Application of Alkali Oxides in LF Refining Slag for Enhancing Inclusion Removal in C96V Saw Wire Steel

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A novel LF refining slag contains K$_2$O has been developed in order to produce ultraclean saw wire steels. The diameter of ultrafine saw wire is between $50 \times 10^{-6}$ m ($50 \mu$m) and $80 \times 10^{-6}$ m ($80 \mu$m), any hard inclusion which diameter more than $5 \times 10^{-6}$ m ($5 \mu$m) should be avoided because it probably will cause wire breaking. In order to enhance inclusion removal in C96V saw wire steel during LF refining process, fundamental work on the effect of alkali oxides (Li$_2$O, K$_2$O) on the absorption ability of inclusions in a typical LF refining slag for C96V saw wire steel has been investigated. The results indicated that K$_2$O additions seems to significantly enhance inclusion removal in steel melts, instead, Li$_2$O additions hindered inclusion removal. In details, K$_2$O improve the cleanliness in the as quenched C96V saw wire steel melts compared to preexisting synthetic LF refining slag compositions: (i) The average diameter of nonmetallic inclusions was decreased sharply with the content of K$_2$O in synthetic LF refining slag increasing. In particular, the diameter of most of inclusions was less than $2.5 \times 10^{-6}$ m ($2.5 \mu$m) when the content of K$_2$O in synthetic LF refining slag more than 10 wt%; (ii) The number of inclusions descend sharply with the content of K$_2$O in synthetic LF refining slag raising. (iii) Both of the SiO$_2$–MnO–Al$_2$O$_3$, SiO$_2$–CaO–Al$_2$O$_3$ inclusions system mainly concentrated in the low melting zone when the composition of K$_2$O in synthetic refining slag was less than 10 wt%. While the Li$_2$O additions has the opposite effect.

KEY WORDS: C96V saw wire steels; LF refining slag; alkali oxides; inclusions.

1. Introduction

Tire cord steel and saw wire steel are the representative productions of super clean steel, it requires no more than once wire broken per 100 000 meters during drawing and standing process. The fracture of wire is the most frequently accident in the process of cord wire or saw wire production, this is mainly caused by large and hard inclusions. In addition, some small inclusions would cause wire broken because they are too hard to deform. According to the exist research results the main kinds of inclusions in tire cord steel or saw wire steel are MnO–SiO$_2$–Al$_2$O$_3$ and CaO–SiO$_2$–Al$_2$O$_3$ system, it has excellent deformability when its compositions are located in the low melting zone. For instance, there are three aspects to control inclusions in cord wire steel and saw wire steel: (i) Excellent deformability, inclusions can deform or break into smaller size easily, which means, the number of inclusion which composition concentrate in low melting zone should be as much as possible; (ii) The total number of inclusions should be as less as possible; (iii) Removed large and hard inclusions should be as much as possible.

Lots of research have been done in order to control inclusions in cord wire steel and saw wire steel. Nevertheless, most of them were concentrate on how to control inclusions’ compositions locate in low melting zone, few have looked at changing the chemical composition of LF refining slag with new components to improve inclusions absorption.

Alkali oxides have been applied to add into mold flux for helping it melting easily. However, the influence of alkali oxides enhance removing inclusion has not been noticed until Sohn I et al. did some research at 2014. The effect of alkali oxides (Li$_2$O, Na$_2$O, K$_2$O, Rb$_2$O and Cs$_2$O) on inclusion (especially for Mg–Ca–Ti–Al and Mg–Ti–Al inclusion system) removal using tundish fluxes have been studied. The results indicated that K$_2$O, Rb$_2$O and Cs$_2$O do seem to have enhanced absorption ability and could possibly be utilized to improve steel cleanliness.

However, the alkali oxides have not been applied in LF refining progress until now, the influence of alkali oxides on the number, size, morphology and compositions (especially for MnO–SiO$_2$–Al$_2$O$_3$ and CaO–SiO$_2$–Al$_2$O$_3$ inclusion system) still not completely understood. For instance, in the present study we have explored the influence of alkali oxides on enhancing inclusion removal by adding 5 wt%, 10 wt%, 15 wt% Li$_2$O, K$_2$O into synthetic LF refining slag, respectively. The influence of alkali oxides (Li$_2$O, K$_2$O) on the average diameter, number, composition and morphology of inclusions have been studied.
2. Experiment

2.1. Experimental Apparatus and Procedure

With respect to simulating LF refining progress, the MoSi$_2$ furnace was utilized to making C96V saw wire steels in this experiment, the schematic diagram of experimental equipment as shown as Fig. 1.

