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Slag Management

Increasing of LF Performance by Controlling the Slag and Steel Oxygen Activities

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ABSTRACT

The most indispensable tasks for steel making industries are outshining as energy, productivity in parallel quality. As one of the critical processes of steel making route ladle furnace is playing an important role for these combined targets. To get reasonable control over the oxygen content during LF process, it is inevitable to maintain equilibrium between steel and slag. This paper reviews the relations between steel and slag oxygen activities during the ladle furnace process and the correlations with the process parameters such as desulphurization efficiency, alloy yields, steel cleanliness in ICDAS steel plant. The practical Ladle furnace process data will be evaluated and analyzed.

Keywords: ICDAS, Heraeus Electro-Nite, Slag, oxygen, steel, equilibrium, ladle furnace, steel cleanliness, alloy fading, DeS efficiency

INTRODUCTION

With the progressing technology the steelmakers are striving to improve productivity and final steel quality. However in todays world that phenomena become insufficient due to the survival conditions. Depending on the decrease of the steel prices and increase of input costs every steel producers trying to reduce operational costs. Controlling of slag composition and its effects during the secondary steel making process has become one of the key parameters for decreasing the production costs. The reaction of steel and slag has regardable effects on steelmaking process and most of steel producers trying to focus and control these reactions with the several internal methods. In secondary steelmaking process desulfurization, deoxidation and inclusion removal are generally performed. Controlling and enabling the slag and steel equilibrium through ladle furnace process can increase the efficiency of these reactions. One of the most disturbing factors creating the undesired slag before ladle furnace is carry – over slag from the furnaces. According to Pistorious research the main benefits of lower carry-over slag are enhanced cleanliness of steel, deoxidizer saving, decreasing of phosphorus reversion and increased refractory life. [1]

Detail research has been conducted by Yang which proves the positive effect of slag oxygen content to aluminum fading in ladle furnace.[2] As it shown in figure 1, the average aluminum fading during the tundish process 100 PPM in the 250 tons of ladle with the 6% of FeO in top slag. Also for the 85 tons of ladle aluminum fading between vacuum and tundish fluctuates around 100 PPM.

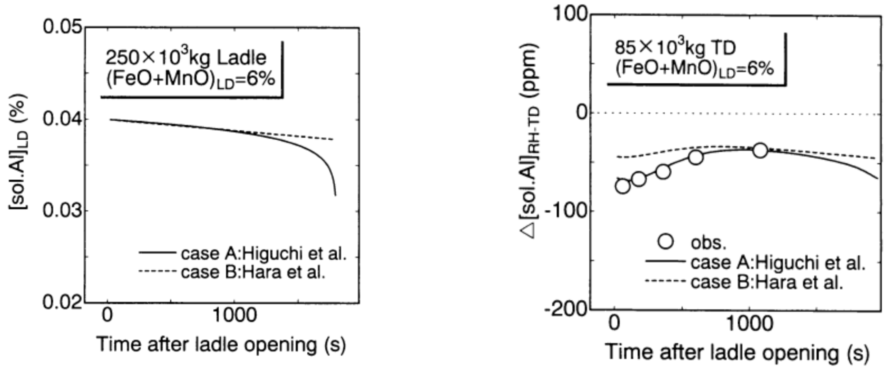

Figure 1: Change in [sol.Al] at ladle during casting. Left: 250 tons ladle Right: 85 tons ladle

Desuphurization process is also one of the most widespread researches regarding with slag management. The effect of top slag to DeS process has been investigated by many researches. One of the key topics of Posch and friends is the relation between slag oxygen and DeS yield. As it seen in figure 2 detailly the FeO in slag prevents relevant desulphurization process during the LF process. [3]

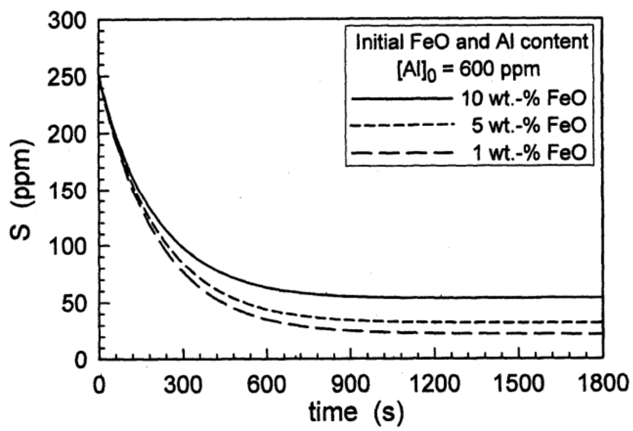

Figure 2: The effect of top slag oxygen potential to DeS efficiency of liquid steel

FeO in Slag

As routine ladle furnace the iron content of top slag can be fluctuated in the range of 1% and 10% Fe. It was studied by Larson that during the ladle furnace process the partial pressure of oxygen decreases to lowest levels $PO_2 = 10^{-9}$ to 10^{-12} thus, iron oxide type will completely be Fe^{+2} which is wustite. [4] Due to these equilibrium with the EMF values coming from Celox Slac sensors, the iron oxide in slag can easily be calculated. Beside that due to defining iron oxide transformations and crystallographic structure of slags during the ladle furnace, XRF and XRD analysis were applied.

