Application of EAF Wall Injectors for High-Alloy Steel Production

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Production of high-alloy special steels in the electric arc furnace (EAF) requires the use of several different melting practices — from standard foaming slag operation through recovery heats with no foaming slag, to heats with large amounts of FeCr charged into the furnace after earlier phosphorus removal. To reach target carbon content in steel, decarburization by oxygen lancing or recarburization by carbon injection are required. This paper presents the operational results after the installation of INTECO PTI JetBurner and Annulus Burner injection tools on the EAF at Metal Ravne, a Slovenian special steel producer. The installed tools proved to be very efficient and successfully replaced previously used door lance manipulator.

The electric arc furnace (EAF) is nowadays recognized as the most flexible melting and scrap recycling tool utilized for the production of a wide range of steel grades, sometimes using completely different raw materials. Standard rebar grades, high-quality low- and medium-alloy engineering steel grades, as well as stainless steel grades can be produced using the same furnace, which can be charged with carbon scrap or a mix of alloy scrap with the addition of the most common iron-rich material (such as direct reduced iron (DRI), hot briquetted iron (HBI) and hot metal) in common with the required ferroalloys and slag builders.

The EAF in operation at the Metal Ravne meltshop is an example of such highly flexible unit employed for the production of carbon and high-alloy steel grades. In March 2015, INTECO was selected to upgrade the existing 45-ton oval bottom tapping (OBT) furnace into a highly productive unit, matching today's technology standards, characterized by safe operations, improved performance and availability, as well as reliable process control.

The typical approach to increase productivity is a revision of the existing chemical energy system and its further optimization with the aim to improve process efficiency with the addition of new tools. In the case of Metal Ravne, the existing conditions needed to be analyzed thoroughly with regard to different steels produced and practices utilized.

Based on this, the final scope of supply was defined, including INTECO PTI chemical energy package with oxygen and carbon injection technology and melting process control with the addition of automated slag door (INTECO PTI SwingDoor™), INTECO ATEC electrode control system, and robotic device for steel temperature measurement and sampling.

Revamping Targets

The EAF was originally equipped only with a door consumable lance manipulator for oxygen and carbon injection. Earlier furnace modification from a standard to an oval shell related to tapping capacity increase resulted in specific problems with more evident hot/cold spot unbalance and extended melting time. Installation of a new injection system was focused on solving

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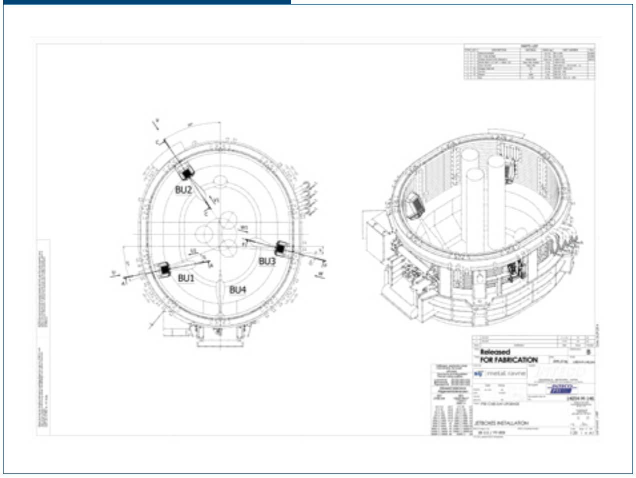
Figure 1

Revamped 45-ton oval bottom tapping (OBT) furnace.

Figure 2



Burners installation after revamping and SwingDoor™.

the existing problems. The new system includes three wall-mounted burner/oxygen injectors (one of them designed for shrouded carbon injection) plus one more dedicated for the automated SwingDoor.

The new injection system installation (Fig. 2) can be characterized as follows:

- Steep inclination angle (50°).
- Close distance to steel level (about 400 mm).
- Operation with variable gas/oxygen flows required by various heat sizes.

The new installation was also analyzed from the point of view of slag splashing intensity reduction as well as minimization of refractory wear.

Carbon injection through the special annulus-type injector contributed the following additional benefits:

- Bigger carbon injection angle (compared to traditional carbon tuyeres) allowing injection directly into liquid steel.
- Unique possibility to maintain fluidity in the slag in front of the injector prior to and during the carbon injection, which proved to be extremely useful during production of high-C and high-Cr tool steels with slags containing a higher percentage of chromite.