In this experiment, the temperature of liquid metal is continuously measured by means of a B-type reference thermocouple. Argon atmosphere was kept in experiments all the time, blowing from the bottom of the furnace tube to the top. The experimental procedures were carried as follows.

Firstly, 1.00 kg industrial pure iron is placed into a MgO crucible with $60 \times 10^{-3}$ m (60 mm) in inner diameter and $80 \times 10^{-3}$ m (80 mm) in depth. Then, the crucible is placed in a graphite crucible to prevent liquid metal from leaking. After the whole crucible is placed in the chamber, the power is switched on and the furnace is heated to experimental temperature [1 873 K (1 600°C)].

Adding alloys into the melts when the temperature reached 1 873 K (1 600°C). Sampling No. 0, which is the original chemical composition in steel without interaction of slag and metal. After that, 0.05 kg synthetic LF refining slag is put onto the surface of the molten metal. Samples No. 1 to No. 3 are taken from the molten metal after the slag has melted for 900, 1 800 and 2 700 s (15, 30, and 45 minutes), respectively. After each sampling, the steel liquid is stirred with a graphite rod for 120 s (2 minutes) to make the molten steel and the refining slag uniform. All of the samples are taken by quarts tube sampler and quenched immediately in water.

In total, there are 10 heats made by treating with different synthetic LF refining slags which were added 5 wt%, 10 wt%, 15 wt% Li$_2$O, K$_2$O, respectively as shown in Table 1. Sampling at 0, 900, 1 800 and 2 700 s (0, 15, 30, and 45 minutes) during the refining progress.

2.2. Analysis Methods

2.2.1. Chemical Composition of Steels Samples

Direct reading spectrometer was utilized to detect the composition of Si, Mn, Cr, V, Mo, Ni, Al, P and so on. For C and S, infrared C/S analyzer was applied, finally, the LECO TC 500 O$_2$/N$_2$ analyzer has been chosen to detect O, N. The chemical composition of C96V saw wire steel were showed in Table 2.

2.2.2. Statistics of Inclusions’ Count, Size

Getting enough photos (more than 50 pieces) around “S” route (On the surface of the sample, take pictures in order from right to left, followed by in order from left to right) after all of these steel samples were treated by 100–2 000 mesh sand papers and polished. For each image, the size and the number of inclusions were characterized using Image J software and the Image J software is a public domain, Java-based image processing program developed at the National Institutes of Health (NIH).

2.2.3. Analysis of Inclusions’ Component and Morphology

Scanning electron microscope (SEM) and energy spectrometer (EDS) were applied to analysis inclusions’ component and morphology.

![Fig. 1. Schematic diagram of experimental equipment (MoSi$_2$ furnace). (Online version in color.)](image-url)

| Table 1. Chemical Composition of Synthesized Refining slag. |
|-------------------------------------------------------------|
|                | CaO (wt%) | SiO$_2$ (wt%) | Al$_2$O$_3$ (wt%) | Li$_2$O (wt%) | K$_2$O (wt%) | time/min | basicity |
| 0°              | 42.22     | 52.78         | 5                  | –             | –            | 0, 15, 30, 45 | 0.8      |
| 1°              | 40.11     | 50.14         | 4.75               | 5             | –            | 0, 15, 30, 45 | 0.8      |
| 2°              | 38.00     | 47.50         | 4.50               | 10            | –            | 0, 15, 30, 45 | 0.8      |
| 3°              | 35.89     | 44.86         | 4.25               | 15            | –            | 0, 15, 30, 45 | 0.8      |
| 4°              | 40.11     | 50.14         | 4.75               | –             | 5            | 0, 15, 30, 45 | 0.8      |
| 5°              | 38.00     | 47.50         | 4.50               | –             | 10           | 0, 15, 30, 45 | 0.8      |
| 6°              | 35.89     | 44.86         | 4.25               | –             | 15           | 0, 15, 30, 45 | 0.8      |

