SLAG ENGINEERING ASPECTS OF THE CRISP STEELMAKING TECHNOLOGY

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ABSTRACT

Continuous Reduced Iron Steelmaking Process (CRISP) is a novel steelmaking technology, being developed by Hatch that utilizes a stationary electric arc furnace to continuously melt and decarburize DRI and other metallic materials to produce steel. The key feature of CRISP technology is significant modification of the conventional EAF process parameters to extend the refectory life beyond one year. This paper discusses the steps taken to "design" a slag that satisfies the requirements of the CRISP, particularly, compatibility with refractory and sufficient decarburization of the steel. The previous steps included thermodynamic modeling of slag-metal equilibrium and bench-scale decarburization experiments for determining the optimum slag. The results of this systematic slag development program were then tested in two campaigns of pilot trials. The successful application of these recommendations is documented through the discussion of the results of this pilot testing.

The pilot plant trials of the technology conducted at MEFOS, Metallurgical Research Institute in Sweden, confirmed the laboratory experiments, showing that the desired steel composition (0.04 – 0.1% C) can be achieved with FeO as low as 15 – 25%, without oxygen lancing. Continuous operation for five days demonstrated that the CRISP technology is feasible. The durability of the refractories, a main design objective, was also confirmed.

INTRODUCTION

Numerous advancements have been made in the DRI-based steelmaking processes in the last decade. Charging hot DRI to the electric arc furnace (EAF), directly from a DR module [1, 4, 8] is arguably the most important improvement in this area. The energy saving associated with the hot charge practice is estimated around 20 to 30% compared to the current cold-fed EAFs. Nevertheless, continuous discharge of hot DRI to EAF is complicated by the batch operation nature of the EAFs. Thus, the energy saving associated with hot charge cannot be fully realized. To overcome this hurdle, and also push forward to a continuous steelmaking process, Hatch has introduced the CRISP technology. The CRISP employs a stationary EAF that continuously melts DRI and scrap as the feedstock. The process can lower the carbon to the level desired for subsequent ladle refining and casting.

The CRISP concept and its economical and environmental benefits have been described in the previous publications [10, 12, 13, 14, 15] and a recent patent [3]. The CRISP technology relies on a process that is capable of (a) operating continuously with periodic tapping of steel and slag, (b) decarburizing the molten DRI to the specified carbon level for steel(c) supporting an extended refractory life in the order of one to three years minimum. The provisions to achieve these objectives include minimum oxygen injection, optimizing slag chemistry, refractory engineering, and reduced power density.

The slag optimization for the CRISP conditions is extremely challenging, as the process requirements impose significant, often conflicting demands on the physical and chemical properties of the slag. For example, on one side, the slag should be fairly oxidizing, to satisfy decarburization, whereas on the other side, highly oxidizing slags tend to be aggressive toward the refractory. Also, the design relies on slag foaming for shielding the electric arc, but this foaming should be achieved with virtually zero oxygen injection, as otherwise the FeO would be driven up excessively, causing damage to the refractory. The engineering of an appropriate slag was thus vital to the viability of the CRISP technology.

An extensive research program was developed to design and test the operating conditions of the CRISP process in term of slag chemistry that can satisfy the process requirement. The study included the following four stages.

1. *Thermodynamic study* [6]: Following the initial desk-top studies at Hatch a program of fundamental research was initiated at the Department of Materials Science and Engineering at the University of Toronto. In this work, the minimum theoretical FeO required to decarburize steel to the desired level was determined by thermodynamic evaluation of the slag-metal system. FactSage Thermodynamic package was used to calculate the equilibrium concentration of FeO in different slags, for a specified carbon content of steel. An example of the calculations is shown in Figure 1, in the form of iso-concentration lines for carbon superimposed on the slag phase diagram. As seen, the slags with a certain basicity, close to 1.5, require the lowest amount of FeO for each carbon level.