Table 1: XRF results of collected slag samples from ladle furnace

SAMPLE	TFE	SIO2	MN	AL2O3	CAO	MGO	P	S	CR	LOI
LF IN	8,125	10,089	1,258	22,766	49,72	4,296	0,061	0,088	0,033	-1,29
LF OUT	2,352	7,587	0,916	24,347	57,70	4,921	0,017	0,106	0,015	-0,27

In order to identifying GA effect in slag to the phases XRD analysis was also performed. The composition of phases was determined using Panalytical Empyrean XRD using a Co Kα source (λ=1,78901 Aº) operated at 40 kV and 40 mA using a step size of 0,01 with a collection time of 23 minutes. An estimation of the volume fraction of each phase was determined by integrating the relative intensities of the peaks. Rietveld refinement was applied using HighScore Plus software and COD, PAN-ICSD mineralogical database.

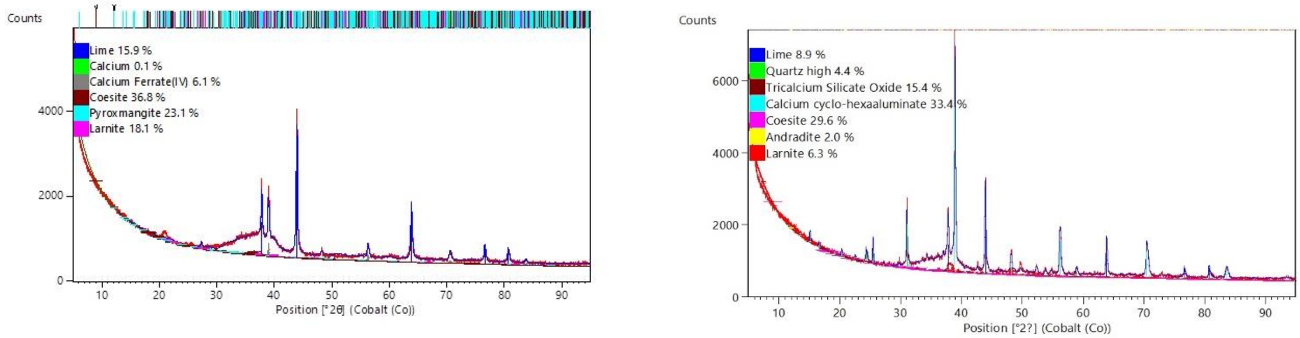

Figure 3: XRD analysis of collected samples.

The aim for the detail analysis with the XRF and XRD, defining the effect of GA addition to slag morphology. The reduction of total iron in slag could not be precisely identified in XRD analysis, however due to increasing of aluminum in slag lime solution was increased free lime was decreased.

ICDAS STEEL PLANTS

ICDAS ranked in the 11th place among the 500 Biggest Industrial Enterprises of Turkey including the public sector in 2021, according to the determinations of Istanbul Chamber of Industry (ISO), has around 6055 employees together with the group companies. The Steelmaking plant has 4 millions of steel production capacity with the 3 EAF's (120 MT, 200MT and 230 MT). As rolling mills for the final products 2 Wire Rod and 2 Bar mills have been operated.

Figure 4: ICDAS Biga Steel Plant

With energy efficiency, process efficiency, environmental awareness, technology usage, and participation of its employees in productivity, ICDAS shares the justified pride of bringing the name of Türkiye to a notable point by putting forth competitive strength in a race, which it started well behind in the world steel sector. Some of outstanding pioneer mega projects;

- ICDAS, which brought the fluidized bed coal combustion technology to Türkiye for the first time and used it in Thermal Power Plants, has 1,605,000 kWh efficient energy and environmentally friendly GES (6.3 kWh), WPP (60.8 kWh) and HEPP (5.7kwh) with its clean combustion technology supercritical power plants producing the 4% of total produced electricity in Türkiye.

- Reducing its carbon emissions by approximately 70,000 tons per year thanks to its environmentally friendly energy production, ICDAS maintains the ecological balance and biodiversity.

- 17000 m3/day sea water is treated and used as drinking, irrigation and cooling water in order to be used in all enterprises. In this way, European standards are not compromised with the awareness of the climate crisis in water management.

HERAEUS ELECTRO-NITE SLAG MANAGEMENT

With the progressing technology Heraeus Electro-Nite supports the partners with not only the measurements but also analysis and solutions. Regarding with the slag management there are several instant measurement abilities with the dedicated products. Celox SLAC® allows for an instant decision to add slag modifiers by measuring the oxygen activity in the slag.

