International Journal of ISSI, Vol. 19(2022), No. 1, pp. 1-7

The optimization of the aluminum deoxidation process to reduce non-metallic inclusions in steel products

H. R. Pakzaman*[1]

Research and Development Department, Iran Alloy Steel Company (IASCO), Yazd, Iran

---

Abstract

Nowadays, clean liquid steel is crucial for improving castability, increasing production efficiency and generating high-quality customer-satisfying products. This research studied the influence of the aluminum deoxidation process on the inclusion content in steel products. The image analysis technique and the calculation of inclusion volume fraction were used to assess the cleanliness of steel products. A total of 37 heats of typical medium carbon Al-Killed steel with aluminum concentrations ranging from 0.015-0.040 wt.% were put to the test. The findings revealed that at least 70% of the total aluminum utilized in the tapping and ladle furnace (LF) must be added during the tapping process in order to produce a clean steel product with an inclusion volume fraction of less than 0.023%. Moreover, aluminum granules need to be added once throughout the LF process during the first 15 minutes of the process. In order to adjust the aluminum content in the liquid steel, the aluminum wire must be fed all at once at the last minute of the LF process.

Keywords: Clean steel; Deoxidation; Aluminum; Inclusion; Image analysis.

---

1. Introduction

There is always an ever-increasing demand for clean steel products [1]. In order to produce clean steels, in addition to lowering the levels of non-metallic oxide inclusions, it is necessary to minimize the presence of impurities such as sulfur, phosphorus, hydrogen, and nitrogen [2]. Several process parameters affect how to clean steel, but the most important one is when and where deoxidizer is used [3].

One of the most common causes leading to generating inclusion in the melt is the aluminum deoxidation treatment. The secondary metallurgy process plays a pivotal role in the production of clean steel by removing the inclusions. Solid alumina is formed when added aluminum reacts with the dissolved oxygen in the manner described in reaction (1) [4,5]:

$$2[Al] + 3[O] = Al_2O_{3(solid)} \qquad \text{Eq. (1)}$$

Hence, the precipitation of alumina inclusions is an easy process that takes place during the deoxidation practice; alternatively stated, the formation of these inclusions is almost unavoidable. Thermodynamically speaking, the maximum amount of aluminum that can dissolve into liquid steel is 5 ppm, and as the aluminum concentration goes above that, alumina inclusions start to form [6]. The brittle alumina inclusions substantially reduce the ductility and fatigue life of steel products. Besides, they induce nozzle clogging during casting process [7]. Owing to the fact that they have a lower density than the liquid steel, these inclusions have a tendency to float out. However, many of the inclusion particles are fine, and as a result, they are unable to move rapidly enough toward the slag, so they are left in the liquid steel. To put it another way, for an inclusion to float, its dimensions must have a specific size; if they are not large enough, the inclusion will remain in the melt [8]. According to a systematic inclusion removal research [9], the

---

*Corresponding author
Email: hr.pakzaman@gmail.com
Address: Research & Development Department, Iran Alloy Steel Company (IASCO), Yazd, P. O. Box: 89451-51694 Iran

[1] Ph.D.

inclusion content in the melt can be decreased by 65-75%, 20-25%, and 5-10% using the ladle, tundish, and mold operation, respectively. This indicates the significance of the ladle treatment in controlling inclusion and steel cleanliness.

The aim of this study is to evaluate the influence of different parameters of aluminum deoxidation process on the cleanliness of a medium carbon Al-Killed steel grade and to establish the ideal deoxidation conditions.

2. Materials and methods

In this research, 37 heats of typical medium carbon Al-Killed steel with the chemical composition given in Table 1 were investigated.

The conventional approach to deoxidation entails the addition of aluminum bars during the tapping process from an electric arc furnace (EAF), as well as the addition of aluminum granules (Al_G) for deoxidation in LF, and the final adjustment of aluminum in accordance with the range shown in Table 1 using aluminum wire (Al_W). The aluminum deoxidation parameters, including the ratio of aluminum added during tapping to the total aluminum used, the number of Al additions in LF, the time interval of Al_G addition in LF, and the time interval of last Al_W addition until the end of the LF process, were investigated. As a result of analyzing the data from 37 heats, Table 2 shows the varied ranges of the aforementioned parameters.

