Cleanliness of Low Carbon Aluminum-Killed Steels during Secondary Refining Processes

Wen Yang, Xinhua Wang, Lifeng Zhang, Qinglin Shan, and Xuefeng Liu

Efficient secondary refining process is necessary for massive and stable production of low carbon aluminum-killed (LCAK) steels. Plant trials were performed to investigate the cleanliness of steels. Characteristics of composition, cleanliness, and inclusions of LCAK steel during different secondary refining processes, including LF, CAS, RH-LIT, and RH, were studied and compared. The results showed that CAS, RH-LIT, and RH processes had better control of low carbon, silicon, and nitrogen than LF process. High cleanliness of LCAK steels could be achieved by all the mentioned refining processes. It was concluded that the total oxygen (T.O.) should be <35 ppm to reduce the amount of inclusions and reach the level of clean steels. The removal rate of inclusions during RH-LIT and RH processes was much higher than that of LF and CAS. The T.O. content and the amounts of inclusions during CAS, RH-LIT, and RH could be quickly decreased to a low value within 10 min. The results showed that CAS and RH-LIT as well as RH refining processes can produce LCAK steels that meet the requirements of high efficient, low cost, clean, and stable production, while LF is more suitable for the heats with poor control of end point of BOF, and for the process with calcium treatment to control sulfur content and lower the clogging of Submerged Entry Nozzle during thin slab continuous casting.

1. Introduction

Low carbon aluminum-killed (LCAK) steels are well used for production of cold rolled sheets used for automobiles, household appliances, etc. It requires that LCAK steel should have low carbon, low silicon, and low nitrogen to obtain good forming property, and the total oxygen (T.O.) and the size of inclusions of LCAK steels should be strictly controlled to guarantee high surface quality of the product.

The secondary refining processes of LCAK steels grades include LT (Ladle Treatment by Gas Stirring), CAS (Composition Adjustment by Sealed Argon Bubbling), RH (Ruhrtal–Heraeus), and LF (Ladle Furnace treatment). Besides improving steel quality, secondary refining process is the important step to link up steelmaking and continuous casting. The LT gas stirring treatment was developed approximately in 1951.[1] This process is simple and low cost,[2] however, slags are needed to be deoxidized to prevent the reoxidation of molten steel and prevent the increase of inclusion amount. Moreover, the molten steel is easy to be reoxidized by air when the stirring is too strong. As the tight quality requirement of the steel, LT is hardly used alone or little used nowadays. The CAS refining process was developed in 1975 by Nippon Steel[3] and expanded gradually at the end of 1970s. Comparing the LT process, the CAS process utilizes a snorkel, which hinders the explosion of the molten steel to air and slag and therefore lowers the reoxidation of the molten steel. Thus, the stirring intensity can be strengthened to promote the removal of inclusions, leading to the short refining time and relatively high cleanliness of steel and high yield of alloy. RH refining process was developed by the two companies of Ruhrtal and Heraeus, so called RH, in 1959.[4] The advantage of RH is degassing and removal of inclusions utilizing high vacuum and circulation flow. Due to the using of vacuum chamber, the RH process can well avoid the reoxidation of molten steel from air and slag, and the stirring of RH can be very strong. Multiple functions of CAS and RH were expanded in the 1970s and 1980s, such as CAS-OB, RH-OB, RH-KTB, RH-PB for additional function.

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of reheating, decarburization, and desulfurization.\textsuperscript{[5]} Besides, the RH light treatment (RH-LIT) was proposed in 1975 to reduce the burden of steelmaking furnace.\textsuperscript{[5,6]} Different with RH route in which deoxidation is performed during BOF tapping, in RH-LIT route there is no deoxidation performance during tapping, and the first stage of RH-LIT refining process is decarburization by the dissolved oxygen in vacuum condition, following by deoxidation with aluminum addition, which leads to a lower dissolved oxygen before deoxidation and less alumina generated after deoxidation. As a result, RH-LIT process allows relatively high carbon and low dissolved oxygen at the end point of BOF. LF refining process was developed in 1971,\textsuperscript{[5,6]} the main characteristic is steel heating by electric arc, thus it can melt ferroalloy by electric arc heating, adjust composition, and temperature, perform desulfurization and deoxidation by a reducing slag, and control the cleanliness and inclusions in the molten steel. The typical advantages of the LF refining process include high cleanliness of steel, modification of inclusions, and stable temperature, thus, it is widely used nowadays although it was developed later than other refining processes.