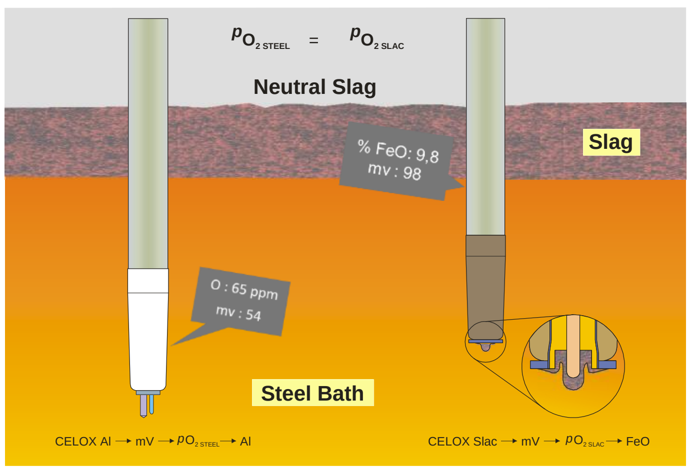

Figure 5: Schematic view of Celox and Celox SLAC sensors.

It can be used in any primary and secondary metallurgy unit, like EAF, Ladle Furnace, VD, Argon stirring station, RH-degasser, VAD or CAS-OB. As it can be seen in figure 5 via in situ measurements the oxygen in liquid steel and slag can be measured and results can be evaluated immediately for the proper process control. During that project via using instant measurement tools efficient deoxidation of the slag, preventing aluminum and silicon fadings, increasing of DeS yield, increasing the steel cleanliness and decreasing of process costs were aimed. The table 2 shows practical measurements and data evaluation in the scope of this project. Both of oxygen measurements in steel and slag were done with the different phases of ladle furnace.

Table 2: Slag Management tracking file through LF process

HEAT INFO		**EMF (Celox) mv**	**Oxygen (ppm)**	**Temp.**	**Slag EMF mv**	**CS FeO %**	**EMF (Celox) mv**	**Oxygen (ppm)**	**Temp.**	**Slag EMF mv**	**CS FeO %**
N	**Grade**	**Entry**					**Out**				
1	Grade_A	-190	2,3	1591	-235	0,67	-173	3,1	1600	-221	0,75
2	Grade_B	-172	3,2	1604	-209	0,82	-160	3,4	1589	-247	0,61

3	Grade_C	-168	2,8	1572	-204	0,86	-222	4,3	1607	-153	0,74
4	Grade_D	-184	1,9	1556	-219	0,76	-181	2,8	1601	-206	0,84

PRACTICAL SITE STUDIES

I. CURRENT PRACTICE ANALYSIS

With the instant oxygen measurements current slag and steel management process had been analyzed. During the defined period all the plant process data were collected and analyzed with the different techniques. In current practice slag deoxidation practice were held in two batch; before LF platform and during LF process. After ladle tapped from Electric Arc Furnace, it was transferred to ladle furnace and between two station the operators have ability to add first batch (primary) of granulated aluminum according to oxygen measurements at EAF and carry-over slag conditions.(Figure 6)

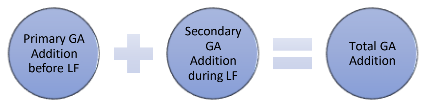

Figure 6: Schematic view of GA addition at Plant

Plant data which recorded for defined period was analyzed and the observed results were shared in figure 7 and figure 8. Aluminum yields, slag and steel oxygen measurements and Aluminum amount in liquid steel were briefly presented in table 3. The primary granulated aluminum addition amounts were fluctuating between 0 to 150 kg in the collected datas. The primary GA additions were leveled in order to observing the ladle furnace process yield. Four levels of GA addition was analyzed as “0_None”, “1_Low”, “2_Med”, “3_High” after the histogram analysis applied.