The image analysis method was utilized to evaluate the effects of different parameters of the aluminum deoxidation treatment on the cleanliness of steel products. Optical microscopy was employed to examine the samples having a longitudinal cross-section of at least 2x1 cm^2 at one-third location of the diameter of the final wrought products after grinding and polishing (without etching). At least 10 different images were taken at a magnification of 200x. These images were analyzed using microstructural image processing (MIP) software, and then the average inclusion volume fraction was reported for each sample. The inclusion volume fraction does not account for extremely small inclusions (1 µm). Furthermore, some of the inclusions found in the samples, were subjected to elemental chemical analysis using scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) in order to determine their nature and chemical composition.

3. Results and discussions

Figure 1 shows the typical optical images of as-polished longitudinal cross-section areas taken from various product samples used for measurement of inclusion content. In Figs. 1a and 1b, the inclusion volume fractions are very low and measured to be equal to 0.021 and 0.024%, respectively. However, Figs. 1c and 1d indicate large inclusions in the product in which the inclusion volume fractions are equal to 0.118 and 0.145% in that order. It is worthy of note that at least ten images were taken from various points of the product samples from each heat number, and they were then examined by the image analysis. In all samples, at least 90% of the investigated images were comparable to Figs. 1a and 1b, indicating a low inclusion volume fraction. In fact, only about 10% of the images evaluated in each heat number showed large inclusions like those seen in Figs. 1c and 1d. It should also be noted that the average inclusion volume fraction in all the studied images out of 37 heats was calculated to be equal to 0.023%.

Table 1. The chemical composition of a typical medium carbon Al-Killed steel (wt.%).

C	Si	Mn	P	S	Cu	Al
0.30-0.40	0.10-0.40	0.50-0.80	0-0.040	0.020-0.040	0-0.40	0.015-0.040

Table 2. The aluminum deoxidation parameters and the classification of them into different ranges on the basis of the data of 37 studied heats.

Parameter	Range		
The ratio of Al added during tapping to total Al added during tapping and LF (%)	40-69	70-79	80-90
The number of Al_G+Al_W additions in LF	1	2	> 2
The time interval of Al_G addition in LF (min)	0-15		> 15
The time interval of last Al_W addition to LF end (min)	< 1	1-10	> 10

