Master Thesis

of

Direct Reduced Iron Production from EAF Slags in Fixed Bed Furnace

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To My Mother...
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ABBREVIATIONS

AAS : Atomic Absorption Spectrometry
DRI : Direct Reduced Iron
EAF : Electric Arc Furnace
ITmk3 : Iron Making Technology Mark 3
HBI : Hot Briquetted Iron
CBI : Cold Briquetted Iron
XRD : X-Ray Diffraction
XRF : X-Ray Fluorescence
BOF : Basic Oxygen Furnace
TDR : Tisco Direct Reduction
EIF : Electric Iron Furnace
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ABSTRACT

Electric arc furnace (EAF) slags are basic characteristic slags that include approximately 40 % iron oxide compounds. Iron oxide can be recycled and re-used in the process to decrease amount of waste product besides reducing loss of raw materials. According to result of survey performed by The European Association Representing Metallurgical Slag Producers and Processors (EUROSLAG) in 2010, 8.5 million tons of EAF slag is produced in Europe. High percentage of EAF slag is re-used in road construction as aggregate. However it can be re-cycled in the internal use for metallurgical processes as well. In order to re-use EAF slag in the process as a raw material, direct reduction is a new approach. Direct reduction is reduction of iron containing raw materials with gas or solid reductants without melting of charge. In this study, reduction conditions of 39 % Fe₂O₃ containing EAF slag in tube furnace was examined. As the reducing agent, metallurgical coke was used. EAF slag was milled and pelletized in raw material preparation step. Pellets were charged to fixed bed type tube furnace in a graphite boat at 1050, 1100 and 1150ºC respectively with 150 and 200% of stoichiometrically required amount of metallurgical coke. 5, 10, 15, 30, 60, 90 and 120 minutes process durations were performed. Direct reduced pellets were milled to be characterized by using X-Ray Diffraction (XRD) and chemical analysis methods. Results indicate that increased temperature, process duration and stoichiometry have a positive impact on direct reduction of EAF slag in terms of iron metallization. 90 % metallization degree has been achieved as the result of the study with the process conditions of 200 % stoichiometry and 90 minutes process duration at 1150 ºC.

Keywords: Direct reduction, direct reduced iron, EAF slag, metallic iron production, iron oxide, steel plant by product.
1. INTRODUCTION

Nowadays, a major part of steel is produced in integrated plants which have a high productivity and unlimited production of various steel qualities. On the other hand, due to disadvantages of integrated steel plants such as high investment cost, electric consumption and environmental issues, steel producers started to seek an alternative production process. As the second cornerstone of iron and steel production, electric arc furnace (EAF) became prominent according to its low investment cost, availability in low productions and no need to secondary plants such as sinter and coke plants. Related to advantages of EAF, iron and steel industry grow mostly based on EAF\textsuperscript{[1,2]}.

Using scrap as the main raw material charge in EAF has disadvantages as unstable composition of scrap, limited availability, abrupt cost changes of scrap etc. As a result of negativeness of scrap usage in EAF, as a cleaner and EAF friendly raw material direct reduced iron will have an important place in iron and steel industry\textsuperscript{[3]}. Direct reduced iron is a product that is obtained by reducing iron containing raw materials and waste products by using hydrocarbons or carbon containing solid reductants, without melting. The final product has a high amount of metallic iron. Direct reduced iron can be charged to EAF with scrap or can be instead of scrap it can be used as raw material. Addition to that, in order to increase productivity, eliminate the problems in production and to provide the desired conditions for production, direct reduced iron can be charged to blast furnace, basic oxygen furnace (BOF) and casting furnaces. By integrating direct reduction plants with secondary plants for melting step, those plants may be able to final product besides the raw material production for other production plants. Consequently, an easier production compared to blast furnace in the sense low cost and usage of raw material without preparation\textsuperscript{[1,3,4]}.

However, as a result of increasing demand on EAF furnace usage, necessity of direct reduced iron is increased as well. The growth in steel production leads problems in providing raw material. Besides, during recent years, in the existed and newly built up EAF plants requires a cleaner steel production. Due to these reasons, amount of scrap and pig iron is not enough to compensate the growth in steel industry and the raw material need is satisfied with direct reduced iron\textsuperscript{[3]}.
In this study carbo-thermic reduction conditions of EAF slag were observed. EAF slag is a waste product of steel production that contains various oxides including a high amount of iron oxide. Experimental set was prepared based on duration, temperature and reductant amount variables and experiments were performed in a fixed bed furnace. Final products which were obtained from the experiments were characterized with different analysis methods and results are expected to define the optimum reduction conditions of iron oxide in EAF slag and lead to light the way of re-use iron containing waste products.
2. MOTIVATION OF THE STUDY

As mentioned in the introduction, crude steel production is provided mainly in integrated steel plants and EAF plants. Approximately 56% of crude steel in integrated steel plants and 43% of it was produced in Europe in 2010. Relatively small amount of production was performed in open hearth furnace plants. Production in EAF is expected to have a larger place in steel world due to its cost and environmental advantages. But the increased demand on EAF will lead to necessity of scrap at the same time and higher import rate of scrap in Europe last 10 years[3,5].

Increased need of scrap may cause some problems; first of all scrap is not a produced raw material and it has a limited increase to meet the scrap need. Scrap as waste product is related to amount of steel of production and number of recycled scrap comes from the previous productions. On the other hand, the metallic remaining in scrap has a negative effect in producing high purity steel in EAF[3].

Pig iron and direct reduced iron are available to be used in EAF plants in order to produce pure steel with scrap or instead of it. It must be considered that, producers would prefer to use the hot metal in steel production rather than pig iron production. When the limited options in raw material selection for EAF taken into account, it can be said that the direct reduced iron usage will be higher in the near future[3].

