Cleanliness and Control of Inclusions in Al-Deoxidized Bearing Steel Refined by Basic Slags during LF-VD-Ar Bubbling

Min JIANG,1)* Kai-lun LI,2) Rui-gang WANG,2) En-jiao YANG2) and Xin-hua WANG1)

1) School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, 100083 P.R. China.
2) Researcher of Nanjing Iron and Steel Co. Ltd., Nanjing, Jiangsu Province, 210035 P.R. China.

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Cleanliness and control of inclusions in Al deoxidized bearing steel were studied by industrial trials, in which three basic slags were used in the LF-VD-Ar bubbling refining process. With basicity (mass ratio of CaO/SiO2) about 3.9–4.2, 5.2–6.5 and 6.9–7.1 while Al2O3 about 30.9–32.5 mass%, 37.2–40 mass% and 29.8–30.4 mass%, T.O content in steel after Ar bubbling was 0.0006 mass%, 0.0007 mass% and 0.0004 mass%, respectively. During the refining, inclusions experienced the evolution from Al2O3 into spinel and finally into CaO–MgO–Al2O3. By comparison, inclusions were more desirably controlled when slag basicity and Al2O3 contents were about 6.9–7.1 and 29.8–30.4 mass%, with lowest number density, smaller sizes within 20 μm and average composition in liquid region. Particularly, after Ar-bubbling, pick-ups in the number density of inclusions were observed for the three heats of trials and large inclusions (even exogenous inclusions over 100 μm) were often seen in heat 2. The obtained results prompted the risk of large inclusions in bearing steel in Ar bubbling, which were detrimental to fatigue lives of bearing.

KEY WORDS: inclusion; alumina; spinel; Al deoxidation; slag; bearing steel.

1. Introduction

High carbon chromium bearing steel is often used as important parts in manufacturing industry. Suffered from periodical dynamic loads, excellent fatigue resistance property is strictly required. Although many factors contribute to fatigue defects in bearings, inclusions have been known as one of the main reasons.1) As inclusions are distinctive from steel in hardness, thermal expansion, deformability and so on, they can easily cause stress concentrations and fatigue cracks in steel.2,3) Hence, number of inclusions should be decreased in bearing steel and higher cleanliness is essential. Besides, nature of inclusions like size and chemistry in bearing steel should also be strictly controlled.

Al is a deoxidant widely used in steelmaking to reduce dissolve oxygen (O2) in steel. Whereas, solid inclusions (like Al2O3 and spinel) would be largely formed in Al deoxidation, which can cause poorer castability of molten steel and fatigue problems in final products. Ca-treatment can help to modify solid inclusions in Al deoxidized steel into semi-liquid/liquid ones in smaller sizes by slag refining.

At present, several basic slag systems have been used to Al deoxidized bearing steel. Kato et al. found that calcium magnesia aluminates (CaO–MgO–Al2O3) and spinel would be formed in bearing steel, when the slag with basicity about 4.5–7.2 while Al2O3 about 20–25 mass% was used and fatigue lives of steel can be improved for several orders if inclusions ≥ 10 μm were efficiently removed.4) Kawakami studied inclusion in bearing steel (SUJ2 in Japan) refined by a slag with basicity and Al2O3 about 5 and 22 mass%, respectively. He pointed out that (CaO) and (MgO) in slag or refractory can be reduced by [Al] to supply [Ca] and [Mg] to steel to produce spinel and CaO–MgO–Al2O3 inclusions.5) Ma et al. studied the effect of Mg-treatment and Ca-treatment in refining on the formation of liquid inclusions in bearing steel, in which basicity and Al2O3 of the slag was 5–8 and 28–35 mass%, respectively. They found that large CaO-contained inclusions can be brought into steel by Ca-treatment.6) Chen et al. studied the precipitation behaviors of sulfide on spinel and CaO–MgO–Al2O3 in bearing steel refined by the 55–60%CaO–30–33%Al2O3–5–6%SiO2–2–4%MgO slag. They found that the formed inclusions were Al2O3, spinel and CaO–MgO–Al2O3 at the end of LF refining.7)