The above-mentioned features help to improve reactions between the steel and the carbon itself, increasing efficiency of recarburization and metallic yield. At the same time, carbon powder losses to the primary offgas suction system are reduced to the absolute minimum.

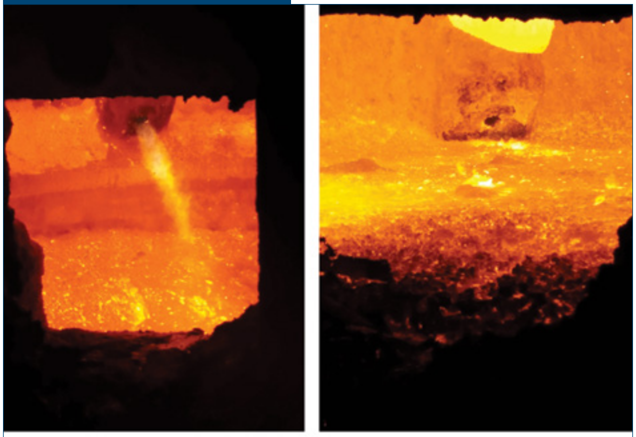
Special Steel Grades Production at Ravne

The Metal Ravne meltshop is focused on the production of special steel grades, including major production (~70%) of high-Cr steels (tool and stainless grades) with relatively smaller quantities (~15%) of carbon and low-alloy structural steels and other special steels (~15%).

The special steel grades produced are mainly characterized by high content of alloying elements, especially chrome, but also molybdenum, nickel and vanadium. Major high-alloy steel grades include:

- High-chromium and high-carbon tool steels (D2, D3, X20Cr13, X160CrMoV121).

Figure 3



(a) (b)

Injection angle (a) and close-to-steel/slag surface injector location (b).

- Medium-alloy hot working tool steels (H13 and X27CrMoV51).
- Austenitic stainless steels (AISI 304 and AISI 316).
- Low- and medium-carbon grades with lower alloy content (50Mn7, 42CrMo4).
- Low- and medium-carbon grades (C45).

High-Cr grade production is particularly challenging, since chromium easily reacts with oxygen, especially when a low carbon level must also be achieved and a huge amount of oxygen must be injected. In such conditions, the risk of chromium losses and consequent metallic yield decrease caused by oxides remaining in furnace slag is very high.

Typical Melting Process for High-Chromium Grades

To achieve the required high percentages of Cr in steel, ferroalloys containing Cr are used in combination with high-Cr scrap, typically available as heavy pieces of forging plant returns and scrap resulting from ingot casting processes.

Such kind of scrap allows for a high quantity of important elements to be recovered, but also has the negative effect on furnace operation with difficult and late melting.

Metal Ravne's melting practices are normally divided into three main groups depending on the final composition, available scrap and charge typology, and capabilities of the available process technology.

Standard Heats — The EAF charge is composed of carbon and alloy steel scrap with the limitation of the maximum Cr content in the charge being below 1.0%, still allowing the standard EAF operation to be carried out with foaming slag, long arcs and a high input of chemical energy.

Recovery Heats — This practice is used to recover precious elements (mainly Cr) from the scrap. The melting process is conducted without this oxidizing period under a reducing slag and with a limited use of oxygen in general. Since the foaming slag practice cannot be used, melting power input has to be set high with clearly shorter arcs.

Buildup Heats — In this case the melting process starts with a charge initially composed of carbon steel scrap and some alloy steel scrap with the limitation of maximum chromium content. By the end of melting, liquid steel is decarburized with simultaneous phosphorus removal to the lowest possible values using oxygen and lime. After reaching the primary composition targets, the oxidizing slag is removed from the furnace and liquid steel is initially deoxidized. After that, the required steel composition is "built up" by adding alloying elements (mainly FeCr) into the furnace. This practice is used for production of high-Cr tool and stainless steel grades with extra-low P requirement.

Slag Experience During Melting of High-Chromium Steel Grades

EAF operation with oxygen and carbon injection is naturally associated with foaming slag generation.[1] Foaming slag practice is the most effective method for optimizing the energy consumption in the EAF, which has been demonstrated in many steelmaking plants producing carbon and low-alloy steels. Covering the electric arcs with a foamy layer leads to an increase in the heat transfer efficiency, decrease in the heat losses to the EAF sidewalls and roof with a consequent lowering of refractory and electrode consumption, more stable arc, lower noise level, and increased power input.