Nowadays based on the advantages of direct reduced iron, there is a rising trend in its production in the world. In direct reduced iron production various type of raw material and manufacturing methods were developed in previous studies. As raw material mainly iron ore, ore powder or pellets are used in commercial processes. But it was observed that EAF slag has approximately 40% iron oxide content. In normal procedure, the EAF slag is sent to magnetic separation to take out the iron particles while the iron oxide is used as aggregate or stored as waste with the rest of the oxides. Once it is thought that in 2010 around 8.5 mt of EAF slag was obtained in Europe, it will be a prominent candidate as raw material to be used in direct reduction process. Additionally, rising demand on steel production in EAF plants will cause to provide a higher amount of EAF slag in the future[3].
3. LITERATURE STUDY

3.1 Direct reduction of Iron oxide

Direct reduction is a process of iron oxide reduction without melting by using hydrocarbon gases or carbon including materials. Direct reduced iron as the product of the reaction is a slag containing solid with a high degree of metallization.

Steps of the iron oxide reduction reactions:

The main steps of the reaction can be listed as below:

1. Mass transfer of the reducing gas through the oxide surface in the reduction atmosphere.
2. Diffusion of the reducing gas through the reaction region by keeping the channels in the oxide.
3. Chemical reaction inside the oxide.
4. Transfer of produced gas as a result of reaction through the outer oxide surface by channels inside the oxide.
5. Mass transfer of produced gas through the reduction atmosphere\(^4\).

It has been observed that, when the reduction behavior of wustite (FeO) was examined, it occurs in four steps. At the first step, reaction on the wustite surface, leads to get a supersaturated solid solution in metal ions terms by sending away the oxygen atoms. In the following step, a metal core forms in the wustite structure. At the next step, metal ions and electrons in the supersaturated wustite are transferred to newly formed metal core. At the last step, metal ions and electrons move to metallic phase from wustite\(^{[11]}\). Gradual reduction of iron oxide is demonstrated as schematically in the figure 1.

Two different reaction mechanisms are operative when iron oxide powder reduction by carbon containing powder is examined. The reaction called direct reduction based on the diffusion at the contact surface of the two reactant, iron and carbon. Indirect reduction reaction is provided by transformation of CO and CO2 gas phases. Reaction between two solid phases can only be possible at the contact points and the solid phase reactions end when one of the solid phases gasify\(^{[11,12]}\).
Iron oxide-carbon composites are formed by pelletizing of iron oxide and reductants together. In these composites, reduction reactions occur step by step respective from hematite (Fe2O3), Magnetite (Fe3O4), wustite to metallic iron (Fe)\textsuperscript{[13]}.

**Figure 1.** Gradual reduction of iron oxide\textsuperscript{[7]}

### 3.2 Reactions of Iron Oxide reduction process

Reactions of iron oxide reduction occur as based of the following equations\textsuperscript{[14,15]};

\[
3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \quad \text{(Eq.1)}
\]

\[
\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2 \quad \text{(Eq.2)}
\]

\[
\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2 \quad \text{(Eq.3)}
\]

\[
3\text{Fe}_2\text{O}_3 + \text{C} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO} \quad \text{(Eq.4)}
\]

\[
\text{Fe}_3\text{O}_4 + \text{C} \rightarrow 3\text{FeO} + \text{CO} \quad \text{(Eq.5)}
\]

\[
\text{FeO} + \text{C} \rightarrow \text{Fe} + \text{CO} \quad \text{(Eq.6)}
\]

\[
3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightarrow 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \quad \text{(Eq.7)}
\]

\[
\text{Fe}_3\text{O}_4 + \text{H}_2 \rightarrow 3\text{FeO} + \text{H}_2\text{O} \quad \text{(Eq.8)}
\]

\[
\text{FeO} + \text{H}_2 \rightarrow \text{Fe} + \text{H}_2\text{O} \quad \text{(Eq.9)}
\]

\[
\text{C} + \text{O}_2 \rightarrow \text{CO}_2 \quad \text{(Eq.10)}
\]
(Eq.10) is combustion of carbon equation and (Eq.11) is called Boudouard equation. Carbon monoxide production is obtained by these reactions. Boudouard reaction is an endothermic reaction and it has high activation energy; therefore this reaction can progress only at high temperature\textsuperscript{[12]}. 

Baur-Glaessner Diagram demonstrates temperature, CO/CO\textsubscript{2} and H\textsubscript{2}/H\textsubscript{2}O ratio to balance the free energy change of reduction reactions of iron oxides. In figure 2 Baur-Glaessner Diagram is given with Boudouard reaction curve and in figure 3, Baur-Glaessner Diagram is given with the reactions of carbon monoxide and hydrogen as the reductant.

Reduction of iron oxide occurs at the oxide surface heterogeneously by gases like CO and H\textsubscript{2}. The surface available to reaction is in the channels inside of the porous iron oxide. In this case, the reducing gases must enter to channels before they react. Therefore, efficiency of the reduction is depending on the structural properties such as channel length and distribution as well as porosity\textsuperscript{[4]}.

When the reduction of hematite with hydrogen is observed, it is seen that reaction moves topochemically and the partially reduced product forms layers around the hematite core. Above 575°C, wustite become stable, and the layers in the structure are defined as from outside to inside, magnetite wustite and iron respectively.

Reduction of hematite with hydrogen can be categorized in 3 regimes. In the first regime, reduction occurs inside the structure. This reaction is effective at low reduction temperature and small particle size but the rate of reduction is independent from particle size. At the end of the reaction a homogenous composition is obtained. In the second regime, gas diffusion is active in reduced iron layer. In this step large particle size and high temperature limits the reaction rate and rate is dependent to diffusion. Rate starts to decrease while the core diameter is decreasing. An interface is exist between reaction rely on topochemical model and reaction independent from topochemical model. The last regime is a controlled regime and transition duration between the other two regimes. Particle size has a negative effect on reduction reaction rate in the third regime\textsuperscript{[17]}.
Figure 2. Baur-Glaessner Diagram is given with Boudard reaction curve\textsuperscript{[16]}

Figure 3. Baur-Glaessner diagram for CO/CO\textsubscript{2} and H\textsubscript{2}/H\textsubscript{2}O atmospheres\textsuperscript{[18]}. 

