Effects of Deoxidation during RH Refining on the Cleanliness and Core Loss of Electrical Steels

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In order to decrease the core loss of 50CS1300, efforts were made to control the formation of inclusions in the RH refining process to improve the cleanliness of steels in this study. Pre-deoxidation by aluminum was usually carried out prior to the addition of ferrosilicon during RH treatment of 50CS1300, but the residual free oxygen (i.e., f[O]) was not monitored after that. Therefore, the effects of the extent of pre-deoxidation on the cleanliness and the core loss of steels were still unclear. By analyzing the steel cleanliness, it was observed that inclusions in high core loss steel coils are more and larger than those in low ones. Furthermore, inclusions broken into small pieces with a long chain during rolling were also found in these samples. The cleanliness of these steel coils was apparently worse. Besides, both of them were SiO_2-Al_2O_3-MnO-TiO_2 composite oxides, but the former had a higher SiO_2 percentage. It could be considered that the high core loss was due to the poor cleanliness of the steels. Insufficient pre-deoxidation would lead to poor cleanliness and high core loss. Accordingly, after improving cleanliness by controlling f[O] prior to addition of ferrosilicon during RH treatment, the core loss was decreased successfully.

Keywords: Core loss, Inclusion, RH refining process

1. INTRODUCTION

The existence of inclusions usually has adverse effects on the magnetic properties of electrical steels. To improve the cleanliness of steels by decreasing the amount of inclusions is one effective method to reduce its core loss. The inclusions in steels are possibly: (1) the products of deoxidation or desulfurization; (2) compounds formed by the precipitation of sulfur, oxygen and nitrogen impurities during the period of steel cooling; (3) oxides formed by the oxidation of liquid steel; or (4) substances from the slag or refractory material.

The inclusions in 50CS1300 are mainly SiO_2-Al_2O_3-MnO-TiO_2 composite oxides. Except from the hot metal itself and slag, these oxides usually form in the processes of deoxidation and the addition of alloys before and/or during secondary refining. The cleanliness of steels is highly related to these processes. The pre-deoxidation of aluminum is usually carried out prior to the addition of ferrosilicon for 50CS1300 during RH treatment, that is, the deoxidation of aluminum proceeds before that of silicon, so the amounts of Si/Al oxides will be higher in the inclusions, especially Si oxides. The temperature and f[O] (i.e., free oxygen) of the liquid steel are measured before addition of aluminum. The amount of Al pellets needed to proceed with the pre-deoxidation is calculated according to the above values and some f[O] usually remains for Si deoxidation. The method of blowing oxygen with addition of Al pellets is adopted if the steel temperature is not high enough for the following processes. These processes provide the opportunities for the formation of Si/Al oxides.

The morphology of inclusions is often related to the process of deoxidation. If aluminum is used as the only deoxidant, the main inclusions are α-Al_2O_3. Most of them can be separated from the molten steel and the residual ones in the steel is in the clustered form of small α-Al_2O_3. If weak deoxidants are added after aluminum, the amount of inclusions will not increase. However, if the strong and weak deoxidants are added at the same time, liquid manganese aluminum silicate will form. This kind of inclusion is very stable and hard to separate from the molten steel(1). It has been found that if deoxidation of Al is carried out before that of Si during RH treatment, its inclusion sizes will be smaller and the Si oxide ratio will be less than those without Al pre-deoxidation[2]. The amount of inclusions with Si deoxidation is usually larger than that with Al deoxidation during the process of solidification. Because Si deoxidant increases the viscosity of molten steel, inclusions are hard to separate from the steel and allow the formation of large inclusions. Reoxidation of molten steel by air is also a possible reason for the formation of large inclusions. Iron and manganese oxide forms through reoxidation and then oxidizes the silicon and aluminum immediately to form manganese aluminum silicate. As a result, in order to improve the cleanliness and therefore to decrease the core loss of 50CS1300, it is very important to control f[O] prior to the addition of ferrosilicon during RH treatment and the reoxidation of molten steel in the following process.