There have been many studies on the cleanliness of LCAK steel at different refining processes,\textsuperscript{[7–23]} the T.O. content in LCAK steel is summarized in Table 1.\textsuperscript{[7–14]} From these studies, it is known that the high cleanliness of LCAK steel can be achieved by all the refining processes discussed above. In recent years, the LCAK steel production faces many challenges, including the requirements of high quality of the steel product and low production costs, less environment pollution, and low energy consumption. Thus, high efficient, low cost, and stable production of high quality steel is necessary for the sustainable development of steel enterprises. However, it is lack of comparison between different refining processes of LCAK steel, leading to considerable divergences on the choice of refining process for LCAK steel. Accordingly, in the current paper, characteristics of steel composition, cleanliness, and inclusions of each refining process including LF, CAS, RH, and RH-LIT were studied and compared to provide a basis for the choice of refining processes.

2. Experimental and Analysis Methodology

Industrial trials for the production of LCAK steel were performed. The production routes are “KR (to remove sulfur from the hot metal) → 300 t BOF → LF + Ca treatment/CAS/RH/RH-LIT → continuous casting.” The LF refining with Ca treatment process is for the production of SPHC steel while the other refining processes are for the production of DC01 steel. The compositions of SPHC and DC01 steel are listed in Table 2.

In this work, calcium treatment was assumed to be a part of LF refining process. In the LF refining route, during tapping of BOF, a certain amount of aluminum was added into the molten steel to decrease the dissolved oxygen to several ppm. Synthetic slag was added into the ladle during tapping to reduce the FeO and MnO in the slag. During LF refining, high basicity slag was used and aluminum was added to improve deoxidation. Steel samples were taken before LF refining, at the earlier stage, the middle stage, the end of LF refining, after Ca treatment, and after soft blowing.

In CAS refining route, during tapping of BOF, a certain amount of Al and synthetic slag were added into the molten steel as well. After tapping, slag modifier was added into the slag to reduce the slag oxidizability. At CAS station, the snorkel was submerged into the molten steel after the slag surface was blown open to a bright face, followed by a strong stirring by argon gas to promote the removal of inclusions. The temperature was decreased by adding steel scraps and be raised by adding aluminum and blowing oxygen. Steel samples were taken before CAS refining, during process of argon blowing with time interval of approximately 7 min, and after argon stop.

In the RH refining route, the end point of BOF was controlled under common practice, deoxidation, and alloying were performed during tapping of BOF. During the RH refining, a large argon gas flow rate was employed to promote the recirculation and removal of inclusions from the molten steel. While in the RH-LIT route, the carbon content at the end point of BOF was relatively higher than the normal RH process, and no deoxidation or alloying were performed during the tapping of BOF. Decarburization was firstly performed during RH-LIT process under a certain vacuum degree. After decarburization, aluminum was added for deoxidation. Then, the generated inclusions were removed by flow transport under excellent dynamic conditions. Steel samples were taken after deoxidation. Since the temperature drop was large during RH process, aluminum addition, and oxygen blowing were performed to increase the temperature of the molten steel.

The schematic operation and sampling scheme of each secondary refining process were shown in Figure 1. Temperature of the molten steel was measured several times during the refining process of each heat. The dissolved oxygen content was measured by a zirconia sensor during RH and RH-LIT refining processes and at the beginning of other refining processes.

The contents of C, S, and T.O. of the steel samples were analyzed using infrared analysis. The concentration of silicon was analyzed using ICP-AES and the nitrogen content was analyzed using the thermal conductance method. Inclusions on the cross-section of each steel sample were detected using ASPEX. ASPEX is a computer-controlled scanning electron microscope that is designed for the automated imaging and elemental analysis of a wide spectrum of surfaces and particulates. The system provides a fully integrated EDX platform for addressing the microscale visualization needs. It can simultaneously

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<th>Tundish</th>
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<td>20</td>
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Table 1. Total oxygen content (ppm) reported during various processing steps for LCAK steel after the year of 2000.
Table 2. Composition of SPHC and DC01 steel (%).