Slag foaming is generated by simultaneous carbon and oxygen injection into the slag. The foaming is dominated by two reactions both generating CO gas. One of them produces iron oxide (FeO), which is transferred to the slag phase where it can be immediately reduced by the injected carbon. The other one takes place when injected or dissolved carbon and injected or dissolved oxygen gas react together, again producing CO gas. Good foaming effect is promoted by suitable slag viscosity with a balanced content of acid (SiO_2, FeO, Al_2O_3) and basic oxides (CaO, MgO, Cr_2O_3), resulting from oxidation and slag-building material additions.

The effective viscosity of the slag increases by the presence of refractory-type oxides with a higher melting point being beyond the actual slag liquidus composition. The addition of fluxing oxides with lower melting point increases the fluidity of the slag.

Although many steel plants producing stainless steels were trying to implement any kind of foaming slag practices, all trials to develop foaming slag for those special steel grades were always difficult and inefficient. The main reason is the fact that the slags always have a higher content of chromium oxides, which are formed by the high affinity of chromium to oxygen and resulting lower content of iron oxide, which has a negative impact on both the foaming capacity and the efficiency of oxygen and carbon injection.

At the same basicity and temperature conditions, solubility of chromium oxides in EAF slags with lower chromite contents ($Cr_2O_3 < 5\%$) is lower than the solubility of iron oxides. When the content of Cr_2O_3 is exceeded, the resulting solid chromite particles in the slag tend to break the foam bubbles, leading to precipitation of solid particles in the bulk and lower intensity of CO gas generation during foaming. This has a strong negative impact on the overall ability of slag to foam.

Table 1 contains some slag sample analyses representative of the production of high-chromium steel grade (OCR12VM) with 1.5%C and 12%Cr taken just before slag reduction.

The elevated Cr_2O_3 content results in very poor foaming with consequent increased thermal radiation to the furnace shell, high arc noise and high energy losses. All high-Cr slags need to be further reduced by Al and/or FeSi addition to not only recover chromium to the maximum extent but also to liquefy slag, making deslagging or tapping operations possible.

In the case of chromite slags, the optimum range for the proper slag composition to achieve a stable foam is relatively narrow. Besides, there is a large probability of uncontrolled oxidation with unpredictable large chromium losses to slag and poor foaming effect.

The best conditions for slag foaming for high-chromium steel can be resumed in a qualitative ternary diagram, shown in Fig. 5.

If the composition targets are not fulfilled, the slag becomes difficult to foam because it is either too fluid (with high content of acid oxides) or too stiff (containing slag components with high melting point).

Why Are Coherent Injectors Not Popular for Chromium Steel Production?

The development of various chemical energy systems for special melting units has always been limited for several reasons. Among them, the most important ones are:

- Increased losses of Cr and consequent low metallic yields with increased transformation costs.
- Burners are forced to work with understoichiometric ratios being less efficient in scrap cutting and melting.
- Resulting high-Cr slags are very dense and difficult to handle.

In view of the above, two main techniques[2] for oxygen injection have been widely employed in stainless steel production:

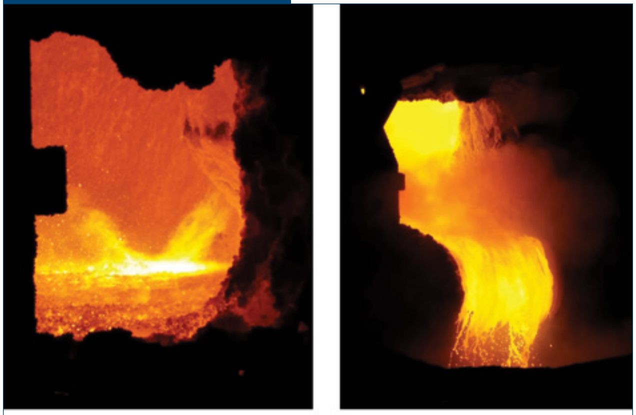
- The older and more common method is injection through a consumable lance (straight pipe), which can be submerged into the bath and further submerged as it is consumed. The tip of the lance is usually positioned at the

