

EFFECT OF BOTTOM STIRRING ON BASIC OXYGEN STEELMAKING

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## **ABSTRACT**

### **EFFECT OF BOTTOM STIRRING ON BASIC OXYGEN STEELMAKING**

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ERDEMİR Steel Plant produces wide range of alloy steel for various industries. Main demand of industries for steel is high quality end product with lower prices. One of the criterion affecting not only the steel cleanliness and also price of the product is bottom stirring in basic oxygen steelmaking. The objective of this study is to investigate effects of bottom stirring on basic oxygen steelmaking. With this objective, process parameters, analysis of produced heats were investigated to determine effects of stirring and optimum stirring program.

For the current study, overall and individual analyses carried out using the turndown slag, the metal composition and the input materials data for many heats in terms of the amounts of oxygen, carbon, manganese, nitrogen, sulphur, and phosphorus at the end of blow.

The results indicated the advantages of bottom stirring since it enables the steel production with lower amounts of oxygen, carbon, sulphur and phosphorus while it makes high manganese containing steel production possible. Additionally, by the help of bottom stirring higher iron yield is possible. The efficient removal of impurities comes along with a cleaner and high quality end product. Moreover, it is possible to have economic savings due to low requirements of deoxidizer and ferromanganese during the production.

**Keywords:** Steel, basic oxygen steelmaking, bottom stirring

## ÖZ

### ALTTAN KARIŞTIRMANIN BAZİK OKSİJEN ÇELİK ÜRETİMİNDEKİ ETKİSİ

Bilgiç, Çağrı Doğan

Yüksek Lisans, Metalurji ve Malzeme Mühendisliği Bölümü

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ERDEMİR Çelik Fabrikaları çeşitli sanayiiler için geniş türde çelikler üretir. Yüksek kaliteli düşük fiyatlı çelikler müşterilerin ana talebidir. Bazik oksijen çelik üretiminde alttan karıştırma hem çelik temizliğini hem de ürün fiyatı etkileyen önemli kriterlerden biridir. Bu çalışmanın amacı bazik oksijen çelik üretiminde alttan karıştırmanın etkisini araştırmaktır. Bu amaçla, proses parametreleri ve döküm analizleri alttan karıştırmanın etkilerini ve optimum karıştırma programını bulmak amacıyla gözden geçirilmiştir.

Bu çalışmada, birçok döküm için cüruf, metal kompozisyonu ve giriş malzemeleri verisi kullanılarak üfleme sonundaki oksijen, karbon, manganez, azot, kükürt ve fosfor genel ve ayrı analizleri gerçekleştirildi.

Sonuçlar alttan karıştırmanın avantajları olarak düşük oksijen, karbon, sülfür ve fosforlu çelik üretimine olanak sağladığını, yüksek manganlı çelik üretimini mümkün kıldığını göstermiştir. İlaveten, yüksek demir verimi alttan karıştırma yardımıyla mümkün olmaktadır. Empüritelerin daha etkili giderilmesi daha temiz ve yüksek kaliteli ürün ortaya çıkarmaktadır. Bununla beraber, üretim esnasındaki

düşük oksijen giderici ve ferro manganez ihtiyacı sebebiyle ekonomik kazanç mümkün olmaktadır.

**Anahtar kelimeler:** Çelik, bazık oksijen çelik üretimi, alttan karıştırma



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## **CHAPTER 1**

### **INTRODUCTION**

High productivity and cost reduction are the main criteria to be fulfilled by the steelmaking industry. Regarding the customer demands, in addition, steel cleanliness is to be accomplished by the steelmaking industry with respect to the importance of competitiveness.

The basic oxygen furnace (BOF) is the widely preferred and effective steel making method due to its higher productivity and considerably low production cost. Most of the crude steel production in the world is met by using the BOF method.

Erdemir Steelmaking Plant provides a wide range of high end quality alloyed steels in different sections and sizes by using BOF method. One of the major objectives of the plant is to produce clean steel with the lowest price.

An important development in steel plant for the improvement of production line was implemented 20 years ago when 6 bottom stirring nozzles were integrated to converter. Together with addition of these nozzles, the capacity of the converter was increased up to 120 tons of liquid steel resulting in the annual built up capacity of 2.8 million tons which is further increased to current annual production capacity of about 4 million tons. Although several research activities have been conducted which turned into improvements implemented on the production line, the effect of bottom stirring has not been studied in detail yet. The current study was carried out with the motivation to investigate the effects of bottom stirring on the amount of carbon, oxygen, sulphur, phosphorus and manganese contents in steel at the end of blow.

The examination of the effect of bottom stirring is crucial since it is not optional for steel-making with BOF. The reason for the requirement of bottom stirring in BOF is the gas flow coming from the porous plug at the bottom of furnace which continues with a minimum level to prevent formation of slag over its surface until it is fully blocked named as bottom built-up.

Bottom stirring is applied during oxygen blowing with different gases such as argon and nitrogen at different rates. The type, volume and flow characteristics of the stirring gas are controlled by stirring parameters. Although nitrogen is cheaper than argon, nitrogen cannot be used during the entire process due to nitrogen pick-up takes place by the steel.

This study was carried out with the objective of investigating effects of bottom stirring on basic oxygen steelmaking. With this objective, the steelmaking practice used was thoroughly investigated. Turndown slag, the hot metal composition and amount of material usage of a large number of BOF heats covering a period of several years, were employed for this purpose.

## **CHAPTER 2**

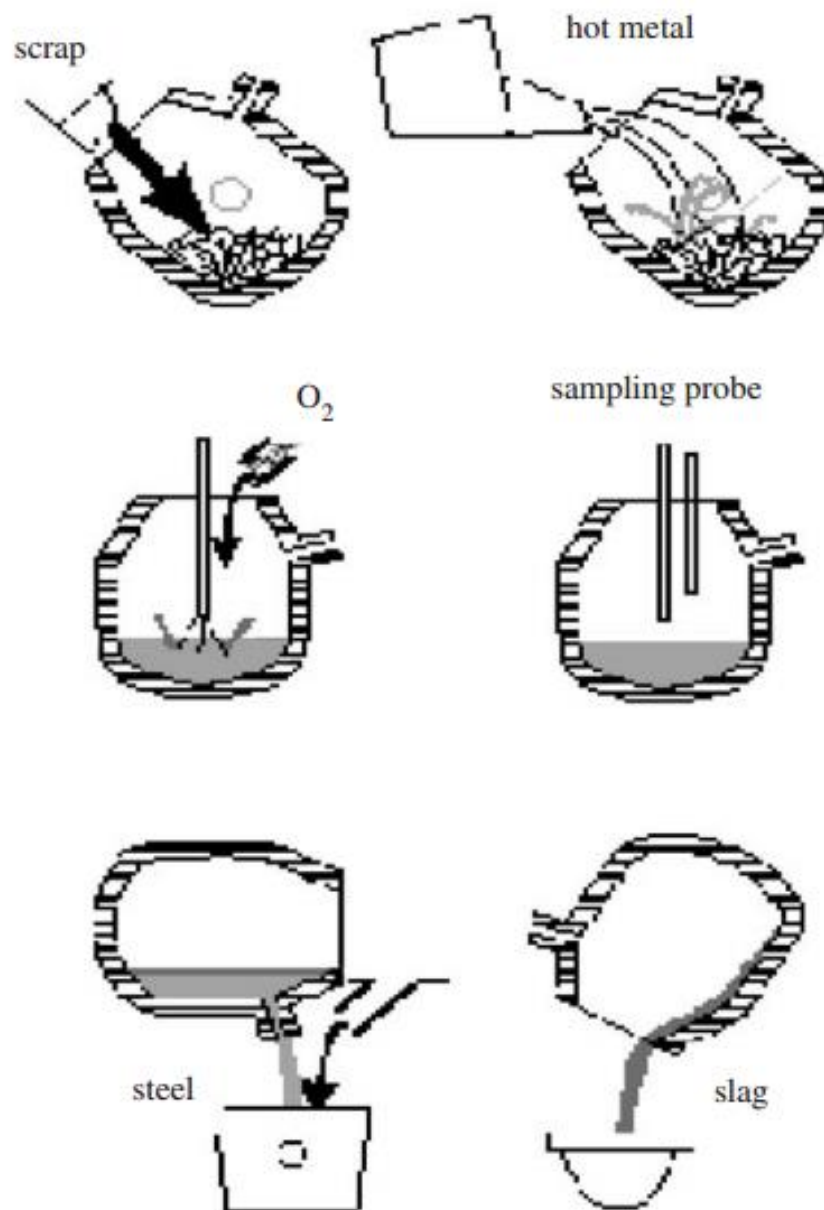
### **LITERATURE REVIEW**

#### **2.1 Process Description**

Basic oxygen steelmaking process includes blowing high purity oxygen over the mixture of carbon rich molten pig iron and ambient scrap at refractory lined converters. Impurities such as carbon, phosphorous, manganese and silicon at pig iron and scrap are reduced to desired level. Steel is produced in discrete batches called heats. The furnace, i.e. BOF, or converter is a barrel shaped, open topped, refractory lined vessel. The basic operational steps of the process are shown schematically in Figure 2.1 [2].

The aim of the process is to reduce carbon content of pig iron from 4% to less than 0.1% by the help of scrap as coolants, to reduce sulphur and phosphorus content to minimum level and to raise temperature of steel produced from BOF about 1680 °C [2]. Flux materials are minerals added as slag builders during oxygen blow not only to control sulphur and phosphorous but also to minimize erosion of the furnace refractory lining. The chemical composition and temperature of input materials, and aimed steel weight, chemistry and temperature are the affecting parameters on the quantity of hot metal, scrap, oxygen, and fluxes. Oxidation of various elements in the charge materials provides the required energy to increase the temperature of fluxes, scrap and hot metal. Iron, silicon, carbon, manganese and phosphorous are the principal elements. Hot metal, scrap, fluxes and additional materials like coolants and heaters are the source of the impurities. Hot metal provides almost all

of the silicon, carbon, manganese and phosphorous, along with a less amount coming from the scrap.

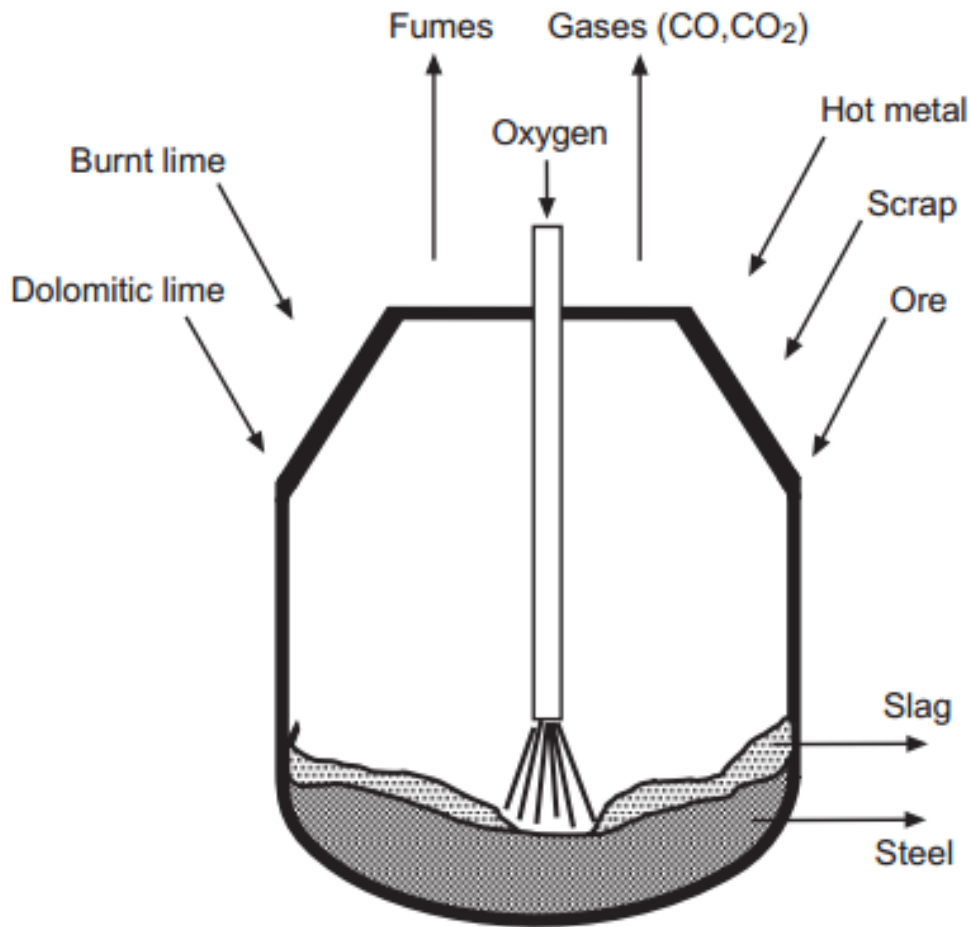


**Figure 2. 1** The basic operational steps in the BOF [2]

High purity oxygen is provided from the top of the converter via oxygen jet during the blowing process. Intense stirring provided from the oxygen jet is introduced and high temperature of the liquid pig iron provide fast oxidation of elements and rapid release of a large amount of energy. Liquid slag is formed in combination with the fluxes and oxides of silicon, manganese, iron and phosphorous. Strong stirring provided from the oxygen jet provides fast reaction and energy transfer between the steel bath and slag. Oxidation of carbon forms carbon monoxide that leaves the process in gaseous form. Slag, steel and the interaction make up a foamy emulsion. Large surface area between steel droplets and slag, vigorous stirring at high temperature allow quick reactions and rapid mass transfer of elements from metal to gas phase [1]. When the blow is finished the slag floats on top of the steel bath. Steel and slag are taken separately from the converter.

## **2.2. Mass and Energy Balances**

Input and output materials in the basic oxygen steelmaking process are shown in Figure 2.2 [2]. Input materials for the BOF are hot metal, scrap, fluxes and oxygen. The fluxes can be grouped as slag builder, coolants and heaters. Burnt lime, dolomitic lime and limestone are mainly used as slag builders. When ferrosilicon and anthracite coke are used as heaters, iron ore and pellets are used as coolants.



**Figure 2. 2** Input and output materials in the BOF [2]

Hot metal, scrap, and iron ore are charged with the fluxes, such as burnt and dolomitic lime, into the furnace. Then, oxygen is injected at high flow rates from the oxygen lance. CO and CO<sub>2</sub> gases and iron oxide fumes (Fe<sub>2</sub>O<sub>3</sub>) exit from the mouth of the converter. Liquid steel and slag are the remaining products at the end of the process.

Produced energy during the blow process from the oxidation reactions is higher than required energy to raise the temperature of the hot metal from 1350 °C to aimed steel temperature (1680 °C). The excess energy in the form of heat is used to

melt the fluxes, scrap and to reduce iron ore to metal. Some of the heat is also lost by conduction, convection, and radiation to the surroundings [2].

Fluxes such as burnt and dolomitic lime are added to the furnace with the iron ore early in the blow. Also some flux materials with coolants or heaters is provided at later stages of the blowing process.

For production of steel at desired temperature and composition, it is important to specify amount, temperature and composition of each input materials such as hot metal, scrap, iron ore, fluxes and oxygen. The specific method for determining these amounts varies with each BOF shop, however, these computations are based on mass and energy balance calculations.

## **2.3 Process Reactions**

### **2.3.1 Refining Reactions in BOF Steelmaking**

Hot metal and scrap are charged into the converter and high purity oxygen is blown at high flow rates through a water cooled lance to react with the metal bath. Impurities such as carbon (C), silicon (Si), manganese (Mn) and phosphorus (P) dissolved in the metal bath are removed by oxidation during the production of liquid steel.