| Table 2. Chemical Composition of C96V Saw Wire Steels. |
|-------------------------------------------------------|
| C | Si | Cr | Mn | V | Al | O | N | P | S | Ni | Cu |
|---|----|----|----|---|----|---|---|---|---|----|----|
| 0° | 0.96 | 0.15 | 0.22 | 0.35 | 0.12 | ≤0.003 | 0.0015 | 0.0028 | 0.0069 | 0.0028 | 0.0027 | 0.0025 |
| 1° | 0.97 | 0.16 | 0.21 | 0.35 | 0.10 | ≤0.003 | 0.0014 | 0.0033 | 0.0072 | 0.0034 | 0.0025 | 0.0040 |
| 2° | 0.95 | 0.17 | 0.20 | 0.34 | 0.11 | ≤0.003 | 0.0012 | 0.0030 | 0.0073 | 0.0032 | 0.0030 | 0.0038 |
| 3° | 0.96 | 0.17 | 0.21 | 0.36 | 0.11 | ≤0.003 | 0.0011 | 0.0032 | 0.0071 | 0.0035 | 0.0028 | 0.0040 |
| 4° | 0.97 | 0.16 | 0.25 | 0.37 | 0.12 | ≤0.003 | 0.0017 | 0.0030 | 0.0071 | 0.0029 | 0.0020 | 0.0029 |
| 5° | 0.95 | 0.17 | 0.24 | 0.36 | 0.10 | ≤0.003 | 0.0012 | 0.0031 | 0.0068 | 0.0027 | 0.0034 | 0.0026 |
| 6° | 0.96 | 0.15 | 0.22 | 0.38 | 0.11 | ≤0.003 | 0.0014 | 0.0026 | 0.0059 | 0.0030 | 0.0032 | 0.0038 |
3. Results

3.1. Influence of Alkali Oxides (Li₂O, K₂O) on the Average Diameter of Inclusions

The change of inclusions' average diameter during refining process were showed in Fig. 2. For normal heat, the count descends slowly with refining time raising from 900 to 2 700 s (15 to 45 minutes).

After treated with refining slag which have added 5 wt%, 10 wt%, 15 wt% Li₂O, respectively, the count were float more severely: (i) Under the same refining time, the average diameter of inclusion was increased sharply with the weight percentage of Li₂O raising from 5% to 15%; (ii) On the other hand, the average diameter of inclusions was raised gently with the refining time raising from 900 to 2 700 s (15 to 45 minutes) when the weight percentage of Li₂O fixed. (iii) Furthermore, any value of experiment heat which was treated by Li₂O was larger than that of normal heat.

In contrast, K₂O addition could caused opposite results obviously. (i) Under the same refining time, the average diameter of inclusions was reduced sharply with the weight percentage of K₂O raised from 5% to 15%; (ii) On the other hand, the average diameter of inclusions decreased gently with the refining time ascending from 900 to 2 700 s (15 to 45 minutes) when the weight percentage of K₂O fixed. (iii) Furthermore, any value of experiment heat which was treated by K₂O was smaller than that of normal heat.

3.2. Influence of Alkali Oxides (Li₂O, K₂O) on the Component of Inclusions

The inclusion distribution overlayed on phase diagram with different refining time in 0#(normal heat), 2#(10 wt%Li₂O), 5#(10 wt%K₂O) steel samples are shown in Figs. 3, 4, 5. Further more, the average content of each component in inclusions during refining are shown in Fig. 6.

For 0# steel samples, it is obviously that the contents of SiO₂ and Al₂O₃ in inclusions increased gradually. In details, SiO₂–MnO–Al₂O₃ inclusion mainly concentrate in the area of 70 wt%– 90 wt% SiO₂, < 18 wt% Al₂O₃, SiO₂–CaO–Al₂O₃ inclusion mainly concentrate in the area of 40 wt%– 60 wt% SiO₂, 10 wt%–25 wt% Al₂O₃ after the steels are refined with 2 700 s (45 minutes). In addition, some SiO₂–CaO–Al₂O₃ inclusions have a small amount of mass fraction of CaO, Al₂O₃ below 10 wt%.