Table 1

Slag Samples

CaO (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	MnO (%)	FeO (%)	Cr_2O_3 (%)	S (ppm)
13.9	9.14	10.9	29.5	4.11	7.58	20.3	0.041
17.7	9.16	13.4	29.6	3.22	7.97	15.7	0.052
9.76	10.3	12.3	27.5	4.39	6.99	25.6	0.038
23.8	2.71	11.7	24.7	3.82	7.17	20.4	0.063
20.0	5.04	19.7	26.5	3.24	4.66	13.7	0.033
17.4	6.22	17.2	28.4	4.29	5.53	15.7	0.037
5.79	9.97	9.91	29.56	4.82	7.91	23.6	0.019

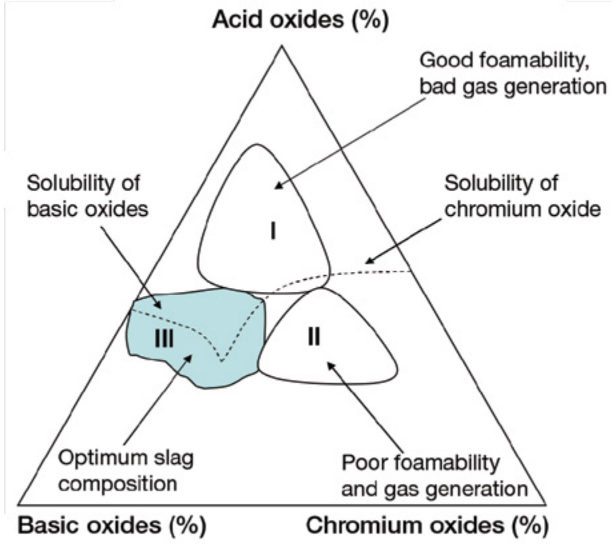
Figure 4



(a) (b)

Example of very hard (after steel decarburization) (a) and very liquid (after slag reduction) (b) high-chromium slags.

Figure 5



Areas of the three-phase diagram with different activities of foaming/reduction.

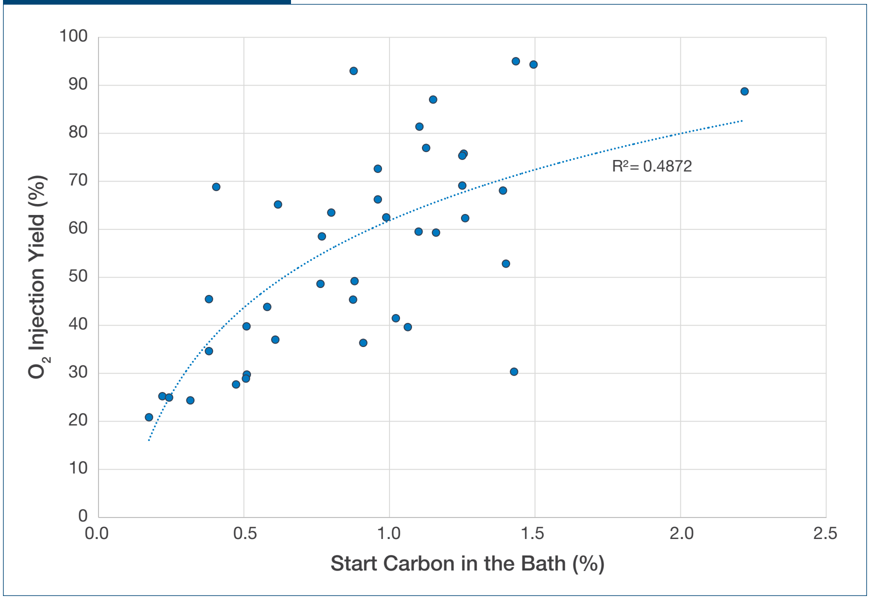
- slag-metal interface with an impact angle in the range of 30–40°.
- Less popular are various water-cooled lances with supersonic nozzle blowing oxygen through the slag onto the metal surface. The copper tip of the lance is not immersed in the slag to avoid its accidental melting. The injection angle is also in the range of 30–40°.