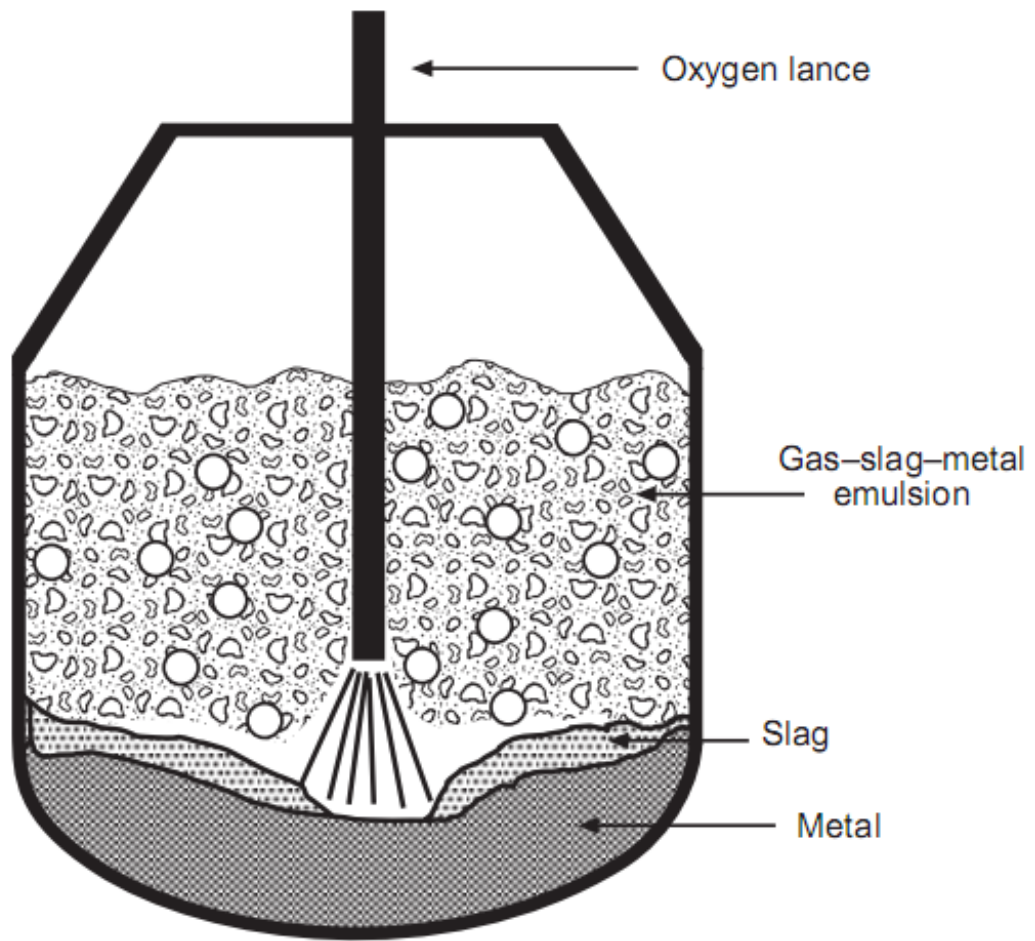
The oxygen blowing process lasts for about 16 to 25 minutes depending on the converter size and the oxidation reactions result in the formation of CO, CO<sub>2</sub>, SiO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub>, MnO, and iron oxides. Flux materials primarily lime (CaO) are added to the converter and the most of these oxides are dissolved to form a liquid slag which makes the removal of sulphur (S) and phosphorus (P) from the metal. The gaseous oxides, composed of about 90% CO and 10% CO<sub>2</sub>, exit the furnace carrying small amounts of iron oxide and lime dust.

Overall process is autogenous that is no external heat sources are required. Necessary energy is provided from the oxidation reactions to melt fluxes and scrap and attain aimed temperature at turndown.

Refining steel at high production rates are provided in the BOF process. The fast reaction rates are reached due to extremely large surface area available for reactions.

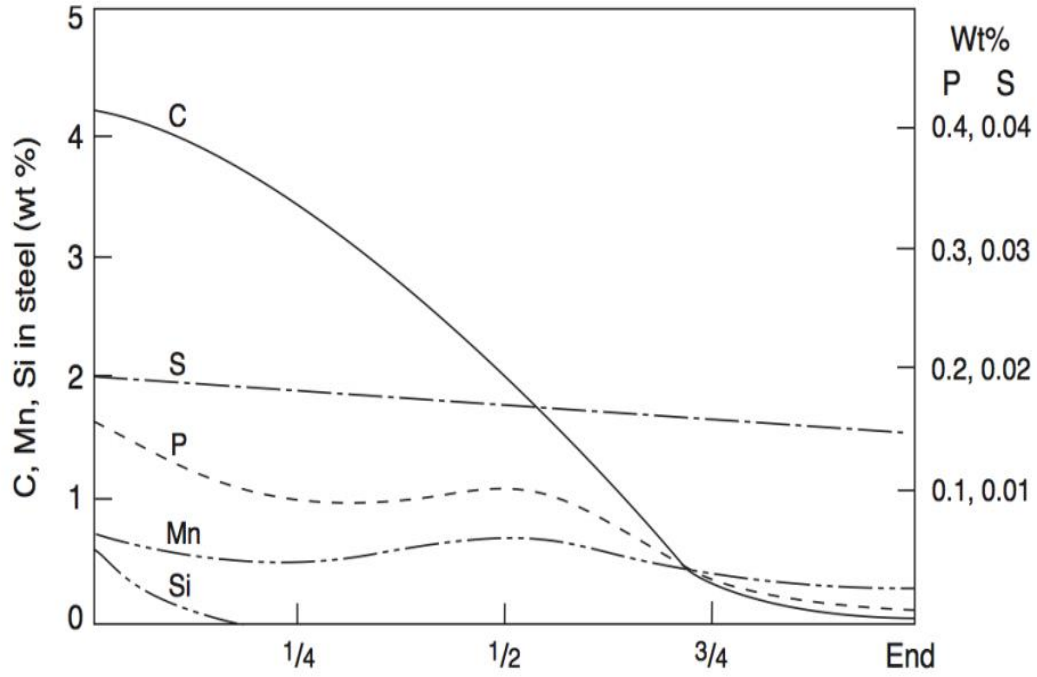
Carbon available in the bath reacts with high purity oxygen supplied from the oxygen lance and high amount of gas is evolved. With evolution of furnace gases and oxygen from the lance, an emulsion forms of liquid slag and tiny metal droplets. This gas-metal-slag emulsion provide the large surface area that increase the rates of refining reactions, shown in Figure 2.3 [2].





**Figure 2. 3** Physical state of the BOF in the middle of blowing [2]

The oxidation of impurity elements such as carbon, silicon, phosphorus and manganese starts when the required oxygen ignites the steel bath. Figure 2.4 is showing the changes in concentrations of the elements in BOF metal bath during oxygen blowing.



**Figure 2. 4** Metal composition change during BOF steelmaking [1]

### 2.3.1.1 Carbon Oxidation

The removal of carbon, decarburization, is the most important reaction during oxygen steelmaking. Carbon in the hot metal reacts with oxygen and forms CO and CO<sub>2</sub>. Oxidation of carbon takes place according to Equation 1.



For slag metal reaction, oxidation takes place according to Equation 2, and equilibrium constant is given Equation 3.

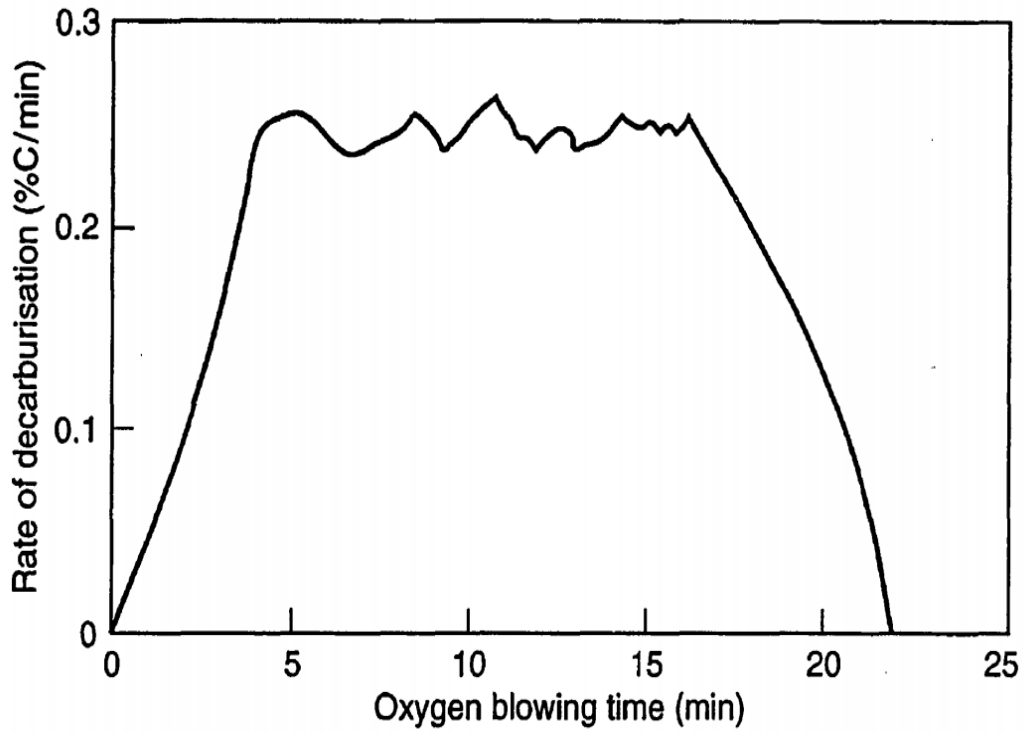


$$K_{FC} = \frac{p_{CO} (atm)}{[\%C] \times \alpha_{FeO}} \quad (3)$$

Carbon oxidation is most important refining reaction due to evolving a large amount of gases CO and CO<sub>2</sub> that causes agitation of metal and slag bath and distract hydrogen, nitrogen and part of non-metallic inclusions from the bath.

Slag, metal, and gas emulsion having an enormous contact surface interacts due to stirring from pressure of supplied oxygen. The oxidation of carbon is self-accelerated and attains a very high rate because of this enhanced contact.

Change in the carbon content during oxygen blown is given Figure 2.4 [1] which shows three distinct phases. In the early stages of blowing, most of the oxygen reacts with the silicon. The rate of the decarburization is slow at this stage as shown in Figure 2.5 [1]. At later stage, maximum rate of decarburization is controlled by the rate of supplied oxygen. Maximum rate of decarburization is in the range of 0.20 to 0.28 wt. %C. The last stage occurs with carbon contents of lower than 0.4 wt. % where decarburization rate gradually decreases. Increase in the consumption of oxygen by the oxidation of phosphorus, manganese, iron and an increasing amount of oxygen dissolution in the steel bath decrease carbon oxidation at this last stage [1].



**Figure 2. 5** Change in decarburization rate during BOF steelmaking [1]

### 2.3.1.2 Silicon Oxidation

The oxidation of almost all of the silicon occurs at the early stage of blowing due to the strong oxygen affinity of silicon. Oxidation of silicon takes place according to Equation 4 and the equilibrium constant  $K$  for this reaction is shown in Equation 5.



$$K_{\text{Si}} = \frac{\alpha_{\text{SiO}_2}}{[\% \text{Si}] \times [\% \text{O}]^2} \quad (5)$$

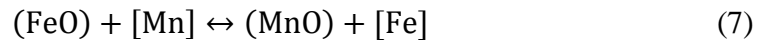
The temperature dependence of  $K_{\text{Si}}$  is shown in Equation 6.

$$\log K_{\text{Si}} = \frac{30,410}{T} - 11.59 \quad (6)$$

Silicon reacts with oxygen to form silica (SiO<sub>2</sub>). This reaction is highly exothermic and provides significant amount of heat which raises the temperature of the steel bath. It forms basic steelmaking slag with reacting with flux materials like lime and dolomitic lime. Amount of silicon determines how much scrap is used in the process due to being the major heat source of the process. Silicon content of hot metal is also important to determine how much flux materials are used in the process which affects the slag volume of the process.

### 2.3.1.3 Manganese Oxidation

At the early stage of blow, Mn is oxidized and forms MnO. Manganese reverts into the metal after silicon oxidation according the Equation 7. Equilibrium constant is given in Equation 8 depends on temperature and slag composition [1].

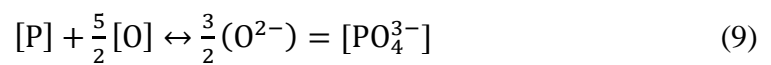


$$K'_{\text{FeMn}} = \frac{(\% \text{MnO})}{(\% \text{FeO}) \times [\% \text{Mn}]} \quad (8)$$

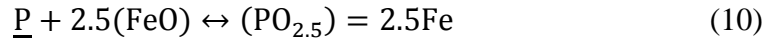
At the end of the blow, the manganese content of steel bath decreases as shown in Figure 2.4 since carbon removal becomes less intense.

### 2.3.1.4 Phosphorus Oxidation

Oxidation of phosphorus is favored by oxidizing condition in the BOF. The change in the phosphorus content of the bath is shown in Figure 2.4. At the beginning of the blow phosphorus content decreases according to Equation 9.



At the main decarburization period, phosphorus reverts into the metal when FeO is reduced and finally decreases at the end of the blow. Dephosphorization between liquid iron and slag takes places according to Equation 10.



Phosphorus reaction between the slag and the molten metal depends on the process condition. High slag basicity (CaO/SiO<sub>2</sub> ratio), high content of FeO in the slag, high slag fluidity, low temperature of slag and good stirring favor dephosphorization [2].

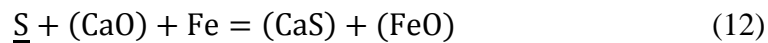
### 2.3.1.5 Sulphur Reaction

Sulphur removal is not very effective in the BOF process. Desulphurization is done before the charge of the hot metal into BOF.

At the beginning of the blow, when the metal is rich in carbon and silicon, the activity of sulphur is high. Part of the dissolved sulphur is directly oxidized into the gaseous phase according to Equation 11 due to turbulence and oxidizing conditions provided from the oxygen lance and low temperature of bath.



The rest of sulphur is removed according to Equation 12 due to interaction between the metal and the slag.

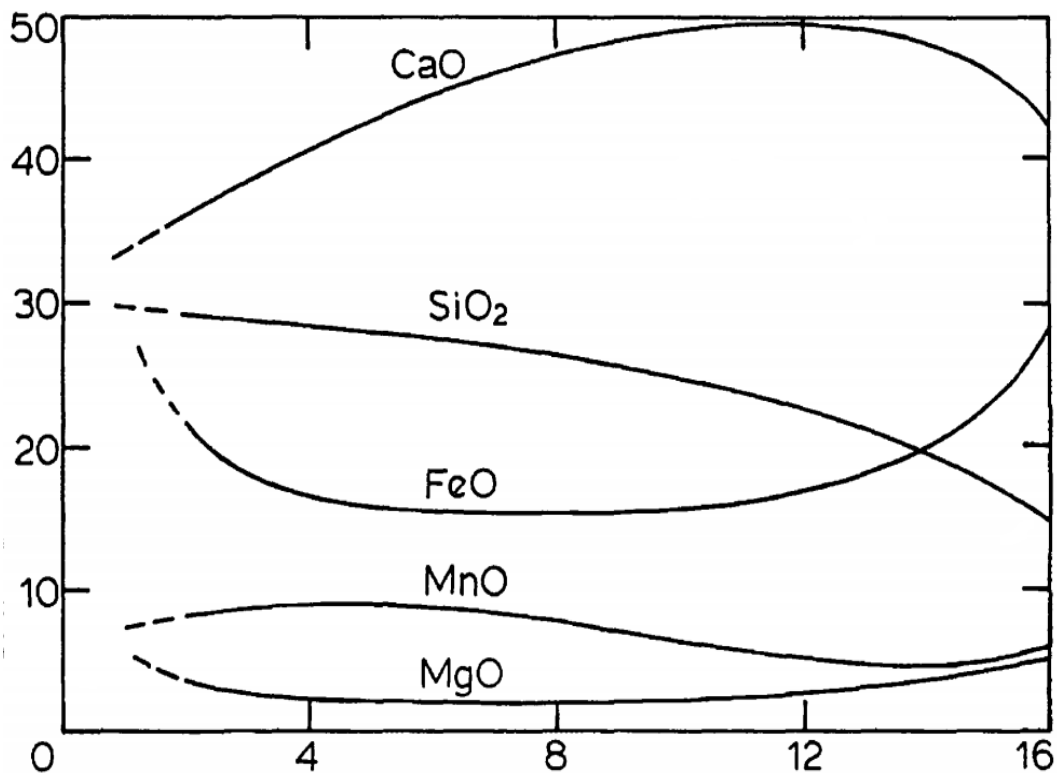


High slag basicity, improved bath mixing, high temperature and high fluidity of the slag favor desulphurization [2].