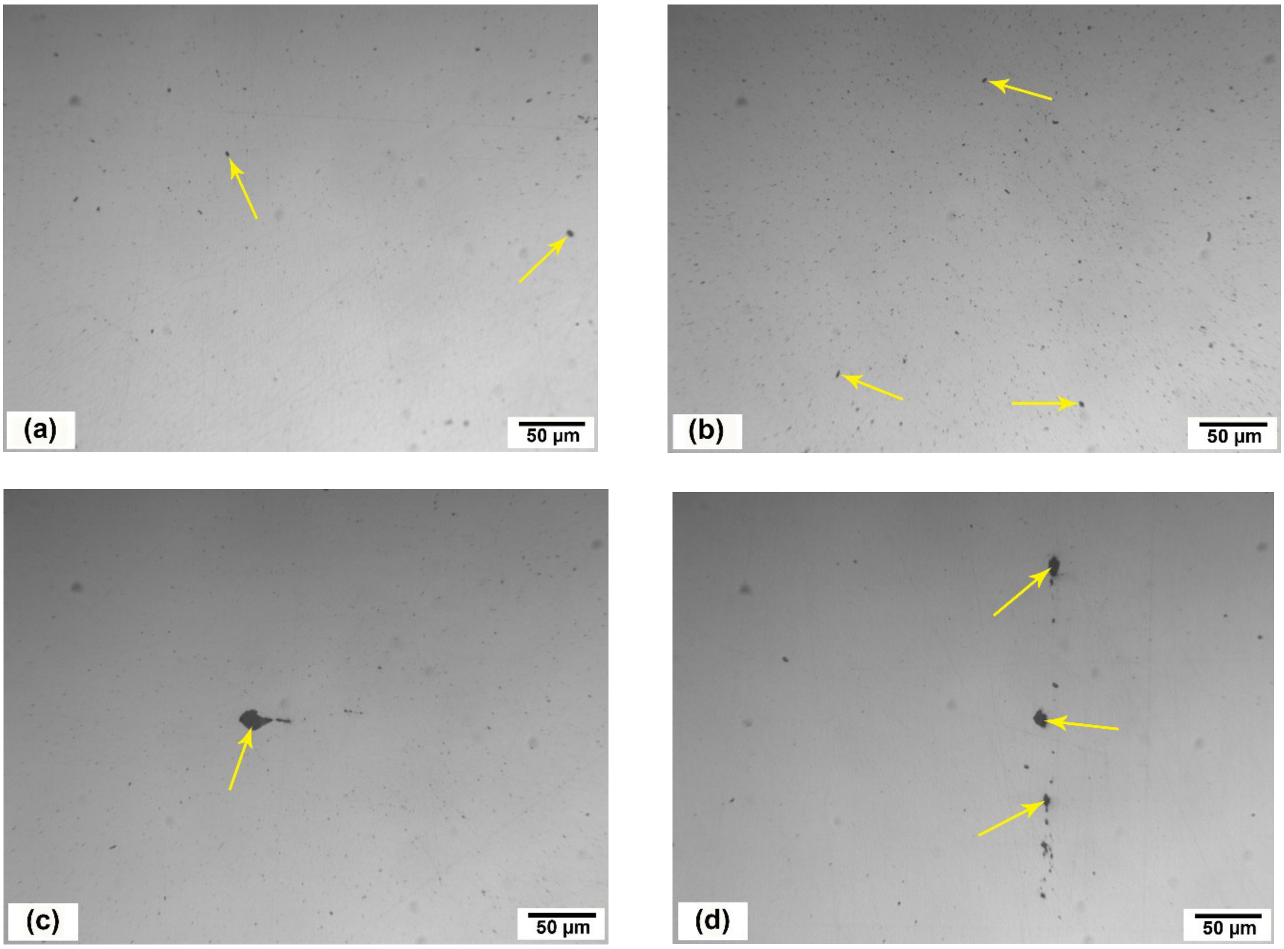

Fig. 1. The typical optical images taken from various product samples to measure the inclusion volume fraction value: (a) 0.021%, (b) 0.024%, (c) 0.118%, and (d) 0.145%. A number of inclusions with dimensions larger than 1 μm are marked with an arrow.

In order to determine the nature of large inclusions existing in some of the samples, SEM-EDS analysis was used and the results are given in Fig. 2. The chemical analysis of inclusions A and B shown in Figs. 2a and 2c is presented in Figs. 2b and 2d, respectively. As can be seen, the atomic concentration of oxygen and aluminum in inclusions A (64.56 and 35.10%) and B (62.70 and 34.31%) can be ascribed to the chemical composition of aluminum oxide (Al_2O_3). When compared to steel matrix, aluminum oxide or alumina inclusions have greater hardness but lower ductility. The initial-to-final cross-section ratio is quite high throughout the process of rolling and converting casting ingots into the final product. For the purpose of illustration, when rolling a 400 mm square primary cast ingot into a 45 mm diameter rod product, the cross-sectional area is decreased by nearly 100 times. Alumina inclusions are elongated to some extent along the rolling direction because of the significant amount of cross-sectional reduction that takes place during the rolling process; however, due to the weak ductility of these inclusions compared to the matrix, they cannot be elongated like the matrix in the rolling direction. Hence, the inclusions in the final product resemble long strings made of several closely spaced fragments that are aligned along the rolling direction (Figs. 2a and 2c). The presence of such long strings has detrimental effects on steel ductility [7]. Oxide, sulfide, and silicate inclusions can be mentioned as the most common inclusions existing in steel products. As shown in Figs. 2b and 2d, inclusions A and B are of the oxide type (Al_2O_3), and as a result, according to reaction (1), the origin of their generation can be related to the interactions between aluminum and oxygen elements, which took place during the aluminum deoxidation practice. It is important to note that the main entrance source of aluminum into liquid steel is attributable to the aluminum bars added during the tapping. Additionally, the added Al_G during the LF process is also a contributing factor. Using reaction (1), the stoichiometric amount of Al_2O_3 inclusions formed in terms of the amount of aluminum added into liquid steel can be calculated by the following equation.

$$Al_2O_3\ (kg) = \frac{M_{Al_2O_3}}{2 \times M_{Al}} \times Al\ (kg) = \qquad \text{Eq. (2)}$$

$$\frac{102}{2 \times 27} \times Al\ (kg) = 1.89\ Al\ (kg)$$

According to Eq. (2), for 1 kg of aluminum that reacts with dissolved oxygen, 1.89 kg of solid Al_2O_3 inclusion forms. This is in good agreement with the observations made by several researchers on the formation of Al_2O_3 inclusions with the origin of deoxidation in Al-Killed steels [10-12]. An important role for deoxidation in which aluminum is used to lower dissolved oxygen content has been shown as a primary cause of Al_2O_3 inclusion formation in steel [11]. According to the findings of Jing et al. [12], the ladle treatment produced Al_2O_3 inclusions with an irregular morphology when aluminum is added at the beginning of the process. Choudhary [7] determined the characteristics of non-deformable inclusions in steel products using SEM-EDS analysis and claimed that the origin of these inclusions may be related to the deoxidation process.