Except bearing steel, effects of refining slags on the control of inclusions were also intensively discussed for...
other Al deoxidized steels. Akifumi Harada et al. found that formation of spinel was prohibited when the mass ratios of CaO/SiO$_2$, CaO/Al$_2$O$_3$ and content of MgO in slag were reduced.\(^{(9)}\) Liu et al. studied the influence of MgO-bearing slag on the evolution of inclusions.\(^{(9)}\) Deng et al. found that the deoxidation ability of slag increased with the rise of slag basicity.\(^{(9)}\) In the production of bearing steel by electroslag remelting process (ESR), control of inclusions was also greatly affected by slag. However, refining slag of ESR was usually composed of Al$_2$O$_3$–CaF$_2$–CaO system, distinctive from conventional steelmaking process.\(^{(11,12)}\)

Despite of these important progress in recent years, influence of refining slag on cleanliness and control of inclusions in bearing steel were rarely compared and discussed in details in the industrial practice. Therefore, present study was carried out to compare the effects of refining slags on cleanliness and control of inclusions in bearing steel in the refining process of LF-VD-Ar bubbling.

### 2. Experiments and Analysis

Industrial experiments were conducted in a special steel plant in China, in which steelmaking process was comprised of electrical arc furnace (EAF), ladle furnace (LF), vacuum degasser (VD) and capacity of the vessel was about 100 t. After the VD refining, liquid steel was softly stirred by argon gas (Ar bubbling, 100 NL/min) for a determined period of time before it was transferred for continuous casting. Slag-making materials were mostly added during EAF tapping and a small part was added during the LF refining. Three kinds of refining slags were used in the trials, which were with varied basicity and Al$_2$O$_3$ contents. While other refining conditions were kept as the same.

Liquid steel was sampled at LF arrival, LF ending, VD ending and the end of Ar bubbling. Total oxygen (T.O) in steel melts was very high with contents in the range of 0.0004–0.0010 mass%. After VD refining, T.O was reduced to 0.0005–0.0014 mass%. After LF refining, T.O was in the range of 0.0004–0.0010 mass%. After Ar bubbling, cleanliness of steel melts was very high with contents of T.O decreased to 0.0004–0.0006 mass%.

### 3. Results

#### 3.1. Chemical Compositions of Slag and Steel

Chemical compositions of refining slags at the end of LF and VD refining were given in Table 1 and compositions of steel were given in Table 2, respectively. As can be seen, basicity (mass ratio of CaO to SiO$_2$) of refining slags at the end of LF and VD were about 3.9–4.2, 5.2–6.5 and 6.9–7.1 in heat 1, heat 2 and heat 3, respectively. Al$_2$O$_3$ contents in slags were about 30.89–32.51 mass%, 37.23–40 mass% and 29.81–30.41 mass% at the end of LF and VD refining of heat 1, heat 2 and heat 3, respectively.

Variations of T.O in steel melts were shown in Fig. 1. As can be seen, T.O was about 0.0014–0.0021 mass% at LF arrival. With the proceeding of LF refining, T.O was reduced to 0.0005–0.0014 mass%. After VD refining, T.O was in the range of 0.0004–0.0010 mass%. After Ar bubbling, cleanliness of steel melts was very high with contents of T.O decreased to 0.0004–0.0006 mass%.

#### Table 1. Chemical compositions of refining slags.

<table>
<thead>
<tr>
<th>Heat</th>
<th>Sampling timing</th>
<th>CaO</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>MgO</th>
<th>FeO</th>
<th>MnO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CaO/SiO$_2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>LF end</td>
<td>45.26</td>
<td>11.63</td>
<td>30.89</td>
<td>7.71</td>
<td>1.04</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td>VD end</td>
<td>43.57</td>
<td>10.52</td>
<td>32.51</td>
<td>7.72</td>
<td>0.84</td>
<td>0.110</td>
</tr>
<tr>
<td>2</td>
<td>LF end</td>
<td>42.17</td>
<td>8.14</td>
<td>37.23</td>
<td>8.25</td>
<td>1.60</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>VD end</td>
<td>41.70</td>
<td>6.43</td>
<td>37.23</td>
<td>8.25</td>
<td>1.66</td>
<td>0.010</td>
</tr>
<tr>
<td>3</td>
<td>LF end</td>
<td>54.19</td>
<td>7.88</td>
<td>30.41</td>
<td>9.08</td>
<td>0.95</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>VD end</td>
<td>54.29</td>
<td>7.69</td>
<td>29.81</td>
<td>4.98</td>
<td>0.85</td>
<td>0.085</td>
</tr>
</tbody>
</table>