### 2.3.2 Slag Formation in BOF Steelmaking

The oxygen steelmaking process is essentially an oxidizing process of refining of the high carbon hot metal to low carbon liquid steel. Oxygen supplied to the molten metal bath causes liquid iron and other metallic and non-metallic impurities present in the bath of the converter to form oxides. These oxides are lighter than the liquid steel and they float to the surface of the bath. Slag is formed during refining of hot metal in converter while oxidation of Si to  $\text{SiO}_2$ , Mn to  $\text{MnO}$ , Fe to  $\text{FeO}$ , and P to  $\text{P}_2\text{O}_5$  etc. takes place, and by addition of fluxes. These fluxes are rich in  $\text{CaO}$  and  $\text{MgO}$  and the two most used are burnt lime and dolomitic lime. The dissolution of these fluxes results in highly basic slag. After the blowing period, the slag floats on top of the metal bath and the steel is poured into a ladle and the slag is removed from the converter.

At the beginning of the blow, oxygen lance is kept high above the surface of the metal. At the first stage of blowing process, silicon is oxidized together with iron forming a slag rich in  $\text{FeO}$  and  $\text{SiO}_2$ . Significant amounts of lime and dolomitic lime are added at the start of process. As the blow continues, solid lime continuously dissolves into the liquid slag increasing the slag mass and basicity. As decarburization continues, the slag starts to become foamy and the  $\text{CO}$  gas generated reduces the  $\text{FeO}$  content in the slag. Change in slag composition during blow is shown in Figure 2.6. Close to the end of the blow, the decarburization rate decreases and iron oxidation becomes significant again.



**Figure 2. 6** Change in slag composition during BOF steelmaking [1]

## 2.4 Bottom Stirring

There are several types of converters used in the oxygen steelmaking process. BOF is the overwhelmingly popular process where all of the oxygen is introduced via water-cooled lance from top of the converter. New design and modification is carried out by the companies to develop process condition. The reason of this is to lower the operating cost and to improve end.

In BOF process, movement in the bath is generated essentially by the oxygen jet impacting over the bath of the converter assisted by the formation of CO. In the initial stage of blowing, CO formation is weak due to the oxidation of silicon. During the main decarburization stage, enormous formation of CO sustains the process. However there are dead zones where variation in concentration occurs in



the boundary area of converter due to the lack of proper mixing in the metal bath. At the end of final decarburization stage, formation of CO is too weak to generate adequate motion in the heat.

Bottom stirring is provided to improve mixing in the bath. In the bottom stirring process, inert gases such as nitrogen and argon or gases such as CO and CO<sub>2</sub> are used to mix the molten metal in the BOF. The gases are introduced via permeable elements located at bottom of the converter. The amount of gases injected from the bottom elements varies according to process phase. During the removal of silicon and decarburization phases, the flow is kept unobstructed by the stirring elements sufficient to ensure homogeneous composition and temperature in the heat. During the final blowing stage, that is low rate of decarburization, the flow of stirring gases is increased to ensure transportation of carbon to the reaction zone. Moreover, bottom stirring assists the slagging reactions of silicon, manganese, phosphorus and iron in approaching equilibrium due to improved surface area between the metal and slag. As the result of this, dissolution of fluxes is accelerated by bottom stirring.

#### **2.4.1 Selection of Stirring Gases**

Argon, nitrogen, carbon dioxide, and carbon monoxide are used in steelmaking industry as stirring gases. There are limited companies using CO and CO<sub>2</sub> as stirring gases [34].

Argon is completely inert to molten steel. It provides stirring and a protective atmosphere with no potential for undesired reactions and no measurable solubility. Its only effect on steel chemistry is to remove dissolved hydrogen, oxygen, and nitrogen from the bath. Nitrogen has solubility in steel that increases with temperature. The presence of elements such as aluminum, titanium, vanadium, etc. further increases nitrogen solubility.

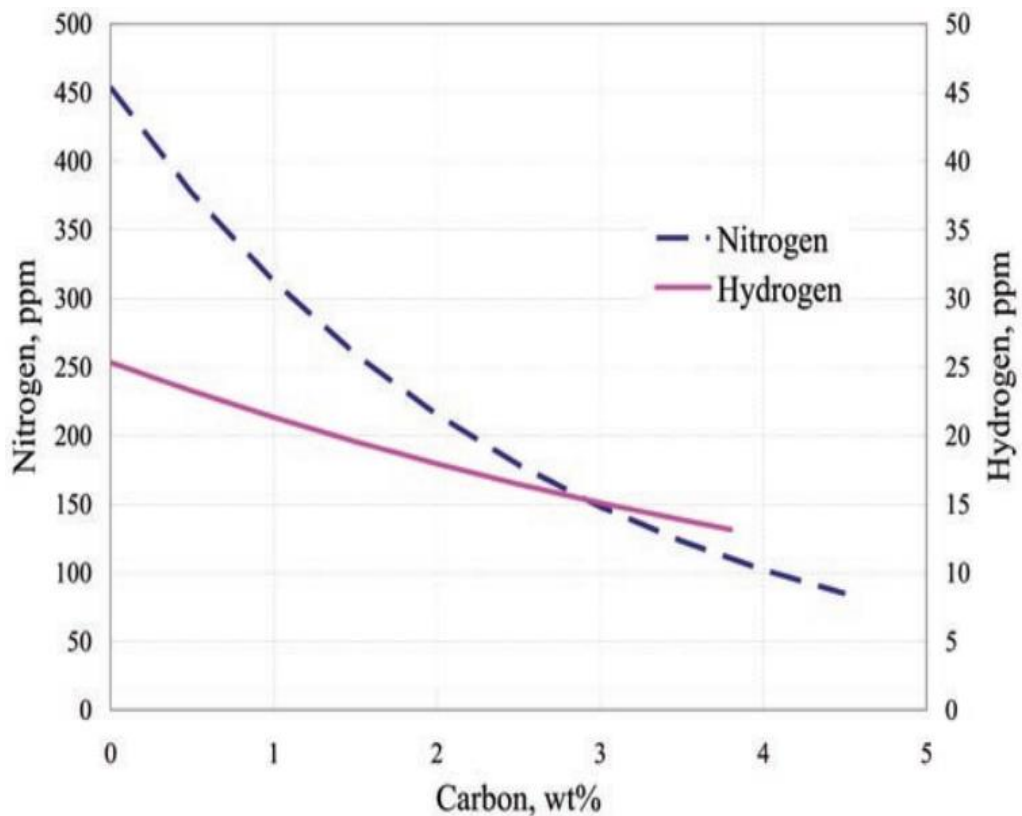
Argon and nitrogen is used extensively as stirring gases. Although nitrogen is cheaper than argon, due to the nitrogen pickup in the steel, nitrogen is not used in

the whole stirring process. The amount of gases injected from the bottom elements varies according to process phase. Generally, nitrogen is used as stirring gases in the first 60 to 80% of the oxygen blow, and switching to argon gas in the last 40 to 20% of the blow. At the decarburization phase the rapid evolution of CO in the first part of the oxygen blow prevents nitrogen pickup in the steel. Switch point from nitrogen to argon varies according to company's application and grade that is produced in the BOF [1, 2].

#### **2.4.2 Nitrogen and Hydrogen Control**

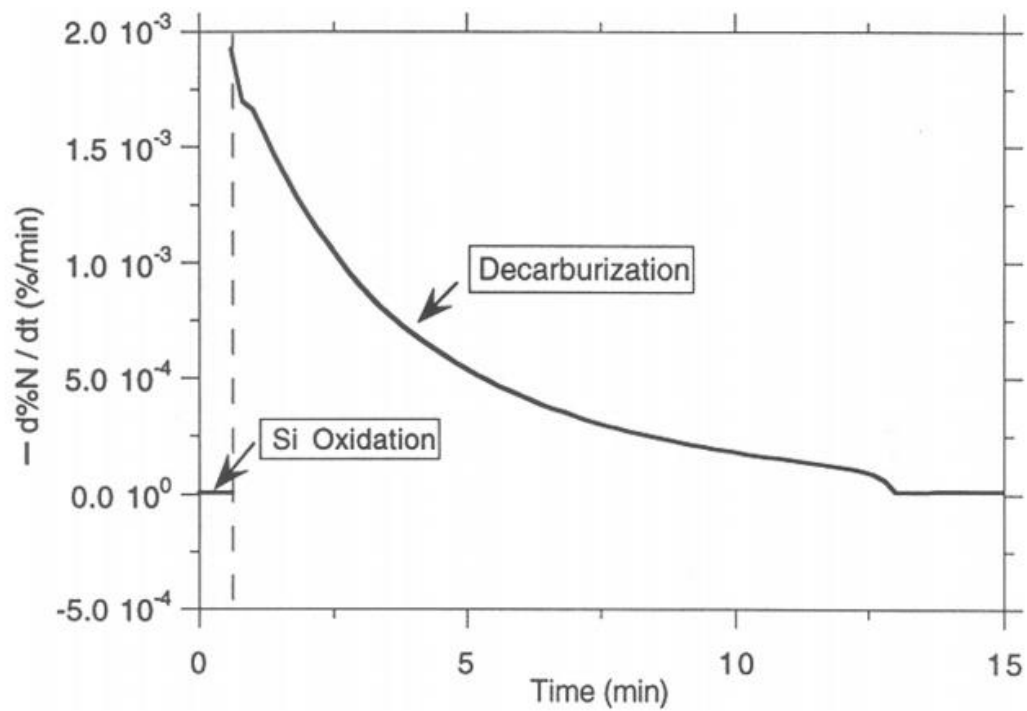
Nitrogen and hydrogen have solubility in steel when dissolved in liquid steel and affect its properties. Both of these gases can enter into the steel by addition to converter, blown oxygen, argon or nitrogen or reaction of liquid metal with the atmospheric elements. Hydrogen pick up is typically from the absorbed moisture coming from the raw materials used in the process. Moreover, water leakage over the lance or hood of the converter can cause hydrogen pick up by the steel [7].

Solubility of nitrogen and hydrogen is given in Figure 2.7 that shows the solubility of them in steel increasing with decreasing carbon content.



**Figure 2. 7** Solubility of hydrogen and nitrogen in iron-carbon alloys (1550 C° and 1 atm) [7]

At the initial stages of oxygen flow, minimal carbon removal present due the silicon oxidation. As the silicon level decreases, rate of decarburization increases until the last stage of blowing. At low carbon levels, rate of decarburization decreases. Removal of hydrogen and nitrogen in the metal bath through the CO bubbles occurs as a result of carbon oxidation which is the primary mechanism for their removal. Rate of nitrogen removal during oxygen blow is given in Figure 2.8. At the initial stage of blowing, due to the limited formation of CO, rate of nitrogen removal is almost zero. Formation of CO during carbon oxidation flushes the nitrogen out of the metal bath and also create protective atmosphere with the slag layer over the melt that reduces nitrogen pickup from air.



**Figure 2. 8** Rate of nitrogen removal during BOF steelmaking [7]

Hydrogen removal is similar to nitrogen removal during the course of the oxygen blow. Nitrogen and hydrogen pickup can take place during the last stages of the blow due to pick up from impurities in oxygen or other gases [7].

## **CHAPTER 3**

### **EXPERIMENTAL WORKS**

#### **3.1 Steel Production at ERDEMİR Steel Plant**

Steel production process at ERDEMİR is starting from the production of pig iron at iron making department. There are two blast furnaces, sinter and coke plant within ironmaking plant of which the responsibility is preparing about 3 million tons pig iron needed for the production of crude steel. After the transportation of pig iron to steelmaking department, desulphurization of hot metal in two stations and skimming of blast furnace slag is performed. There are two hot metal pouring pits, two skimming stations, three LD-type Basic oxygen furnaces (BOF) and scrap preparation yard for production of steel.

Following the production, molten steel is transferred to secondary metallurgy department for ladle refining and vacuum degassing. There are two ladle furnaces and one RH station which is primarily applied to produce ultra-low carbon steel. Ultra-low carbon, ultra-low nitrogen and hydrogen contents, as well as a high degree of steel cleanliness are achieved through the application of vacuum degassing. Before casting, all metallurgical requirements have to be accomplished in secondary metallurgy. The secondary metallurgy works as a multi-tasking unit which includes a wide range of treatments: deoxidation, deep decarburization, deep desulphurization, dehydrogenation, denitrogenation, alloying, heating, homogenization, inclusion modification, control of steel cleanliness, and temperature setting for casting.

After the final chemical composition is achieved and the desired input temperature for caster is attained for crude steel production, molten steel is transferred to continuous casting department. There are four casters with a production capacity of 4 million tons of slab.

## **3.2 Steel Production Process with BOF**

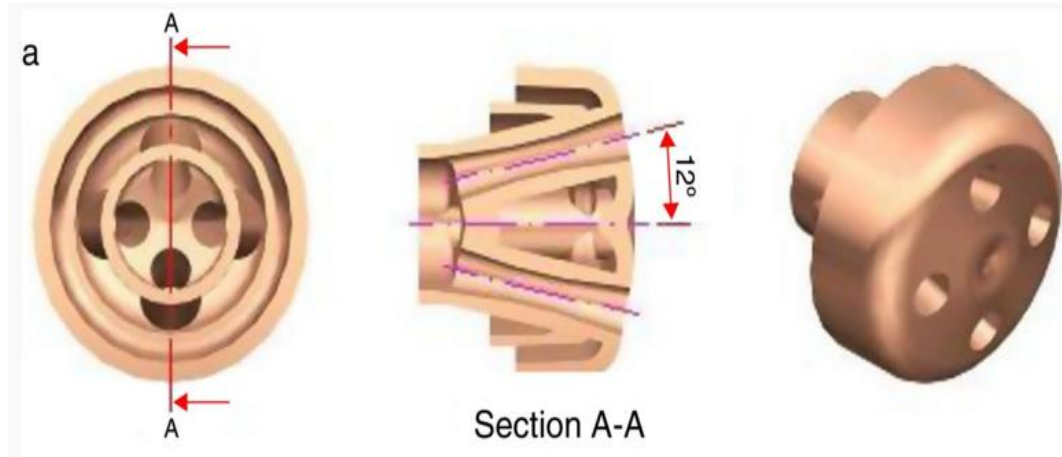
### **3.2.1 BOF General Information**

Erdemir has three identical converters with a capacity of 120 tons of steel. Modernization of converters that are named as BOF1, BOF2 and BOF3 was undertaken at 1991, 1992 and 1993, respectively under capacity increment program. Although annual design capacity is designed to reach 2.8 million tons of liquid steel, 3.8 million tons were produced as maximum and 3.4 million tons were produced as average of last 4 years.

Converter wall is covered with carbon saturated CaO refractory lining with varying chemical compositions for different zone of the converter. These areas are charge side, tap side, trunnion area and bottom of the converter. Two different types of lining are used as working lining and safety lining and these linings are renewed under campaign maintenance at every approximately 6500-7500 heats. The renewal of lining is carried out according to production program, life and condition of lining. The life of lining is increased with the slag splashing application, gunning material and shut-crete material application.