Over 1000°C, the dominant reactions are gas based reduction reactions of iron containing phases. Above 1000°C, CO and H2 formation reactions from CO2 and H2O (water vapor) occur which lead to an increase in reduction potential of the gas in the system. Metallic iron absorbs carbon in the environment above 1200°C and the formed phase can melt below the melting temperature. Wherefore, 1200°C defines the border between direct reduction and melting procedure. But in practical terms, carbon absorption becomes faster in melting process over 1300°C\[19\].

3.3 Usage area of direct reduced iron

3.3.1 Direct reduced iron usage in EAF

Direct reduced iron can be used as iron containing raw material in EAF as to be melted and converted into liquid steel. There are some advantages of direct reduced iron usage as charge despite of scrap. First of all, DRI offers a homogeneous chemical compound of the charge and low gangue elements which leads to make easier to control of steel qualifications. Opposite of scrap, DRI can be charged directly from the opening of the furnace roof which provides an effective charging without turning power of and open the furnace roof. As a result of that, a stable arc and an increase in the average power applied to charge can be obtained. DRI does not need any preparation to get the homogeneous melt. Also the appropriate shape of DRI provides an easy charging procedure and prevents of electrode breaking. Since DRI denser than scrap, with less charge shifts, furnace can be fed that lowers the charging time and as a result of that, there will be a positive impact on efficiency. As another advantage of DRI usage in EAF, it promotes the foamy slag formation that reduces harsh effect of arc radiation\[1\].

Besides the advantages of DRI, there are some disadvantages of decreasing the scrap amount in charge. DRI requires more energy than scrap to be melted which results in increased electrode and power consumption. This situation also ends up with longer tap to tap time. Additions to that, DRI charge without an appropriate amount of scrap in the furnace at the beginning of the process, makes defenseless the furnace wall and roof to electric arc radiation\[20\].

3.3.2 Direct reduced iron usage in Blast Furnace

DRI may be used in case of increasing production, compensate the demand and if there is any trouble in coke plant, to recover the production lost in the blast furnace. Since the coke in the blast furnace, consumed for oxide removal, when DRI charged to blast furnace, coke required for oxide removal can be used for melting which leads to lower coke consumption\[1\].
However, experimental study done by Kaushik and Fruehan (2006) indicated that, hot briquetted iron and DRI charged to blast furnace, may be re-oxidized during the process. Highly porous DRI re-oxidized more that hot briquetted iron due to higher density of HBI\textsuperscript{[21]}.

### 3.3.3 Direct reduced iron usage in Casting Furnace

Direct reduced iron can be used in casting plants despite of scrap due to its advantages to scrap. Initially, since DRI has a more stable composition than scrap, it can provide higher purity in the final product. Therefore it may be more preferable in the processes which require a high purity such as gray cast iron, ductile cast iron and nodular cast iron. Additionally, DRI provides easiness in the process that needs to be charged continuously due to its appropriate shape. As a result of increased DRI usage and producing a better slag, more efficient phosphorus and sulfur removal can be achieved\textsuperscript{[1]}.

Even though the advantages of DRI, usage of DRI in casting processes is not widespread. This is caused by the inappropriate oxide and gangue element level of DRI that reduces the melting efficiency and increases the required power and time of the process. Also the iron oxide content of DRI causes formation of foamy slag that is not desired in induction, cupola and reverb furnaces contrary to EAF. Addition to that, metallic iron can be oxidized and lost in the slag phase due to porous structure of DRI\textsuperscript{[1]}.

### 3.3.4 Usage of DRI in EAF, BOF and casting cupola as coolant

In order to balance the temperature increase in EAF, BOF and casting furnace as a result of exothermic reactions, DRI can be used to cooling charge. Especially, DRI which produced to meet the requirements of the process, such as appropriate particle size and density, can cool the furnace to desired temperature without a negative effect to process\textsuperscript{[1]}. The study done by Pastucha et al. indicates that charging of HBI to BOF has the same cooling effect with scrap. In case of charging HBI despite of scrap, it had been observed that purity of the final product was increased as well as better sulfur and phosphor removal was achieved\textsuperscript{[22]}.

### 3.4 Direct Reduction Technologies

Direct reduction technologies are process conversion of iron containing raw materials and iron and steel by products with direct reduction into products that have high metallization. Besides the usage of direct reduced iron in integrated steel plants or EAF plants, it can be used as final product. Direct reduction processes can be evaluated as alternative iron production method
according to its availability in economical case. In addition, increasing demand on steel production by EAF leads to rise the attention on direct reduced iron concurrently[1].

3.4.1 Products of Direct Reduction

Direct reduced iron containing raw materials can gain different properties after reduction by applying different procedures. The general properties of direct reduced iron are given in the table 1. As a result of cooling the product obtained after direct reduction is called direct reduced iron. If the product after direct reduction, briquetted as hot, it is named as hot briquetted iron and the product that is briquetted after cooling than it is called cold briquetted iron[23].

**TABLE1.** Features of direct reduced iron[1].

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.5 - 4.0 g/cm³</td>
</tr>
<tr>
<td>Packing density</td>
<td>1.5 - 1.9 ton/m³</td>
</tr>
<tr>
<td>Surface area</td>
<td>0.5 - 4.0 m²/g</td>
</tr>
<tr>
<td>Compression strength</td>
<td>50 - 110 kg/cm²</td>
</tr>
<tr>
<td>Metallization ratio</td>
<td>% 90 - 95 (ave. % 91 - 93)</td>
</tr>
<tr>
<td>Metallic iron %</td>
<td>~ % 85</td>
</tr>
</tbody>
</table>

3.4.1.1 Direct Reduced Iron

Direct reduced iron is produced by leaving the direct reduced product to cool without any additional procedure. DRI generally produce near EAF or plants with capacity of melting. DRI is transferred with conveyor to the production area without cooling if the plant is close to DRI production plant[24].