Utilization of both the above-mentioned practices requires the slag door to be partly or completely open during the injection with all the well-known consequences related to energy losses, slag oxidation, increased load on the offgas system with elevated risk of uncontrolled emissions, excess electrode oxidation, etc.

Wall-mounted injector systems are now commonly installed in all new standard EAFs with increasing tendency to replace older injection systems, to allow for operation with the slag door closed for as long as possible and to promote automatic and dynamic injection control while reducing maintenance efforts and improving safety of operations. The other well-known advantages of such wall-mounted injection systems are accelerated decarburization, fast foaming slag generation and improved homogeneity of steel temperature and composition.

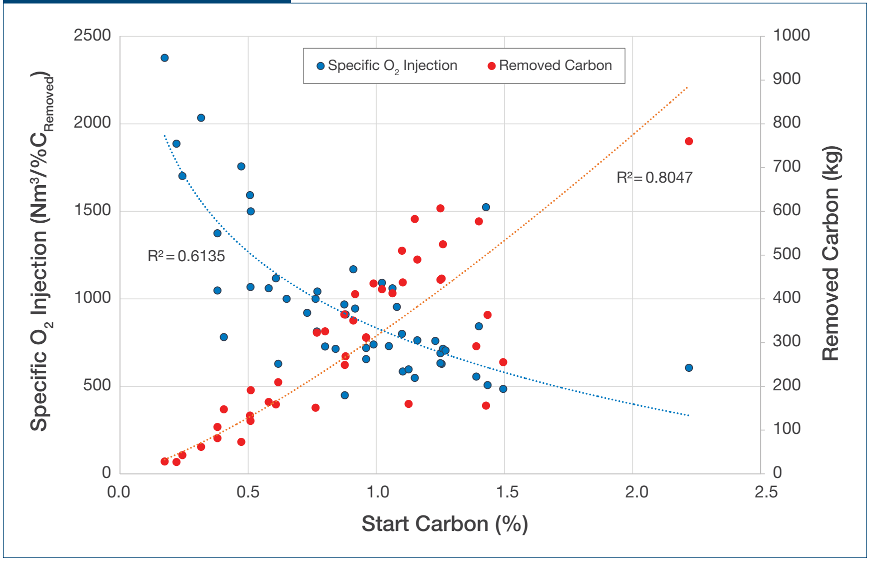
Unfortunately not all of the apparent advantages of wall-mounted injectors can be easily utilized during high-Cr steel melting. Also at Metal Ravne, the existing door manipulator with consumable lances has been maintained as a backup tool in case of unexpected problems that could arise during utilization of the newly supplied INTECO PTI injectors.

Figure 6



Injection yield and initial carbon in the liquid bath.

Figure 7



Specific O_2 injection and removed carbon referred to initial carbon in steel.

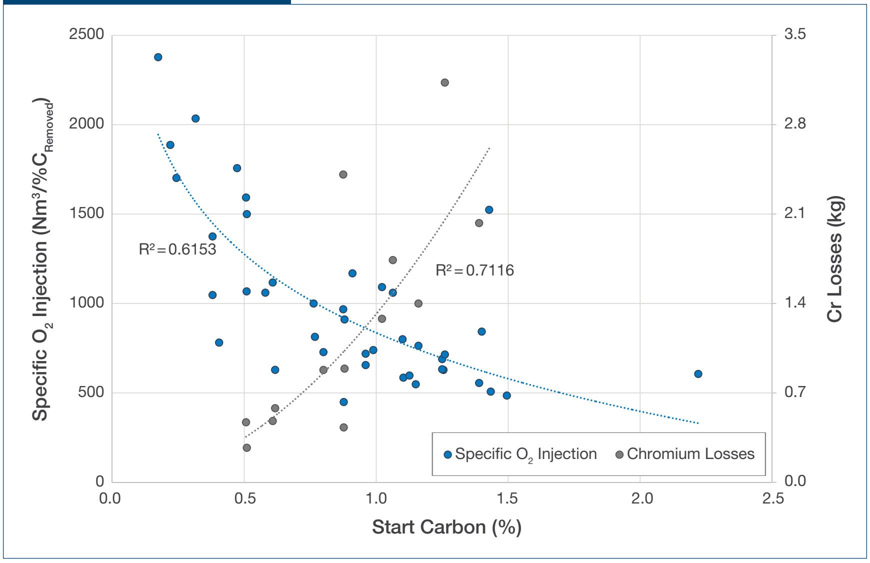
Experimental Trials With Decarburization

After the start-up of the new equipment, it was possible to run some tests to evaluate both the decarburization efficiency and the recarburization capabilities of the new tools installed in the furnace.