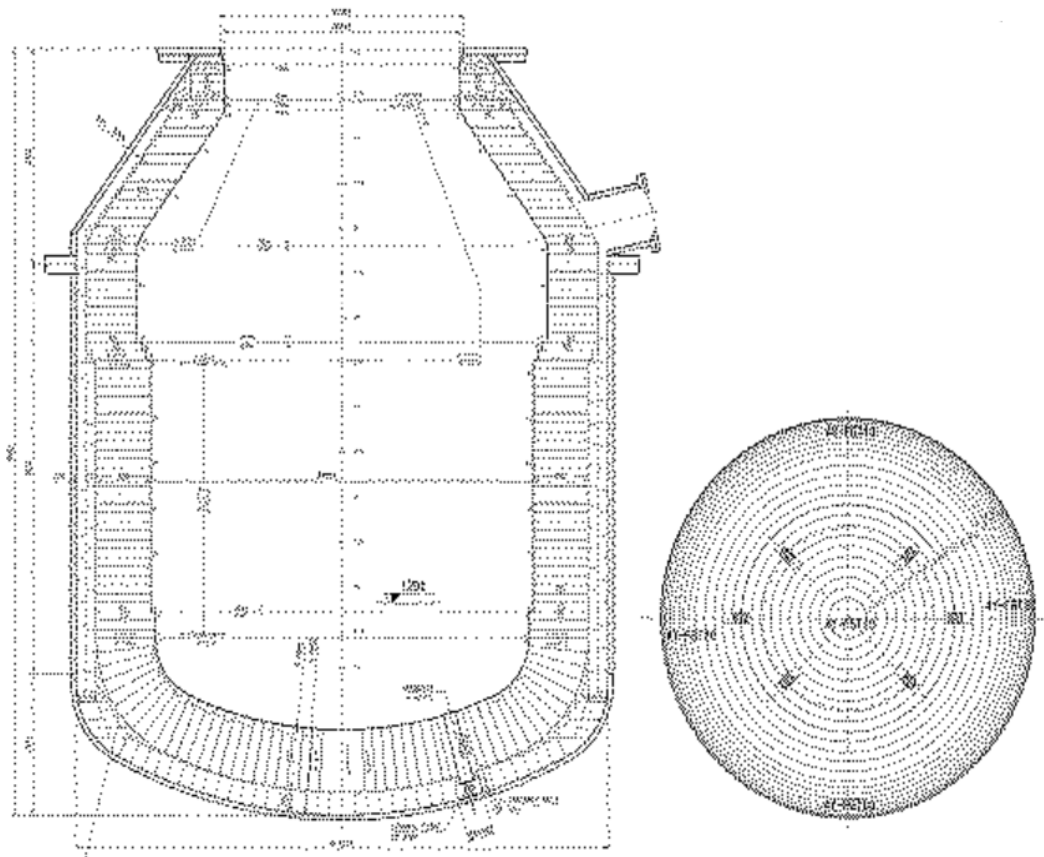
Combined blowing is provided from the LD-type converter where a purity of 99.9% oxygen is delivered from the top of the converter by water cooled oxygen lance. One of the critical design parameters is the tip of the lance chosen according to the design of converter such as bath level and working regimes like total blowing time. In general, 12 degrees inclined five-holed-lance is used for oxygen blowing.

Although the oxygen flow is provided with different programs, the common practice is with tip flow rate of  $420 \text{ Nm}^3$ .



**Figure 3. 1** Oxygen lance tip design [9]

Bottom stirring is provided from the bottom of the converter by argon and nitrogen from the six identical nozzles. Multijet type stirring nozzles with 32 holes is used for stirring of which the life varies between 2500-3500 heats.



**Figure 3. 2** Design of converter and location of bottom stirring nozzles

### 3.2.2 BOF Process

Pig iron produced at blast furnace is transferred by torpedo to desulphurization station firstly. After desulphurization process depending of the sulphur content of pig iron and target sulphur content of new heat pig iron is transferred to hot metal pouring pit. At this station hot metal at desired weight and sulphur content according to heat request is transferred from torpedo to hot metal ladle. Triggering mechanism is creating the new heat at requested grade depending the availability of secondary metallurgy station and continues caster. Grade selection will be produced at any converter is done to catch availability of the continuous caster.



Steel production with BOF is carried out according to process objectives such as target steel weight, target grade composition in terms of carbon, manganese, silicon, and phosphorus and target temperature. In order to obtain desired end product, flux material such as coolants and heaters are used within allowable limits.

Process tracking and calculations is carried out by automation system named as Level2 system. Moreover, burnt lime and dolomitic lime are used as slag builder at BOF of which the amounts are calculated according to aimed basicity of 3.5. In case of any deviation from the calculations during production, coolants like iron ore, dolomite, and pellets, and heaters like ferrosilicon, and coke are used. The flux materials and burnt lime are delivered into BOF from a hopper located over the converter. In order to illustrate the automation procedure, the composition, the amounts and temperature of input materials to produce 120 tons of liquid steel are given in Table 3.1.

**Table 3. 1** Analysis of heat

|                |          |
|----------------|----------|
| GRADE          | 7***K    |
| Basicity Aim   | 3,5      |
| Blowing Time   | 14.8 min |
| Blowing Oxygen | 5400 m3  |

| Input Materials |          |           |        |          |            |           |                |
|-----------------|----------|-----------|--------|----------|------------|-----------|----------------|
| Target Steel W. | Steel W. | Hot Metal | Scrap  | Iron Ore | Burnt Lime | Dol. Lime | Deox. Aliminum |
| 120 ton         | 122 ton  | 107 ton   | 25 ton | 661 kg   | 5450 kg    | 769 kg    | 227 kg         |

| ANALYSIS  |      |        |         |           |           |       |       |       |       |       |       |       |       |       |
|-----------|------|--------|---------|-----------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|           | Temp | O(ppm) | N (PPM) | C         | Mn        | P     | S     | Si    | Cr    | Ti    | Cu    | V     | Ni    | Mo    |
| Hot Metal | 1375 |        | 22      | 4,085     | 0,238     | 0,090 | 0,009 | 0,534 | 0,029 | 0,027 | 0,015 | 0,070 | 0,041 | 0,002 |
| InBlow    | 1603 |        | 25      | 0,444     | 0,209     | 0,017 | 0,009 | 0,003 | 0,029 | 0,001 | 0,027 | 0,008 | 0,043 | 0,002 |
| EndBlow   | 1678 | 747    | 38      | 0,039     | 0,092     | 0,008 | 0,009 | 0,004 | 0,018 | 0,001 | 0,028 | 0,001 | 0,043 | 0,002 |
| Target    | 1675 |        | 60      | 0,02-0,05 | 0,15-0,25 | 0,018 | 0,012 | 0,030 | 0,080 | 0,010 | 0,120 | 0,008 | 0,080 | 0,015 |

After charging the scrap and the hot metal into BOF, oxygen blow is started. Process step and approximate time is given in Table 3.2. After the start of ignition, flux material is provided from the hopper. Total process time is generally about 15 minutes depending on the grade. During oxygen blowing, inblow measurement is carried out from sublance located near the oxygen lance. At 81% of blowing, sublance dives into the converter to collect instantaneous temperature data and to take a sample from molten metal. A Temperature-Sample-Carbon (TSC) type probe is often used for the inblow measurement. The inblow measurement leads to a correction of the blow model in order to achieve the target temperature and the carbon content at the end of the blow. This sample is called spoon sample and sent to laboratory for detailed chemical analyses.

At the end of blowing, sublance dives into BOF for the second time and this measurement is called as end of blow (EOB) analysis. This end point measurement is carried out with a Temperature-Sample-Oxygen (TSO) type probe. This probe measures the steel temperature and the active oxygen of the steel, and also provides a laboratory sample for checking the final composition of the steel. Furthermore, a pre-calculation of the required amount of deoxidant (aluminum) during tap, can be given. Combined with the analysis of the in-blow sample, the temperature measurement and the oxygen/carbon measurement may lead to a decision to quick tap the heat. The in-blow carbon prediction is based on the measurement of the liquidus temperature of the steel. Liquidus temperature is defined by the amount of carbon in steel, however, other elements present in the steel can depress the liquidus temperature.

The time between the TSC sample point and the end of the process is known as the end-blow period. The end-blow model is designed to calculate corrections of oxygen and coolant requirements in order to achieve the desired end-point carbon and end-point temperature in the steel. By the help of the temperature and the carbon level, deviation is calculated by Level2 system and flux materials are provided if required.

At the end of blowing slag floats at top of the converter. Steel inside the BOF is poured into the steel ladle from taphole of the converter. Taphole is covered with special refractory material which is changed after approximately 90 heats. Tapping lasts between 4 to 9 minutes depending on life of taphole refractory. Ideal and approximate tapping time is about 5 minutes. During tapping period, calculations on the amounts of alloying materials are carried out and they are provided into the steel ladle. These alloying materials, e.g. ferrosilicon, ferromanganese, ferrochromium etc., are selected according to difference between aim analysis and EOB analysis. Moreover, ingot aluminum is used as deoxidant and delivered during tapping. By EOB analysis, oxygen dissolved in the steel is measured in terms of ppm from which the deoxidant requirement is calculated and aluminum is provided in to steel as deoxidant.

Another analysis is conducted from the slag sample formed during steelmaking process. Before tapping, slag sample is taken by the help of hand rod from the charge side of the converter. Slag sampling is not done as usual but it is done for special heats or tracking material usage. Sample is sent to laboratory and analysis generally takes two days.

### **3.2.3 BOF Blowing Process and Regimes**

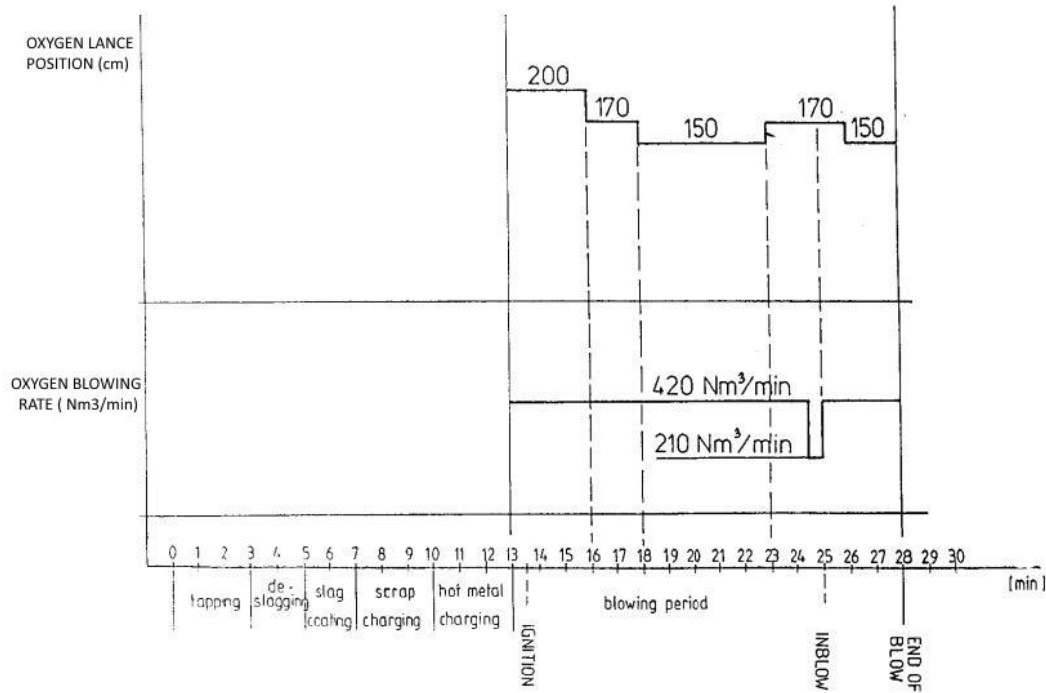
The general steelmaking process in terms of a time graph without any delay of the BOF process is given in Table 3.2.

**Table 3. 2** BOF process time distribution without any delay

| STATUS             |              | TIME (min) |
|--------------------|--------------|------------|
| BOF Empty          |              | 0          |
| Scrap Charging     |              | 3          |
| Hot Metal Charging |              | 5          |
| Standby Full       |              | 5,5        |
| Blowing Period     | Ignition     | 6          |
|                    | Inblow       | 18         |
|                    | End of Blow  | 21         |
|                    | Poststirring | 22         |
|                    | Reblow       | 24         |
| Tapping            | Start        | 25         |
|                    | End          | 31         |
| Standby Empty      |              | 32         |
| Deslagging         |              | 34         |
| Slag Splashing     |              | 36         |

After the ignition, the required oxygen to precede the process is provided according to input and output materials depending on grade by Level2 system. During blow, this amount is recalculated by the help of inblow (TSC) and end of blow (TSO) analysis in case of any deviation from the grade.

The top lance basically supplies oxygen, and by changing the lance height (the distance between the lance tip and the top of the bath), the distribution of oxygen between the metal and slag phases can be altered. Oxygen is not provided as fixed flow but instead a changing flow with an attainable maximum rate of 420 Nm<sup>3</sup> depending on the tip design. Different blowing programs including differentiating oxygen flow and lance height are defined in Level2 system. This program is selected before starting the process according to grade definition. The mostly used blowing program is given in Figure 3.3



**Figure 3. 3** The oxygen blowing program including flow rate and lance height

The characteristics of blowing are described as soft or hard blow practices. In hard blow, a greater penetration of the oxygen jet into the steel bath is provided by bringing the lance closer to the steel bath which cause more intensive iron bath mixing. Soft blow, on the other hand, provides less oxygen penetration in the metal bath. Mass transfer is slow due to weak mixing in soft blow. While soft blow provides rapid slag formation and a foamy slag, better condition for phosphorus removal, increasing oxidation rate of manganese, titanium, and vanadium etc., hard blow provides better decarburization efficiency [31].

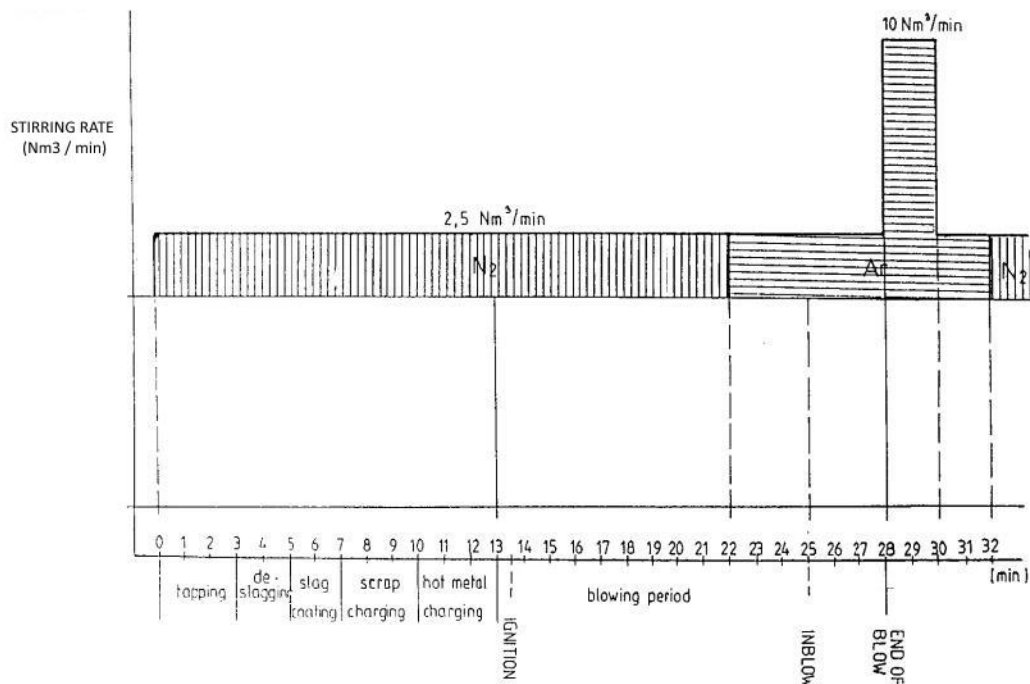
### 3.2.4 BOF Stirring Process and Regimes

Stirring is provided from the six identical types of nozzles during and after the blow. Argon or nitrogen is selected as stirring gas at different regimes of blowing.

This percentage, type and flow of stirring gas are defined in different programs and can be selected before starting the process.

Stirring phase can be divided into five separate steps depending on the amount of oxygen blow. For each single step, the gas flow rate in addition to gas type can be selected and presented in the program.

In Figure 3.5, different programs for stirring are shown. Up to now, different programs have been used along which the mostly used one is program 2. By this program, up to the 40% of blowing, nitrogen is used as stirring agent due to being cheaper than argon. Because of the high CO formation at the beginning of process, nitrogen pickup of steel is limited to some extent. Near to the end of blowing, higher flow of stirring gas is selected to obtain better carbon removal.