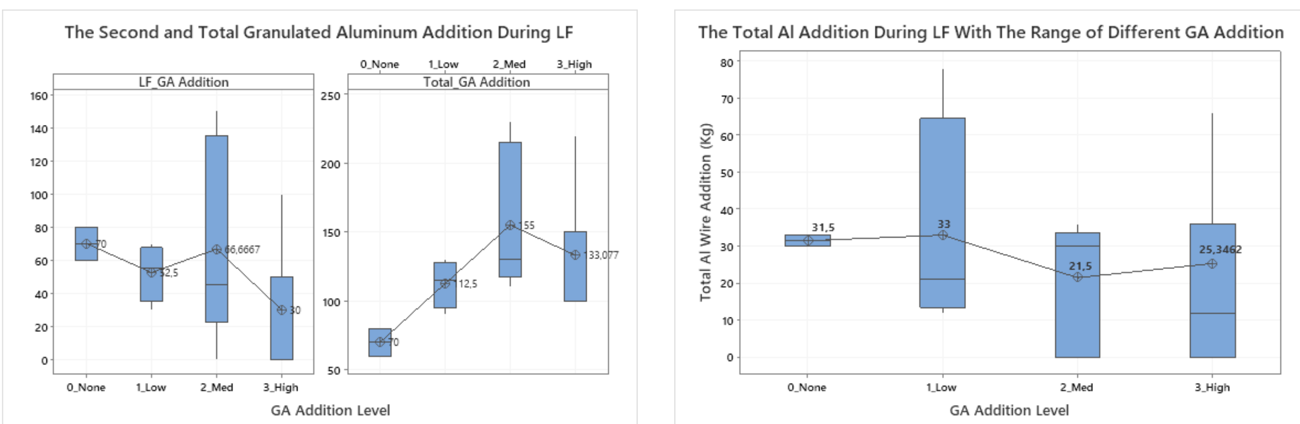

Figure 7: The granulated and wire aluminum additions. Left: Total and second batch GA additions with different range of primary GA addition level, Right: Aluminum wire additions with different range of primary GA addition level

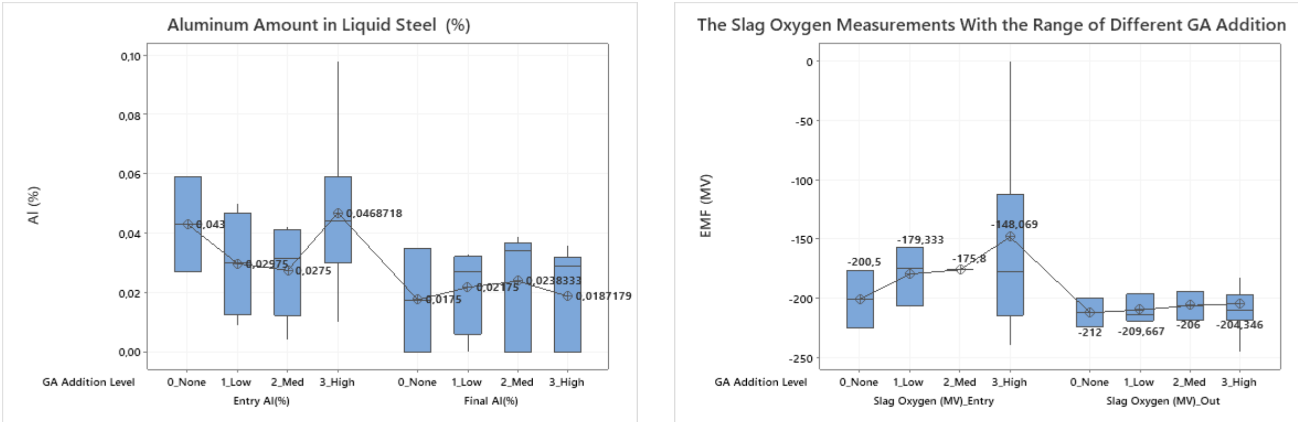

Figure 8: Left: Measured aluminum in steel with different range of primary GA addition level, Right: Slag oxygen measurements with different range of primary GA addition level

Table 3: The brief result after analyzing the current process parameters

Primary Granulated Aluminum Addition (kg)	0	60	80	110
Primary Granulated Aluminum Addition Level	None	Low	Med	High
Secondary Granulated Aluminum Addition (Kg)	70	50	70	30
Total Granulated Aluminum Addition (Kg)	**70**	110	150	**140**
Total Aluminum Wire Addition (Kg)	32	33	22	26
Aluminum in Steel (%) LF Entry	0,043	0,03	0,028	0,046
Aluminum in Steel (%) LF Out	0,018	0,021	0,023	0,018
Al Fading (%)	**0,025**	0,009	0,005	**0,026**
Oxygen in Steel (mv) Enrty	-182	-164	-154	-180
Oxygen in Steel (mv) Out	-152	-152	-166	-160
Oxygen in Slag (mv) Enrty	-200	-178	-176	-150
Oxygen in Slag (mv) Out	-212	-210	-207	-206
DeS Yield (%)	86	87	87	83

After discussing and evaluating the long term datas, project team has decided to held controlled trials. In SMP-2 especially for the special steel grades zero carry over slag practice were being applied. Before process analysis slag treatment were being applied with eye control and alloy yields. With the measurement tools it was proved that primary GA addition was not working efficiently and not required for all the heats.

During the trials primary GA additions were cancelled and according to oxygen measurements in both steel and slag the required slag deoxdizer and steel alloys were added. In practical application starting from EAF all the process datas were collected and operators trained. When the ladle came to ladle furnace after heating 2-3 minutes and homogenization of steel and slag oxygen values were measured. If the steel – slag oxygen values were out of limited area operators have added needed required slag deoxidizer. Both in Aluminum and silicon killed steels these methods were applied. During the controlled trials all the alloy yields, desulphurization efficiency, Ca treatment yields, clogging effect and steel cleanliness parameters were observed. Moreover due to checking slag oxygen effect to process parameters as supportive studies factsage analysis, XRF and XRD analysis were applied and T.O samples were collected and examined.