2. EXPERIMENTAL METHOD

The steel chosen for analysis is the final product of 50CS1300 steel coil with a thickness of 0.5 mm. The sample was cut as the sheet of about 1.5×1.5 cm and then fixed by hot mounting. Mechanical polishing was performed with silicon carbide paper followed by micro-polishing, using diamond pastes with the particle size of 3 and 1 μm, respectively.

Inclusion analyses were performed with an optical microscope (OM) and a scanning electron microscope (SEM) together with energy dispersive spectrometer (EDS) on the steel sheets after mechanical polishing.

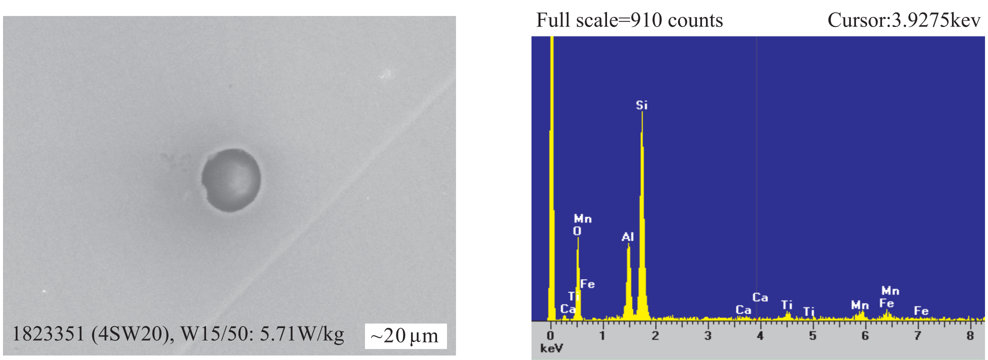
According to the results of inclusion analyses, including morphology, size, and composition, f[O] prior to the addition of ferrosilicon during RH treatment was re-adjusted by Al pre-deoxidation. The residual f[O] was predicted by the empirical formula. Generally speaking, Al pre-deoxidation usually accomplished during the KTB (Kawasaki top blowing) operation, which was used to increase steel temperature. Accordingly, when calculating the amount of aluminum, both operations should be concerned simultaneously.

3. RESULTS AND DISCUSSION

3.1 Analyses of inclusion

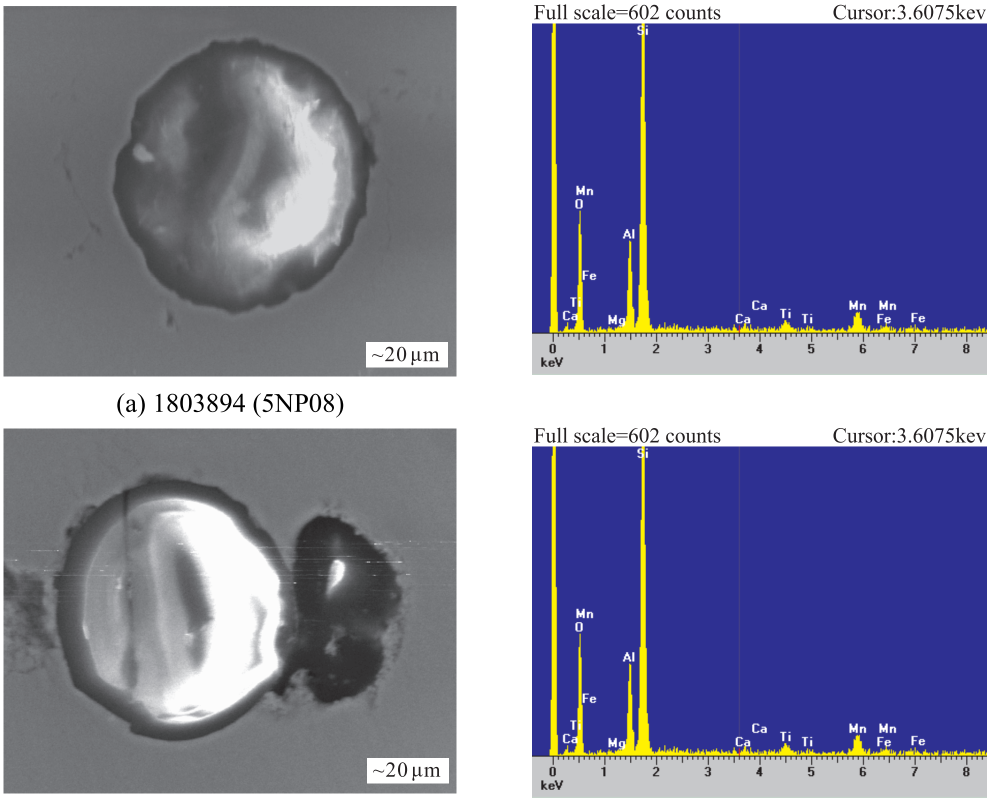
Figures 1(a) and 1(b) are the analyses of inclusions of 50CS1300 with low core loss. Figure 1(b) shows that the inclusions are mostly SiO_2-Al_2O_3-MnO-TiO_2 composite oxides with sizes of around 5~7 μm. The ratios of SiO_2 and Al_2O_3 are higher than other oxides. Figure 1(b) depicts the inclusion shape in 50CS1300 steel with a low core loss of 5.71 W/kg. Figures 2(a) and 2(b) are the analyses of inclusions of 50CS1300 with high core loss. It is also found that the inclusions are mostly SiO_2-Al_2O_3-MnO-TiO_2 composite oxides, but their size is larger than those in low core loss steel. Inclusions over 20 μm are also found in the steel sheet with a high core loss. EDS analysis also shows that the ratio of SiO_2 is relatively high in the cases with large inclusions. The core loss value of the steel sheet 1803894 (5NP08), which has the highest SiO_2 ratio, is up to 6.03 W/kg.