The process conditions to conduct these trials in this furnace were optimal since most of the produced steel grades require a high amount of oxygen injection to reach the desired carbon content before tapping.

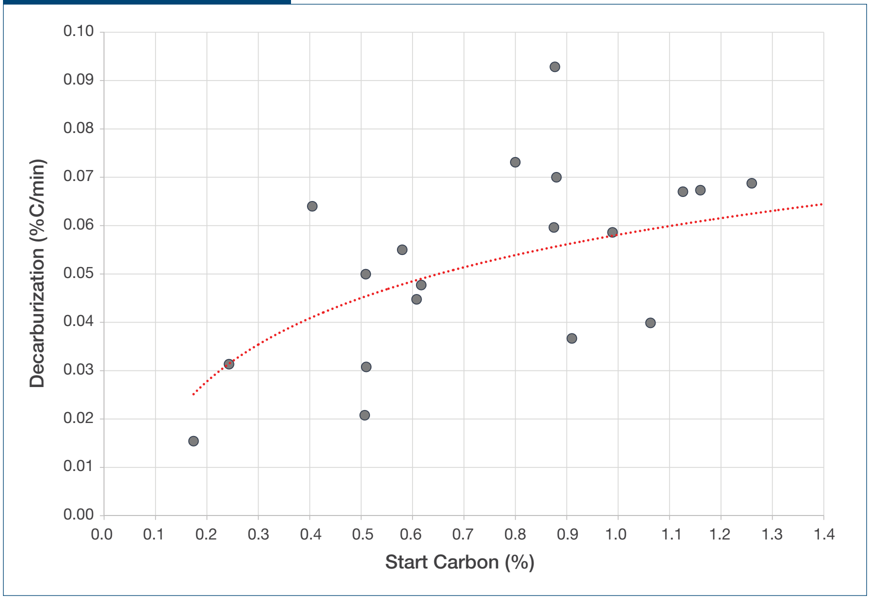
Once the known amount of C was removed from the liquid steel, the theoretical (i.e., close to stoichiometric) O_2 volume required to burn carbon could be compared with the total volume of injected oxygen.

Figure 8



Specific O_2 injection rates and chromium losses with respect to initial carbon in steel.

Figure 9



Decarburization rate analysis.

The diagram (Fig. 6) shows the different oxygen efficiency (expressed as ratio between the theoretical oxygen volume and the real blown oxygen volume) for different start carbon content in the liquid steel with Cr contents >10%.

From Fig. 6 it can be concluded that the injection efficiency decreases with the decreasing content of carbon in the liquid bath. With higher content of carbon in the bath, the decarburization reaction is more effective and faster. With lower carbon contents the reaction speed reduces mostly due to increasing Cr oxide content in slag and its reduced fluidity.

The loss of decarburization efficiency can also be seen in Fig. 7, which illustrates the specific amount of oxygen consumed for actually removed carbon (Nm^3 O_2/%C removed) in common with the quantity of carbon removed (kg of C) for different initial carbon contents in steel.

The specific O_2 injected volume increases with the decrease of carbon in the liquid bath. Consequently the removed carbon during decarburization is almost proportional to the carbon content in steel.

A similar behavior can be seen with respect to observed chromium losses (Fig. 8). Less carbon in the liquid bath requires less stoichiometric oxygen to be injected, which consequently results in reduced chromium loss. The loss of oxygen injection efficiency is balanced by the decrease of its yield.

The above observations are important to establish guidelines for development of charging and melting practices. The optimum furnace charge should be prepared — depending on actual steel grade and the available raw materials — with a higher amount of carbon (approx. 0.80 ÷ 0.90%) in the charge, which allows for the oxygen consumption to be optimized, maintaining ideal decarburization rates with reduced chromium losses.