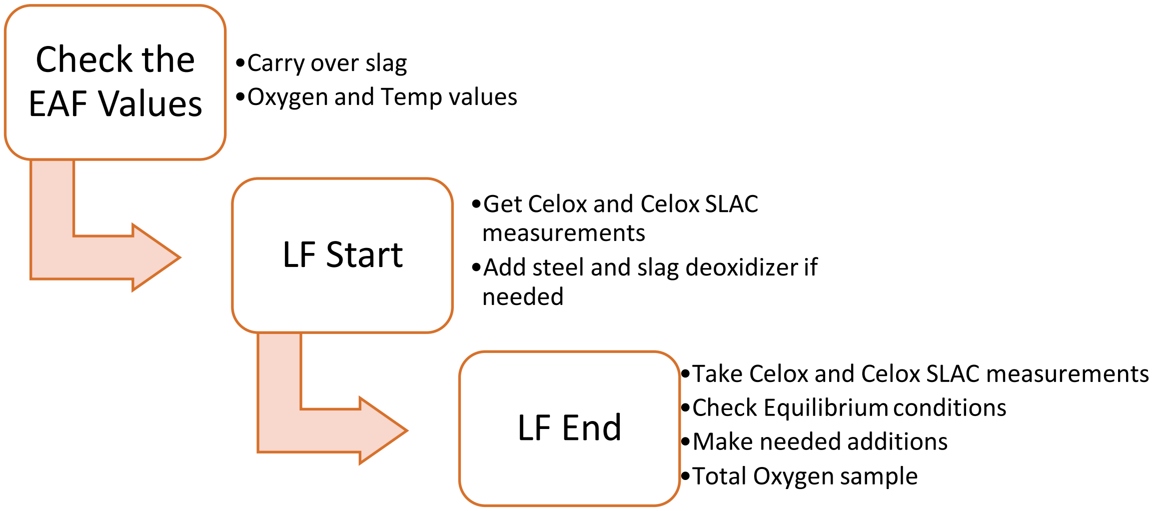

Figure 9: Schematic view of controlled trials

1. Al – Killed Grades

The controlled trial period has been continued for the all type of steel grades respectively. After the efficiency of primary GA addition was defined, Al- Killed steel grades were followed with the selected procedure. (Figure 9) During the ladle furnace process and continues casting process trial parameters and process results were tracked strictly.

Table 4: The brief results of controlled plant trials with dynamic slag management.

Process Parameters	Before	After	Difference
Primary Granulated Aluminum Addition (kg)	88	0	-88
Secondary Granulated Aluminum Addition (Kg)	8	15	7
Total Granulated Aluminum Addition (Kg)	96	15	-81
Total Aluminum Wire Addition (Kg)	18	53	35
Aluminum in Steel (%) LF Entry	0,0405	0,041	0,0005
Aluminum in Steel (%) LF Out	0,027	0,025	-0,002
Al Fading (%)	0,0135	0,016	0,0025
Total Si Addition (Kg)	393	488	95
Silicon in Steel (%) LF Entry	0,135	0,134	-0,001
Silicon in Steel (%) LF Out	0,19	0,21	0,02
Total Mn Addition (Kg)	1821	1886	65
Manganese in Steel (%) LF Entry	0,74	0,73	-0,01
Manganese in Steel (%) LF Out	1,17	1,14	-0,03
Oxygen in Steel (mv) Enrty	-182	-164	18
Oxygen in Steel (mv) Out	-152	-152	0
Oxygen in Slag (mv) Enrty	-200	-178	22
Oxygen in Slag (mv) Out	-212	-210	2
LS Entry	43	42	-1
LS Out	324	385	61
DeS Yield (%)	86	87	1

Alloy Yield

As it can be seen in table 4 brief results has shown that with the help of controlled and dynamic slag and steel deoxidation practice avg. 85% GA Aluminum per heat was saved. The Aluminum wire addition was increased with the increase of steel soluble Al. The total silicon and manganese consumptions were not changed during the trials. Through the steel making process and final product it was not seen and observed any unwanted affects for the spesifications.