It is easy to get the variation tendency of inclusion in 2#(10 wt%Li₂O) steel samples form Fig. 4. (i) The inclusion distribution overlaid on phase diagram moved quickly with refining time increasing from 900 to 2 700 s (15 to 45 minutes). In particular, SiO₂–MnO–Al₂O₃ inclusion mainly concentrate in the area of > 85 wt%SiO₂, at the same time,
SiO₂–CaO–Al₂O₃ inclusion mainly concentrate in the area of > 60 wt%SiO₂. (ii) Compared with 0# steel samples, it can be found that the content of SiO₂, Al₂O₃ in the SiO₂–MnO–Al₂O₃ and SiO₂–CaO–Al₂O₃ inclusion system are higher while both of them are under the same refining time. As a result, both of the two kinds of inclusions in 2# steel samples deviated from the lower melting zone.

Figure 5 describes the distribution of inclusion in SiO₂–MnO–Al₂O₃, SiO₂–CaO–Al₂O₃ phase diagram with 10 wt% K₂O. Contrary to the effects of Li₂O, some opposite results are observed. As the reaction time increased, there is a strong tendency for inclusions to be distributed toward the less SiO₂, Al₂O₃ phase. In details, The SiO₂–MnO–Al₂O₃ inclusion system mainly concentrate in the low melting

Fig. 4. Inclusion distribution overlaid on phase diagram with refining time in 2# steel sample (a) 900 s (15 minutes) (b) 1800 s (30 minutes) (c) 2700 s (45 minutes). (Online version in color.)

Fig. 5. Inclusion distribution overlaid on phase diagram with refining time in 5# steel sample (a) 900 s (15 minutes) (b) 1800 s (30 minutes) (c) 2700 s (45 minutes). (Online version in color.)
area of 40 wt%–50 wt% SiO2, <10 wt% Al2O3, and the 
SiO2–CaO–Al2O3 inclusion system mainly concentrate in 
the low melting area of 40 wt%–50 wt% SiO2, <20 wt% 
Al2O3 at the same time. For instance, addition K2O seems 
to concentrate the distribution of inclusions toward the less 
SiO2, Al2O3 phase, which is clearly approved in Fig. 5.

In summary, at longer reaction times, the distribution of 
inclusions are spread across the ternary phase diagram sug-
gesting Li2O addition and an increase in Li2O would likely 
be detrimental to the inclusions removal in the C96V saw 
wire steel samples. In contrast, K2O addition would likely be 
helpful to control both SiO2–MnO–Al2O3 and SiO2–CaO– 
Al2O3 inclusion system concentrate in low melting area. 
This also would in turn as described by Fig. 6.

**Figure 7** compares the change in the inclusion chemistry 
within the SiO2–MnO–Al2O3, SiO2–CaO–Al2O3 ternary
phase diagram after 2700 s (45 minutes) with varying amounts of K$_2$O additions spanning from 5 to 15 weight percentage. Further more, the average content of each component in inclusions during refining are shown in Fig. 8.

It should be paid more attention that both of the SiO$_2$–MnO–Al$_2$O$_3$, SiO$_2$–CaO–Al$_2$O$_3$ inclusions system concentrated in the low melting zone with the K$_2$O addition at not only 5 wt% but also 10 wt%, however, neither SiO$_2$–MnO–Al$_2$O$_3$ nor SiO$_2$–CaO–Al$_2$O$_3$ inclusions system would be that when the K$_2$O addition increased to 15 wt%. Therefore, high melting and hard inclusions as described in Fig. 7 should be avoided in consideration of excellent deformability. This also would in turn as described by Fig. 8.

3.3. Influence of Alkali Oxides (Li$_2$O, K$_2$O) on the Number of Inclusions

Figure 9 shows the influence of alkali oxides on the number of inclusions at various concentrations as a function of reaction time. For normal heat, it could be found that the number of inclusions reduced gently with the reaction time increased form 900 to 2700 s (15 to 45 minutes). For heats that with Li$_2$O addition from 5 wt% to 15 wt%, obviously, the number of inclusions exceeds normal level for all the concentrations of Li$_2$O. On the contrast, unlike Li$_2$O, reaction of the C96V saw wore steel samples with K$_2$O containing synthesized refining slag samples resulted in a significant decrease in the number of inclusions observed with both longer reaction times and higher concentrations of K$_2$O.