A similar analysis can be done with regard to the speed of decarburization. Fig. 9 reflects all the aspects of the decarburization process kinetics.[3]

Considering that oxidation of silicon takes place at the very beginning with rather low oxidation of manganese and iron, the fundamental reaction taking place during decarburization of chromium steel defined by oxidation of chromium and its reduction by carbon is as follows:

$$(Cr_2O_3) + 3[C] \leftrightarrow 2[Cr] + 3\{CO\} \quad \text{(Eq. 1)}$$

Above a critical value of carbon in the liquid metal, the decarburization speed is independent from the carbon content but depends only on the oxygen flow and its efficiency, which can be expressed by the following equation:

$$\frac{d(\%C)}{dt} = C1 \cdot V_{oxy}\left[\frac{Nm^3}{h}\right] \qquad \text{(Eq. 2)}$$

where C1 is a decarburization constant depending on weight of the melt.

This is why the decarburization speed is almost linear above the critical value of 0.3–0.4%C. This line is not horizontal, since the efficiency of carbon removal also decreases with lowering carbon content in the melt.

Below critical carbon, the rate of carbon removal is controlled by the decreasing rate of mass transfer according to the following simplified equation:

$$\frac{d(\%C)}{dt} = C2 \cdot \left([\%C]_{bath} - [\%C]_{cr}\right) \qquad \text{(Eq. 3)}$$

where C2 is a constant depending on carbon mass transfer coefficient, area and volume of the melt.

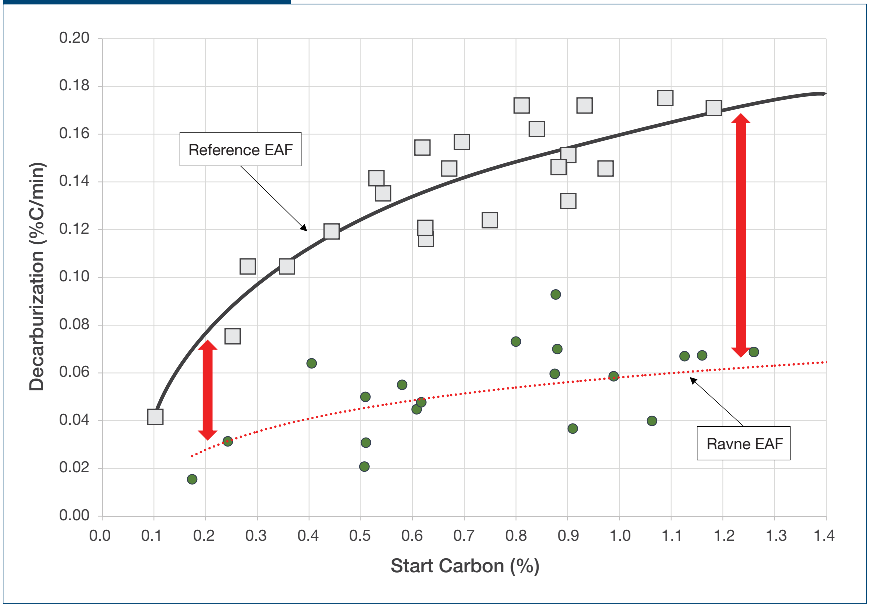
The reaction is then slower for lower values of carbon in the bath since less carbon is available and as a consequence the excess oxygen reacts with metals producing Cr_2O_3 and FeO.

The above results have been compared with similar tests found in some publications[4] where the decarburization tests were made for a furnace operating with high percentage of hot metal (Fig. 10).

As it can be seen, the decarburization speed trend is quite similar, confirming the previous theory of two different mechanisms for the reaction kinetic.

Nevertheless, the decarburization rates observed in the case of the Metal Ravne EAF are considerably lower than the reference ones, especially with higher contents of carbon in the bath. This can be explained by the fundamental differences between two furnaces related to both charge condition (chromium steels versus carbon steels) and especially to oxygen injection density.

Figure 10



Comparison of decarburization rate curves.