Figure 3 depicts an example of the images analyzed using MIP software (corresponding to Fig. 1d) in order to compute the inclusion volume fraction. To better distinguish inclusions from a steel matrix, they are highlighted in white and black, respectively. Besides, the inclusions smaller than 1 μm were neglected when calculating the inclusion volume fraction.

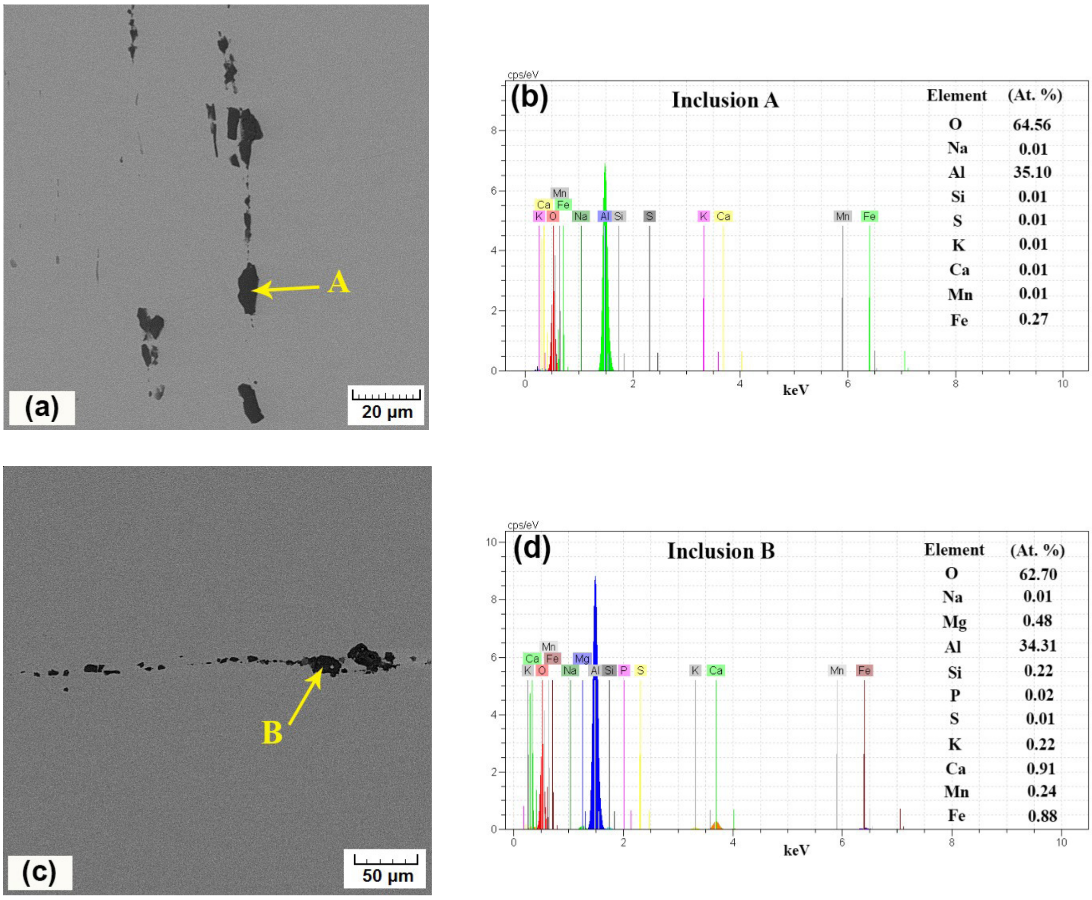

Fig. 2. (a), (c) Some typical SEM micrographs of large inclusions in steel products; (b), (d) EDS spectra and semi-quantitative chemical analysis of inclusions A and B shown in Figs. (a) and (c), respectively.