3.4. Morphological Observations of Typical Inclusions

Morphological observations of typical inclusions using SEM–EDS are shown in Figs. 10, 11, 12. Majority of inclusions in all of the experimental heats are SiO$_2$–MnO–
Al₂O₃ and SiO₂–CaO–Al₂O₃ system, the differences about inclusions’ component, size and so on have been discussed above.

3.5. Element Distribution in Complex Inclusion

As mentioned, complex inclusions were discovered in all of the experimental steel samples. In order to describe inclusions’ structure exactly, SEM mappings have been done as shown in Figs. 13, 14 and 15. Obviously, both SiO₂–MnO–Al₂O₃ and SiO₂–CaO–Al₂O₃ inclusions are multi-layered composite structure in all of experimental steel samples. In details, there was SiO₂, MnO, CaO and Al₂O₃ homogeneous composited in center and a periphery of MnS precipitate around it.

4. Discussion

The content of alkali oxides in the metallurgical slag is
usually low, but its influence is significant. This comprehensive change in the slag composition has a dramatic impact on the thermochemical and thermophysical properties of the slag, including their density, surface tension and viscosity. In particular, surface tension has a direct impact on the melt/slag separation efficiency, the melt/slag reaction kinetics, and the permeability of the intermediate gases used for reduction and heat transfer.

Studies that discuss the structure and properties of metallurgical slags have been reviewed by Waseda and Toguri.8,9 It’s well known that increase Li2O, Na2O content in SiO2–CaO–Al2O3–R2O slag would like to change owing to the modification of complex silicate structure into simple [Si2O7]− due to the above-mentioned ionic charge-compensating effect. According to literatures11,12 that the structure of slag is very complex. Including chains, rings, and three-dimensional network structures and so on as shown in Fig. 16.

(i) The effect by Li2O on the surface tension can be understood when considering the change in the degree of polymerization (DOP) of slag structure:13

\[ \text{R}_2\text{O} = 2\text{R}^+ + \text{O}^{2-} \]  

(1)

\[ [\text{Si}_2\text{O}_5]^{6-} (\text{ring}) + \text{O}^{2-} = [\text{Si}_2\text{O}_{10}]^{8-} (\text{chain}) \]  

(2)

\[ [\text{Si}_2\text{O}_{10}] (\text{chain}) + \text{O}^{2-} = [\text{Si}_2\text{O}_7]^{6-} (\text{dimer}) + [\text{SiO}_4]^{6+} (\text{monomer}) \]  

(3)

Where R+ is the cation of the basic oxide such as Li+. Addition of Li2O would provide O2−, which can modify the complex silicate structure into simple [Si2O7]− and [SiO4]2−. On the other hand, according to Sohn14 after treated by Li2O, the [AlO3]2−-tetrahedral structure was depolymerized. Therefore, and then the surface tension of slag decrease sharply.

We have applied the schematic diagram of how Li2O depolymerize the slag network structure as shown in Fig. 17 that could help us understand Eqs. (2) and (3).

Therefore, the surface tension of slag decreases significantly with the content of Li2O increasing.

(ii) The effect of K2O can also be approached with respect to the change in slag structure according to two distinctively different roles. One role is the modification of the complex silicate melts with supply of O2−, as expressed by Eqs. (1) to (3).14 The other role of K2O is expressed by Eq. (4) which can be adapted to aluminates structures:14

\[ 2\text{Al}^{3+} + 7\text{O}^{2-} + \text{K}_2\text{O} = 2[\text{AlO}_4]^{3-} + 2\text{K}^+ \]  

(4)

As shown by Eq. (4), although K2O provides additional O2−, K2O accelerates the formation of [AlO4]3− - tetrahedral units due to the above-mentioned ionic charge-compensation effect of K+ cations, which act as a network former in slag structure.15,16 Thus, the change of slag structure with K2O seems to be determined by the dual balance of the following conditions: (i) the modification of complex silicate structures to simpler dimers and monomers of [Si2O7]−,

[SiO4]2− with the supply of O2−, and (ii) the formation of [AlO4]3− due to the ionic charge-compensating effect. According to a series of literatures17–19 it is likely that the abovementioned effect of K2O on the aluminate structure is more dominant. Furthermore, according to Sohn14 after treated by K2O, the Si–O–Al bonding within the slag increased, thus polymerizing the slag to form complex aluminates and aluminosilicate structures.