Table 1 shows the inclusion rating and grain size analysis of the steel sheets with high core loss. It can be found that the inclusion rating ranges from OS3 to OS8 (OS: Oxide inclusions of elongated type), which means that there exist inclusions with long chains in the steel sheets. In general, the inclusion rating usually ranges from OS0 to OS1 for the steel sheets with low core loss. The larger the number is, the longer the inclusion chain is. The cleanliness is apparently poor for the high core loss steel sheet as shown in Fig.3. Although inclusions in long chains appear in the steel sheets, the grain size numbers (the number calculated by the ASTM grain size equation, $N = 2^{n-1}$; where N is the number of grains per in^2 at 100X, and n is ASTM grain size



(a) (b)

Fig.1. Inclusion shape and composition of 50CS1300 with low core loss.



(a) 1803894 (5NP08)

(b) 1304119 (4SP81)

Fig.2. Inclusion shape and composition of 50CS1300 with high core loss.

Table 1 Analyses of steel coils with high core loss

	Heat no.	Coil no.	Core loss $W_{15/50}$ (W/kg)	Inclusion rating	Grain size no.
a	4SP81	1304093	6.05	OS=3	#7.5
b	4SP82	1304103	6.06	OS=3	#7.5
c	4SP82	1304100	5.99	OS=3	#7.5
d	4SP82	1304102	6.12	OS=4	#8.0
e	5NP08	1304105	6.31	OS=8	#8.5

number) range from 7.5 to 8.5, which is close to the range of low core loss steel sheets. It has been reported that the oxide with high degree of elongation will prohibit grain growth during annealing, thus making core loss higher[3]. The inclusions in long chains found in this study are composed of many fragments of several microns (as shown in Fig.4), but the case in the literature is presented in the form of thin layer. Their morphologies are quite different. These fragments should come from the fracture of large inclusions during rolling. They are not very small, and therefore can be considered to affect the grain growth insignificantly. A reasonable mechanism for inclusion formation to affect core loss will be discussed later.

3.2 Improvements of cleanliness and core loss

Because large inclusions are found in the steel sheets with high core loss and their SiO_2 ratios are relatively high, it can be inferred to relate to f[O] prior to the addition of ferrosilicon during RH treatment or the reoxidation of molten steel. In order to understand whether reoxidation happens or not, the amount of nitrogen in the steel within the tundish can be chosen as an index to estimate any further reoxidation. When the air permeates into the molten steel from the surroundings, it leads not only to the oxidation of steel but also to an increase in the nitrogen amount due to the oxygen and nitrogen. However, Figure 5 shows that the nitrogen amounts in the tundish for steel sheets with both high and low core loss are very small, being lower than 20 ppm. As a result, it can be concluded that the reoxidation of steel does not affect the formation of large silicon oxide.