3.4.1.2 Hot briquetted iron

The term hot briquetted iron means to produce dense briquettes by squeezing the direct reduced iron without letting to cool down. DRI is defenseless to oxidation and reaction with water due to its large surface area. In order to protect the product from oxidation, surface area must be reduced by briquetting. Hot briquetting process is applied over 650°C and material should reach 5g/cm³ density. Briquetting process provides to stock the material without moisture and losing its metallization. As a result of that HBI can be used such as scrap and be subjected to preheating before melting[25,26].
3.4.1.3 Cold briquetted iron

Cold briquetted iron is produced by briquetting the too small powder to be used for production by mixing with binder and slag formers. Production dust of integrated plants can be briquetted too in order to use later[1,23].

3.4.2 Direct Reduction Technologies

Direct reduction processes can be categorized according to reductant in the reduction. Even though, direct reduction technology is a reduction process in solid state, with addition of a melting unit, liquid metal production can be obtained. In the table 2, some commercial reduction procedures are summarized.

**Table 2.** Most common direct reduction technologies[14,19].

<table>
<thead>
<tr>
<th>Reduction Type</th>
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<th>Commercial Name</th>
<th>Charge</th>
<th>Product</th>
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<td>MIDREX</td>
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<td>DRI, HBI, Crude steel</td>
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<td>ITmk3</td>
<td>Pellet</td>
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3.4.2.1 Gas reductant based direct reduction processes

The gas based direct reduction process rely on the principle of moving reducing gas and solid charge opposite to each other that provides high reaction efficiency in a shaft or fluidized bed furnace. In the gas based processes reducing gas mixture is produced by partial oxidation reaction of natural gas with water vapor or waste gases of the process[27].

In the single step processes, gasification and reduction occur in the same reactor. Eq.12 shows the partial oxidation gasification reaction[27].

11
In the two steps processes, reducing gas is produced in an external reactor with catalytic vapor transformation reaction or partial oxidation reaction. Catalytic transformation reaction runs with help of catalyst, water vapor or waste gases of reduction reactor. Eq.13 given below shows the catalytic vapor transformation and Eq.14 and Eq.15 are reactions with waste gas^{[27]}.

\[
\text{CH}_4 + 0.5\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2 \quad \text{(Eq.12)}
\]

\[
\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \quad \text{(Catalytic vapor transformation)} \quad \text{(Eq.13)}
\]

\[
\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \quad \text{(transformation with waste reactor gas)} \quad \text{(Eq.14)}
\]

\[
\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \quad \text{(transformation with waste reactor gas)} \quad \text{(Eq.15)}
\]

a. **MIDREX Process**

MIDREX process consists of shaft reactor where reduction occurs, gas transformer to convert natural gas into CO and H2 and cooling gas system components. Natural gas enters to system after heated up to 400°C. H2 and CO that are produced by using waste gases or reduction, are fed to system reduction region from bottom of shaft reactor while feeding the iron ore from top of the shaft reactor. Iron ore reduction is provided during the moving iron ore and reducing gas opposite to each other in the furnace. Direct reduced iron is taken out after it is cooled in the cooling system placed beneath of the reactor. The shaft furnace can be modified in order to discharge hot DRI and production of HBI. HOTLINK Process that was developed by MIDREX obtains to transfer hot DRI directly to EAF without cooling. MIDREX is an approved, widespread to world process with its ability to advanced gas transforming system and flexible raw material option^{[27,28]}. Flow chart of MIDREX process is given in figure 4.
b. **HYL III Process**

HYL III process is based on a moving bed shaft furnace with consists of gas transformer and reducing gas heater. Conversely to MIDREX, HYL III works under high pressure. Iron ore that is fed from top of the furnace is reduced when it met with the reducing gas during the opposite movement to each other. Reduced product is cooled to 50°C in the cooling system at the bottom of the reactor and then it is taken out. Reducing gas is produced by using water vapor[27].

c. **FINMET Process.**

Iron containing raw material charge in FINMET process is comprised of powder with particle size under 12 mm. The process incorporates several reactors and at the first reactor, iron containing powder is heated up to 550°C. While the powder passes through the other reactors, reduction occurs. Reducing CO and H2 gas mixture is produced by using the reaction of natural gas and water vapor. FINMET process offers up to 93% metallization. At the last step, produced DRI powder is squeezed as 0.5kg briquettes with 5g/cm3 density[29]. In the Figure, FINMET process flow chart is given.
d. **Circored Process**

Circored process is based on two steps fluidized bed furnace to produce reducing gas and it works at low temperature. Dried iron ore powder is heated up to 800°C before it is charged to fluidized bed. Process runs under 4 bar pressure and at 630°C for 15-20 minutes. Low temperature prevents the sticking of powder problem. Products are left the system at 630°C and heated up to 680°C to be briquetted. Circored process is available for treating low price ore powders and low production cost[^28].

### 3.4.2.2 Solid reductant based direct reduction processes

The solid reductant based direct reduction technologies, uses the reduction effect of carbon inside the solid reductant and CO, produced by gasification. In this kind of direct reduction, iron containing raw material and reductant must contact to each other. As a result of it gasification occurs inside which provides an efficient reduction[^1].

a. **SL/RN Process**

SL/RN process is applied in a rotary kiln with refractory lining and having its charge unit placed upper than discharge unit. Gasification and reduction occur in the same reactor. Process can be divided into two stages. At the first stage, charge is pre-heated in the first 40-50% length of the furnace. At the second stage, charge reaches to reduction region at 1050°C and 1100°C. Reducing gas is gasified carbon formed based on Boudouard reaction. Result of 10 hours

[^1]: Footnote 1
[^28]: Footnote 28
process, 93% metallization can be achieved. SL/RN process has opportunity use a wide range of iron containing raw material and reductant\textsuperscript{[28]}. Flow chart of the process is shown in the figure 6.