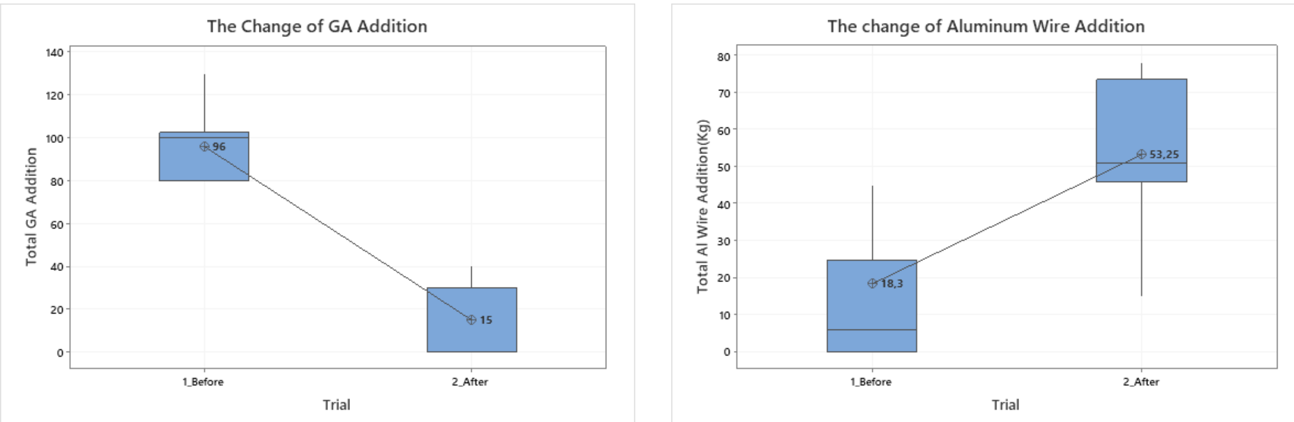

Figure 10: The change of GA and aluminum wire addition before and after controlled trials in grade A

Desulphurization Efficiency

With the dynamic slag treatment process the steel desulphurization efficiency was also examined. Before trials the effect of top slag oxygen to desulphurization efficiency and slag – steel characteristics had been investigated with thermodynamic software program, Factsage. Due to controlling and underlining the trial plan, the thermodynamic analyses are applied. The databases used in this study were: FSstel (compound and solution database for steel), FactPS (gas species, solid and liquid compound database) and FToxid (compounds and solutions for oxide databases) with “Equilib” module of FactSage 6.4. In Factsage thermodynamic model ladle furnace conditions of ICDAS simulated with the changing oxides in slag. As it can be seen in figure 11 the equilibrium sulphur in steel is increasing with the slag oxygen activity. Also the aluminum addition to top slag increased the soluble aluminum level in liquid steel when slag oxygen activity is lower.

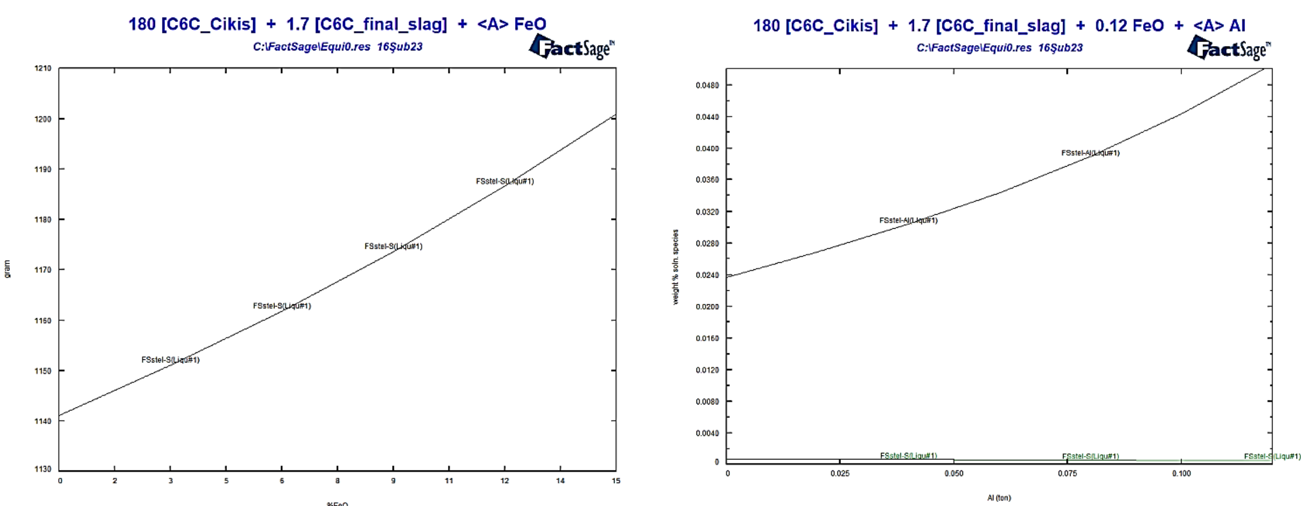

Figure 11: Thermodynamic analysis of ladle furnace slag – steel conditions. Left: The change in sulphur in steel with the increasing FeO in slag Right: Change of soluble aluminum in steel with the increase of Al addition to slag

As Posch and friends mentioned their study the slag oxygen effects steel desulphurization yield negatively. After dynamic slag and steel oxygen measurement the excess granulated aluminum addition was prevented and process results were observed. In figure 8 LS (Sulphur distribution ratio) and DeS yield were calculated respectively. Before dynamic controlling process the LF at the beginning of ladle treatment 43 and it was increasing through to ladle furnace end as 323. After controlled GA additions the values changed at the beginning 41 and at the end 385. Moreover the desulphurization yield was increased from 78% to 85% with the controlled trials.