#### Note:
- Al refers to dissolved aluminum content in steel.

#### Table 2. Chemical compositions of steel samples (mass%).

<table>
<thead>
<tr>
<th>Heat</th>
<th>Process</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Al</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LF arrival</td>
<td>0.98</td>
<td>0.09</td>
<td>0.33</td>
<td>0.016</td>
<td>0.025</td>
<td>1.40</td>
<td>0.070</td>
<td>0.0003</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>LF ending</td>
<td>0.96</td>
<td>0.22</td>
<td>0.35</td>
<td>0.017</td>
<td>0.011</td>
<td>1.48</td>
<td>0.024</td>
<td>0.0016</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>VD ending</td>
<td>0.97</td>
<td>0.22</td>
<td>0.35</td>
<td>0.016</td>
<td>0.009</td>
<td>1.46</td>
<td>0.012</td>
<td>0.0006</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>Ar bubbling</td>
<td>0.96</td>
<td>0.21</td>
<td>0.35</td>
<td>0.016</td>
<td>0.009</td>
<td>1.46</td>
<td>0.012</td>
<td>0.0004</td>
<td>0.0005</td>
</tr>
<tr>
<td>2</td>
<td>LF arrival</td>
<td>0.89</td>
<td>0.07</td>
<td>0.31</td>
<td>0.014</td>
<td>0.014</td>
<td>1.34</td>
<td>0.080</td>
<td>0.0004</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>LF ending</td>
<td>0.97</td>
<td>0.21</td>
<td>0.35</td>
<td>0.015</td>
<td>0.012</td>
<td>1.46</td>
<td>0.041</td>
<td>0.0011</td>
<td>0.0004</td>
</tr>
<tr>
<td></td>
<td>VD ending</td>
<td>0.97</td>
<td>0.22</td>
<td>0.35</td>
<td>0.015</td>
<td>0.009</td>
<td>1.47</td>
<td>0.015</td>
<td>0.0005</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>Ar bubbling</td>
<td>0.97</td>
<td>0.21</td>
<td>0.34</td>
<td>0.015</td>
<td>0.009</td>
<td>1.45</td>
<td>0.014</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>3</td>
<td>LF arrival</td>
<td>0.83</td>
<td>0.17</td>
<td>0.30</td>
<td>0.014</td>
<td>0.003</td>
<td>1.43</td>
<td>0.049</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>LF ending</td>
<td>0.97</td>
<td>0.24</td>
<td>0.36</td>
<td>0.015</td>
<td>0.001</td>
<td>1.47</td>
<td>0.029</td>
<td>0.0008</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>VD ending</td>
<td>0.96</td>
<td>0.25</td>
<td>0.35</td>
<td>0.014</td>
<td>0.001</td>
<td>1.46</td>
<td>0.012</td>
<td>0.0005</td>
<td>0.0006</td>
</tr>
<tr>
<td></td>
<td>Ar bubbling</td>
<td>0.96</td>
<td>0.25</td>
<td>0.35</td>
<td>0.013</td>
<td>0.001</td>
<td>1.45</td>
<td>0.012</td>
<td>0.0002</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Note: Al refers to dissolved aluminum content in steel.
3.2. Characterization of Inclusions

3.2.1. Types and Morphology of Inclusions

Typical inclusions at different stages of refining were shown in Fig. 2. At LF arrival, Al$_2$O$_3$ in cluster-shape were largely produced, with sizes in several-ten microns. At the end of LF refining, inclusions were mainly changed into CaO–MgO–Al$_2$O$_3$, which were in near-spherical-shape or blocky shape. After VD refining and Ar bubbling, inclusions in heat 3 were all in spherical or near-spherical shapes. By contrast, inclusions in blocky shapes still existed in heat 1 and heat 2 at the end of refining.