Figure 6. Flow Chart of SL/RN Process\textsuperscript{[35]}

b. TDR Process

TDR (Tisco Direct Reduction) technology has been developed in TATA Sponge Iron Ltd. Process occurs in a rotary kiln by using iron ore and non-coking coal as raw materials. Heating of the furnace and keeping the temperature at 950°C - 1050°C is obtained by coal. Process takes 10 to 12 hours from reducing of iron ore in rotary kiln to cooling to 100°C. Burning of coal and CO formation provided by air blowing from secondary tuyeres on furnace wall and air injection nozzles are placed in preheating region\textsuperscript{[30]}. TDR process is demonstrated in figure 7.
c. FASTMET Process

Green pellets of iron ore powder or iron containing waste material with coal is reduced in rotating hearth furnace in the FASTMET process. Green pellets are dried before charging to furnace. In a rotary hearth furnace there are various burners located in the different regions of the furnace. 3 burners are placed in the first region, 5 in the second region and 3 in third region. When charge reaches to the third region, it is cooled down to 1000°C - 1200°C by water cooled plates. Charge is heated to maximum 1280°C - 1350°C and stays in the system 6-10 minutes. TDR process can provide 85-95% metallization and carbon content can be controlled to achieve desired metallization of final product. Produced final product is transferred directly to EAF or kept in transfer barrels that are washed with nitrogen. FASTMELT is a kind of electric arc furnace with water cooled roof that is aimed to combine with FASTMET. By using totally hot DRI charge, a product named FASTIRON that is a carbon containing liquid iron is produced. Electric arc furnace used in the FASTMELT process is different than traditional EAF; therefore it is called electric iron furnace EIF. EIF maintains efficient melting, gangue, residual iron oxide and sulfur removal of the FASTMET product as well as continuous operation. Figure 8 summarizes the FASTMET process.
Similar to the FASTMET process, iron ore, reductant, and binder-containing pellets are reduced and then melted in a rotary hearth furnace in the ITmk3 process. Green pellets which are ranged between 17-19mm are chosen and dried for treating. After the pellets placed in the furnace, they are heated up to 1350°C for gasification of coal and reduction reactions to occur. High reaction rate is a feature of the process due to high temperature and close contact of iron oxide and carbon. Product of the system has high ability of metallization and an empty core shell structure. Melted slag presents in the core. The product is sent to the melting unit while it is still hot. At this step, by extra heating the iron shell is dispersed and melted iron droplets are formed. Separation of iron from slag is completed when the iron droplets merge and form iron nugget. ITmk3 process is available for producing pig iron to be used in EAF. In addition, there is no need any extra care to prevent the product during transportation and product can be continuously charged to EAF\cite{28,32}. ITmk3 process flow chart is given in figure 9.

Figure 8. Flow Chart of FASTMET Process\cite{37}
Figure 9. Flow Chart of ITmk3 Process
4. EXPERIMENTAL STUDIES

In this study direct reduction conditions of EAF slag and metallization degree with respect to direct reduction were observed. Experiments were performed in fixed type bed furnace with metallurgical coke.

4.1 Materials

Inputs of the experimental studies can be listed as EAF slag which includes iron oxide components, solid reductant to provide reduction reaction and binder to make slag pellets that are shown in figure 10.

![Figure 10](image.png)

**Figure 10.** a) EAF slag, b) Metallurgical coke, c) Molass

4.1.1 Electric Arc Furnace Slag

Slag which was used in the experiments provided from Çolakoğlu Metalurji A.Ş. Chemical analysis of EAF slag is given in the table 3.
Experimental studies were conducted with metallurgical coke according to its low ash and volatile content in order to obtain a residue free reaction. The table 4 gives the chemical analysis of metallurgical coke which was used in this study.

### Table 4. Chemical analysis of metallurgical coke

<table>
<thead>
<tr>
<th>Slag Analysis</th>
<th>( \text{Fe}_\text{M}% )</th>
<th>( \text{Fe}_2\text{O}_3% )</th>
<th>( \text{CaO}% )</th>
<th>( \text{SiO}_2% )</th>
<th>( \text{Al}_2\text{O}_3% )</th>
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<tbody>
<tr>
<td>( \text{MgO}% )</td>
<td>0.84</td>
<td>39.26</td>
<td>25.45</td>
<td>16.81</td>
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<tr>
<td>( \text{Na}_2\text{O}% )</td>
<td>5.79</td>
<td>18.00</td>
<td>13.00</td>
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<tr>
<td>( \text{ZnO}% )</td>
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<td>0.18</td>
<td>0.13</td>
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<tr>
<td>( \text{K}_2\text{O}% )</td>
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<td>0.57</td>
<td>1.28</td>
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<tr>
<td>( \text{S}% )</td>
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<td></td>
<td>0.04</td>
<td>5.76</td>
<td>1.28</td>
</tr>
<tr>
<td>( \text{C}% )</td>
<td></td>
<td></td>
<td>0.04</td>
<td>0.47</td>
<td>1.28</td>
</tr>
</tbody>
</table>

4.1.2 Reducing Agent

Molass was used in pelletizing step as the binder according to its easiness to procure and having not a significant effect on slag formation or mass balance. Molass that was used in this study provided from Çolakoğlu Kimya A.Ş.

### Table 4. Chemical analysis of metallurgical coke

<table>
<thead>
<tr>
<th></th>
<th>( \text{C}_{\text{fix}} )</th>
</tr>
</thead>
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<td>( \text{C}_{\text{fix}} )</td>
<td>87.78%</td>
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<td>Ash</td>
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</tr>
<tr>
<td>Volatile</td>
<td>3.39%</td>
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<tr>
<td>Humidity</td>
<td>3.07%</td>
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</tbody>
</table>
4.2.1 Fixed Type Bed Furnace

The reduction reaction experiments were performed in a Protherm brand laboratory type fixed type bed furnace with a capacity up to 1500°C which is demonstrated in figure 11. Reaction environment provided by a closed one-sided steel retort placed in the furnace in order to obtain a homogeneously heated reaction environment. Raw materials were fed to the furnace system with a graphite boat. Temperature control in the reaction environment was done by using PtRh10/Pt thermocouple.