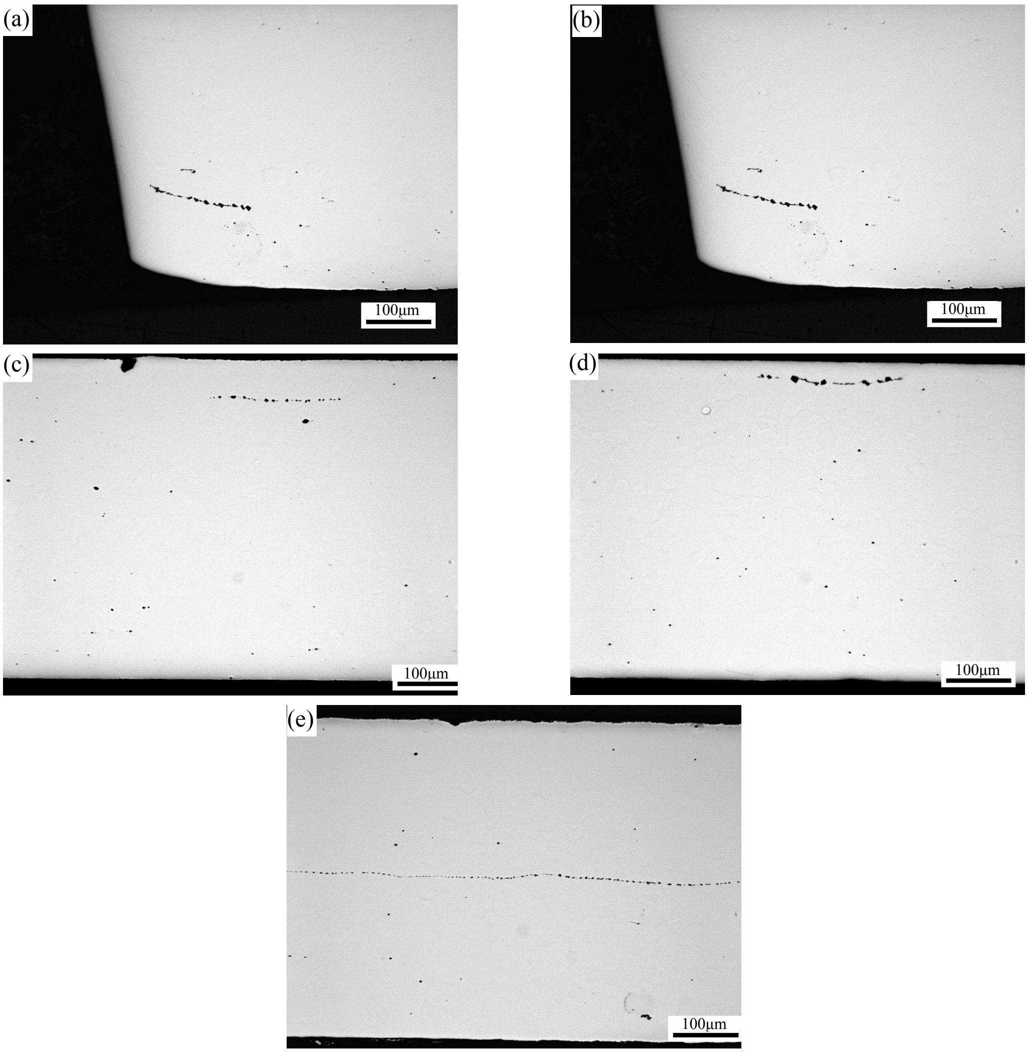


Fig.3. Inclusion shape of 50CS1300 with high core loss. (Corresponding to Table 1)

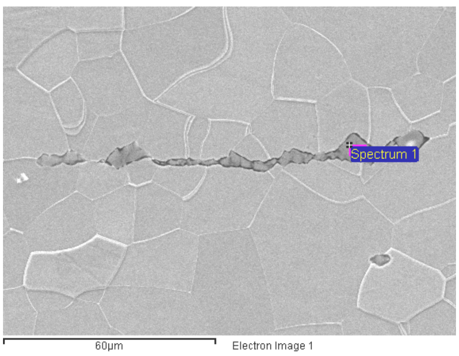


Fig.4. Inclusions broken into small pieces with a long chain.

