table 3, as shown in Fig. 9. It should be noted that the pressure changes resulted by the molten slag pool has been considered. The pressure resulted by molten slag pool can be calculated by following Eq. (10):

\[
P = \rho \cdot g \cdot h \tag{10}
\]

where \(P\) is the pressure (Pa), \(\rho\) is the density of molten slag (kg·m\textsuperscript{-3}) and \(h\) is the thickness of molten slag (m). The density of slag is about 2800 kg·m\textsuperscript{-3} [5], and pressure resulted by molten slag is about 2 kPa. So the pressure value on thermodynamic calculation of liquid steel-inclusion-gas phase interaction during vacuum ESR is 22 kPa. The Al and C contents for Ar-ESR ingot and vacuum-ESR ingot are also shown as points in Fig. 9. It can be seen from Fig. 9a that only Al deoxidation occurs in molten steel during the Ar gas protective ESR. It implies that Al\textsubscript{2}O\textsubscript{3} inclusions formed by Al deoxidation have more time to grow during ESR, and thus the inclusion size is larger in Ar-ESR ingot. Whereas, the new equilibriums among liquid steel, inclusions and gas phase are established during vacuum ESR (Fig. 9b). Upon 1635 \(\degree\)C, the equilibrium among liquid steel, inclusions and gas phase proceeds in the direction of CO formation. Fig. 10 shows the C-O equilibrium curve for CO phase and Al-O equilibrium curve for Al\textsubscript{2}O\textsubscript{3} phase at 1750 \(\degree\)C. It indicates that the dissolved oxygen content in liquid steel equilibrized with C is 7.1 ppm under vacuum, which is lower than that in liquid steel equilibrized with Al under Ar atmosphere (12.5 ppm). It implies that below 1635 \(\degree\)C, there

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**Figures:**

8. The Al-Si equilibrium curves at different temperatures for the Al\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2} phases in liquid steel.

9. The Al-C equilibrium curves at different temperatures for the Al\textsubscript{2}O\textsubscript{3} and CO phases under Ar atmosphere (a) and vacuum (b).

10. The C-O equilibrium curve for CO phase and Al-O equilibrium curve for Al\textsubscript{2}O\textsubscript{3} phase at 1750 \(\degree\)C.
is less dissolved oxygen in liquid steel to combine with Al to form Al₂O₃ inclusions in the test of vacuum ESR, and the time for inclusion growth is shorter during solidification. Thus, the inclusion size is smaller in vacuum-ESR ingot, and the C and O contents are lower (As mentioned in Section 3.1). The total oxygen content in vacuum-ESR ingot is lower due to the carbon deoxidation and the less steel reoxidation.

3.3. Effect of vacuum on the microstructure characteristics and properties of ESR ingot

The secondary dendrite arm-spacing (SDAS) is an important parameter to evaluate the ingot microstructure. The reduction in the SDAS can relieve the interdendritic composition segregation and dramatically improve the quality of ingot [31]. Fig. 11 shows the optical micrographs of dendrite structure in ingots processed by Ar gas protective ESR and vacuum ESR. It indicates that the SDAS in vacuum-ESR ingot (72 μm) is smaller than that in Ar-ESR ingot (104 μm), implying that the finer microstructure is obtained in the ingot processed by vacuum ESR. The SDAS can be affected by the local solidification rate. The faster the local solidification rate is, the smaller the SDAS is [20]. As shown in Fig. 12, the local solidification rate (v) is perpendicular to the tangent of the solidus curve and has a certain angle (θ) to the axis of the ingot, and the angle (θ) is affected by the shape of liquid metal pool. The remelting rate (v_M) is parallel to axis, which represents the rising velocity of solidus. So the local solidification rate (v) can be calculated using the remelting rate (v_M) as this geometric relation [31]:

\[ v = v_M \times \cos \theta \]  

Fig. 12 – Schematic of solidification interface and the relationship between remelting rate and cooling rate.