<table>
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<tr>
<th>Steel</th>
<th>C</th>
<th>Si≤</th>
<th>Mn</th>
<th>P≤</th>
<th>S≤</th>
<th>Al&lt;sub&gt;i&lt;/sub&gt;</th>
<th>N≤</th>
</tr>
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<tbody>
<tr>
<td>SPHC</td>
<td>0.05</td>
<td>0.03</td>
<td>0.2</td>
<td>0.015</td>
<td>0.012</td>
<td>0.015–0.05</td>
<td>0.006</td>
</tr>
<tr>
<td>DC01</td>
<td>0.03</td>
<td>0.03</td>
<td>0.2</td>
<td>0.015</td>
<td>0.012</td>
<td>0.015–0.05</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Figure 1. Key operation and sampling scheme of each refining process (Sam., sampling; meas., measuring; add., adding).
detect the size, shape, area, number, location, and elemental composition of inclusions in steel samples. The working magnification was set at ×225 and the minimum detectable inclusion was ~1.0 μm in the current study.

A statistical parameter, area fraction, is defined as the following formula to characterize the amount of non-metallic inclusions.

\[
AF = \frac{A_{\text{inclusion}}}{A_{\text{total}}}
\]  

(1)

where, AF is the area fraction of inclusions, ppm; \(A_{\text{inclusion}}\) is the total area of detected inclusions, μm²; and \(A_{\text{total}}\) is the sample detection area, mm².

Since an inclusion with irregular shape especially a cluster might be cut into two or more particles on one cross section, AF is more accurate than the number density to describe the amount of the irregular shape inclusions since the area contains the information of both number and size.

In the current study, in order to reveal the three-dimensional morphology of inclusions in the steel produced by CAS and RH refining processes, inclusions were extracted from steel samples. After the surface of the steel sample being polished, about 3 g of each steel sample was dissolved in hydrochloric acid solution (1:1 in volume) at 70°C. After the iron matrix was completely dissolved, deionized water was added to dilute the solution. Then, the inclusions were filtered out using a polycarbonate filter paper propelled by a vacuum pump. The pore size of the filter was 0.2 μm in order to capture most of the inclusions. As alumina-based inclusions are insoluble to HCl acid, they will remain on the filter paper. The extracted inclusions were then observed using SEM after depositing carbon powder over the filter paper under vacuum conditions.

3. Results and Discussions

The content of carbon, silicon, sulfur, T.O., nitrogen, and inclusions in steel samples taken during steel refining processes were evaluated.

3.1. Carbon Content

Figure 2 shows the carbon content in steel during secondary refining processes. Since the carbon content of SPHC is a little higher than that of DC01, the carbon content in steel during LF refining process is higher than other processes. This figure shows that the carbon content during LF, CAS, and RH was slightly changed during refining. While at the initial stage of RH-LIT process the carbon content decreased significantly to <0.01% due to the decarburization, after the addition of carburant, the carbon content increased to the target value. Since decarburization can be performed in RH-LIT process route, the carbon content at the end point of BOF can be controlled in a higher value and wider range than the normal RH process, leading to an easier control to reach the target value at the end point of BOF. While in other refining routes, since no decarburization was performed and might occur carbon pick-up during refining, it is required that the carbon content in steel should be controlled to a low value and in a narrow range at the end point of BOF, which increases the difficulty of BOF control and increases the damage possibility of the BOF refractory.

3.2. Silicon Content

To obtain good forming property of LCAK sheets, [Si] in LCAK steel should be <0.03%. The variation of [Si] in each refining process as well as the comparison of [Si] content and [Si] pick-up after different refining processes are shown in Figure 3, indicating that the order from high to low [Si] content by different refining processes is: LF > CAS, RH > RH-LIT, while the order from large to small silicon pick-up during refining is: LF > CAS, RH, and RH-LIT.

The reaction inducing the increasing of silicon is

\[
3(SiO_2) + 4[Al] = 2(Al_2O_3) + 3[Si]
\]

(1)

The larger [Si] pick-up in LF refining process is due to the active reaction between slag and molten steel. During the LF refining process, the activity of SiO₂ in slag is improved by decreasing the oxidizability of the slag. Besides, the stirring of steel caused by argon blowing provides a good dynamic condition to the reaction.
3.3. Desulfurization

The casting speed of the thin slab continuous casting is higher than that of the traditional continuous casting process. Low sulfur content is required to avoid slab breakout during casting. Besides, calcium treatment is usually used to modify inclusions from solid to liquid to prevent the submerged entry nozzle from being clogged, and low sulfur content is needed to improve the efficiency and stability of the calcium treatment. Thus, the desulfurization during different refining processes is discussed as well.