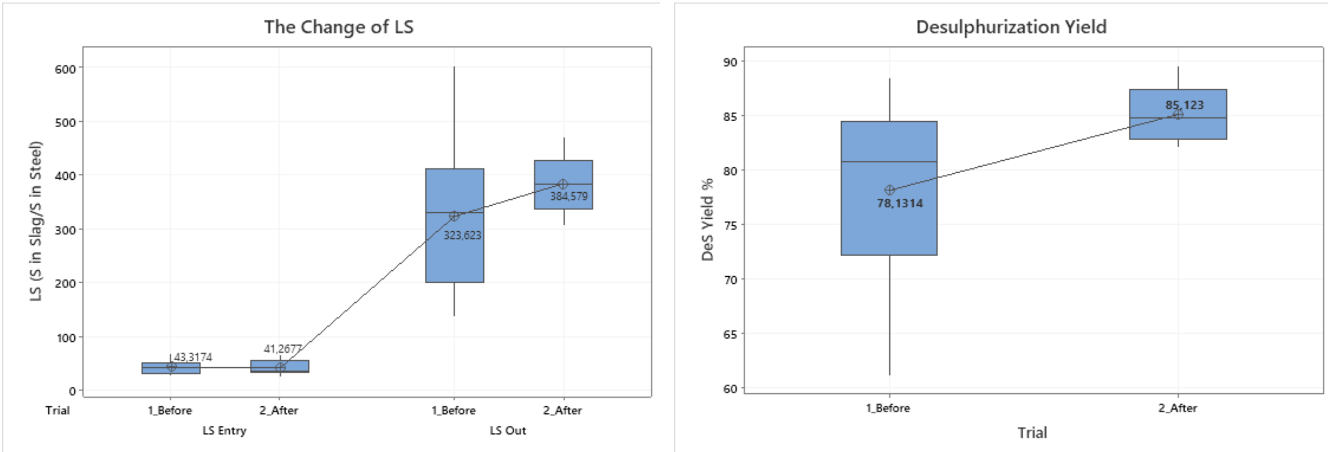

Figure 12: The comparison of LS (Sulphur distribution ratio) and DeS efficiency during controlled trials.

Steel Cleanliness

For the steel cleanliness studies total oxygen samples were collected during the trials. Ruby and his friends has performed a study which showing the relation and reliability of total oxygen samples for the defining of steel cleanliness.[5] With the thermodynamic modellings and calculations it was aimed that due to eliminating excess aluminum in steel and over slag deoxidation the total oxygen in steel should be decreased. The collected steel samples were prepared for combustion analysis and total oxygen measurements were handled. In figure 13 it can be seen clearly that total oxygen in steel is being decreased with the decreasing of slag oxygen.

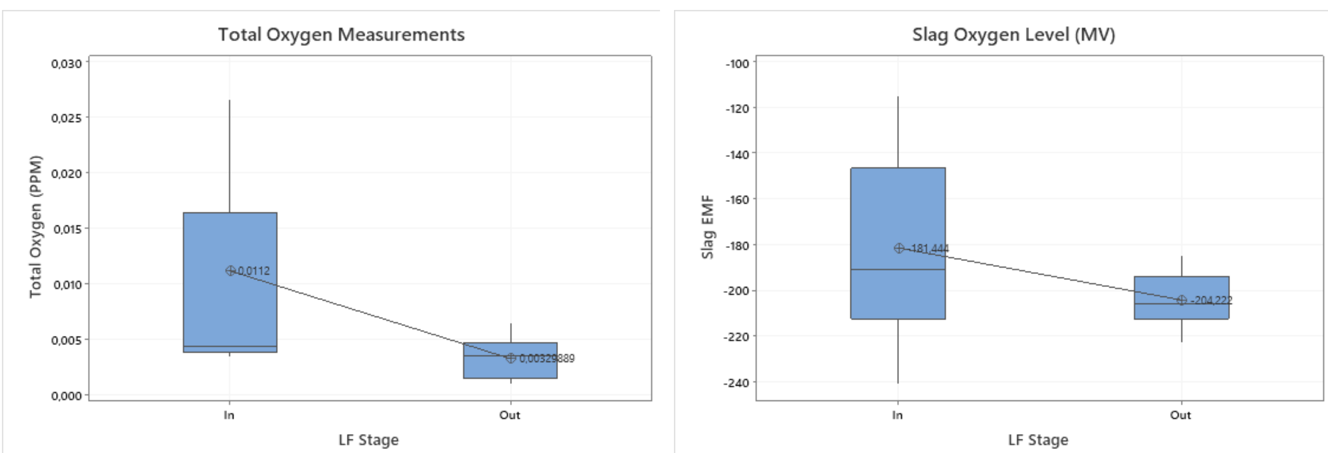

Figure 13: The comparison of LS (Sulphur distribution ratio) and DeS efficiency during controlled trials.