**Figure 3. 4** Bottom stirring program including rate, gas type

There are currently seven different stirring programs available which are manually selected by the process responsible according to metallurgical heat preconditions and the specifications of the steel grade to be produced. Type and flow rate of stirring gases defined in the programs is illustrated in Figure 3.5.



|           | BOF EMPTY<br>KONV. BOS<br>NL/MIN | CHARGING<br>SARJ<br>NL/MIN | STANDBY<br>KONV.<br>DOLU<br>NL/MIN | BLOW 1<br>UFL. 1<br>NL/MIN | BLOW 2<br>UFL. 2<br>NL/MIN | BLOW 3<br>UFL. 3<br>NL/MIN | BLOW 4<br>UFL. 4<br>NL/MIN | BLOW 5<br>UFL. 5<br>NL/MIN | POST ST.<br>UFL. SONU<br>(1 dakika)<br>NL/MIN | STANDBY<br>KONV.<br>DOLU<br>NL/MIN | RE-BLOW<br>TEKRAR<br>UFL.<br>NL/MIN | TAPPING<br>DÖKÜM<br>NL/MIN | CURUFLAMA<br>NL/MIN | CURU<br>BOSALT<br>NL/MIN |
|-----------|----------------------------------|----------------------------|------------------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---|------------------------------------|-------------------------------------|----------------------------|---------------------|--------------------------|
| PROGR. 1  | 120                              | 200                        | 200                                | 200                        | 200                        | 300                        | 300                        | 300                        | 1000  | 200                                | 200                                 | 200                        | 500                 | 200                      |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |
| PROGR. 2  |                                  |                            |                                    | 200                        | 200                        | 200                        | 400                        | 400                        | 600   |                                    | 800                                 |                            | 600                 |                          |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |
| PROGR. 3  |                                  |                            |                                    | 200                        | 200                        | 600                        | 600                        | 600                        | 1000  |                                    | 200                                 |                            | 1200                |                          |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |
| PROGR. 4  |                                  |                            |                                    | 200                        | 200                        | 200                        | 200                        | 800                        | 1000  |                                    | 200                                 |                            | 1200                |                          |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | AZOT                       | AZOT                       | AZOT                       | AZOT                       | AZOT  | AZOT                               | AZOT                                | AZOT                       | AZOT                | AZOT                     |
| PROGR. 5  |                                  |                            |                                    | 200                        | 200                        | 800                        | 800                        | 800                        | 1000  |                                    | 200                                 |                            | 1200                |                          |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |
| PROGR. 6  |                                  |                            |                                    | 200                        | 200                        | 800                        | 800                        | 800                        | 1000  |                                    | 200                                 |                            | 1200                |                          |
|           | AZOT                             | AZOT                       | AZOT                               | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |
| PROGR. 10 |                                  |                            |                                    | 300                        | 300                        | 1000                       | 1000                       | 1000                       | 1200  |                                    | 300                                 |                            | 1200                |                          |
|           | AZOT                             | AZOT                       | AZOT                               | AZOT                       | ARGON                      | ARGON                      | ARGON                      | ARGON                      | ARGON   | ARGON                              | ARGON                               | ARGON                      | AZOT                | AZOT                     |

Figure 3. 5 Bottom stirring programs (Azot: Nitrogen / Argon: Argon)

The flow rate and the gas type for each single line can be either manually altered or automatically controlled using stirring programs. Each line's flow rate can be changed by a constant factor. This is useful for balancing the plug wear by decreasing or increasing the flow through each individual element. Pressure over the each plug, as well as the set and actual flow rate of each plug is shown in Figure 3.6.



**Figure 3. 6** Bottom stirring actual condition

### 3.3 Experimental Procedure

Several heats were chosen for this current work and, during the production of these heats, analyses and quantities of additives were noted. The bottom stirring process is not optional, therefore, the effects are tracked during the entire BOF steelmaking process for the whole converter life. In addition to individual analyses, different

heats from all of the three BOFs with same blowing and stirring patterns were compared for 20,000 heats.

Another study was conducted to show the effects of fully argon stirring and partial argon stirring. For this purpose, several heats are selected to demonstrate EOB difference in nitrogen contents. Moreover, the effect of stirring on nitrogen pickup is also presented based for the conditions where stirring is activated or deactivated.

Slag analyses were carried out in order to compare the effect of bottom stirring for same process conditions. By these analyses, iron oxide, metallic iron, total iron in the slag and basicity differences was compared.

One of the largest benefits of stirring is obtaining lower dissolved oxygen content in steel. Since aluminum is used as deoxidant, the amount of aluminum used in the heats where stirring is activated or not are collected and compared.

## **CHAPTER 4**

### **RESULTS AND DISCUSSION**

#### **4.1 Introduction**

Erdemir is the largest steel factory of Turkey, supplying a wide range of high quality steels not only to domestic market but also to international customers. The successful operation of the production line without any interruption, therefore, is very critical in order to satisfy this continuous and high volume of demand. An important development in steel plant for the improvement of production line was implemented 20 years ago when 6 bottom stirring nozzles were integrated to converter. Together with addition of nozzles, the capacity of the converter was increased up to 120 tons of liquid steel resulting in the annual built up capacity of 2.8 million tons which is further increased to current annual production capacity of about 4 million tons.

Although several research activities have been conducted which turned into improvements implemented on the production line, the effect of bottom stirring has not been studied in detail. The current study was carried out with the motivation to investigate the effects of bottom stirring on the amount of carbon, oxygen, sulphur, phosphorus and manganese contents in steel at the end of blow.

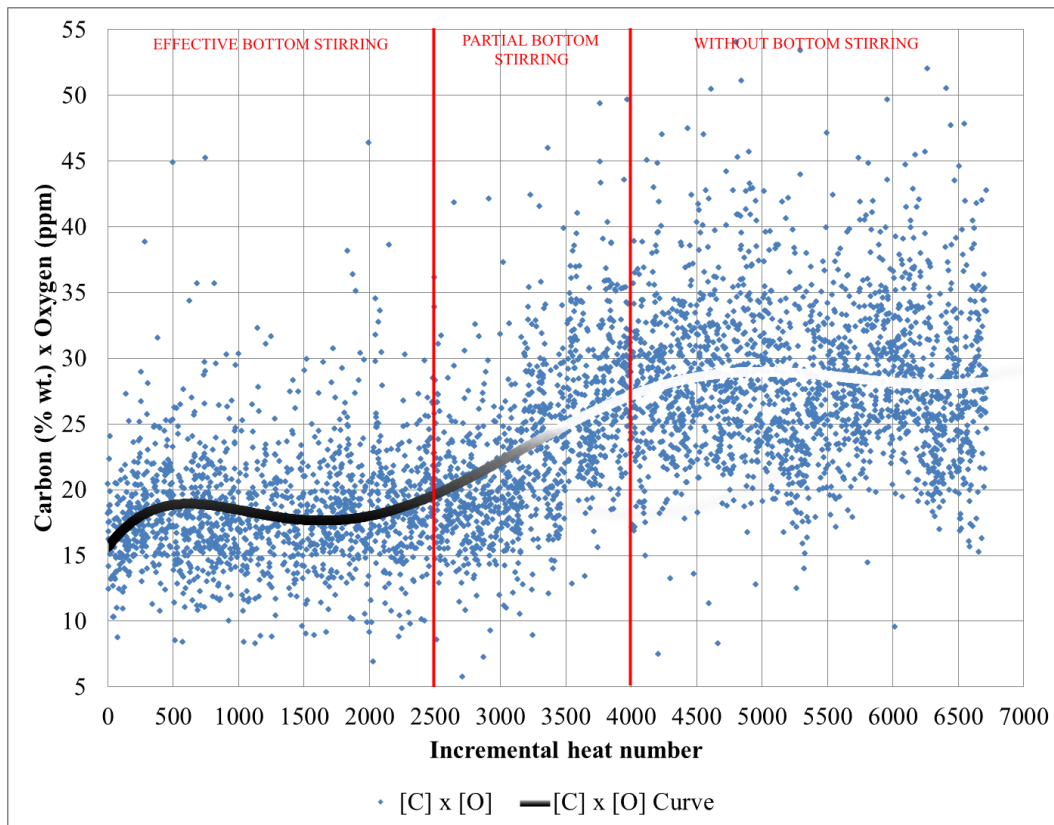
The average converter life at Erdemir is about 7500 heats. Bottom stirring is effectively used up to 2500 heats of the converter. Due to the bottom built up, slag blocks the stirring nozzles one by one, and, after the 4000 heats, the flow of stirring gases from the porous plug is completely shut down.

Bottom stirring is applied during oxygen blowing with different gases such as argon and nitrogen at different rates. The type, volume and flow characteristics of the stirring gas are controlled by the stirring program. Although nitrogen is cheaper than argon, nitrogen cannot be used during the entire process due to nitrogen pick-up takes place by the steel.

In this study, specifically, bottom stirring process is examined utilizing the turndown slag, metal composition and amount of material usage of numerous BOF heats from BOF1, BOF2 and BOF3, covering several years.

#### **4.2 The Analyses of Overall Production History of BOF**

A specific value is used in literature to measure the effectiveness of bottom stirring which is equal to the product of carbon content in weight percent and amount of dissolved oxygen in ppm. This value is calculated starting from the first heat of relined converter to the last heat to demonstrate the effectiveness of bottom stirring. The carbon and oxygen data collected from BOF2 that was used for 6700 heats and the corresponding heat numbers are shown in Figure 4.1.



**Figure 4. 1** Product of carbon and oxygen measurements over the whole life of the converter

The current findings have shown that the oxygen level at the end of blow is higher when bottom stirring is not effectively used which corresponds to the later heats of production history. Injection of inert gas (argon or nitrogen) lowers the partial pressure of CO, and hence, lowers the oxygen content in the bath. The energy coming from the blowing of stirring gas and the formation of the carbon monoxide starting from the bottom of the metal bath result in the intensive stirring of the liquid steel in the converter. Along with the effective stirring of molten metal, a low level of carbon is achieved. The attainable values of the C x O product were reported within the range of 15 to 20 provided the bottom stirring is effective while this value is higher than 25 when stirring is stopped [9,12,16,18].



In the current study, this product was found to be lower than 20 and averaged at 18 as shown in Figure 4.1 before 2500<sup>th</sup> heat. The 2500<sup>th</sup> heat of the converter is the onset of decay in the effectiveness of bottom stirring starting with the failure of the first bottom stirring plug. The stirring process was stopped at the 4000<sup>th</sup> heat due to complete blockage of all stirring plugs. After this heat, bottom stirring was regarded as deactivated. Starting from the 4000<sup>th</sup> heat, the C x O product is around 30. According to this preliminary results, the analyses carried out in the current study was divided into three regimes as effective bottom stirring (before 2500<sup>th</sup> heat), partial bottom stirring (2500-4000<sup>th</sup> heat), and without bottom stirring (after 4000<sup>th</sup> heat).

The oxygen, carbon and C x O product values were averaged for the first and the last regimes which are demonstrated in Table 4.1. According to these results, when stirring is active, the amount of oxygen and carbon at the end of blow are about 646 ppm and 0.029%, respectively. The C x O product, on the other hand, is 18. On the contrary, when stirring is deactivated, the amount of oxygen and carbon are about 818 ppm and 0.038%, respectively, while the C x O product is about 30. This decrease in oxygen content stems from the decrease in the partial pressure of CO which makes the CO formation easier in the metal bath. Moreover, with the bottom stirring activated, the diffusion in molten metal is enhanced resulting in an increase in C activity which decreases the C content in the liquid steel.

**Table 4. 1** C%, O (ppm) and [C] x [O] comparison

|                  | Average<br>Carbon ( % wt.) | Average<br>Oxygen (ppm) | Average<br>[C] x [O] |
|------------------|----------------------------|-------------------------|----------------------|
| With stirring    | 0.029                      | 646                     | 18                   |
| Without stirring | 0.038                      | 818                     | 30                   |

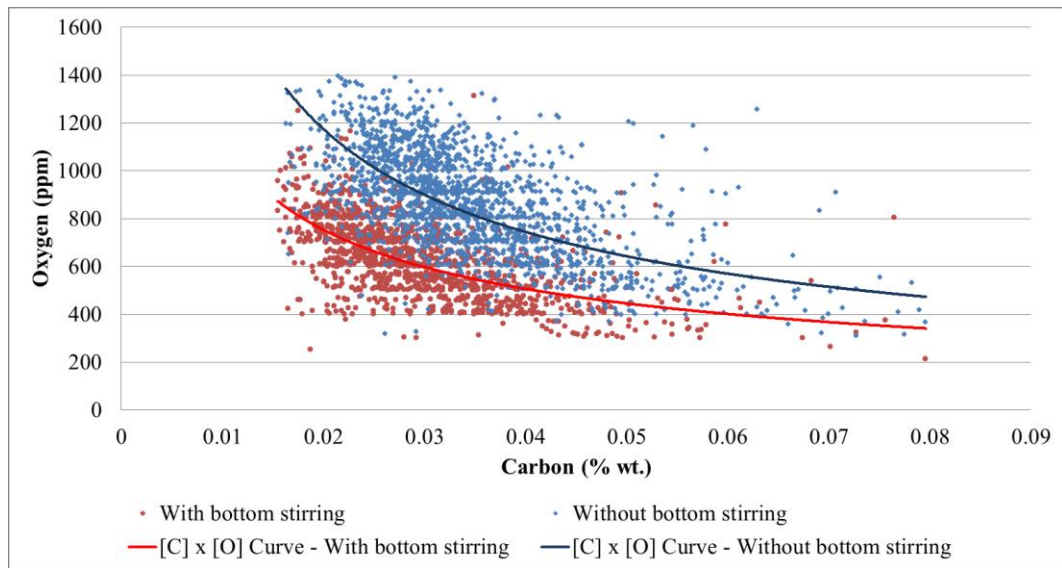
### **4.3 The Comparison of Specific Cases**

In addition to the overall analyses for BOF2, a comparative approach was utilized in order to observe the effect of bottom stirring on steel composition in a more detailed manner. In general, hot metal, scrap and flux material such as burnt lime, iron or dolomitic lime are used in steelmaking processes. The effect of the content of scrap is difficult to be eliminated. However, the content of hot metal and flux usage were systematically studied for the comparison of specific heats of steelmaking process. In addition to hot metal and flux, the process parameters such as blowing and stirring patterns are also effective in the composition of the end product. The analyses carried out where these factors were selectively utilized to demonstrate the results of oxygen and carbon contents at the end of blow. For this purpose, five cases were selected by setting the hot metal content and process parameters to be fixed for each case. Specifically, for each case, same blowing and stirring patterns and additives were utilized and the hot metal content was taken constant in terms of carbon, manganese, silicon and phosphorus.

#### **4.3.1 Carbon and Oxygen Comparison**

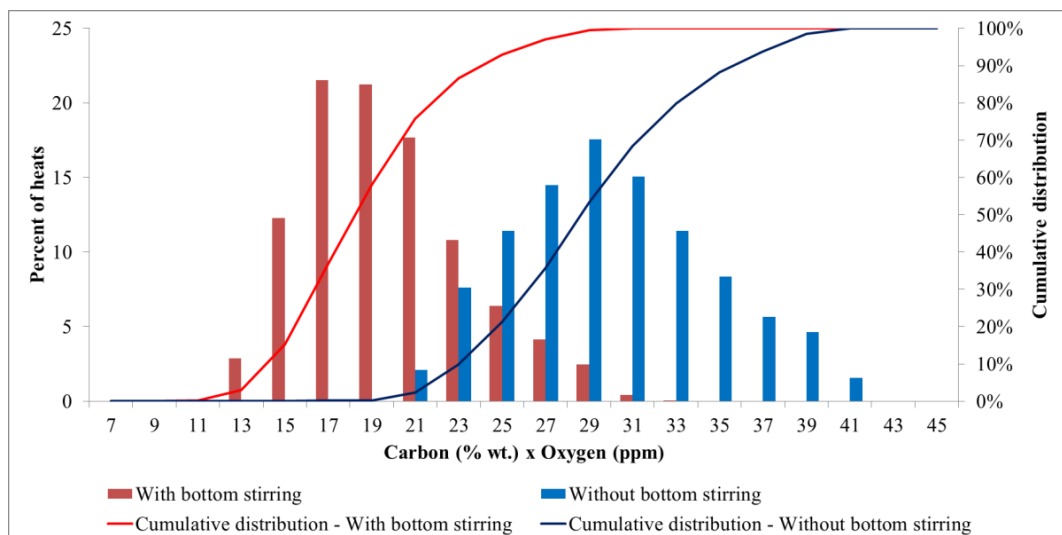
The data collected with fixed affecting parameters is plotted on Figure 4.2. The red curve in the figure refers to the regime where stirring is activated. The oxygen and carbon contents lying on this curve were found to be smaller than the ones on the blue curve which corresponds to the regime where bottom stirring is blocked. The average values for oxygen and carbon contents with bottom stirring applied were found to be 598 ppm and 0.028%, respectively. Without bottom stirring, on the other hand, these values were detected as 808 ppm and 0.038%, respectively. Although these results agree well with the former findings from overall analyses, the difference between the regimes of effective and deactivated stirring is pronounced.