The [S] content in steel and the efficiency of desulfurization of each secondary refining process are shown in Figure 4, which indicates that the LF refining process has the best desulfurization efficiency and with the lowest [S] content in steel after refining.

Figure 3. Variation of [Si] during refining processes (a), and comparisons of [Si] content and [Si] pick-up after different refining processes (b).

Figure 4. Variation of [S] content during refining processes (a), [S] content in steel after secondary refining (b), and efficiency of desulfurization (c) of each refining process.
The desulfurization reaction is expressed by\(^{26}\)

\[
3(CaO) + 3[S] + 2[Al] = 3(CaS) + (Al_2O_3) \tag{2}
\]

According to Equation 2, in order to increase the efficiency of desulfurization, the activities of CaO and [Al] should be higher. Since the steel grade decides the [Al] content in steel, the desulfurization mainly depends on the activity of CaO in slag. Because a high basicity slag was used in LF refining process in the current study, the activity of CaO was high, leading to the highest desulfurization efficiency. On the other hand, LF process is designed to desulfurize because the heating method is more suitable for the use of high basicity slag.

### 3.4. Temperature Control

Larger temperature drop rate requires more temperature compensation to ensure castability of the molten steel, leading to more cost and possible worse steel cleanliness. Thus, small temperature drop rate is usually respected.

In the current study, the temperature drop rate is defined as the average drop rate in the range from the beginning of refining to the first temperature rising operation except for the LF refining process, in which the parameter is defined as average temperature drop in the refining time except the time period of slag addition, electric arc heating, and soft blowing. Figure 5 presents the variation of temperature of molten steel during refining processes and the average temperature drop rate of each refining process. The arrows in Figure 5a show the first temperature rising operations during refining processes. It is indicated that the order of temperature drop from large to small during different refining processes is: RH > RH-LIT > LF and CAS. The large temperature drop rate during RH and RH-LIT refining which is owing to the strong argon blowing and the larger circulation rate of the molten steel will increase the burden of BOF for higher temperature requirement.

The heating methods of the refining processes are different from each other. The attribute of LF refining process is electric arc heating of steel, thus the temperature control is much easier and more accurate, which is good for discharging the burden for the furnace, slagging during the refining, and keeping suitable temperature of the melt to caster, but it may induce carbon pick-up and nitrogen pick-up. While the temperature of the molten steel during CAS or RH refining is raised by aluminum addition and oxygen blowing, which increases the T.O. and the amount of inclusions in steel.

### 3.5. Total Oxygen and Nitrogen

In most refining processes except RH-LIT, deoxidation were performed by adding aluminum during tapping of BOF, thus the oxygen content at the end point of BOF is assumed to be the dissolved oxygen before deoxidation. Figure 6 shows the contents of [C] and [O] before deoxidation in CAS, RH, and RH-LIT process, and at

![Figure 5](image_url)

**Figure 5.** Variation of temperature (a) and the average temperature drop rate (b) of each refining process.

![Figure 6](image_url)

**Figure 6.** Contents of [C] and [O] of steel in different refining processes.
the end point of BOF in RH-LIT process is shown in the figure as well. The dissolved oxygen content increased with the decreasing of carbon at the end of BOF, and smaller carbon content induced more deviation of dissolved oxygen from its equilibrium value, which is calculated at the pressure of 1 atm. In RH-LIT refining route, the [O] content before deoxidation was smallest, ≈215 ppm. In RH refining route, the value was 645 ppm higher than that of RH-LIT. The [O] content before deoxidation was highest in CAS route, ≈1225 ppm higher than that in RH-LIT. The high oxygen content at the end point of BOF might be due to the excessive oxidation of melt by oxygen blowing. Lower carbon content induces higher oxygen content and easier excessive oxidation. Thus, it is harmful to pursue too low carbon content at the end point of BOF.