2. Si– Killed Grades

The same method was applied for the silicon killed grades casting in plant. Both of the steel and slag oxygen measurements were held due to determining the current values. With the help of dynamic slag deoxidation method 40% of silicon powder consumption were saved. During the controlled trials all the other process parameters were controlled and there was not considerable alterations with the decreasing of silicon powder to slag. Figure 14.

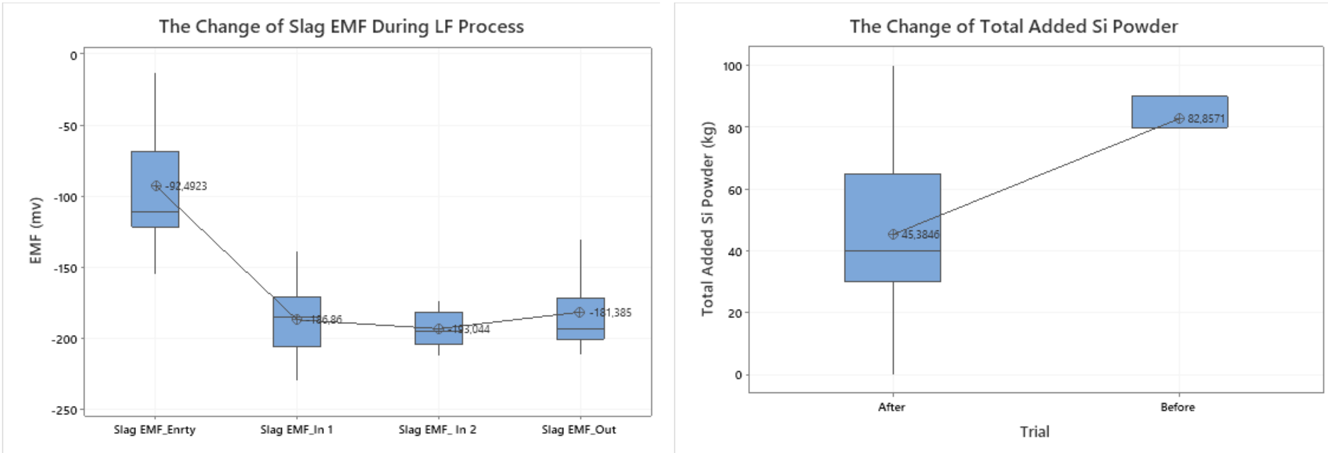

Figure 14: The change of slag oxygen and silicon powder addition during the LF process in Grade A

CONCLUSIONS

- With dedicated slag and steel oxygen measurement sensors the ladle furnace process parameters were enhanced. After data collection and analysis for defined period it was understood that in steel group which has efficient carry over slag control from EAF, primary GA addition was not needed.
- As theoretical and laboratory analysis, XRF, XRD and Factsage analysis were performed. The effects of slag oxygen in steelmaking process and alloyings were defined with these analysis. New dynamic slag and steel oxygen control practice were implemented at ladle furnace.
- In Al-Killed steel grades due to dynamic slag deoxidation practice, the total aluminum consumption (Granulated Aluminum and Aluminum wire) was decreased 80 % per heat in average.
- As Granulated aluminum addition was decreased, the silicon reversion from slag to steel was eliminated. As silicon pick -up prevented by slag modification FeSiMn – FeMnLC/Metallic Manganese conversion was provided. The total FeSiMn production was increased 30% per heat.
- In all the heats, slag – steel oxygen equilibrium was provided, especially in vacuum grades due to that equilibrium practice foaming of slag and splashing eliminated regardably.
- In silicon killed steels due to slag deoxidation silicon powder has been utilizing. With precise measurement tools slag deoxidizer addition applied dynamically. With that practice 70 % per heat silicon powder saved.
- Total Oxygen measurements were performed due to observing the outputs of new method from the steel cleanliness aspect. The total oxygen values were decreased and there was not considerable difference regarding with nozzle clogging compared with current practice.
- The validated slag management practice were standardized through the all the operators in shifts and different and subjective deoxidation practice were eliminated.
- At the beginning of LF process with instant oxygen measurements in slag and steel, carry-over slag control of EAF were precisely tracked and controlled.
- For dedicated special steel grades via dynamic slag management practice total potential value in use of plant was calculated minimum 600K USD yearly.

FUTURE STUDIES

- Regarding with all the steel grades dynamic slag deoxidation will be spread precisely.
- After determining the relation between deoxidant addition and oxygen in both steel and slag, AI based calculation models will be implemented in plant.
- With the help of thermodynamic calculation software LS, CS and efficient DeS conditions will be matched with dynamic oxygen measurements.
- For the fast steel cleanliness measurements total oxygen samples will be collected and steel – slag oxygen equilibrium conditions will be matched with T.O. values.

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**This study is dedicated to all our people who lost their lives and were affected by the earthquake that took place in Kahramanmaraş, Türkiye on February 6, 2023.*