In order to help us understand this process easier, we provided the schematic diagram of how K2O polymerize the slag network structure as shown in Fig. 18.

Therefore, the surface tension of slag increases significantly with the content of K2O increasing.

4.2. Influence of Alkali Oxides (Li2O, K2O) on the Number, Average Diameter and Content of Inclusions

The process of slag absorbing solid oxide inclusions was shown in Fig. 19(a). The free energy change of inclusion can be expressed by:

\[ \Delta G = 4\pi r^2 \sigma_{\text{i-s}} + \Delta G = 4\pi r^2 \sigma_{\text{m-s}} - n4\pi (r + a)^2 \sigma_{\text{m-s}} \]  

(5)

\( \Delta G \) — Free energy change of inclusions moving into molten slag;

\( r \) — radius of inclusion;
\( \sigma_{i-s} \) — Interfacial tension between inclusions and slag, N/m;

\( \Delta G \) — Change of free energy of inclusions dissolving in slag;

\( \sigma_{m-i} \) — Interfacial tension between inclusions and metal liquid, N/m;

\( n \) — The proportion of the surface area in contact between inclusions and molten steel before the molten steel membrane broken;

\( \sigma_{m-s} \) — Interfacial tension between metal liquid and slag, N/m;

In the process of slag absorbing solid inclusions, the value of \( n \) change from zero to one:

\[
\Delta G = 4\pi r^2 (\sigma_{i-s} + \Delta G - 4\pi r^2 (\sigma_{m-i} - 4\pi r^2 \sigma_{m-s})) + \frac{1}{6} \pi n dh
\]

\[
= 4\pi r^2 (\sigma_{i-s} + \Delta G - 4\pi r^2 \sigma_{m-s} - 2\pi r^2 \sigma_{m-s})
\]

\[
= -2\pi r^2 (2\sigma_{m-s} + \sigma_{m-s} - 2\sigma_{i-s}) + \Delta G
\]

for \( \Delta G < 0 \):

\[
\Delta G - 2\pi r^2 (2\sigma_{m-s} + \sigma_{m-s} - 2\sigma_{i-s}) < 0 \quad \cdots \cdots (6)
\]

The inclusions can move into the slag spontaneously at this time.

If the effect of the interface energy was considered, the Change of free energy between inclusions dissolved in slag could be neglected:

\[
4\pi r^3 \left( \sigma_{i-s} - \sigma_{m-i} - \frac{1}{2} \sigma_{m-s} \right) < 0 \quad \cdots \cdots (7)
\]

It’s obviously that, the inclusions would move into the slag spontaneously easier when the value of \( \sigma_{i-s} \) decrease, \( \sigma_{m-i} \) and \( \sigma_{m-s} \) increase.

The equilibrium relationship of surface tension between slag and solid inclusion was shown in Fig. 19(b). The equation could be described as:

\[
\sigma_{i-s} = \sigma_i - \sigma_s \cos \theta \quad \cdots \cdots (8)
\]

\( \sigma_i, \sigma_s \) — the surface tension of solid inclusions and slag

\( \sigma_{i-s} \) — The interfacial tension between slag and solid inclusions

The value of \( \sigma_i \) and \( \theta \) are constants, and the value of \( \sigma_{i-s} \) will become smaller when the \( \sigma_i \) increase. In addition, the value of \( \sigma_{m-s} \) will become larger with \( \sigma_i \) increasing. On the other hand, the value of \( \sigma_{m-i} \) is a constant.

According to Eq. (7), the inclusions would enter the slag spontaneously easier when the value of \( \sigma_i \) raised with the content of K2O increasing. Therefore, the number and average diameter of inclusions decreased significantly.

However, Li2O have an opposite influence.

In terms of the influence of alkali oxides (Li2O, K2O) on the content of inclusions with refining times changing, it’s vividly shown in Figs. 20, 21.

When Li2O, was added into slag, the ability of slags
to absorb inclusions will decrease. Furthermore, the reaction products ([Si\textsubscript{3}O\textsubscript{9}]\textsuperscript{6−}, [Si\textsubscript{3}O\textsubscript{10}]\textsuperscript{8−}, [Si\textsubscript{2}O\textsubscript{7}]\textsuperscript{6−}, [SiO\textsubscript{4}]\textsuperscript{4−}, [AlO\textsubscript{4}]\textsuperscript{5−}, and so on) from Eqs. (1), (2) and (3) might be involved into steel liquid. Therefore, the content of SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} contained in inclusions increasing rapidly, as described in Fig. 20.