SEM-mapping of CaO–MgO–Al$_2$O$_3$ system inclusions in steel were shown in Fig. 3. In heat 1 and heat 1, core of the inclusion was enriched with Mg and Al, while outer surface of it was enriched with Ca and Al. Moreover, O and S were not overlapped but complementary with each other in the inclusion. Hence, it can be pointed out that inclusions in heat 1 and heat 2 were with a multi-layer structure of spinel + (CaO–Al$_2$O$_3$) + CaS. In heat 3, concentration of Mg was also observed in the inclusion center but Ca distributed more homogenously in the whole inclusion than heat 1 and heat 2. Because of lower [S] content in steel melt, two types of CaO–MgO–Al$_2$O$_3$ were observed in heat 3. One type was also featured by the multi-layer structure of spinel + (CaO–Al$_2$O$_3$) + CaS.
3.2.2. Number Density and Size Distribution of Inclusions

Changes in number density of inclusions (number of inclusions divided by inspected area under SEM) was shown in Fig. 4. It can be found that number density of inclusions decreased greatly in VD refining, from 13.3/mm$^2$ to 2.1/mm$^2$, from 8.8/mm$^2$ to 5.5/mm$^2$ and from 5.0/mm$^2$ to 1.4/mm$^2$ in heats 1, 2 and 3, respectively. Particularly, heat 3 indicated the lowest number density of inclusions at the end of refining. However, number density of inclusion increased in all the three heats of trials and inclusions over 20 $\mu$m were frequently observed in heat 2 after Ar bubbling. An unexpected increase in the number density of inclusions was noticed in heat 1 at the initial stage of LF refining and the reason was not clear. Hence, attentions would be paid to this phenomenon in the future.

3.2.3. Composition Distribution of Inclusions

Compositions of inclusions in steel at different stages of refining were shown in Fig. 5. Components of $\text{Al}_2\text{O}_3$, $\text{MgO}$ and $\text{CaO}$ were converted from Al, Mg and Ca obtained by EDS method, during which enough oxygen was assumed to contain in inclusions. As $\text{CaS}$ was considered as precipitation phase on $\text{CaO}-\text{MgO}-\text{Al}_2\text{O}_3$ inclusions during the cooling of steel, it was not taken into account during the estimation of inclusions compositions in refining. In this figure, solid circle in red color was the average composition of inclusions and the polygonal zone surrounded by red-colored solid lines was the liquid region at 1873 K. As can be seen, $\text{Al}_2\text{O}_3$-based inclusions were mainly formed at LF arrival. Afterwards, $\text{Al}_2\text{O}_3$ was gradually changed into $\text{MgO}-\text{Al}_2\text{O}_3$ and $\text{CaO}-\text{MgO}-\text{Al}_2\text{O}_3$. In VD refining, compositions of inclusions became more concentrated and many inclusions entered into the liquid region. In the following Ar bubbling, compositions of inclusions slightly changed. Moreover, liquid inclusions in heat 3 were more desirably targeted, with average composition inside liquid region after VD refining and Ar bubbling. By contrast, average compositions of inclusions in heat 1 and heat 2 located outside liquid zone.

Variations in the average composition of inclusions were shown in details in Fig. 6. As can be seen, average content of $\text{Al}_2\text{O}_3$ in inclusions decreased sharply in LF refining.
Fig. 4. Number density and size distribution of inclusions at different stages of refining (a) heat 1, (b) heat 2, (c) heat 3. (Online version in color.)

Fig. 5. Chemical compositions of inclusions at different stages of refining: (a) heat 1, (b) heat 1, (c) heat 3. (Online version in color.)
while average content of MgO in inclusions increased in LF refining but decreased in VD refining and Ar bubbling. And content of CaO in inclusions continuously increased in refining. Moreover, the rise of CaO in inclusions increased ever faster with the increase of slag basicity. Particularly, the increase of CaO exceeded the rise of MgO in inclusions in heat 3.