2. *Bench scale experiments* [6, 7]: A range of slag compositions with different basicity and FeO levels was used to decarburize DRI melts. Samples were withdrawn at certain time intervals to quantify the kinetics of the reaction as well as the steady-state carbon level of the bath. The results showed that it is possible to reduce the carbon of steel below 0.1% with FeO as low as 15%, almost independent of the basicity. The final carbon content was controlled by the slag FeO. The required time for reaching the quasi-steady conditions varied from 5 to 20 minutes depending on the slag composition. The reaction rate was found to be controlled by the rate of FeO mass transfer in the slag. These experiments reduced the number of slag compositions to be tested, setting the stage for efficient pilot testing.

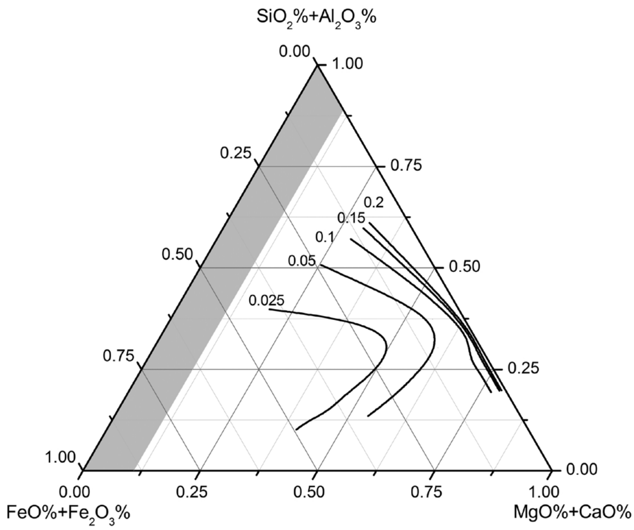

Figure 1: Iso-carbon lines in SiO_2-Al_2O_3-CaO-MgO-FeO system with MgO%=8

3. *Phase I pilot trials* [16]: The main objective of the Phase I pilot campaign, carried out at the MEFOS Metallurgical research Institute in Luleå, Sweden in August 2007, was to study interaction of steel-slag-refractory for steel bath covered with selected slag compositions, and continuously fed with DRI. It was found that producing low-carbon steel (below 0.10% C) with a good foaming slag and low FeO (below 18 – 20%) is possible. This could be achieved without the use of gaseous oxygen. In total 14 heats were made in the four-day period, with nine slag compositions tested. An operating range that could potentially fulfill the CSRIP process requirements was defined. It was decided that in another set of tests, the range of slag composition should be limited to one or a few and the continuous operation aspect of the process as well as carbon control be examined.
4. *Phase II pilot trials*: Following the successful completion of the Phase I trials, a second round of trials were held in spring of 2008 at MEFOS. These trials focussed on demonstrating the viability of a key principle of this technology: the *continuous* melting. Also, the capability of the process in terms of manipulating the steel chemistry (carbon) was examined.

The previous publications cited above provide details of the first three stages of slag engineering for the CRISP technology. This paper presents the results obtained in the second pilot campaign, with an emphasis on the interactions between steel, slag and refractory.

METHODOLOGY

Test Conditions

The Phase II Pilot Testing of the CRISP technology was a logical extension of the Phase I Pilot testing. The objective of the first round of trials was to test a set of selected slags, aiming to identify a window of appropriate operating parameters for the technology. Having established workable slag compositions in the first trials, the Phase II Pilot Trials were to examine the feasibility of continuous steelmaking using DRI as the metallic charge. The objectives were to (a) attain the specified carbon level in the range 0.04 – 0.1 wt% with minimal or no use of gaseous oxygen, (b) prove stability and controllability of the process for a minimum 4 days of operation, (c) practice a slag compatible with the refractory, i.e., minimum refractory wear, and (d) produce good slag foaming. The target conditions, based on the previous slag engineering works were defined as following.

- Basicity (V ratio): 2.0
- Bath carbon content: three levels (0.04, 0.06, 0.1 wt%)
- FeO of slag: as low as possible for each carbon level
- MgO of slag: slightly oversaturated (1-2%) [9, LeMar and Pretorious, 2001] for the basicity and given FeO
- Steel bath temperature: 1600 °C.