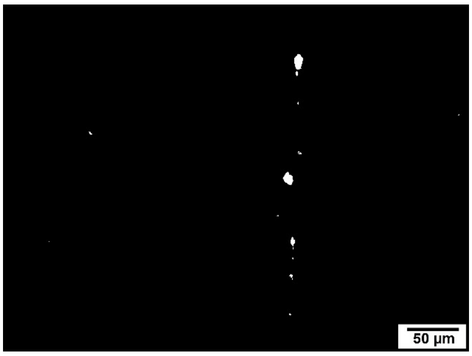

Fig. 3. The image correspondent to Fig. 1(d) is analyzed by MIP software in order to calculate the inclusion volume fraction. The steel matrix and inclusions are distinguishable from each other in black and white colors, respectively.

Image analysis was used to measure the inclusion volume fraction in a variety of samples to determine how different parameters of aluminum deoxidation treatment (introduced in Table 2) affect steel cleanliness, as shown in Fig. 4. It was previously reported that the average inclusion volume fraction in all the heats investigated was 0.023%, which is depicted in Fig. 4 as a red horizontal line. This value was utilized as a criteria to compare the cleanliness level of steel products. Admittedly, the products with dispersedly fine inclusion distribution (Figs. 1a and 1b) compared to the ones with nonuniform distribution of large inclusions (Figs. 1c and 1d) have a lower inclusion volume fraction (close to the average value of 0.023%) and higher cleanliness.

On the inclusion volume fraction, the influence of the ratio of aluminum added during tapping to the total aluminum added during tapping and LF are shown in Fig. 4a. As can be seen, with an increase in the ratio from 40-69 to 70-79 and 80-90%, the average inclusion volume fraction declines from 0.031 to 0.021 and 0.019%, respectively. In other words, the more Al added into liquid steel during tapping and the less Al in the subsequent LF process are, the cleaner the final product will be in terms of inclusion. To achieve clean steel, Fig. 4a indicates that at least 70% of the aluminum used in the whole process must be added into liquid steel during the tapping process. Clearly, the larger the size of the inclusion is, the simpler and more quickly it is absorbed by the slag and removed from the liquid steel. On the other hand, smaller inclusions need more time to float out. Furthermore, according to Eq. (1), the more aluminum bars are added into liquid steel with high oxygen content during tapping, the more alumina inclusions are formed. These inclusions float easily, which means that the subsequent LF treatment results in the lower generation of finer alumina inclusions which are problematic [13].

The effect of the number of Al_G+Al_W additions in LF on steel cleanliness is shown in Fig. 4b. It can be clearly seen that in cases where the number of Al additions in LF is twice at most, steel products are in a good situation in terms of the inclusion content. It is striking to be mentioned that increasing the number of Al additions more than twice, severely increases the inclusion content in steel products. Rout et al. [14] realized that the multi-step addition of aluminum leads to creating faceted alumina clusters; they hardly float as a result of their lower tendency to cluster. It is obvious that with the difficulty of flotation and adsorption of inclusions to the slag, the