According to the average composition of inclusions, molar ratios of CaO to Al$_2$O$_3$ in CaO–MgO–Al$_2$O$_3$ inclusions can be estimated. As shown in Table 3, molar ratios of CaO/Al$_2$O$_3$ in CaO–MgO–Al$_2$O$_3$ inclusions during VD refining and Ar bubbling were about 0.63–0.78, 0.48–0.54 and 1.45–1.82 in heat 1, heat 2 and heat 3, respectively. So, it can be reasonably inferred that CaO·2Al$_2$O$_3$ phase was formed in CaO–MgO–Al$_2$O$_3$ inclusions in heat 1 and heat 2 while liquid CaO·Al$_2$O$_3$ or 12CaO·7Al$_2$O$_3$ was formed in CaO–MgO–Al$_2$O$_3$ inclusions in heat 3.

### 4. Discussion

To evaluate the variations in cleanliness and evolution of inclusions in the experiments, thermodynamic calculations were carried out. Involved fundamental reactions were listed in Table 4. Where, $K$ was the equilibrium constant of chemical reaction.

Firstly, Al–O deoxidation equilibrium was calculated from chemical reaction (1),\(^{(13)}\) from which Eq. (7) can be deduced. $a_{[Al]}$ and $a_{[O]}$ were activities of [Al] and [O] in steel, which can be calculated by Eq. (8). Where, $e_i$ was the first order interaction co-efficient between solutes $i$ and $j$ in steel, as given in Table 5. With composition of steel in Table 2, activity coefficients of [Al] and [O] can be obtained. With composition of slag given in Table 1, activities of Al$_2$O$_3$ in the used three slags, $a_{Al_2O_3}$, were calculated about 0.002 by software FactSage 8.1. Hence, contents of [O] at the end of LF refining can be calculated as 0.00015 mass% , 0.00012 mass% and 0.00014 mass% in heat 1, heat 2 and heat 3, respectively. While the contents of [O] in VD refining was calculated about 0.00022 mass%, 0.00019 mass% and 0.00022 mass% in heat 1, heat 2 and heat 3, respectively. Because of similar [Al] contents, contents of [O] in Ar bubbling were considered identical to that in VD refining.
The activity of MgO and spinel was taken as unity and 0.47, respectively, to calculate the boundary of MgO/spinel. Whereas, spinel is not stable when steel contained a certain level of [Ca] and would be modified into CaO–MgO–Al₂O₃. From above results of inclusions, it has known that modification of spinel was proceeded from its surface towards inner core. As a result, outer surface of CaO–MgO–Al₂O₃ was a layer of CaO–Al₂O₃ while the core is still composed of spinel. Moreover, CaO·2Al₂O₃ phase was formed in the CaO–MgO–Al₂O₃ inclusions in heat 1 and heat 2, while CaO·Al₂O₃ was produced in the CaO–MgO–Al₂O₃ inclusions in heat 3.

Hence, reactions (13) and (15) were obtained. As a result, Eqs. (14) and (16) were deduced to calculate stability phase diagram of Al₂O₃/spinel/CaO·2Al₂O₃ was calculated for inclusions in heat 3, in which activities of spinel and CaO·Al₂O₃ were both taken as unity.

\[
7(\text{MgO} \cdot \text{Al}_2\text{O}_3) + 4[\text{Ca}] + 2[\text{Al}] = 4(\text{CaO} \cdot \text{2Al}_2\text{O}_3) + 7[\text{Mg}] \tag{13}
\]

\[
\log K_{12,1873K} = -5.15 = \log \left( \frac{a_{\text{Mg}}^3 \cdot a_{\text{Ca}}^4}{a_{\text{spinel}}^7 \cdot a_{\text{Ca}}^2 \cdot a_{\text{Al}}^2} \right) \tag{14}
\]

\[
7(\text{Al}_2\text{O}_3) + 3[\text{Ca}] = 3(\text{CaO} \cdot \text{2Al}_2\text{O}_3) + 2[\text{Al}] \tag{15}
\]

\[
\log K_{14,1873K} = 14.25 = \log \left( \frac{a_{\text{Al}}^3 \cdot a_{\text{Ca}}^4}{a_{\text{Al},\text{O}}^7 \cdot a_{\text{Ca}}^2} \right) \tag{16}
\]