Table 2

Furnace Main Data

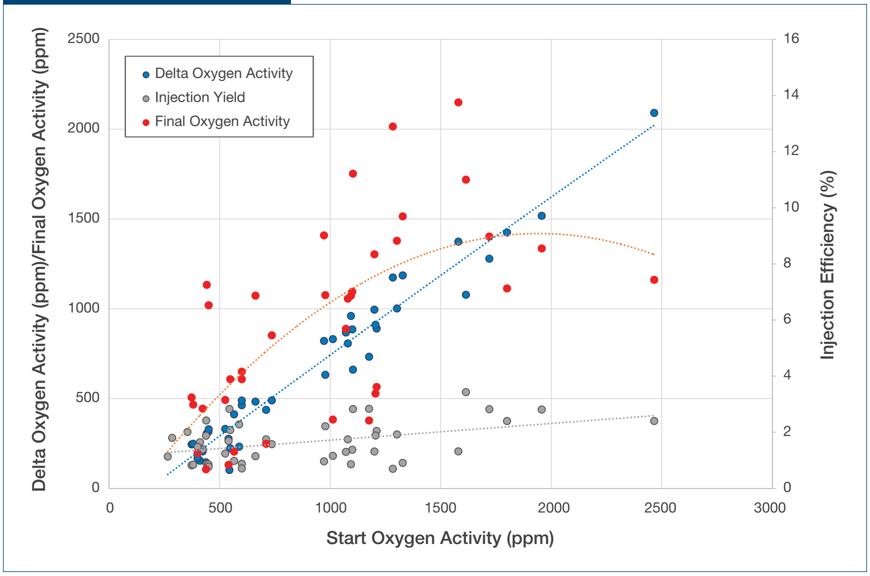
Parameter	Ravne EAF	Reference EAF
Tapping weight	45 t	110 t
Metal bath surface	11.2 m^2	27 m^2
O_2 injection capability (max.)	4 x 1,300 Nm^3/hour	6 x 2,500 Nm^3/hour
Average utilized O_2 flow	2 x 1,300 Nm^3/hour	4 x 2,000 Nm^3/hour
Injection specific density	230 Nm^3/hour/m^2	300 Nm^3/hour/m^2
Charge raw material	Alloy steel scrap	Scrap + hot metal
Slag chemistry	High-Cr slags	Standard slags

Higher available bath surface as well as higher oxygen injected flow can speed up the carbon removal reaction very clearly. High chromium content in the steel can considerably slow down the reaction, especially when higher percentages of carbon are present in the bath. The difference between the two decarburization curves shown on Fig. 10 is significant for higher carbon contents and becomes less visible with a decrease of initial carbon percentage.

Experimental Trials With Recarburization

The second objective of the trials was to check the capability of the annulus burner for shrouded submerged carbon injection and yield of carbon pickup by the liquid steel. The carbon injection was used to decrease the oxygen activity before tapping below

Figure 11



Recarburization trials.

The oxygen injection sequence is managed entirely by the melting profile manager with recipes adjusted for particular steel grades and charge mixtures.

Once more, the installed process tools proved to be a reliable solution for high-alloy steel production where especially hard high-chromium slags are a common part of the process. Advantages such as satisfactory decarburization efficiency and reliability of the injection tools in common with effective recarburization capability obtained by only a single carbon injection point create conditions for wider application of coherent burner and lances and carbon injectors in special steel meltshops.

400 ppm, which was the practice required to decrease the risk of boiling reaction during tapping.

As it can be seen (Fig. 11), the final oxygen activity target is reached with removed oxygen proportional to the starting level of oxygen activity.

The injection oxygen efficiency is not quite linear with respect to changes in the oxygen activity. This is mostly related to the different slag conditions and intensity of metal bath agitation, which is the real key for deep penetration of the carbon into the liquid steel.

Summary

The revamping experience at Ravne can be considered highly positive from several points of view. After the implementation of new injection tools, the furnace is apparently operated with much higher efficiency and reduced specific electric energy consumption (–16.1%), shorter power-on time (–13.5%) and increased productivity (+20.8%).

Currently the slag door manipulator is not used for decarburization of high-Cr steels except for the cases where hard slag behind the sill needs to be liquefied before steel sampling or temperature measurements. Drastic reduction of operators' activities in front of the slag door and improvement of safety in the working environment are positive side effects.

Conclusions

Standard EAF sidewall-mounted combined injectors with burner/oxygen lance function can be effectively used for melting of and refining of high-Cr steels. Burner operational function can be set up for minimum Cr losses with understoichiometric flames while the non-immersed oxygen lance with relatively high distance from the liquid steel level can be used for efficient carbon removal.

Specially designed tools for submerged carbon injection below the slag have proved their functionality and efficiency even in the case of typically hard slags associated with stainless steelmaking.

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