![Figure11. Protherm laboratory type fixed type bed furnace](image1)

4.2.2 Raw Material Preparation

EAF slag and metallurgical coke which were used in the experiments were grinded to desired particle size by using SIEBTECHNIK ring crusher. The slag powder was pelletized by a laboratory type 40 cm diameter pelletizing disk which is demonstrated in figure 12 to reduce the surface area and protect the specimen after reduction reaction from re-oxidation. Green pellets were dried in Heraeus drying oven.

![Figure12. Laboratory type 40 cm diameter pelletizing disk and pellets](image2)
4.2.3 Characterization

As characterization, chemical and optical methods were used. Chemical analysis was performed by Pelkin Elmer A800 Atomic Absorption Spectrophotometry (AAS), the phase analysis was done by PANalytical PW3040/60 XRD (X-Ray Diffraction) and elemental analysis of samples were done by Scientific NITON XL3t XRF (X-Ray Fluorescence). Microstructure analysis was obtained by using Nikon Microscope, and micro photos of the samples were taken with Nikon camera attached to microscope. In figure 10 the XRD analysis of EAF slag is given.

![XRD analysis of EAF slag](image)

**Figure 13.** XRD analysis of EAF slag

4.3 Design of Experiments

The study started with milling by using ring crasher of metallurgical coke and EAF slag to obtain the particle size homogeneity. Particle size distribution of grinded slag is given in graph 1. The powderized coke and slag were dried in drying oven at 105°C. The next step was to pelletize slag powder by using molass as binder. Molass was prepared to constitute of 5 mass percentage of slag and applied by a plastic spray. To make it possible the pelletizing, molass sprayed through the slag powder placed in an angular rotating disk. Once the pellets were become appropriate in size, the process was ended. The green pellets were dried in the drying oven for about 4 hours at 105°C. At the end of drying, pellets were become ready to be subjected to furnace experiments. Among the produced pellets, 17-20mm in size and 7-10 gr in weight pellets were chosen as appropriate for experiments.
In this study, effects of reduction temperature (1050 °C, 1100 °C, 1150 °C), reaction duration (0, 5, 10, 15, 30, 60, 90, and 120 minutes), and stoichiometric ratio of reducing agent (1.5 and 2.0 times of stoichiometrically required reducing agent) were examined to the metallization ratio of the final product.

![Graph](image.png)

**Graph1.** Particle size distribution of grinded slag

Each furnace experiment was started with preparation of reaction environment and inputs. Fixed type bed furnace was set to experiment temperature and time to keep the temperature fixed to required level. Raw materials were weighed by using Sartorius laboratory type balance with 0.1g accuracy. For each experiment set was done by selecting five pellets with total weight range 40-45 g and metallurgical coke calculated based on 1.5 and 2.0 times of stoichiometrically required amount. Raw materials were placed on graphite boat shown in figure 14 and fed to steel retort.

![Figure14. Graphite boat](image.png)
that was placed inside of the fixed type bed furnace what the furnace was reached to desired temperature. For each temperature and coke composition, seven different duration (5, 10, 15, 30, 60, 90 and 120 minutes) trials were applied. Each trial was exposed to furnace cooling for 30 minutes by dragging the graphite boat to the cold region of the retort that was approximately 700-550°C and then air-cooled. Experimental parameters are listed in the Table 5.

![Graphite boat and the reaction products after furnace experiment](image)

**Figure15.** Graphite boat and the reaction products after furnace experiment

Once the graphite boat and the reaction products shown in figure 15 were cooled to room temperature, they were weighed and saved for further studies. Three of obtained reduced pellets were crashed for chemical, XRD and XRF analysis. And the rest of two pellets were kept for microstructure analysis. During chemical analysis, metallic iron content in the product was calculated by using AAS device and total iron amount was found by titration. The XRD analysis was done with Cu-Kα X-ray tube, 20 angle between 5-90 ° and 0.04° angle rise. For each analysis was set to be completed in 45 minutes. For elemental analysis of the samples Thermo Scientific NITON XL3t XRF device with a capacity of 50kv voltage and 40 µA current was used. One of the pellets was cut into two pieces and bakalited to be subjected to microanalysis by optical microscope. Micro photos of the samples were taken with 10X, 20X and 50X magnifications.
### Table 5. Design of experimental parameters

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<th>Stoichiometry</th>
<th>Duration, min</th>
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<th>Temperature °C</th>
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</table>
5. RESULTS AND DISCUSSION

5.1 Experiment Parameters

The direct reduction experiments were based on temperature, duration and amount of reducing agent parameters in this study.

Temperature of experiments was decided by considering steel retort capacity which can handle 1500°C safely. On the other hand, the maximum temperature for direct reduction process is assumed as 1200°C due to pressure of the environment may cause to melting of the sample before its melting temperature. The minimum temperature value was decided according to the fact that below 1050°C, metallization will not be productive. Temperature difference was taken 50°C since the metallization differences may be observed clearly.

Amount of reducing was decided as 1.5 and 2.0 times of stoichiometrically required coke since stoichiometrically calculated amount may not be enough to provide the required reducing environment. To examine the differences on the results easier, range between the amount of reducing agent designed as 1.5. Over 2.0 times of stoichiometrically required coke would be effective only to reduce the time of reducing and has on negative effect on feasibility of the experiment set to the real life practices, therefore higher amounts than 2.0 times was not included in the experiments. As the reducing agent, metallurgical coke which has high fix carbon, low volatile and low ash content was decided as best for experiments.