In present study, the tests under Ar atmosphere and vacuum are carried out with the same AC current condition. The
Joule heat created by molten slag should be at the same level. The temperature distribution of molten slag that affects the shape of liquid metal pool is the dominant factor to influence the microstructure. During vacuum ESR, the fluoride vaporization from molten slag becomes severer, and the flows in the molten slag pool also become more intense. Thus, the temperature distribution in molten slag pool is more uniform, which is conducive to the transformation of liquid metal pool from V-type to U-type. The liquid metal pool becomes wider and flatter, and the angle (θ) between the grain growth direction and axis decreases. As a result, the smaller SDAS is acquired in vacuum-ESR ingot.

The SDAS has an important influence on the size of primary carbides, which is formed due to the enrichment of solute elements during solidifying. The distribution of interdendritic primary carbides in steel processed by Ar gas protective ESR and vacuum ESR is shown in Fig. 13. It indicates that the area fraction and size of primary carbides in ingot processed by Ar gas protective ESR is larger than that in ingot processed by vacuum ESR. Fig. 14 shows the three-dimensional morphology of primary carbides extracted from steel. The morphology of primary carbides in space is a long chain, and has large size. The EDS results show the carbides consists of Cr, Mo, V, Fe and C. The large-size primary carbides can hardly be eliminated by heat treatment process, which would deteriorate the properties of steel. Different from the distribution of primary carbides, there are more small-size carbides in ingot processed by vacuum ESR, as shown in Fig. 15. The small-size carbides are formed during the cooling process after solidification of liquid steel. The less primary carbides in ingot processed by vacuum ESR implies that less carbon exist in the primary carbides, and more carbon would be retained to form the small-size carbides during cooling after solidification.

The tensile test result show that the tensile strength of steels processed by Ar gas protective ESR and vacuum ESR is 771 MPa and 920 MPa, respectively. Fig. 16 shows the SEM micrographs of fracture surface in steel after tensile test. In the fracture surface of Ar-ESR ingot, there are many hollow cracks, and large carbides are found in the hollow (Fig. 16a,b). In contrast, there are more dimples on the fracture surface of vacuum-ESR ingot. The steel processed by vacuum ESR shows a better performance due to the higher cleanliness, microstructure refinement and smaller size of carbides.

4. Conclusions

Two heats under Ar atmosphere and vacuum were designed to investigate the mechanisms of cleanliness improvement and microstructure refinement of ingot processed by vacuum ESR and the following conclusions can be reached:

1. The Al contents in both ingots increase, resulting from that Si in liquid steel reacts with Al2O3 in molten slag because the activity of Al in liquid steel and the activity of
SiO$_2$ in molten slag are relatively low. Compared with the ingot processed by Ar gas protective ESR, the Al pickup of vacuum-ESR ingot is less because the lower Al$_2$O$_3$ activity in molten slag resulted by fluoride vaporization under vacuum. The less Al pickup in vacuum-ESR ingot also implies that the less steel reoxidation occurs.

(2) After remelting, the differences in the inclusion type of both ingots are little, but the inclusions in ingot processed by vacuum ESR are finer and more dispersed. SiO$_2$ inclusions are not found in both ingots after ESR because the affinity of Al and O in liquid steel is stronger than that of Si and O. During Ar gas protective ESR, only Al deoxidation occurs in molten steel. Whereas, during vacuum ESR, the new equilibriums among liquid steel, inclusions and gas phase are established. Upon 1635 °C, the carbon deoxidation occurs, and the product is gas and no new inclusion are formed. There is less dissolved oxygen in liquid steel combines with Al to form Al$_2$O$_3$ inclusions, and the inclusion is finer due to shorter time for inclusion growth during solidification. The lower oxygen content in vacuum-ESR ingot is attributed to the carbon deoxidation and the less steel reoxidation.

(3) The vacuum ESR process gives full play to the advantages of the vacuum carbon deoxidization without formation of inclusions and ESR that can effectively remove large inclusions. Furthermore, the denser microstructure is acquired in ingot processed by vacuum ESR due to more even temperature distribution in molten slag pool. The higher cleanliness, microstructure refinement and smaller size of carbides contribute to the performance enhancement of ingot processed by vacuum ESR.
Fig. 16 – SEM micrographs of fracture surface in steel processed by (a,b) Ar gas protective ESR and (c,d) vacuum ESR.

Conflict of interest

The authors declare no conflicts of interest.

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