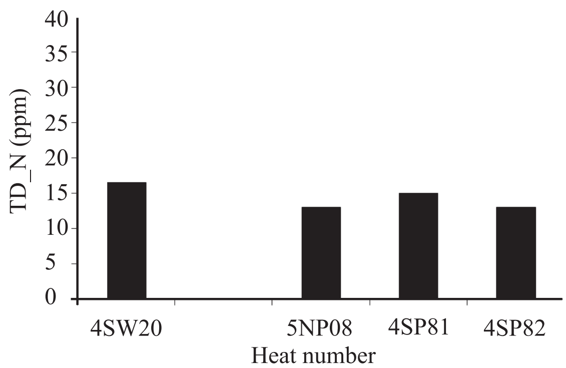


Fig.5. Comparison of [N] in tundish for 50CS1300.

Due to the low possibility of reoxidation, attention was next focused on the control of f[O] prior to addition of ferrosilicon during RH treatment. Because f[O] was estimated only by calculation previously instead by practical measurement for 50CS1000/1300, the f[O] was measured and monitored practically in the subsquent heats. As shown in Fig.6, a well-controlled f[O] makes the inclusion sizes of the steel sheet as small as expected, and nearly smaller than 5 μm. The inclusions became broken up into small pieces with long chains almost not being found in the sheet, resulting in greatly improved cleanliness (OS = 1). The grain size number is 7.5. Besides, the SiO_2 ratio is decreased meaning that the proportion of Si deoxidation has been lowered under low f[O] conditions. The results in Table 2 also show that the core loss is improved, and exceeds the best levels previously recorded at CSC. As a result, a smaller core loss can be obtained if the addition of ferrosilicon proceeds under low f[O], ensuring that steel sheets with good quality can be produced using this process.

3.3 Mechanism for improving core loss

Core loss is significantly affected by the grain size of the steel sheet. Steel sheet with smaller grain size makes more grain boundaries, thus leading to higher core loss. Grain size is further affected by the inclusions and precipitates of steel. AlN, TiN, Ti(CN), MnS are the known precipitates to prohibit the grain growth of steels[4-7]. Inclusions with high degree of elongation will also prohibit grain growth[3]. However, the particles found in the steel sheets with high core loss in this study are large inclusions, some of which are broken into small pieces forming a long chain. These broken pieces are around several microns, and affect grain growth only slightly. Although large inclusions prohibit the grain growth insignificantly, too many large inclusions have an adverse effect on the movement of the