The raw materials used for the trails were DRI, with the composition given in Table 1, fluxes (lime, dolomite) and solid oxidizers (iron oxide, as mill scale and iron ore pellets). The ratio of materials in the mix except the oxidizer was calculated using an optimization program that minimizes the slag weight based on the constraints (basicity and MgO), to yield the mix ratio of the materials. The proportion of iron oxide in the mix was adjusted by an iterative process as discussed later, to achieve the minimum FeO required for a specified carbon content.

Table 1: Composition of DRI representative sample

Total Fe	Metallization	C	SiO_2	Al_2O_3	CaO	MgO
91.6	95.5	2.2	1.9	0.5	0.8	0.5

Test Procedure

The MEFOS eight-tonnes AC EAF was used for the trials. The raw materials were premixed and fed to a top bin located above the furnace. The furnace power was set at 2.0 MW and the mix feederate was manipulated around 3000 kg/h using a vibratory feeder, to yield a bath temperature of 1600°C. Feeding stopped only for periodical tapping of steel and slag that took less than five minutes each time. Steel and slag samples were taken every hour. The steel samples were analyzed for carbon by LECO and the slag composition was determined by XRF analysis. Oxygen activity and temperature were also measured using oxygen and temperature probes every hour. DRI feeding continued during sampling and temperature measurement.

The trials were continued for 115 hours in a five-day campaign. A total of 254 tonnes of DRI was melted during this campaign and 52 steel heats were made, producing 243 tonnes of steel.

RESULTS AND DISCUSSION

The process was manipulated to control the parameters (primarily carbon) in four differencing phases, by adjusting the slag chemistry. These *process phases* are described in the following sub-sections. Also, other findings of the trials including FeO-C relationship and refractory wear are discussed.

Carbon Control

Phase 1 – Natural Melting of DRI and Subsequent Addition of Iron Oxide

One of the critical objectives of these trials was to obtain information about the minimum practical FeO required for sufficient decarburization. Although the approximate FeO needed was known from the previous trials and bench scale experiments, the amount of oxygen source (mill scale or iron ore) required to reach this FeO concentration could not be calculated before the trials, because the amount of infiltration air and the natural oxidation of slag could not be determined beforehand. Therefore, it was decided that the steady-state carbon of the bath formed by natural melting of DRI could be established. Subsequently, gradual additions of mill scale were made to determine the minimum FeO required in the slag. This FeO level could then be kept constant to maintain the carbon at the desired level.

This first phase of the process is marked on Figure. 2. As seen, the carbon increases to a relatively steady state value of 0.5 – 0.6 wt% in about 14 hours. Due to accumulation of slag and inherent foaming by melting of DRI, air ingress to the steel bath is minimized at this stage, and the carbon concentration observed may be considered as the bath carbon associated with natural melting of DRI. Slightly higher carbon levels (0.6 – 0.7 %) were obtained in the laboratory studies [6] by melting of DRI under argon purging.

After the steady state carbon was reached, oxygen in the form of mill scale was added to the slag bath, by mixing the material with other slag forming oxides. Adding iron oxide at a constant rate, it took about 15 hours to lower the carbon to the desired level (0.1%). Faster decarburization could be achieved by increasing the oxide addition rate but it was deliberately kept low to avoid overshooting the minimum FeO required. It was interesting to note that there is a consistent relationship between the steel carbon and the slag FeO. This feature of the process will be discussed further in the section on FeO-C relation.

Phase 2 – Controlling Carbon at 0.1%

After the first phase of carbon control that was a *process stabilization* phase, the slag FeO was maintained at the minimum level to obtain a carbon of 0.1 wt%. The variation of carbon is shown in Figure 2. As shown, in a period of about 33 hours, carbon content is hovering around 0.1 wt%, indicating the controllability and stability of the process.

It was noted that to maintain carbon at 0.1 wt%, FeO should be around 15 – 17 wt%. The important slag chemistry parameters for this phase of trials are presented in Table 2.