Similarly, reactions (17) and (19) were obtained. As a result, Eqs. (18) and (20) were deduced to calculate stability phase diagram of Al₂O₃/spinel/AlO·Al₂O₃ was calculated for inclusions in heat 3, in which activities of spinel and CaO·Al₂O₃ were both taken as unity.

\[
(\text{MgO} \cdot \text{Al}_2\text{O}_3) + [\text{Ca}] = (\text{CaO} \cdot \text{Al}_2\text{O}_3) + [\text{Mg}] \tag{17}
\]

\[
\log K_{16,1873} = 0.92 = \log \left( \frac{a_{\text{Mg}}^4 \cdot a_{\text{Ca}}^4}{a_{\text{spinel}}^7 \cdot a_{\text{Ca}}^2} \right) \tag{18}
\]

\[
4(\text{Al}_2\text{O}_3) + 3[\text{Ca}] = 3(\text{CaO} \cdot \text{Al}_2\text{O}_3) + 2[\text{Al}] \tag{19}
\]

\[
\log K_{18,1873K} = 13.11 = \log \left( \frac{a_{\text{Al}}^3 \cdot a_{\text{Ca}}^4}{a_{\text{Al},\text{O}}^7 \cdot a_{\text{Ca}}^2} \right) \tag{20}
\]

Calculated Al₂O₃/spinel/AlO·Al₂O₃ and Al₂O₃/spinel/CAO·Al₂O₃ stability phase diagrams were plotted as Fig. 8.
Ca and O varied from each other, which mainly caused by easy vaporization of Ca at high temperature. As a result, consistent measurements of this parameter are still not easy until now. In the calculation, the authors also tried other values of interaction coefficients of Ca and O issued in other previous literatures, but the calculations deviated a lot from the experimental results.

Based on experimental results and thermodynamic calculations, evolution mechanisms of inclusions from $\text{Al}_2\text{O}_3$ into spinel and into $\text{CaO–MgO–Al}_2\text{O}_3$ can be briefly described as following:

- After Al deoxidation, $\text{Al}_2\text{O}_3$ inclusions would be largely produced in steel.
- With the proceeding of refining, (CaO) and (MgO) in slag or ladle lining can be reduced by [Al] to supply [Ca] and [Mg] into steel bulk, as expressed by chemical reactions (21) and (22).

$$3(\text{MgO})_{\text{lag/inclusion}} + 2[\text{Al}] = 2(\text{Al}_2\text{O}_3)_{\text{lag/inclusion}} + 3[\text{Mg}] \quad \ldots \quad (21)$$

$$3(\text{CaO})_{\text{lag}} + 2[\text{Al}] = 2(\text{Al}_2\text{O}_3)_{\text{lag}} + 3[\text{Ca}] \quad \ldots \quad (22)$$

- $\text{Al}_2\text{O}_3$ inclusions reacted with [Mg] in steel and was modified into spinel by chemical reaction (23). Besides, reaction (24) can also possibly occur to form spinel.

$$n(\text{Al}_2\text{O}_3)_{\text{inclusion}} + 3[\text{Mg}] = (3\text{MgO} \cdot (n-1)\text{Al}_2\text{O}_3)_{\text{inclusion}} + 2[\text{Al}] \quad \ldots \quad (23)$$

$$[\text{Mg}] + 2[\text{Al}] + 4[\text{O}] = (\text{MgO} \cdot \text{Al}_2\text{O}_3)_{\text{inclusion}} \quad \ldots \quad (24)$$

- As [Ca] was also supplied into steel, reaction (25) can occur. Spinel would be gradually changed into calcium magnesia aluminate from surface towards the core. So, CaO–MgO–Al$_2$O$_3$ inclusions were featured by a multi-layer structure, with CaO–Al$_2$O$_3$ on the surface while spinel as the core.