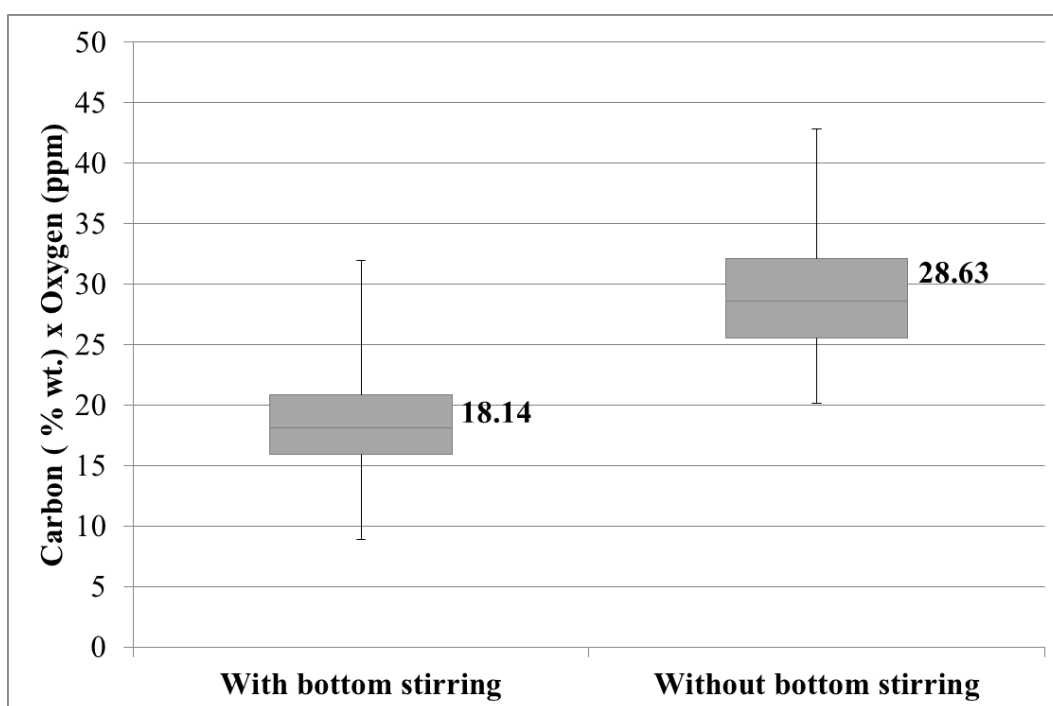
**Figure 4. 2** Carbon and oxygen distribution for stirring condition

Along with the individual contents of oxygen and carbon, the C x O product for this specific case is shown in Figure 4.3. The product was found to be in between 11 and 33 while it is densely distributed within the range of 15 and 25 where bottom stirring is activated. These ranges, however, is 21 to 41 and 23 to 35, respectively, for the case without bottom stirring.



**Figure 4. 3** Product of carbon and oxygen comparison

Product of carbon and oxygen distribution for with and without bottom stirring condition is plotted on Figure 4.4 with using boxplot distribution which shows median value as a line within the box, first and third quartiles of data as lower and upper level and whiskers as standard deviation. The average values of carbon and oxygen product for with and without bottom stirring condition are 18.14 and 28.63, respectively.

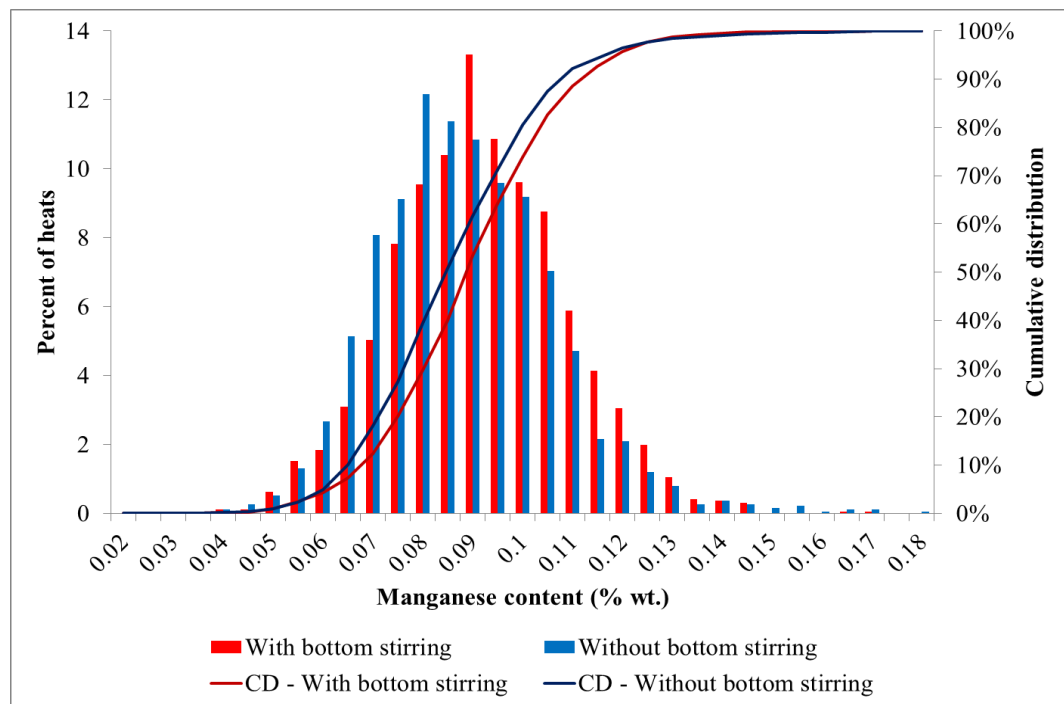


**Figure 4. 4** Boxplot of carbon and oxygen product for stirring condition

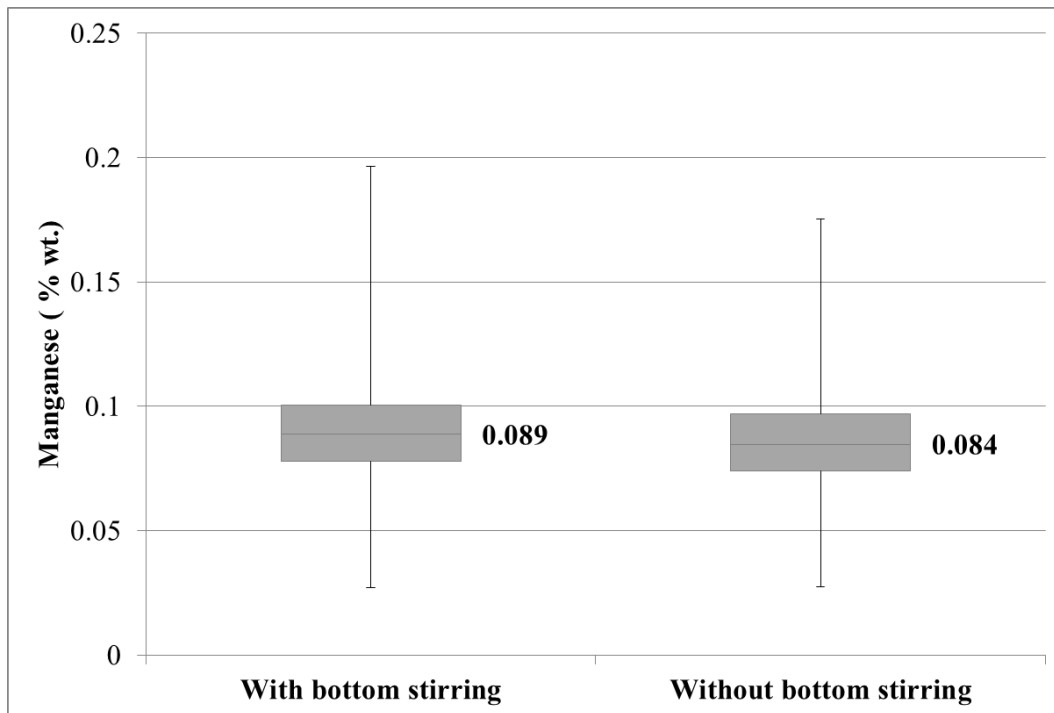
#### 4.3.2. Manganese Comparison

The steel with higher manganese content is more valuable due to improved mechanical performance. The manganese coming from the hot metal is oxidized during steelmaking starting from the early stages of blowing. Some of the oxidized manganese, then, reverts to the molten metal with proceeding blowing process. Then, close to the end of blowing, due to lowered carbon content in the metal bath,

manganese reacts with the dissolved oxygen and form manganese oxides. Together with the bottom stirring, excess oxygen dissolved reacts with carbon and hence, manganese oxidation is limited. This means that the end of blow manganese content should be higher for the steelmaking with bottom stirring than without bottom stirring. The distribution of manganese content at the end of blow for stirring condition is shown in Figure 4.5. The difference in manganese content with the addition bottom stirring is about 50 ppm as shown in Figure 4.6



**Figure 4. 5** Manganese comparison



**Figure 4. 6** Boxplot of manganese content for stirring condition

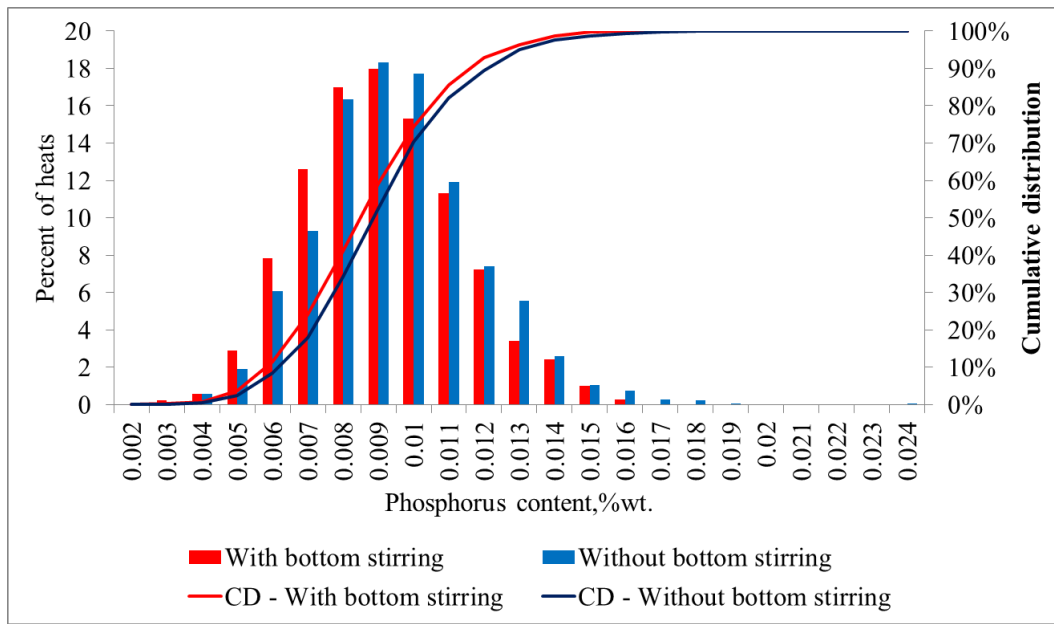
For the production of high end manganese grade steel with BOF, higher amount of ferromanganese addition which is about 10 kg/heat is needed in without bottom stirring condition. Considering an additional ferromanganese of 350 tons/year, the direct return of the bottom stirring can be calculated as about 500.000 \$/year.

Alloy addition to increase manganese content of steel is done by using high-carbon ferromanganese (7 %C) or medium-carbon ferromanganese (1,45 %C). Although, yield and manganese content are almost same for both alloys, high carbon ferromanganese usage is limited in low carbon steel grade due to its' high content of carbon. Due to the low end of carbon provided from the bottom stirring, up to 180 kg of high-carbon ferromanganese can be used instead of medium-carbon ferromanganese. Thus, 2000 tons/year high carbon ferromanganese can be used instead of low carbon ferromanganese. Price difference between high and medium ferromanganese is about 400 \$/ton and, 800.000 \$/year can be saved with the help of bottom stirring in BOF.

### 4.3.3 Phosphorus Comparison

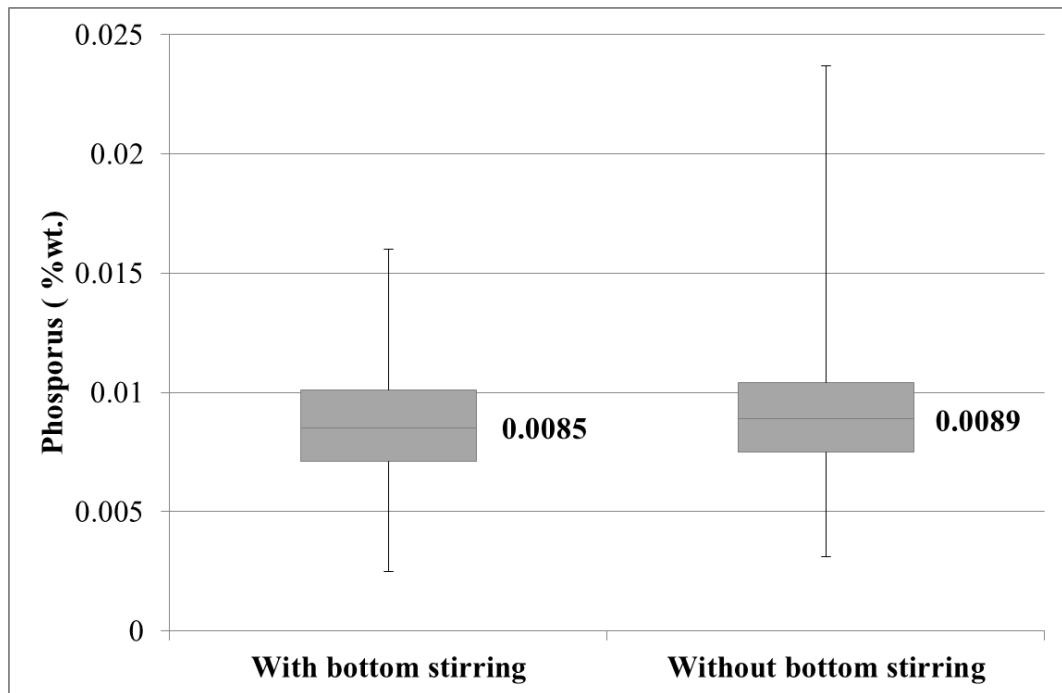
The low amount of phosphorus in steel is required for superior mechanical performance such as high ductility and better wear resistance. The elimination of phosphorus from molten metal during steelmaking is very complicated. Specifically, during the beginning of the blow where the oxygen lance is kept high, good ejection of droplets is achieved and phosphorus removal happens fast. After the first stage of blowing, decarburization phase starts where the large evolution of CO gas take place resulting in lower FeO content in the slag. At this phase, some of phosphorus returns to the molten metal. At the end of the blow, decarburization slows down and the FeO content in the slag increases favoring the dephosphorization again.

Bottom stirring decreases the oxygen dissolved in the bath at the later stage of blowing when compared to the process without bottom stirring. Therefore, FeO content in the slag is lowered and poorer phosphorus removal with bottom stirring condition is expected. However, the distribution of P content shows that, bottom stirring has an increasing effect on the amount of end of blow phosphorus as shown in Figure 4.7. The general decreasing effect of bottom stirring on the amount of phosphorus at the end of blow, on the other hand, can be explained with the enhanced metal-slag interaction provided by bottom stirring. This enhancement is due to better mixing in stirring condition, resulting in the evolution of CO gas at the later stages of blowing which causes good interaction between the metal and slag phases.



**Figure 4. 7 Phosphorus Comparison**

Boxplot of phosphorus content for stirring condition is shown in Figure 4.8. The difference in phosphorus content with the addition bottom stirring is about 5 ppm. Deviation from the upper level of boxplot as shown in Figure 4.8 for without stirring condition is higher. The current findings have shown that phosphorus level at the end of blow is a little bit higher and phosphorus distribution shows more deviation when bottom stirring is not effectively used.