5.2 Chemical Analysis Results

Evaluation of chemical analysis results were based on the metallization degrees of the samples that was calculated by using the equation given in Eq.16.

\[
\% \text{ Metallization} = \frac{\% \text{ Metallic Iron}}{\% \text{ Total Iron}}
\]  
(Eq.16)

Metallization degree that was calculated according to equation in the expression increases by increasing metallic iron ratio in the sample. Metallic iron increases by reducing the oxide phases
containing iron in the sample. Metallic iron and iron amount in the oxide phase distribution is shown in the graphs 2-7.

**Graph 2.** Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 1.5 times stoichiometrically required coke addition at 1050°C

**Graph 3.** Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 2.0 times stoichiometrically required coke addition at 1050°C
**Graph4.** Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 1.5 times stoichiometrically required coke addition at 1100°C

**Graph5.** Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 2.0 times stoichiometrically required coke addition at 1100°C
Graph 6. Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 1.5 times stoichiometrically required coke addition at 1150°C

Graph 7. Metallic iron, 2 and 3 valency iron distribution in the samples prepared with 2.0 times stoichiometrically required coke addition at 1150°C

5.2.1 Effect of Experiment Temperature

In order to observe the effect of temperature on reduction, experiments were categorized due to reducing agent amount of the experiments.
5.2.1.1 Comparison of experiments that was performed by 1,5 times stoichiometrically required metallurgical coke

Graph 8 demonstrates the comparison of samples that include 1,5 times stoichiometrically required metallurgical coke experiments performed in 1050 °C, 1100 °C and 1150 °C.

Graph 8. Metallization degree of include 1,5 times stoichiometrically required metallurgical coke samples with respect to temperature and duration.

Metallization trend of the three temperatures with respect to duration observed as the trend of metallization is similar for the all samples. For all temperatures 5, 10 and 15 minutes were not enough for a proper reducing reaction. After 15 minutes metallization occurs faster till 60th minute and starts to decrease from then on. The best metallization was observed at the 90th minute for the all three temperatures. From 90th to 120th minute it was seen that metallization degree decreases due to lack of reducing agent that was lost because of the semi-closed furnace design. Except the 5th minute step of the results of 1150°C were given the highest metallization among the other temperature sets. The highest metallization degree of these three temperature sets were recorded as: 52.3% for 1050°C, 67.6% for 1100°C and 72.8% for 1150°C.
5.2.1.2 Comparison of experiments that was performed by 2,0 times stoichiometrically required metallurgical coke

Graph 9 demonstrates the comparison of samples that include 2,0 times stoichiometrically required metallurgical coke experiments performed in 1050 °C, 1100 °C and 1150 °C.

Graph9. Metallization degree of include 2,0 times stoichiometrically required metallurgical coke samples with respect to temperature and duration.

Even though the metallization trend in the samples containing 2,0 times stoichiometrically required metallurgical coke is similar to the samples prepared with 1,5 times stoichiometrically required metallurgical coke there are some difference between the them. In the first 5 minutes of the metallization occur in the similar trend for three temperatures but 5th to 30th minutes of experiment, the metallization degree increases with different accelerations. From 30th to 120th minutes of the experiments metallization values for each temperature have become close to each other. As similar to 1,5 times stoichiometrically required metallurgical coke added samples the highest metallization was observed in the 90th minute for each temperature. The highest metallization degree of these three temperature sets were recorded as: 88,8% for 1050°C, 85,3% for 1100°C and 90,3% for 1150°C.

The reason of achieving higher metallization degree by increasing the experiment temperature is interpreted by obtaining faster diffusion and chemical reactions by increasing temperature.
Besides, heat necessary for reduction reaction and gasification of solid reducing agent is provided easier at higher temperatures.

5.2.2 Effect of Reducing Agent Amount

To examine the effect of reducing agent amount metallization ratio of the samples prepared by using same amount of reducing agent at the same temperature. Graph 10, 11 and 12 indicate the metallization comparison of 1,5 and 2,0 times stoichiometrically required metallurgical coke added experiment results for each temperature. For each temperature set dependence of reducing agent amount is similar to one another. In the first 30 minutes, no difference was observed in the metallization degree between 1,5 and 2,0 times stoichiometrically required metallurgical coke added samples. After 30th minute, reduction rate was increased in the samples prepared with include 2,0 times stoichiometrically required metallurgical coke metallization and observed higher metallization degree than the samples containing 1,5 times stoichiometrically required metallurgical coke. Reduction rate difference between 1,5 and 2,0 times stoichiometrically required metallurgical coke added experiments were observed higher at lower temperatures and increases by increasing temperature.

Enhanced reducing agent amount was provided higher reducing effect by increasing the solid reductant to be used in the reducing environment for reactions. It was thought that increased reducing agent amount has a positive effect on chemical reactions and diffusion. The reason of having a significant effect of enhanced reducing agent amount at lower temperatures has been thought as insufficient gasification in the furnace atmosphere at low temperature and compensation by increased amount of reducing agent.
Graph10. Metallization comparison of 1,5 and 2,0 times stoichiometrically required metallurgical coke added experiment results at 1050°C.

Graph11. Metallization comparison of 1,5 and 2,0 times stoichiometrically required metallurgical coke added experiment results at 1100°C.
5.3 XRD Results

Phase analysis and dependence of phases on duration was examined by subjecting the all samples to XRD analysis. Evaluating the chemical analysis results and XRD analysis together has a crucial importance to proving the experiments had consistent values. The detected phases were marked on the each XRD analysis result graph in order to provide clear understanding.