Table 2: Slag and steel chemistry in phase 2 of the continuous trials

Parameter	Target	Actual			
		Min	Max	Avg	STD
C	0.1 wt%	0.050	0.136	0.090	0.018
MgO	12 wt%	8.90	13.13	10.74	1.096
V ratio	2.0	1.72	1.98	1.850	0.072
FeO	Lowest possible	13.6	20.9	16.45	1.65

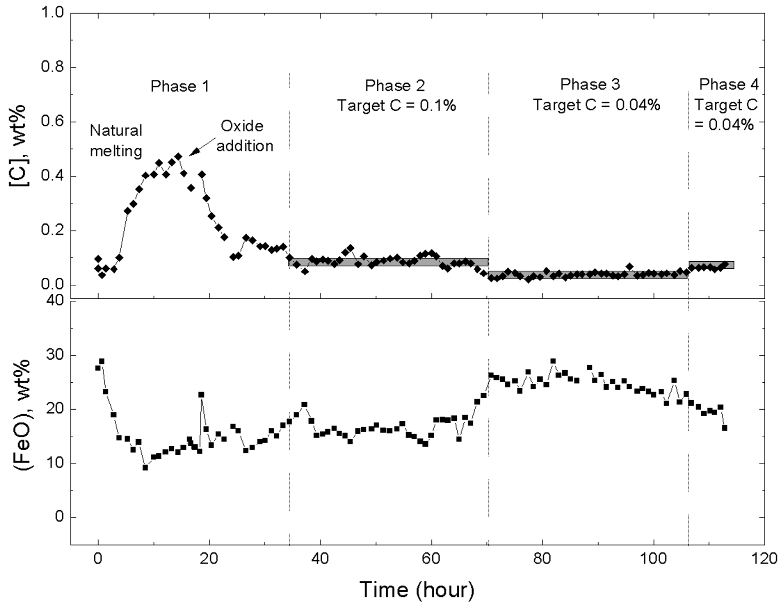

Figure 2: Variation of carbon and FeO content during the campaign

Phase 3 – Controlling Carbon at 0.04%

In the third process control phase, it was decided to lower the carbon to 0.04%. This was achieved within three hours by increasing the FeO to an average of 25 wt%. It was a good indication that the process can be manipulated quite readily, by iron oxide addition to the flux mix. For a period lasting 38 hours, the carbon was maintained at an average of 0.04%. Other parameters of slag and steel chemistry are provided in Table 3. According to the results obtained from the steel and slag analysis on this phase of the campaign, it is evident that the CRISP is a stable process with only minor adjustments needed to maintain the slag chemistry and obtain steel with very low carbon levels.

Table 3: Slag and steel chemistry in phase 3 of the continuous trials

Parameter	Target	Actual			
		Min	Max	Avg	STD
C	0.04 wt%	0.020	0.067	0.038	0.009
MgO	14 wt%	11.0	17.13	13.89	1.480
V ratio	2.0	1.76	2.31	2.06	0.13
FeO	Lowest possible	21.07	28.92	24.92	1.63

Phase 4 – Controlling Carbon at 0.06%

Once it was realized that the stable conditions at 0.04 and 0.1 wt% carbon levels can be established and continued as long as needed, it was decided to drive the conditions towards an intermediate level, i.e., 0.06 wt% C. By reducing the iron oxide proportion in the feed, this was reached in two hours and the carbon was maintained at this level for the remaining duration of the campaign. The stable carbon and slag chemistry obtained in this phase are presented in Table 4.

Table 4: Slag and steel chemistry in phase 4 of the continuous trials

Parameter	Target	Actual			
		Min	Max	Avg	STD
C	0.06 wt%	0.047	0.076	0.061	0.009
MgO	14 wt%	12.62	18.06	14.73	1.63
V ratio	2.0	1.99	2.22	2.08	0.08
FeO	Lowest possible	16.53	22.83	20.13	1.74

It is worth pointing out that the iron oxide source was changed from mill scale to hematite pellets after the second day (phase 2) of the campaign. The transition was made smoothly with no significant variation in the slag FeO and bath carbon, indicating the flexibility of the process in accepting different types of oxidizers.