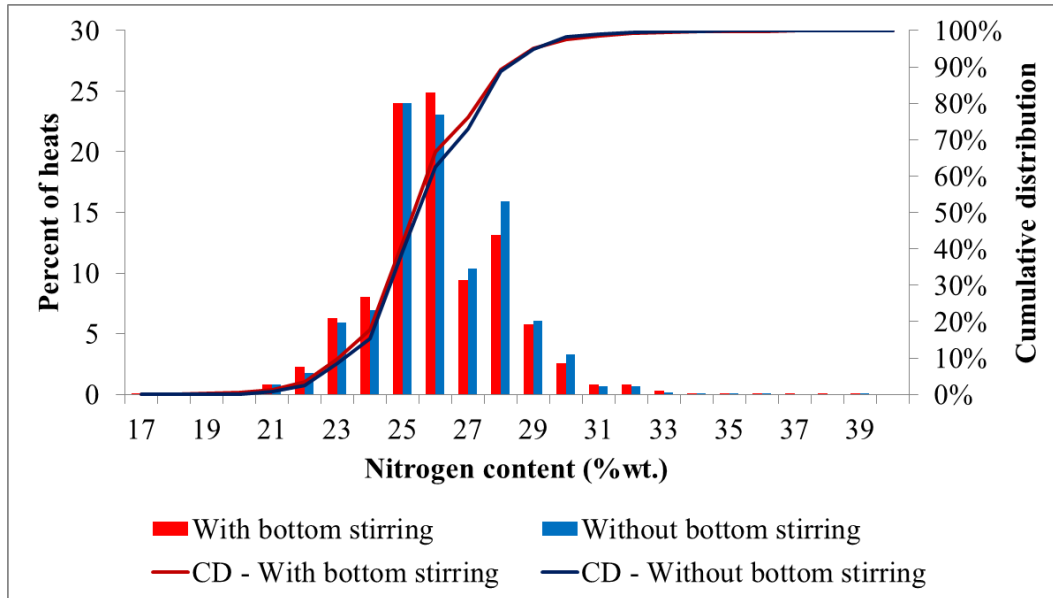
**Figure 4. 8** Boxplot of phosphorus content for stirring condition

#### 4.3.4 Nitrogen Comparison

Control of nitrogen content of steel is important because of low content requirements for steel with better mechanical properties. During gas blow, the CO generated in the molten metal helps the transport of nitrogen to the surface. The oxygen coming from the lance and the generated CO gas lowers the nitrogen partial pressure in the atmosphere inside the converter. The effect of both enhanced transport and low nitrogen partial pressure improves the elimination of nitrogen in metal bath. As the decarburization rate decreases, the nitrogen desorption decreases as well. Decarburization is the most effective way of reducing the nitrogen content of steel during steelmaking.

In general, during steelmaking with BOF, nitrogen is used as stirring gases up to 40% of oxygen blow. After this level, the stirring continues with argon. The end of blow nitrogen content up to 40% nitrogen stirring was compared to the case where

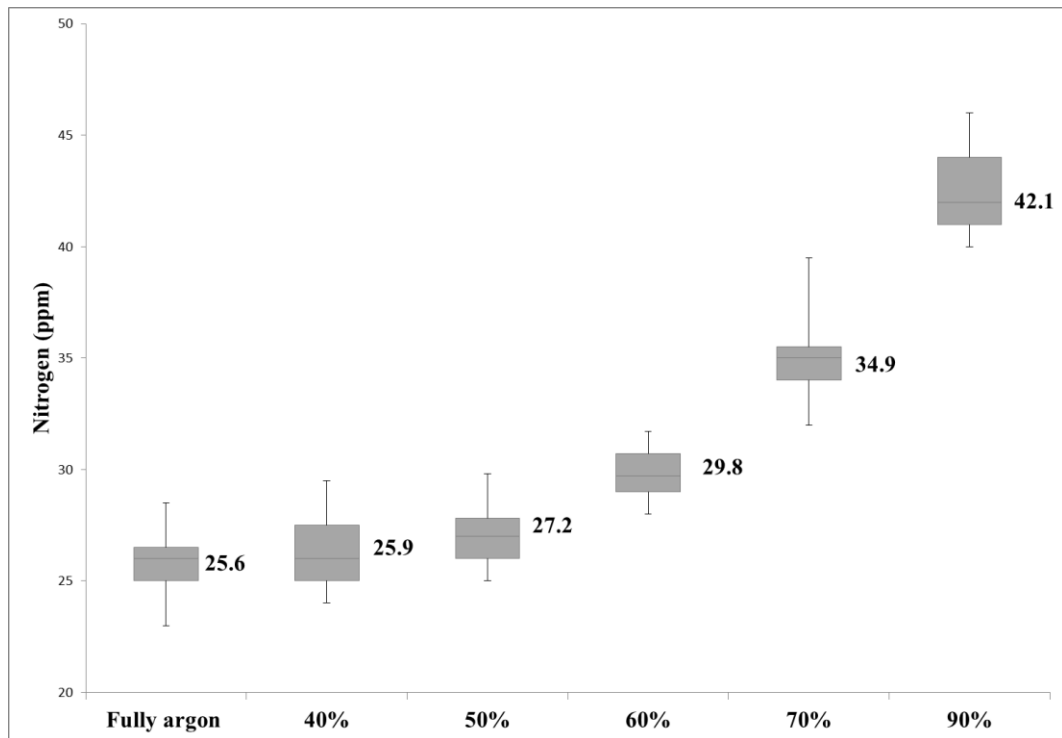
the stirring is deactivated and the results are shown in Figure 4.9. There is no significant difference between the two cases in terms of nitrogen content in steel.



**Figure 4. 9** Nitrogen comparison

After the observation of nitrogen content under normal production procedure, experiments were conducted to detect the nitrogen content with increased switch point to argon stirring. Namely the switch point is increased to 50%, 60%, 70% and 90%. The results shown in Figure 4.10 indicated that it is possible to utilize nitrogen stirring up to 70% switch point. Starting from 70%, the nitrogen pickup from stirring gas occurs and the amount of nitrogen at the end of blow increases significantly. Hence, it is possible to take advantage of nitrogen stirring for the elimination of nitrogen in the molten metal up to 70% before switching into argon.





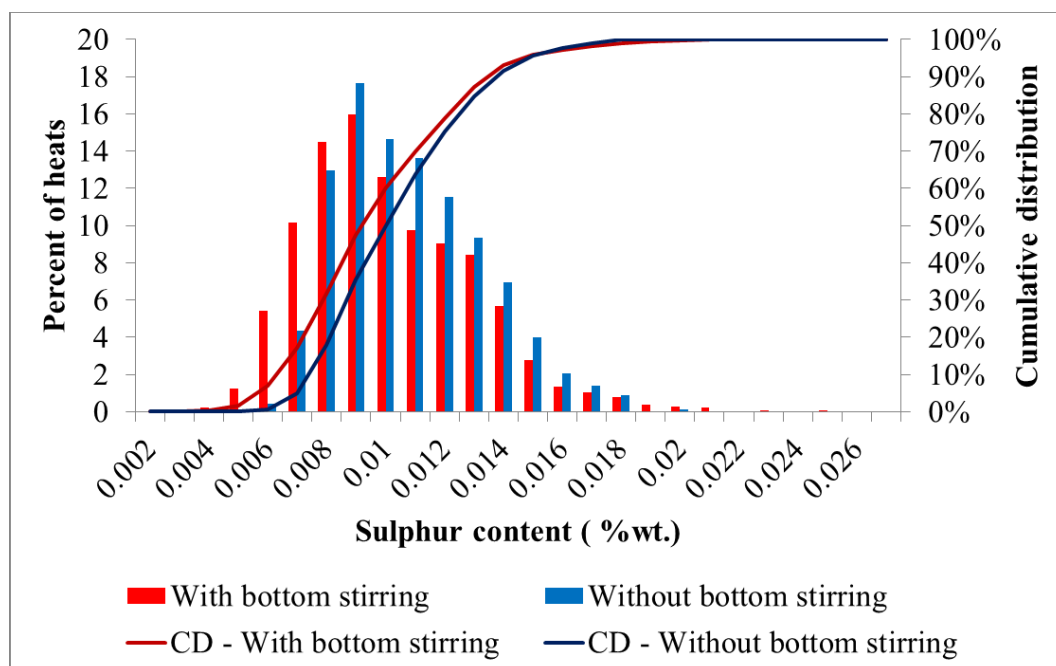
**Figure 4. 10** Boxplot of nitrogen content for varying stirring gas amounts (The horizontal axis depicts the blow percentage where the stirring gas is switched from nitrogen to argon.)

#### 4.3.5 Sulphur Comparison

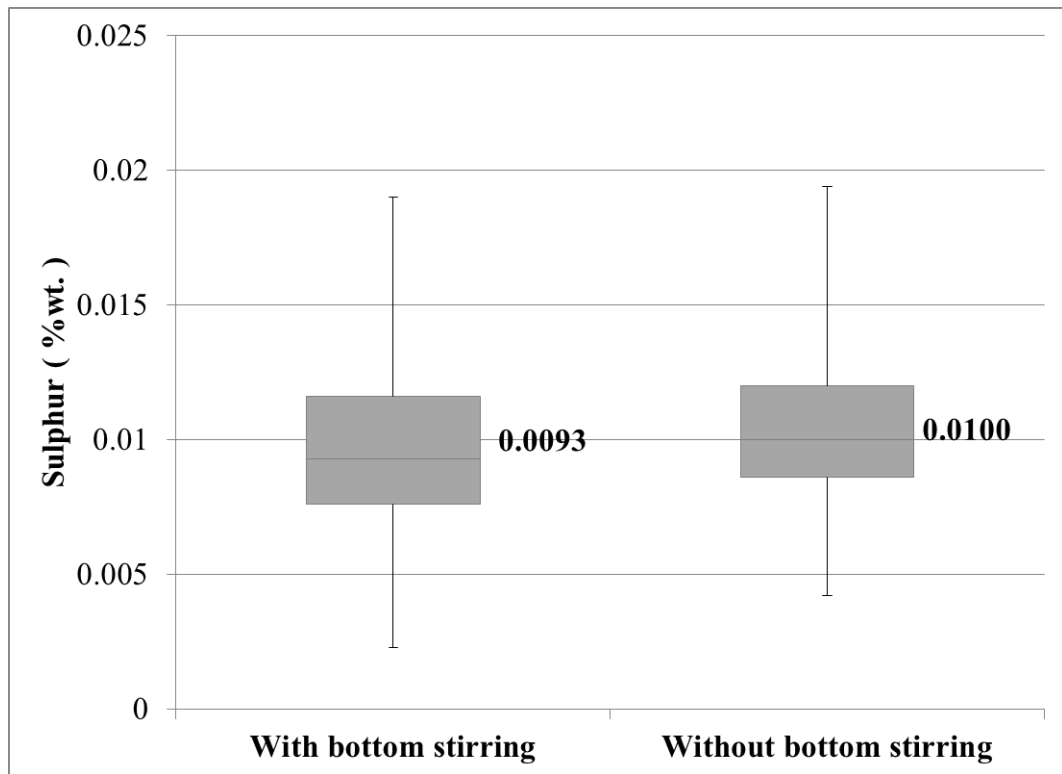
Desulphurization is also an important step of steelmaking and performed majorly before the BOF operation in transfer vessel from BF to BOF. Therefore, the removal of sulphur is not very effective during BOF steelmaking process due to the highly oxidizing conditions and highly oxidized slag. Specifically, during the BOF process, approximately 10% to 20% of sulphur in the bath reacts with oxygen and directly forms  $\text{SO}_2$ . The remaining sulphur is removed by slag-metal a reaction which is assisted by high basicity and low Fe content of the slag.

The end of blow sulphur content distribution with and without bottom stirring is plotted in Figure 4.11. During the collection of data, the amount of sulphur content in hot metal and the slag basicity were kept same to demonstrate the difference

better. The difference in phosphorus content with the addition bottom stirring is about 7 ppm as shown in Figure 4.12. The lower sulphur content attained with bottom stirring activated is due to improved slag-metal interaction and lower iron content of slag provided with bottom stirring.



**Figure 4. 11** Sulphur comparison



**Figure 4. 12** Boxplot of sulphur content for stirring condition

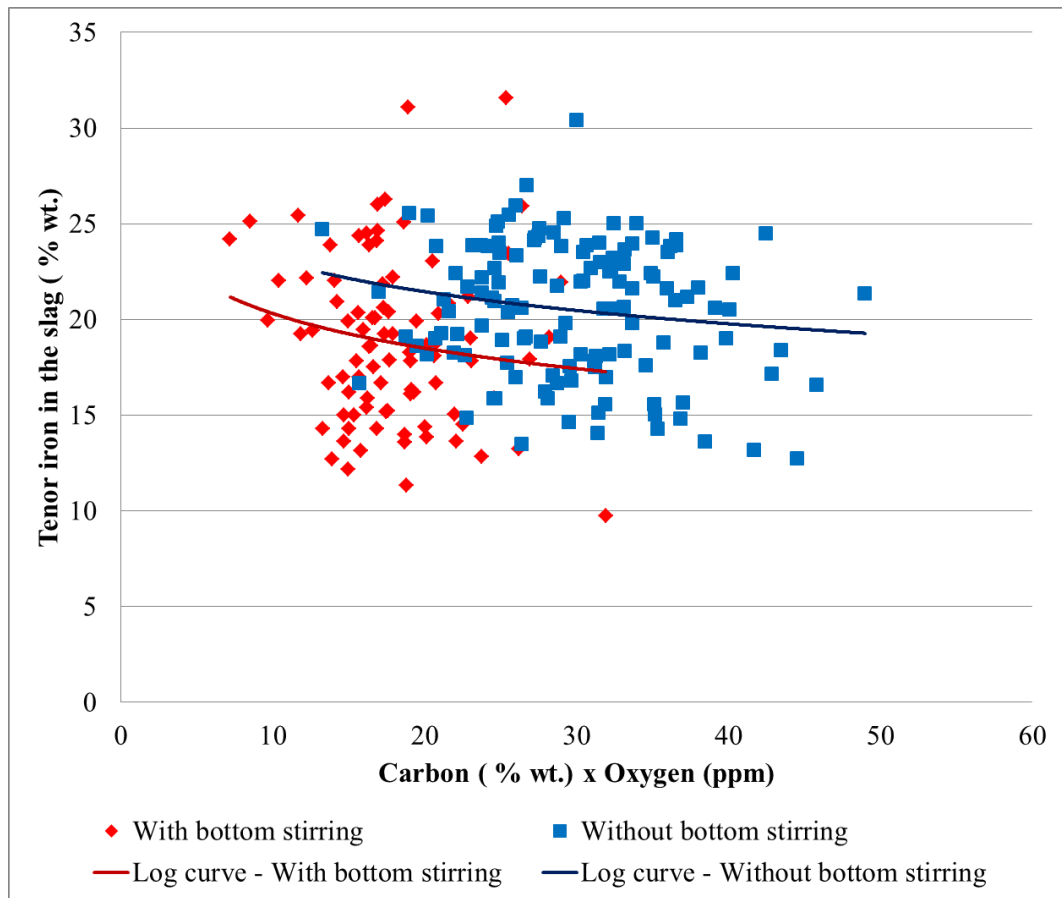
#### 4.4 Analysis of Slag

Slag can be considered as the second product of the steelmaking after the steel itself. Therefore, it is also possible to observe the effect of bottom stirring on the slag composition. The result of slag composition analyses conducted with XRD is tabulated in Table 4.2. According to these results, the effect of bottom stirring is evident such that the MnO and T-Fe contents are decreased while  $P_2O_5$  and S contents are increased with the bottom stirring during the blow.