Figure 7 shows the variation of T.O. and N contents during each secondary refining process. At the earlier stage of refining processes of CAS and RH, the content of T.O. decreased significantly, with a decreasing speed of ≈4 ppm min⁻¹, as shown in Figure 8a. During LF refining...
process, the T.O. decreased gradually, while during CAS and RH refining, after a fast decreasing at the first 8–9 min, the T.O. content kept almost constant. During RH-LIT and RH refining processes, the heating of steel by the addition of aluminum and oxygen blowing caused a sharp increase of T.O. At the end of each refining process, the T.O. decreased to a low value – 33 ppm by LF, 34 ppm by CAS, 45 ppm by RH-LIT, and 28 ppm by RH, as shown in Figure 8b, indicating that high cleanliness of steel can be achieved by all the refining processes discussed. However, T.O. during RH-LIT was relatively higher than that of other refining processes due to the shorter net time for the removal of inclusions.

Figure 9 shows the nitrogen content and nitrogen pick-up for each refining process. It is indicated that the order of nitrogen content from high to low is: LF > CAS and RH > RH-LIT, and the nitrogen pick-up was largest during LF refining process, which was as high as 12 ppm and mainly occurred during Ca treatment, as shown in Figure 7a, which might be attributed to the air absorption caused by the boiling of molten steel on the near-surface of the molten pool at time of Ca–Fe wire injection that was induced by the high steam pressure of calcium.

3.6. Inclusions in Steel during Refining

Inclusions in LCAK steel after deoxidation are mainly alumina-based. Large alumina-based inclusions have a detrimental effect on the castability of the molten steel and the surface quality of the steel sheet. Currently, large alumina-based inclusions are either modified into low melting ones by calcium treatment, or removed by flow transport, or become defects of the steel product.

Some aspects of inclusion characteristics, including composition, morphology, amount, size, and removal rate in each refining process, were analyzed.

3.6.1. Composition and Morphology

Figure 10 shows the composition of inclusions at the end of each refining process, detected by ASPEX. The curve in the figure represents the boundary of liquid inclusion region. In LF route, after calcium treatment the oxide inclusions transferred to CaO–MgO–Al2O3 (Figure 10a), and many of them were located in the liquid region, which is good for preventing nozzle clogging and improving the castability of the steel. However, Figure 10b represents that after calcium treatment a vast amount of CaS generated, most of them were precipitated on the oxides, this would decrease the modification effect of alumina inclusions. Thus, lower sulfur content is required to improve the inclusion modification. At the end of CAS, RH-LIT, and RH refining processes, since there was no calcium treatment, inclusions were solid alumina, which would induce nozzle clogging during casting. Thus, on the point of view of the castability of the molten steel, LF refining (including calcium treatment) is better than CAS, RH-LIT, and RH.

The transformation of inclusions during LF refining process was owing to the reaction of calcium treatment. High basicity reductive slag was used during LF refining, the reaction between the slag and the molten steel changed the composition of inclusions, especially after calcium addition. Inclusions were modified to liquid ones mainly according to the following reaction.

\[
7(\text{Al}_2\text{O}_3) + 12[\text{Ca}] + 12[\text{O}] = (12\text{CaO} - 7\text{Al}_2\text{O}_3)
\]

As mentioned above, oxide inclusions after LF refining was mainly MgO–CaO–Al2O3 that could be partially dissolved by hydrochloric acid, while after CAS and RH refining inclusions were mainly alumina that would not be dissolved by hydrochloric acid. Accordingly, the morphology of inclusions after LF refining was directly observed by SEM, and inclusions after CAS and RH refining were firstly extracted using HCl acid and then observed by SEM to reveal the three-dimensional morphology of alumina inclusions.

Figure 11 shows the morphology of inclusions at the end of each refining process. Since inclusions after RH refining were the same as those after RH-LIT refining, inclusions only after RH-LIT refining are shown here. After LF refining, inclusions were transformed to spherical, and most of them were small. CaS was precipitated on the gap part of the spheres shown in Figure 11a. However, after CAS and RH-LIT refining, there were still many irregular inclusions, and large clusters and aggregates were observed, which were very detrimental to the subsequent casting process. Besides clusters and aggregates, many small spherical and polyhedral particles were observed as well in the steel samples after CAS and RH refining.