Equilibrium State of the Reactions

Carbon – FeO Relationship

In the course of the trials, particularly in Phase I, a relatively wide range of carbon concentration was obtained. At the same time, it was found that the carbon and FeO follow a mirror image of each other versus time, i.e., one is inversely related to the other. This relationship can be clearly seen in Figure. 3, where all data obtained for carbon and FeO are presented in a single graph. The results are also compared with the data obtained in the first trials as well as typical conditions of the conventional steelmaking processes. As shown, the relationship is between BOF and Q-BOP, and below that of EAF operations, indicating that the desired carbon content can be obtained with a less oxidizing slag. Obviously, this is an advantage of the CRISP process from several aspects:

- Reduced affinity of slag toward refractory, i.e., lower refractory corrosion
- Higher yield of iron
- Lower slag volume (reduction of energy loss, slag handling, etc).

The relationship between FeO and C concentrations can be theoretically established through the reaction:

$$(FeO) + [C] = Fe + CO_{(g)} \tag{1}$$

In equilibrium state, this reaction yields a relationship of the form presented below:

$$\%FeO = \frac{K'}{\%C} \tag{2}$$

where k' in this equation is primarily a function of the slag chemistry and temperature.

It is clear that the inverse relationship of FeO and C is a fundamental behavior in the steelmaking systems. Nevertheless, comparing the results with the equilibrium line in Figure. 3 shows that the correlation obtained in CRISP trials is above the equilibrium curve, and below the conventional EAFs. This can be readily explained by considering the process condition pertaining to the trials. The longer residence time of steel in the furnace in the CRISP tests contributes to approaching the equilibrium. Therefore, the FeO content is lower than the conditions of typical EAFs, where the refining time is much shorter. Also, using oxidizing agent as iron oxide rather than oxygen gas further promotes a reaction regime that is less oxidizing, and is closer to the equilibrium conditions. It is expected that in the commercial size CRISP furnace, due to a much longer residence time of the steel, a relationship even closer to the equilibrium state will be achieved.

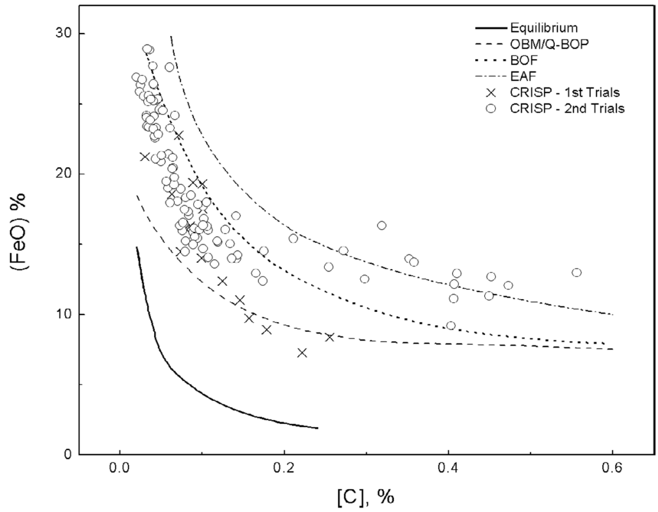

Figure 3: Relationship between carbon and FeO

It is worth emphasizing that the strong correlation seen between FeO and C is one of the most important findings of these trials. The relationship shows that by adjusting the slag FeO, the bath carbon can be controlled in a consistent manner. This leads to the following conclusions.

- The CRISP process can be used to produce a variety of steel grades including grades for both flat and long products.
- The FeO-C correlation can be used as a means of process control, the flux adjustments to be an automated practice.
- A Direct Reduction process with its capability to independently controlling metallization and C of the DRI would tie to a CRISP furnace with the minimum required operational interventions.