**Table 4. 2** Slag sample analysis (average)

|           | % T-Fe | % MnO | % P <sub>2</sub> O <sub>5</sub> | % S   | % (FeO+MnO) |
|-----------|--------|-------|---------------------------------|-------|-------------|
| Stirred   | 18.443 | 2.843 | 1.955                           | 0.074 | 21.686      |
| Unstirred | 21.690 | 3.243 | 1.900                           | 0.066 | 24.533      |

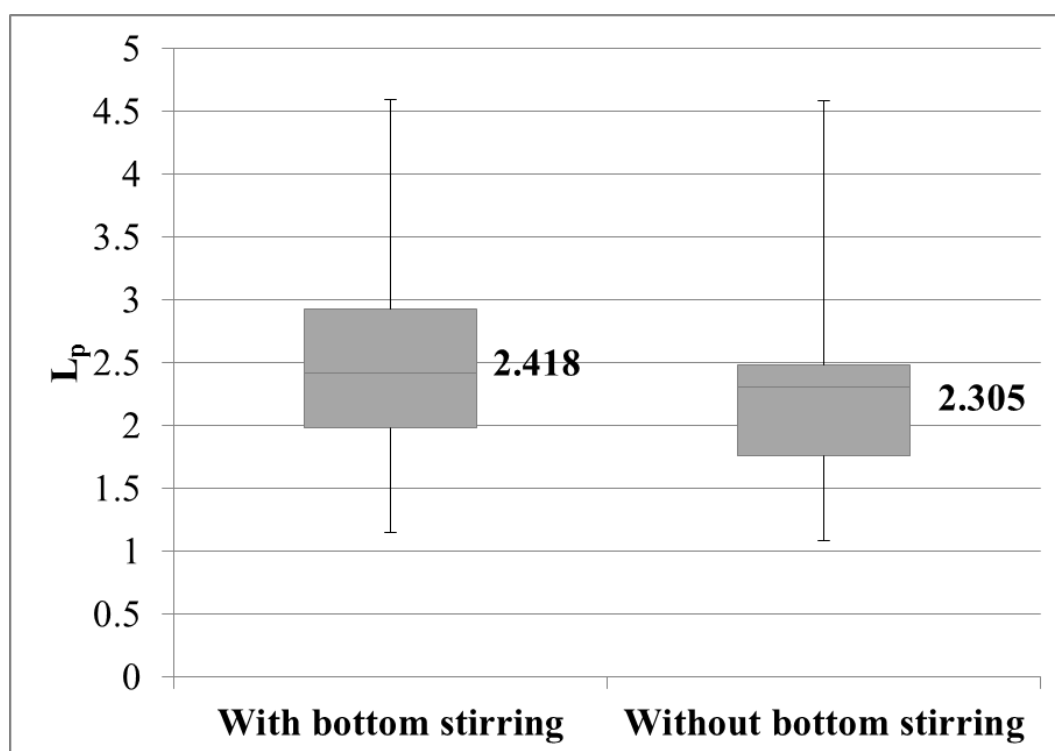
In addition to the effect of bottom stirring on impurities, the effect on Fe itself was also examined by the help of slag analyses. For this purpose, calcium oxide and iron oxide which are the two major chemical constituents in the steel slag were observed. As expected, due to lower oxidation and better mixing, tenor iron in the slag for stirred heats is lower than for unstirred heats. Therefore, in absence of bottom stirring, iron loss is higher and the steel yield is lower. The C x O product in molten metal and tenor iron amount in slag are plotted in Figure 4.13. The results show that for stirred heats, iron loss stays low with lowered carbon content at the end of blow. Therefore, high yield is possible when stirring is active where iron loss is less than 3%. Total amount of slag is approximately 15 ton/heat and iron loss difference between the stirred and unstirred heats is about 240 kg/heat. Thus with bottom stirring, 7680 tons of liquid steel which corresponds to about 64 heats can be recovered annually in BOF.



**Figure 4. 13** Tenor iron content of slag vs.  $[C] \times [O]$

By slag analyses, furthermore, the determination of phosphorus removal is possible during steelmaking process. Specifically, a number named as dephosphorization coefficient ( $L_P$ ) is defined for the comparison of heats with and without bottom stirring in terms of phosphorus removal. This coefficient is equal to the amount of phosphorus in the slag to the amount of phosphorus in the steel at the end of blow in weight percentages. In other words, the dephosphorization coefficient represents the distribution of phosphorus between the slag and the metal.  $L_P$  depends on temperature of the melt, tenor iron and MgO contents in the slag, the slag basicity i.e. the  $\text{CaO}/\text{SiO}_2$  ratio in the slag and volume of the slag. In addition to slag constituents, phosphorus content of the hot metal put in the melt and the target phosphorus amount according to the steel grade play an important role on  $L_P$ . In

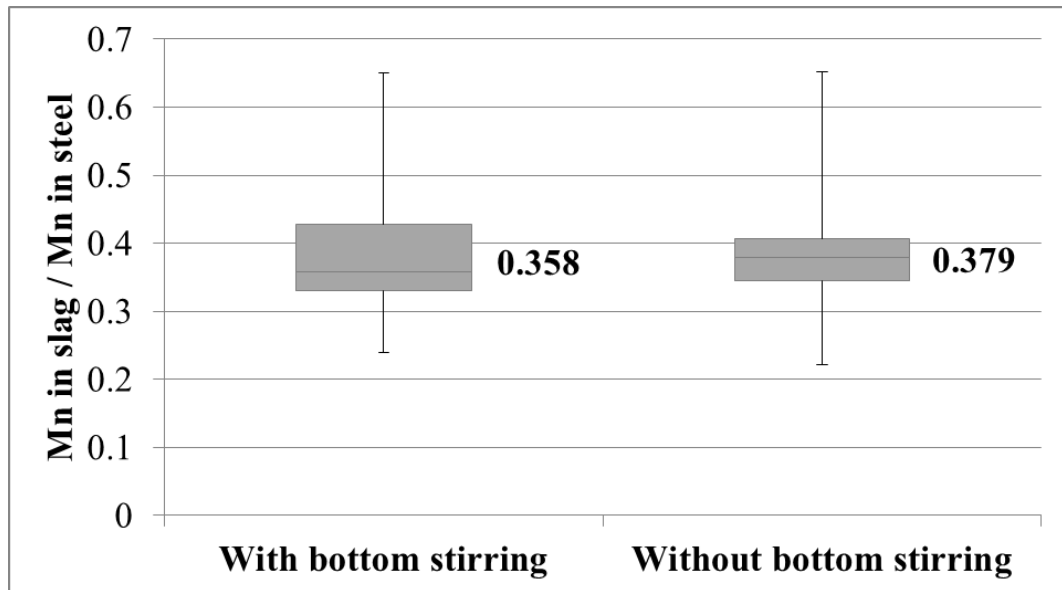
order to simplify the analyses, blowing and stirring parameters and the phosphorus content in the hot metal kept constant. The results showing the  $L_p$  for stirred and unstirred heats are shown in Figure 4.14. According to this figure, average  $L_p$  for stirred heats is slightly higher than that of unstirred heats which indicates the positive effect of bottom stirring on the phosphorus removal during steelmaking process.



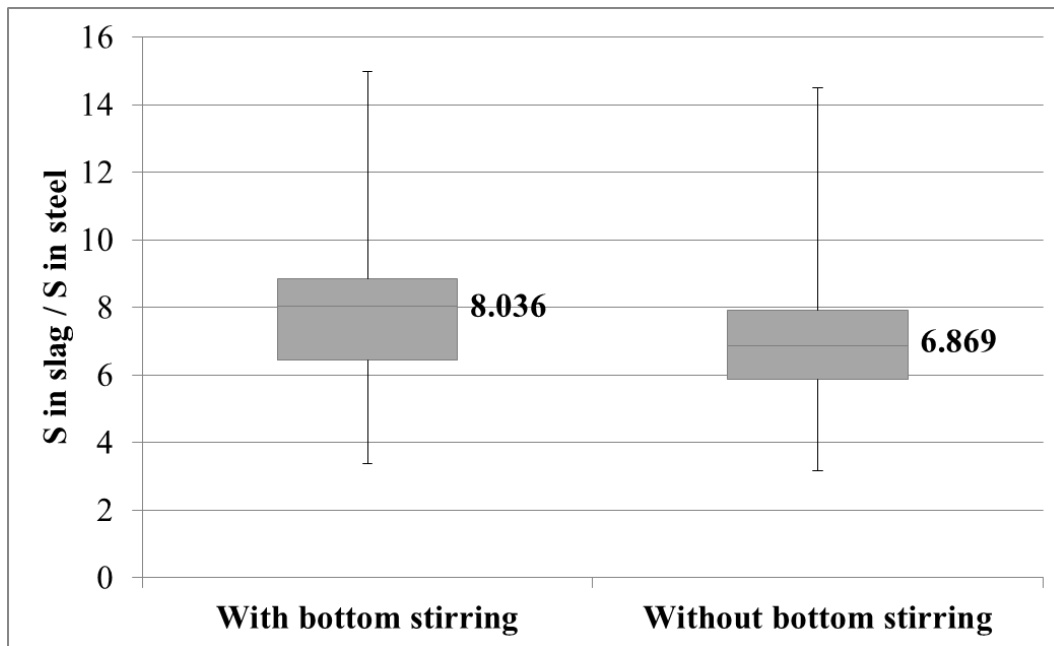
**Figure 4. 14** Boxplot of  $L_p$  (phosphorus in slag / phosphorus in steel) for stirring condition

Moreover, similar analysis for sulphur and manganese are carried out. Amount of manganese in the slag to the amount of manganese in the steel at the end of blow in weight percentages is higher for without bottom stirring condition as shown in Figure 4.15. High amount of manganese loss from steel bath leads higher manganese oxide in the slag for without bottom stirring condition and thus, this ratio is higher for without stirring condition. The results showing amount of sulphur

in the slag to the amount of sulphur in the steel at the end of blow in weight percentages for stirred and unstirred heats are shown in Figure 4.16. According to this figure, S in slag/ S in steel for stirred heats is higher than that of unstirred heats which indicates the positive effect of bottom stirring on the sulphur removal during steelmaking process.



**Figure 4. 15** Boxplot of manganese in slag / manganese in steel for stirring condition



**Figure 4. 16** Box of sulphur in slag / sulphur in steel for stirring condition

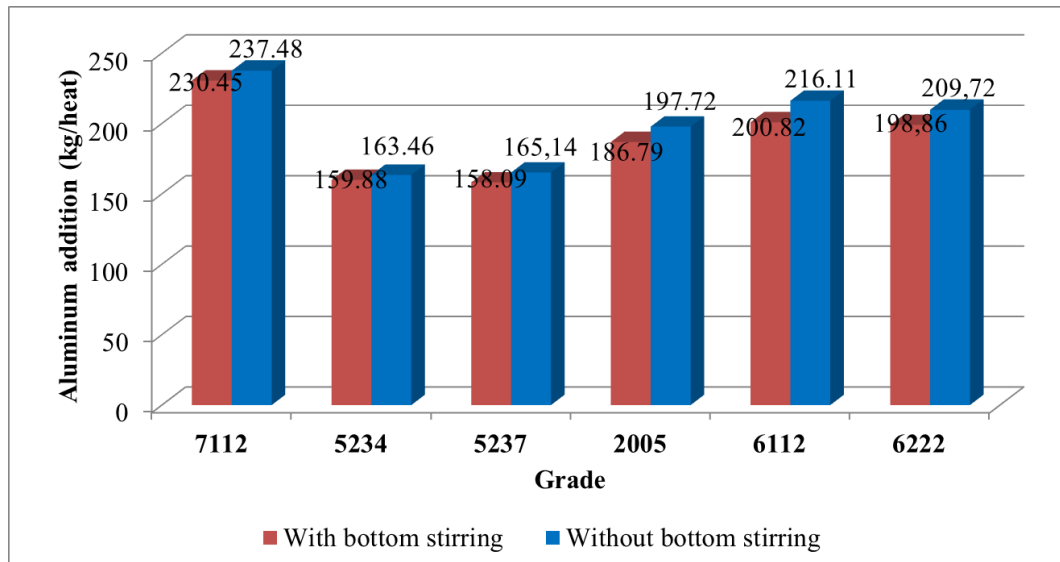
Henceforth, it possible to derive the conclusions on the effect of bottom stirring as higher dephosphorization and desulphurization efficiency, lower tenor iron and manganese content in the slag and lower slag volume, i.e. higher yield.

#### 4.5 Steel De-oxidation Comparison

The elimination of oxygen from liquid steel is carried out by the addition of elements which have higher affinity for oxygen than iron such as aluminum, silicon and manganese. Generally, aluminum is utilized as deoxidizer in BOF steelmaking during tapping from converter to ladle. In addition to aluminum, carbon is also used as pre-deoxidizer at the beginning of the tapping. The most significant advantage taken by bottom stirring is the low value of oxygen attained at the end of blow which decreases the deoxidizer requirements. The end of blow oxygen difference is



about 172 ppm between stirred and unstirred. Without bottom stirring, in order to deoxidize this additional oxygen, 33kg/heat aluminum is required.



**Figure 4. 17** Grade dependent aluminum addition

The aluminum yield and deoxidation practice show differences for different grades of steel to be produced. The average deoxidant aluminum usage per heat for different grades is shown in Figure 4.17. According to these results, the average aluminum requirement difference between the stirred and unstirred heats is about 12 kg/heat. Therefore, with the help of bottom stirring in BOF, 310 tons/year of aluminum can be saved which corresponds to 700.000 \$/year.

#### 4.6 Steel Cleanliness

The cleanliness of the steel is critical for steel products due to mechanical performance considerations. The cleanliness of steel can be attained by not only lowering non-metallic oxide inclusions and controlling their morphology,

composition and size distribution but also lowering other residual impurity elements such as sulphur, phosphorus, hydrogen, nitrogen and even carbon.

Inclusions can be classified as oxides, sulfides and nitrides based on the chemical composition. In addition to classification based on composition, they can be exogenous or indigenous depending on their sources. The exogenous inclusions are formed due to interaction with slag or atmosphere. Thus, it is not easy to control over the amount of exogenous inclusion by bottom stirring. However, it is possible to decrease the number of indigenous inclusions by the help of bottom stirring.

The end of blow oxygen level was shown to be decreased for stirred heat which decreased the need for deoxidizing aluminum. Therefore, for stirred heats, indigenous inclusions caused by aluminum, i.e. alumina is eliminated to an extent by bottom stirring.

In addition to the alumina stemming from deoxidizer aluminum, an important source of reoxidation is the carryover slag when transferring steel from the converter to the ladle, which contains a high amount of FeO and MnO. These oxides react with the dissolved aluminum to generate alumina in liquid steel. For stirred heats, the amount of FeO and MnO in the slag is lower than that of for unstirred heats as shown in Table 4.2. Thus, alumina formation by carryover slag is decreased by the help of bottom stirring.

## **CHAPTER 5**

### **SUMMARY AND CONCLUSIONS**

In this study, specifically, bottom stirring process is examined utilizing data taken from numerous BOF heats based on the turndown slag, the metal composition and amount of input materials.

According to the results taken from overall and individual analyses conducted the advantages of stirring at Erdemir converter can be drawn as:

- Amount of dissolved oxygen at the end of blow in the steel can be decreased to 600 ppm.
- Better carbon removal is possible.
- A lower sulphur and phosphorus content at the end of blow is attainable.
- A higher amount of manganese at the end of blow in the steel is possible that is about 50 ppm. Ferromanganese addition corresponding to this Mn content is decreased about 10 kg/heat by bottom stirring which is equal to 350 tons of ferromanganese saved annually.
- Amount of aluminum used for deoxidizing the steel is decreased about 12 kg/heat which corresponds to 310 tons of aluminum is saved annually.
- Higher yield is possible when stirring is active. Iron loss is decreased about 240 kg/heat which mean 7680 tons of iron is recovered.
- The better removal of impurities from the steel and less amount of deoxidizer requirements leads to cleaner steel production.

Moreover, by the analyses on nitrogen, the possibility to use nitrogen up to a content of 70% of blow instead of 40%, which is the current practice, was demonstrated. Nitrogen to argon switch at 70% is of importance due to economic considerations such that cheap nitrogen can be used for longer period than expensive argon as stirring gas.

The common practice in several competitive factories is based on the steel production within the range of bottom stirring. However, in Erdemir, relining operations are conducted after a period of steel production with stirring losses. This not only decrease the aforementioned savings but also yields a lower quality steel at the end. Consequently, by the results of this study, the relining operation is shown to be economically reasonable and practical due to savings stemming from high iron yield, low consumption of deoxidizers and ferromanganese, and prolonged maintenance periods required for lining.

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