3.6.2. Amount and Removal Rate

The amount of inclusions is characterized by their area fraction (AF). Figure 12 shows the variation of AF of inclusions during each secondary refining process.
Figure 10. Composition of inclusions at the end of each refining process: a, b) LF, c) CAS, d) RH-LIT, e) RH.
During LF refining process, before calcium treatment, the AF of inclusions decreased, while after calcium treatment, the amount of inclusions increased sharply, which was caused by the massive generation of new inclusions especially sulfide (as shown in Figure 10b) and slight reoxidation of molten steel (as shown in Figure 7a) during calcium treatment. During other refining processes, the variation of AF was consistent with the tendency of T.O. At the early stage of refining process (≈10 min), the AF of inclusions decreased significantly, and then decreased slowly. During RH-LIT and RH refining processes, the heating of molten steel by adding aluminum and blowing oxygen extremely increased the AF of inclusions due to the massive generation of new alumina inclusions.

The relationship between the AF of alumina-based inclusions and the T.O. is shown in Figure 13. It is clearly indicated that the AF of alumina-based inclusions increased with the increasing of T.O. in steel, and it increased slowly when the T.O. was <35 ppm but increased exponentially after the T.O. was over 35 ppm. Thus, the T.O. in steel should be controlled to <35 ppm to reduce the amount of inclusions. As discussed by Zhang, the T.O. only represents the inclusions smaller than 50 μm. How to control large inclusions that are mainly exogenous ones

![Morphology of inclusions after refining processes a) LF, b) CAS, and c) RH-LIT.](image-url)
from slag and lining refractory materials is another important task of steelmakers.

The AF of inclusions at the end of each refining process is shown in Figure 14, where LF(−Ca) means before calcium treatment and LF(+/Ca) means after calcium treatment. The AF of inclusions was smallest by refining of RH-LIT or RH, ≈37 ppm, around 52 ppm at the end of CAS refining and before calcium treatment in LF refining process. However, after calcium treatment, the AF was sharply increased to ≈232 ppm owing to the massive generation of CaS and slight reoxidation of the steel during the practice of calcium treatment.

The minimum AF of inclusions characterizes the removal ability of inclusions from the molten steel, while...
the removal efficiency of inclusions is characterized by average removal rate of the AF at the fast decreasing stage of AF, defined as Equation 4.

$$\eta_{IR} = \frac{[AF]_{in} - [AF]_{low}}{\Delta t_{IR}}$$

(4)

where, $\eta_{IR}$ is the removal rate of inclusions in AF, ppm/min; $[AF]_{in}$ is the initial AF of inclusions, ppm; $[AF]_{low}$ is the AF of inclusions at the end of fast decreasing stage shown in Figure 12, ppm; $\Delta t_{IR}$ is the time of the fast decreasing stage, min. The schematic diagram is shown in Figure 15.

The calculated removal rate of inclusions during each refining process is shown in Figure 16, indicating that the removal rate of inclusions in AF in RH-LIT and RH was far larger than that in LF and CAS owing to the quick circulation flow of molten steel. The very low removal rate during LF refining was due to the relatively small bottom argon blowing rate. Another reason is that the initial AF of inclusions considered in the calculation (at 14 min) might not be included in the actual initial fast decreasing stage that is generally during the initial 10 min of the refining process.

3.6.3. Size Distribution

Figure 17 shows the average size and size distribution of inclusions during refining processes. The number density (ND) of inclusions is defined as the number of inclusions per unit detection area. The tendency of average size of the inclusions was similar to the AF of inclusions. During LF refining, before calcium treatment, the size of inclusions decreased gradually because of the removal of >2 $\mu$m inclusions. Immediately after calcium treatment, the average size decreased to only 1.53 $\mu$m owing to the massive generation of 1–2 $\mu$m inclusions by the calcium treatment. As the time increasing during soft blowing, inclusions aggregated and their average size increased. During CAS refining, during argon blowing process, the average size decreased, while after argon blowing was off, the average size increased firstly due to the aggregation of small inclusions and then decreased due to the floating removal of large inclusions. During RH-LIT refining, at the early stage of steel heating, many large alumina generated which led to a large average size. At the later stage of heating, it quickly deceased due to the fast removal of large inclusions. During RH refining, at the early stage, it decreased significantly due to the removal of inclusions, and increased obviously during the heating stage for the same reason as that during RH-LIT.