Oxygen – Carbon Relationship

The concentrations of dissolved oxygen and carbon in metal are related together through the following reaction.

$$[O] + [C] = CO_{(g)} \quad (3)$$

In the ternary Fe-O-C system, the equilibrium relationship between carbon and oxygen concentrations at 1600 °C can be established as following, by using interaction coefficients [2].

$$\log [\text{ppm O}] + \log [\%C] + 0.09 [\%C] - 2.90\text{x}10^{-5} [\text{ppm O}] = 1.322 + \log[pCO] \quad (4)$$

When comparing the results from the first trials, the second trials and the equilibrium state

(Figure. 4), it proves that the data generated from the continuous trials demonstrated an oxygen – carbon relationship close to the equilibrium state with pressure of CO between 1.0 and 1.5 atm.

The figure also shows that C-O relation is very close to the state of reactions in Q-BOP process, i.e. equilibrium at lower pressure of CO gas. It has been discussed [11] that at low carbon contents, the partial pressure of CO is smaller in Q-BOP than in BOP, due to higher fraction of hydrogen (in Q-BOP) than argon (in BOP) in the gas bubbles. The lower pressure of CO in CRISP trials can be attributed to the fact that decarburization of molten DRI takes place primarily in the slag phase, where the static pressure is smaller (close to 1) than inside a deep metal bath. Thus the CO bubbles at a lower pressure.

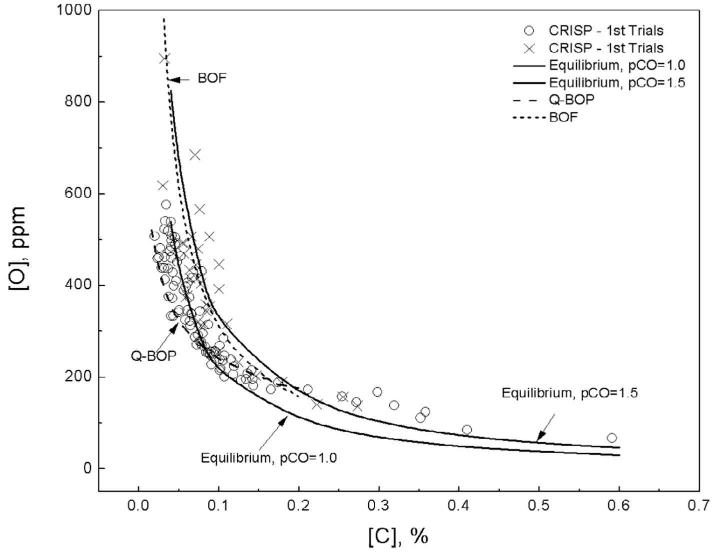

Figure 4: Oxygen – carbon relation

Refractory Profile Measurements

Extended life of the refractory lining is essential to the economic viability of the CRISP technology. Thus, information on the impact of the continuous melting operation on the furnace lining was an important part of the Phase II trials.

The profile of the EAF lining before and after the trial campaign was established through detailed measurements. The dimensions from the furnace centre were taken manually from a vertical steel rod held in place at the centre of the furnace by a custom-made jig. Measurements were taken at eight points (every 45º) around the circumference at six levels (A to F). Each measurement was repeated and averaged.

Figure 5 depicts the furnace wall profile at three points:

- Before the first trials when the furnace was just re-bricked
- Between the two trials
- And after the second trials.

The average variations in the thickness of the refractory for each section are also provided in Table 11. The values are in mm with positive numbers showing deposition on the wall and the negative numbers representing wear. From Table 5 and Figure. 5, along with the observations made during the trials, the following conclusions can be drawn.