On the contrast, When K\textsubscript{2}O was added into slag, the inclusions, such as SiO\textsubscript{2}, MnO, Al\textsubscript{2}O\textsubscript{3} will be absorbed into slag, that would cause the content of SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} contained in inclusions decrease sharply, as described in Fig. 21.

5. Conclusions

Effect of Li\textsubscript{2}O, K\textsubscript{2}O containing synthetic LF refining slag on the absorption ability of inclusions for C96V saw wire steels has been studied. It was found that:

1. Li\textsubscript{2}O additions in some case hindered inclusion removal. However, K\textsubscript{2}O additions seems to significantly enhance inclusion removal in steel melts.

2. With K\textsubscript{2}O additions, not only did the number of inclusions decrease but also the average inclusions diameter in the steel samples. In particular, the diameter of almost inclusions was less than 2.5×10\textsuperscript{−6} m (2.5 μm) when the content of K\textsubscript{2}O in synthetic LF refining slag more than 10 wt%.

3. On the other hand, With K\textsubscript{2}O additions, both of the SiO\textsubscript{2}–MnO–Al\textsubscript{2}O\textsubscript{3}, SiO\textsubscript{2}–CaO–Al\textsubscript{2}O\textsubscript{3} inclusions system mainly concentrated in the low melting zone when the composition of K\textsubscript{2}O in synthetic refining slag was less than 10 wt%.

In one word, K\textsubscript{2}O additions seems to significantly improve the cleanliness in the as-quenched C96V saw wire steel melts compared with preexisting synthetic refining slag compositions.

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REFERENCES

1) L. F. Zhang: Steel Res. Int., 76 (2005), 784.
2) C. X. Fu, H. J. Lu and L. Zhao: Phys. Test, 31 (2013), 34.
3) L. Zhang: Steel Res. Int., 77 (2006), 158.
4) J. Y. Yu, Y. Kang and I. Sohn: Metall. Mater. Trans. B, 45 (2014), 113.
5) K. Choi, Y. Kang and I. Sohn: Metall. Mater. Trans. B, 47 (2016), 1520.
6) X. H. H: Principle of Iron and Steel Metallurgy, Vol. 4, Metallurgical Industry Press, Beijing, (2014), 328.
7) B. O. Mysen and P. Richet: Silicate Glasses and Melts: Properties and Structure, Elsevier, Amsterdam, (2005).
8) Y. Waseda and J. M. Toguri: The Structure and Properties of Oxide Melts: Application of Basic Science to Metallurgical Processing, World Scientific, Singapore, (1998), 113.
9) Y. Waseda and J. M. Toguri: Metall. Mater. Trans. B, 8 (1977), 563.
10) S. Suenaga, S. Haruki, Y. Nomoto, N. Saito and K. Nakashima: ISIJ Int., 51 (2011), 1265.
11) B. E. Warren, H. Krutter and O. Morningstar: J. Am. Ceram. Soc., 12 (1936), 202.
12) Y. Waseda: Can. Metall. Q., 20 (1981), 57.
13) N. Sano, W. K. Lu and P. V. Riboud: Advanced Physical Chemistry for Process Metallurgy, Academic Press, San Diego, (1997), 45.
14) B. O. Mysen, D. Virgo and I. Kushiro: Am. Mineral., 66 (1981), 678.
15) Y. Iguchi, K. Yonezawa, Y. Funaoka, S. Ban-ya and Y. Nishina: Proc. 3rd Int. Conf. on Molten Slags and Fluxes, Institute of Metals, Glasgow, London, (1988), 169.
16) L. G. Hwa, S. L. Hwang and L. C. Liu: J. Non-Cryst. Solids, 238 (1998), 193.
17) H. Kim, W. H. Kim, J. H. Park and D. J. Min: Steel Res. Int., 81 (2010), 17.
18) W. H. Kim, I. Sohn and D. J. Min: Steel Res. Int., 81 (2010), 735.
19) I. Sohn and D. J. Min: Steel Res. Int., 83 (2012), 611.