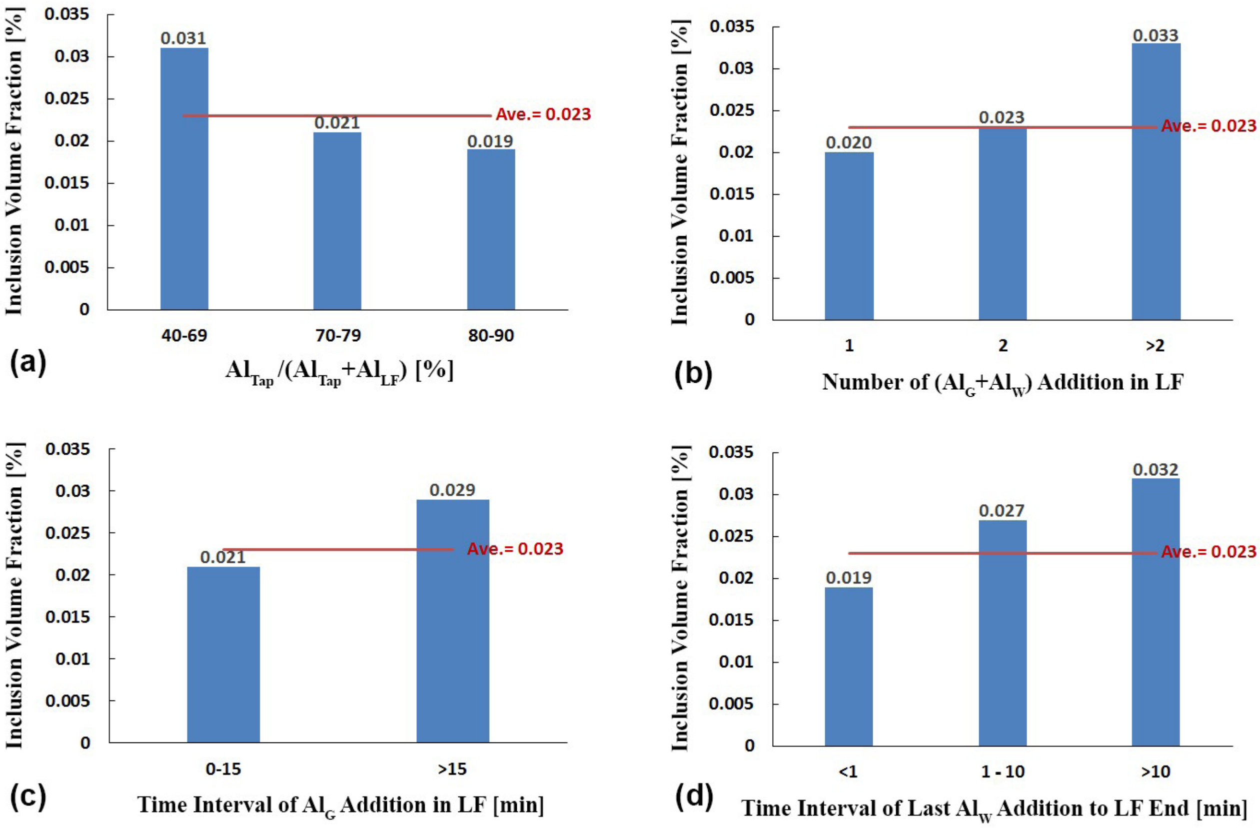

Fig. 4. The effect of different parameters of the aluminum deoxidation process on the average inclusion volume fraction. The parameters investigated are as follows: (a) the ratio of Al added during tapping to the total amount of Al added during tapping and LF, (b) the number of Al_G+Al_W additions in LF, (c) the time interval of Al_G addition in LF, and (d) the time interval of last Al_W addition until the end of LF process. The average inclusion volume fraction in all the studied samples is equal to 0.023% and is identified as a horizontal line.

amount of inclusions in the final product will be higher.

Figure 4c reveals the influence of the time interval of Al_G addition in LF on the average inclusion volume fraction in steel products. As can be seen, in the first 15 minutes of the LF process, provided that Al_G is added into liquid steel, a cleaner steel product will be produced. It has been claimed that 85% of the alumina clusters that are formed following the aluminum addition in the LF process (for deoxidation) are readily able to be floated and absorbed towards slag, and that the remaining 15% are smaller than 30 µm [9]. When there is a low saturation level of oxygen in liquid steel (i.e., the late of the LF process), the aluminum addition results in the formation of alumina inclusions, which have a flat and angular morphology and very poor clustering tendency to float out [11,15]. In fact, faceted alumina inclusions may be prevented by avoiding late addition of aluminum. Figure 4c shows that the increased inclusion content that happens when Al_G is added late to LF may be related to the formation of faceted alumina inclusions with low buoyancy which are hard to be removed from the liquid steel.

Moreover, the effect of the time interval of last Al_W addition until the end of the LF process on the inclusion content is indicated in Fig. 4d. The average inclusion volume fraction is computed to be 0.019% when Al_W is added into liquid steel shortly before the end of the LF process and before the steel ladle is transported to the casting unit (less than one minute until the end), while by increasing the time interval of last Al_W addition until LF end, the average inclusion volume fraction in the steel product can be reached 0.032%. Compared to Al_G, the yield of Al_W is substantially higher because it is able to diffuse deeper into the melt at higher intensities and dissolve much more. Accordingly, the Al_W injection is utilized to adjust the aluminum content in liquid steel in accordance with the ranges defined in Table 1. It is reported that the addition of Al_W increases the clogging of the casting nozzle owing to generation of fine alumina inclusions inside the liquid steel [14]. Figure 4d shows that it is best to add Al_W as soon as it is possible at the end of the LF process and promptly transfer the ladle to the casting unit.