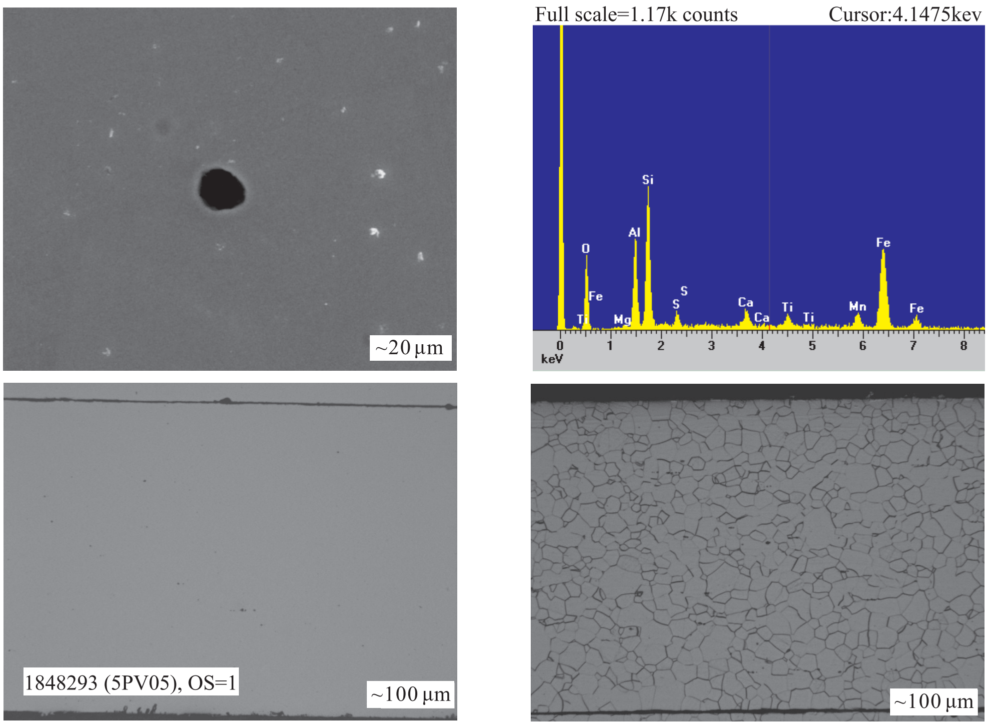


Fig.6. Analyses of steel coils with control of f[O] prior to addition of ferrosilicon.

Table 2 Analyses of steel coils with control of f[O] prior to addition of ferrosilicon

Heat no.	f[O]	Number of coils	Average core loss $W_{15/50}$ (W/kg)
5PV05	Low level	10	5.63
5PV06	Low level	12	5.74
5PV07	Low level	11	5.76
4TF66	Low level	12	5.87

magnetic domain wall, which makes it more difficult to magnetize the steel. Besides, the inclusion itself is usually a non-magnetic or weak-magnetic particle. Both mechanisms mentioned above will make core loss worse(8,9).

The results show that if the addition of ferrosilicon proceeds under low f[O], better cleanliness and core loss of steel sheet can be obtained. It is also observed in the results of the practically measured and monitored heats (as shown in Fig.7) that the value of core loss of a steel sheet will increase with an increase of f[O]. According to the above analyses and results, controlling f[O] prior to the addition of ferrosilicon during RH treatment is a feasible method in practice to improve the steel cleanliness and thus to lower the core loss.

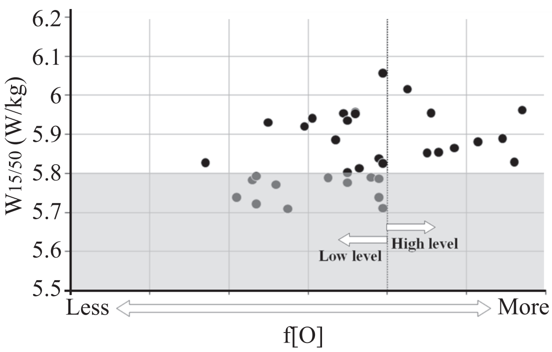


Fig.7. Effect of f[O] prior to addition of ferrosilicon on core loss.

4. CONCLUSIONS

(1) For the steel sheet with low core loss, the inclusions are mostly SiO_2-Al_2O_3-MnO-TiO_2 composite oxides with the size of around 5~7 μm, and the percentage of SiO_2 and Al_2O_3 are higher than other oxides. In the case of steel sheet with high core loss, the inclusions are also mostly SiO_2-Al_2O_3-MnO-TiO_2 composite oxides, with some of them exceeding 20 μm. EDS analyses also show that the percentage of SiO_2 in high core loss steel is much higher than that of low core loss steel and has a poor inclusion rating.

(2) Although inclusions breaking into small pieces and forming long chains are found in the steel sheets with high core loss, the grain size numbers are similar to those of low core loss steel sheets. The long chain inclusion found in this study was composed of many fragments of several microns, which could have come from the fracture of large inclusions during rolling. They are not very small, and therefore can be considered to affect the grain growth insignificantly. According to the analyses, the mechanism of making core loss high for this case should result from poor cleanliness.

(3) By means of adding ferrosilicon under low f[O], better cleanliness and core loss of steel sheet can be obtained. It is observed from the results of practically measured and monitored heats that the value of core loss of the steel sheet will increase with the increase of f[O]. Accordingly, adding ferrosilicon under a controlled f[O] environment during RH treatment is a feasible method to improve steel cleanliness and to lower the core loss.

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