The average size of inclusions at the end of each refining process is shown in Figure 18, indicating that the average size of inclusions after LF refining was smallest due to the modification by slag–steel reaction and calcium treatment. The actual size of inclusion in CAS or RH refining may be larger than the measured one because of the dominant irregular and clustered alumina inclusions.

3.7. Total Refining Time

The secondary refining process is a connection link between the preceding steelmaking and the following casting, thus besides functions mentioned previously, the secondary refining process is also a regulation of the production tempo. To improve the production efficiency and reduce manufacturing costs, high speed continuous casting is expected, which requires shorter secondary refining time.

The refining time in the current work is defined as the time from start to the end of treatment, e.g., for LF and CAS refining it is the time from the start of to the end of argon blowing, and for RH-LIT and RH refining it is the time from the start to the end of vacuum. The refining time of each process is shown in Figure 19, indicating that the refining time of LF was longest and that of CAS was shortest. Here, the LF refining process included calcium treatment. RH-LIT process contained a decarburization stage and a steel heating process, leading to a relatively long refining time. Although there was no decarburization stage during RH process, however, there were two steel heating processes.
Figure 17. Average size and size distribution of inclusions during each refining process.
which induced much longer time than expected. Therefore, the temperature rising operation should be shortened as far as possible to lower the total refining time. This requires a compact and reasonable plants layout and more scientific management of the manufacturing process.

### 3.8. Material Consumption

Low cost manufacturing is necessary and urgent nowadays for the environmentally friendly and sustainable development of steel industries. The key of low cost manufacturing is to produce high quality products with the least consumption of resource raw materials. In the current study, material consumption of each refining process was analyzed.

Material consumption mainly includes the consumption of: alloys, slags, argon gas, oxygen gas, power, and so on. For the current study, the steel grade was similar and the consumption of Mn–Fe for alloying was almost the same. The slags added during the tapping of BOF were nearly the identical except that the slag modifier added after tapping in RH-LIT route was less. Thus, the materials with large consumption mainly includes aluminum metal for deoxidation and alloying such as Al–Fe, Al gravel, other alloy such as Ca–Fe, slags added during refining process such as synthetic slag and fluorite, argon gas for stirring, and materials for temperature rising such as electrical power during LF refining and aluminum and oxygen during RH-LIT and RH refining.

Table 3 shows the consumption of the main auxiliary materials for each refining process, the power for vacuum pumps in RH-LIT and RH was not considered. It indicates that the material consumption during LF refining process was much larger than those during other processes.

The comparison on the aspects analyzed above among the four secondary refining processes is summarized in Table 4, indicating that CAS and RH-LIT as well as RH can well meet the requirements of high efficient, low cost, and stable production of LCAK steels, while LF is

<table>
<thead>
<tr>
<th>Materials</th>
<th>LF</th>
<th>CAS</th>
<th>RH-LIT</th>
<th>RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al–Fe (kg t⁻¹-steel)</td>
<td>3.45</td>
<td>6.94</td>
<td>0</td>
<td>5.55</td>
</tr>
<tr>
<td>Al grain (kg t⁻¹-steel)</td>
<td>1.29</td>
<td>0.30</td>
<td>1.11</td>
<td>0.70</td>
</tr>
<tr>
<td>Ca–Fe (kg t⁻¹-steel)</td>
<td>3.82</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Synthetic slag (kg t⁻¹-steel)</td>
<td>8.77</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fluorite (kg t⁻¹-steel)</td>
<td>4.62</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Argon (Nm³ t⁻¹-steel)</td>
<td>0.091</td>
<td>0.088</td>
<td>0.408</td>
<td>0.387</td>
</tr>
<tr>
<td>Electricity for heating (kWh t⁻¹-steel)</td>
<td>23.37</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Al grain for heating (kg t⁻¹-steel)</td>
<td>0</td>
<td>0</td>
<td>1.34</td>
<td>0.87</td>
</tr>
<tr>
<td>Oxygen for heating (m³ t⁻¹-steel)</td>
<td>0</td>
<td>0</td>
<td>1.08</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 3. Main materials consumption of each secondary refining process.
more suitable for the case with a low level of refining technology, or for the case with poor control of end points of BOF steelmaking, or for thin slab continuous casting process.