4. Conclusions

In this research, the effect of various parameters of the aluminum deoxidation practice on steel cleanliness was investigated. According to the findings, the following requirements must be met in order to achieve products with an inclusion volume fraction less than 0.023% and a high level of cleanliness:

- In order to remove oxygen and adjust the aluminum content, at least 70% of the total weight of aluminum used, is added into liquid steel during the tapping process and no more than 30% is added in the LF process.
- The maximum number of times that aluminum may be added in the form of granules and wires in LF is two. To put it another way, Al_G should be added once at the beginning of the LF process, and Al_W should be fed once at the end of the LF process.
- The appropriate time for aluminum addition into liquid steel in the LF process is the initial 15 minutes and the last one minute for Al_G and Al_W, respectively.

Reference

[1] K. Wünnenberg, IISI study on clean steel, Metallurgical Research & Technology. 102 (2005) 687-692. https://doi.org/10.1051/metal:2005104.

[2] J. Yang, X.H.Wang, M. Jiang, W.J. Wang, Effect of calcium treatment on non-metallic inclusions in ultra-low oxygen steel refined by high basicity high Al_2O_3 slag, Journal of Iron and Steel Research, International. 18 (2011) 8-14. https://doi.org/10.1016/S1006-706X(11)60083-6.

[3] S. Abdelaziz, G. Megahed, I. El-Mahallawi, H. Ahmed, Control of Ca addition for improved cleanness of low C, Al killed steel, Ironmaking and Steelmaking. 36 (2009) 432-441. https://doi.org/10.1179/174328109X401578.

[4] K. Wasai, K. Mukai, A. Miyanaga, Observation of inclusion in aluminum deoxidized iron, ISIJ International. 42 (2002) 459-466. https://doi.org/10.2355/isijinternational.42.459.

[5] A. Kumar, G.M. Kumar, S.K. Ajmani, S.K. Singh, Resolving operational issues encountered during continuous casting of micro-alloyed Al killed steel, Ironmaking and Steelmaking. 44 (2017) 210-219. https://doi.org/10.1080/03019233.2016.1209899.

[6] C. Garlick, M. Griffiths, P. Whitehouse, C. Gore, Inclusion engineering: a keytool in achieving steelmaking operations stability at OneSteel Whyalla, Ironmaking and Steelmaking. 29 (2002) 140-146. https://doi.org/10.1179/030192302225004098.

[7] S.K. Choudhary, Influence of modified casting practice on steel cleanliness, ISIJ International. 51 (2011) 557-565. https://doi.org/10.2355/isijinternational.51.557.

[8] R. Dekkers, B. Blanpain, P. Wollants, F. Haers, C. Vercruyssen, B. Gommers, Non-metallic inclusions in aluminium killed steels, Ironmaking and Steelmaking. 29 (2002) 437-444. https://doi.org/10.1179/030192302225004584.

[9] L. Zhang, B.G. Thomas, State of the art in evaluation and control of steel cleanliness, ISIJ International. 43 (2003) 271-291. https://doi.org/10.2355/isijinternational.43.271.

[10] S.N. Singh, Mechanism of alumina buildup in tundish nozzles during continuous casting of aluminum-killed steels, Metallurgical and Materials Transactions B. 5 (1974) 2165-2178. https://doi.org/10.1007/BF02643930.

[11] M.A. Van Ende, Formation and morphology of non-metallic inclusions in aluminium killed steels, Ph.D.Thesis, Katholieke Universiteit Leuven, Belgium, 2010.

[12] G. Jing, C. Shu-Sen, C. Zi-Jian, Mechanism of non-metallic inclusion formation and modification and their deformation during compact strip production (CSP) process for aluminum-killed steel, ISIJ International. 53 (2013) 2142-2151. https://doi.org/10.2355/isijinternational.53.2142.

[13] A. Kumar, S.K. Choudhary, S.K. Ajmani, S.K. Singh, Improvement and stabilization of nozzle clogging index performance of Al killed steel, Asia Steel International Conference, Bhubaneswar, India, 2018.

[14] B.K. Rout, S. Awasthi, S.K. Choudhary, R.K. Singh, S.K. Ajmani, Development of nozzle clogging index to assess the casting behavior during continuous slab caster at Tata Steel, STIS Conference, Jamshedpur, India, 2013.

[15] B.K. Rout, R.K. Singh, C.K.L. Das, S.K. Choudhary, P.P. Sahoo, Establishing correlation between secondary steelmaking parameters with rate of nozzle clogging and clog morphology during slab casting, Tata Search, 2016, pp.187-194.