- The overall effect of the first set of trials was small deposition on the refractory. However, visual observations made during the trials revealed that this overall effect is in fact the result of deposition- wear cycles depending on the slag chemistry. In some instances when the FeO content increased to about 30 wt pct, the slag line wear was clearly seen whereas in the following heats with lower FeO and high MgO, the refectory repaired itself to its original profile. The slight erosion around the slag line (sections E and F) for this campaign is believed to be the result of several heats with highly oxidized slag (caused by significant air ingress and the slag being removed after each heat, leaving a bare metal surface). Nevertheless, the wall condition after the trials is excellent, particularly in view of the not fully controllable periods of oxidized slags experienced in the Phase I trials. Also, the fact that the refectory can self-repair itself by proper control of the slag chemistry adds to the confidence that the refractory can be maintained without a need for interrupting the process.
- In the second trials, the slag over-oxidation was minimized and a thick layer of slag was always retained in the furnace. The result on the refractory appears to be very good, as in this phase, a net deposition of 62 mm is seen. More interestingly, the slag line (Section E), which is the area most prone to refractory loss, has gained an average thickness of 30 mm. The only point where the slag line has experienced a wear is opposite Phase B, the *hot* phase. This could be expected as it is customarily experienced in this area on conventional AC arc furnaces and is caused by the arc deflection towards the transformer. The CRISP six-in-line furnace geometry and electrics are however different and this phenomenon should not occur.
- The overall effect of the two campaigns together lasting about 200 hours of operation is a net deposition of 66 mm. This is regarded as the one of the most promising outcomes of the CRISP trials, showing an excellent refractory endurance. These encouraging results can be attributed primarily to the properties of the slag: good foaming action with low FeO levels and MgO saturation

Table 5: Average variation of the furnace refractory thickness (in mm) across each section

Section →	A	B	C	D	E	F	Average
After 1st Trials	12.5	10.0	15.0	28.1	-18.1	-20.6	4.5
After 2nd Trials	3.7	-11.5	135.5	92.2	29.9	120.0	61.6
After both campaigns							
(combined effect)	16.2	-1.5	150.5	120.3	11.8	99.4	66.1

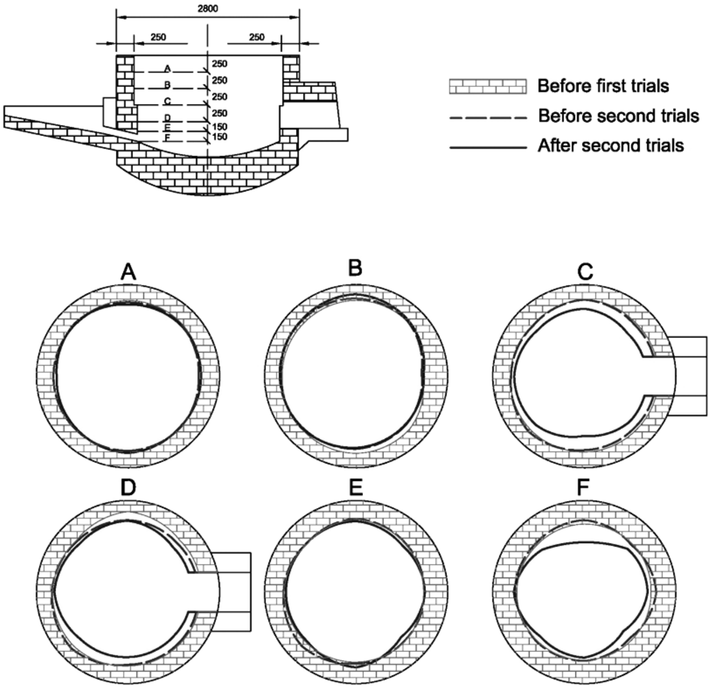

Figure 5: Refractory profiles before and after the two trials

CONCLUSIONS

The continuous pilot trials for the CRISP technology proved to be a successful. The key findings can be summarized as follows.

- The five-day pilot campaign proved the concept of CRISP process: producing steel in a continuous fashion from DRI feedstock.
- The CRISP process is capable of producing various grades of steel from low to high carbon in a reproducible and sustainable fashion.
- Carbon levels as low as 0.04% could be achieved consistently without oxygen lancing, while maintaining a good foaming slag and a low FeO (below 25%).
- The control of steel carbon is readily made by adjusting FeO level of the slag. A transition period of 2-4 hours between each carbon level was observed.
- A strong relationship between FeO and C was established that is closer to the equilibrium state than the conventional EAFs. The relationship proves controllability and the potential for improved process automation.
- After about 200 hours of operation in two trials, no major refractory loss was observed. Some sections of the furnace even experienced a net thickness gain over the period.

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