4. Conclusions

Characteristics of the composition, cleanliness, and inclusions of LCAK steels by different secondary refining processes were studied based on the plant trials, and then a comprehensive comparison was performed. The following conclusions were obtained:

(1) The processes of CAS, RH-LIT, and RH could keep low values of carbon, silicon, and nitrogen which are required for the production of LCAK steels, while higher pick-up of silicon and nitrogen were found for LF refining process.

(2) High cleanliness of LCAK steels could be achieved by all the mentioned refining processes. The T.O., e.g., was 33 ppm for LF, 34 ppm for CAS, 45 ppm for RH-LIT, and 28 ppm for RH. The T.O. should be <35 ppm to reduce the amount of inclusions.

(3) The amount of inclusions characterized by the AF after each refining was: 52 ppm before calcium treatment and 232 ppm after calcium treatment for LF process, 52 ppm for CAS, 37 ppm for both RH-LIT and RH processes. The higher amount of inclusions after calcium treatment was due to the massive generation of CaS and slight reoxidation during calcium treatment.

(4) The removal rate of inclusions during RH-LIT and RH was much higher than during LF and CAS processes. The T.O. content and the amount of inclusions during CAS, RH-LIT, and RH could be quickly decreased to a low value within 10 min refining.

(5) According to the comprehensive comparison, it is known that CAS and RH-LIT as well as RH can well meet the requirements of high efficient, low cost, and

<table>
<thead>
<tr>
<th>Aspects</th>
<th>Items</th>
<th>LF</th>
<th>CAS</th>
<th>RH-LIT</th>
<th>RH</th>
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</thead>
<tbody>
<tr>
<td>Composition and temperature control</td>
<td>Resist [C] fluctuation at the end of BOF</td>
<td>Δ</td>
<td>Δ</td>
<td>〇</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>Resist temperature fluctuation at the end of BOF</td>
<td>〇</td>
<td>Δ</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>Decarburization</td>
<td>×</td>
<td>×</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Desulfurization</td>
<td>〇</td>
<td>Δ</td>
<td>×</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Avoid Si pick-up</td>
<td>×</td>
<td>〇</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Temperature drop</td>
<td>〇</td>
<td>〇</td>
<td>×</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Temperature compensation</td>
<td>〇</td>
<td>Δ</td>
<td>Δ</td>
<td>〇</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>[O] before deoxidation</td>
<td>×</td>
<td>×</td>
<td>〇</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>T.O. after refining</td>
<td>〇</td>
<td>〇</td>
<td>Δ</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>[N] after refining</td>
<td>×</td>
<td>Δ</td>
<td>〇</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>Avoid [N] pick-up</td>
<td>Δ</td>
<td>〇</td>
<td>〇</td>
<td>〇</td>
</tr>
<tr>
<td>Inclusions</td>
<td>Modification</td>
<td>〇</td>
<td>×</td>
<td>×</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Amount</td>
<td>×</td>
<td>Δ</td>
<td>〇</td>
<td>〇</td>
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<tr>
<td></td>
<td>Average size</td>
<td>〇</td>
<td>Δ</td>
<td>Δ</td>
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<td></td>
<td>Removal rate</td>
<td>×</td>
<td>Δ</td>
<td>〇</td>
<td>〇</td>
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<tr>
<td></td>
<td>Castability of steel</td>
<td>〇</td>
<td>Δ</td>
<td>Δ</td>
<td>Δ</td>
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<tr>
<td>Efficiency and cost</td>
<td>Refining time</td>
<td>×</td>
<td>〇</td>
<td>Δ</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>Production cost</td>
<td>×</td>
<td>Δ</td>
<td>〇</td>
<td>Δ</td>
</tr>
<tr>
<td></td>
<td>Construction cost</td>
<td>Δ</td>
<td>〇</td>
<td>×</td>
<td>〇</td>
</tr>
</tbody>
</table>

Note: 〇, Good; Δ, Fair; ×, Poor.

Table 4. Comparison of different refining processes.
stable production of LCAK steels, while LF is more suitable for the case with low level of refining technology, or the case with poor control of end points of BOF, or for thin slab continuous casting process.

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References