$$x[\text{Ca}] + (y\text{MgO} \cdot z\text{Al}_2\text{O}_3)_{\text{inclusion}} = (x\text{CaO} \cdot (y-x)\text{MgO} \cdot z\text{Al}_2\text{O}_3)_{\text{inclusion}} + x[\text{Mg}] \quad \ldots \quad (25)$$

As mentioned above, pick-ups in number density of inclusions were observed in all the three heats of experiments. Moreover, large inclusions can be observed frequently in heat 2. Such large inclusions are very detrimental because they contributed to more scattered fatigue lives of bearings. Hence, the results prompted the necessity of more accurate control of Ar bubbling. As it known, flow rate of Ar gas into ladle is actually not easy to be accurately targeted in the practice of steelmaking. Steelmakers often have to carry out Ar bubbling based on the movement of slag. If the slag surface slightly fluctuated without “open-eyes”, the operation was considered as ok. Despite of that, “open-eyes” can still be seen from time to time in the steelmaking practice. The resulted re-oxidation or slag entrapment probably attributed to large inclusion and a loss of [Al] about 10 ppm in heat 2 (as can be seen in Table 2). As shown in Fig. 9, there were two types of large inclusions in heat 2. One kind was composed of CaO–MgO–Al$_2$O$_3$ with few SiO$_2$. The other kind was also composed of CaO–MgO–Al$_2$O$_3$ but contained higher contents of SiO$_2$. As basicity of the refining slag was about 5.2–6.5 in heat 2, endogenous inclusions in heat 2 should be with very low level of SiO$_2$. The inclusion with few SiO$_2$ in Fig. 9(a) can be an endogenous particle, but it can also be a smaller exogenous particle which had reacted with liquid steel and resulted in low SiO$_2$ content. While the large inclusion in Fig. 9(b), which was larger than 100 $\mu$m and with higher content of SiO$_2$, should be an entrapped slag particle.
5. Conclusions

Cleanliness and control of inclusions in bearing steel were studied by industrial trials. Three basic slags varied basicity and Al$_2$O$_3$ contents were used in the LF-VD-Ar bubbling refining process. Based on obtained results, following conclusions were drawn.

(1) With slag basicity (CaO/SiO$_2$) about 3.9–4.2, 5.2–6.5 and 6.9–7.1 while Al$_2$O$_3$ about 30.9–32.5 mass%, 37.2–40 mass% and 29.8–30.4 mass%, T.O contents in steel were 0.0006 mass%, 0.0007 mass% and 0.0004 mass% at the end of Ar bubbling, respectively. Moreover, number density of inclusions was also the lowest and all the inclusions were smaller than 20 μm. Furthermore, average composition of inclusions located in liquid zone of CaO–MgO–Al$_2$O$_3$ diagram at the end of Ar bubbling.

(2) In the refining, inclusions were changed from Al$_2$O$_3$ into spinel and finally into CaO–MgO–Al$_2$O$_3$. By comparison, inclusions were more desirable targeted when slag basicity and Al$_2$O$_3$ was about 6.9–7.1 and 29.8–30.4 mass%, respectively. Moreover, number density of inclusions was also the lowest and all the inclusions were smaller than 20 μm. Furthermore, average composition of inclusions located in liquid zone of CaO–MgO–Al$_2$O$_3$ diagram at the end of Ar bubbling.

(3) Because of chemical reactions among slag-steel-ladle lining in the refining, [Mg] and [Ca] would be supplied into steel. Thermodynamic calculation showed that evolutions of inclusions from Al$_2$O$_3$ into spinel and finally into CaO–MgO–Al$_2$O$_3$ were inevitable. As modification of spinel followed the unreacted core model, the CaO–MgO–Al$_2$O$_3$ inclusions were featured by a multi-layer structure, with spinel core surrounded by a CaO–Al$_2$O$_3$ surface layer.

(4) Abnormal Ar bubbling accounted for the pick-ups in the number density of inclusions in the three heats of experiments. It also contributed to the existence of large inclusions in heat 2, which were in several-tent microns or bigger. Exogenous entrapped slag particles bigger than 100 μm were also observed in heat 2, which were detrimental to the fatigue lives of bearings.

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