5.3.1 Dependence of Phases in the Samples on Duration

XRD analysis results indicate that reduction reaction was occurred in steps and the phase transformation was observed starting from iron oxide phase with higher valency to lower valency and ended as metallic iron phase. In order to demonstrate the phase transformations depending on duration, XRD analysis result curves with same temperature and reducing agent amount samples were shown in the same diagram as given in graph 13-18.
Graph13. Phase transformations depending on duration of the samples at 1050°C with 1,5 times stoichiometrically required coke addition

Graph14. Phase transformations depending on duration of the samples at 1050°C with 2,0 times stoichiometrically required coke addition

Graph15. Phase transformations depending on duration of the samples at 1100°C with 1,5 times stoichiometrically required coke addition
Graph 16. Phase transformations depending on duration of the samples at 1100°C with 2,0 times stoichiometrically required coke addition

Graph 17. Phase transformations depending on duration of the samples at 1150°C with 1,5 times stoichiometrically required coke addition

Graph 18. Phase transformations depending on duration of the samples at 1150°C with 2,0 times stoichiometrically required coke addition
As seen in the graph 13-18, increasing process duration has a positive effect on reduction reaction. Except the in the set of 1,5 times stoichiometrically required metallurgical coke added samples at 1050°C, hematite phase was not much enough to detected by XRD. At the higher temperatures it was observed that hematite phase was reduced fast at the beginning of reduction to wustite phase. After 10th minute of the reduction a significant phase transformation can be seen clearly. The highest metallic iron was detected at 90th minute for all sets and slightly lower metallization was observed at the 120th minute samples. There was no change observed on the remaining oxide phases existed in EAF slag.

5.3.2 Effect of Temperature

In order to examine effect of temperature on phase transformation the samples that have same parameters except for temperature were combined. Among the combined results the clearest one was chosen to interpret the temperature effect on phase transformation between iron containing oxides and metallic iron.

5.3.2.1 Comparison of experiments that was performed by 1,5 times stoichiometrically required metallurgical coke

Graph19. Temperature comparison of three samples prepared with 1,5 times stoichiometrically required metallurgical coke at 60th minute

Graph 19 shows the comparison of three samples prepared with 1,5 times stoichiometrically required metallurgical coke and subjected to three different temperatures for 60 minutes. As demonstrated in the graph increasing temperature leads to an increase on metallic iron phase and
decrease in wustite phase. Hematite could not be detected by XRD analysis at 60th minute for all temperatures due to low amount of hematite at that time. Metallic iron peak was stated as the highest peak for all three temperatures at 60th minute for samples prepared with 1,5 times stoichiometrically required metallurgical coke. There was no change observed on the remaining oxide phases existed in EAF slag.

5.3.2.2 Comparison of experiments that was performed by 2,0 times stoichiometrically required metallurgical coke

Graph 20 shows the comparison of three samples prepared with 2,0 times stoichiometrically required metallurgical coke and subjected to three different temperatures for 60 minutes. As indicated before, graph increasing temperature leads to an increase on metallic iron phase and decrease in wustite phase. No hematite phase was detected in XRD analysis of samples subjected to reduction environment for 60 minutes. Difference between intensities of metallic iron peaks at 60th minute was not significant for the samples prepared with 2,0 times stoichiometrically required metallurgical coke as observed in samples prepared with 1,5 times stoichiometrically required metallurgical coke since higher amount of reducing agent compensates the lack of necessary heat for reactions, therefore it was evaluated at 1050°C and 1100°C it can be possible to achieve metallization as high as at 1150°C.

Graph20. Temperature comparison of three samples prepared with 2,0 times stoichiometrically required metallurgical coke at 60th minute
High metallization degree, metallic iron peak intensity and low wustite peak intensity that has been observed in the samples subjected to higher temperature and reducing agent amount verify the reliability of the results obtained from chemical analysis. Relatively higher intensity of metallic iron peak than iron oxide peaks verifies the idea that higher temperature leads to better metallization performance.

5.4 Optical Analysis Results

By optical analysis metallic iron formation and distribution inside the samples was aimed to examine. For that purpose the samples were cut into two pieces and inside surface of the each sample examined under microscope with using 5X, 10X, 20X and 50X magnification. Since the samples were consisted of majorly oxides, the required surface finish could not be provided during sample preparation. For comparative analysis it was seen that the best option among the micro photos was the one was taken with 20X magnification.

5.4.1 Dependence on Duration

To be able to interpret effect of experiment duration on the metallization, 20X magnified micro photos of samples prepared with 2,0 times stoichiometrically required metallurgical coke and subjected to 1150°C process temperature for 5, 10, 15, 30, 60, 90 and 120 minutes which is demonstrated in Figure 11.

![Figure16. 20X magnified micro photos of samples with 2,0 stoichiometrically added coke and 1150°C](image)
Metallic iron can be distinguished visually from slag content due to shiny silver color of metallic phase. At the 5th minute metallic iron was only seen as small spots close to the edge of the surface. By increasing duration, metallic iron regions were started to become more visible and distributed on the sample surface. There until 30th minute dark areas were dominating the microstructure but after 60th minute shiny silver metallic iron regions significantly fade in and relatively distributed homogeneously compared to samples that were exposed to reduction less than 30 minutes. Having larger metallic iron regions spread on the sample surface verifies the increase in metallization degree by enhancing process duration. In addition, after 60th minute, the micro photos could be taken with relatively in a better quality. This phenomena was correlated to increased metallic iron content in the sample had provided a better surface preparation.

5.4.2 Effect of Temperature and Reducing Agent Amount

20X magnified micro photos of the samples that were subjected to reduction for 90 minute are given in figure 12 to be able to compare the temperature and stoichiometry effect on the samples. The micro photos is given in a row from left to right hand side for comparison of temperature and sorted tow by two from up to down for stoichiometrical difference effect in the samples. For both stoichiometries, changes in microstructure in the photos were observed depending on temperature increase. While shiny silver areas are few in the photos of 1050°C, significant increase in metallic iron areas can be observed in the micro photos of 1150°C. Correlation between metallic iron content and sample surface preparation that was mentioned in the previous section, still valid for given photos and increased metallic iron content was made easier to provide micro photos of samples.

However, when the micro photos were examined two by two in order to compare stoichiometry change of samples, reduction was occurred in a better efficiency by increased stoichiometry at each three different temperatures. In addition, metallic iron areas became enlarged in the samples prepared with 2,0 times stoichiometrically added coke with respect to samples prepared with 1,5 times stoichiometrically required coke addition.
Figure 17. 20X magnified micro photos of samples at 90th minute
6. CONCLUSIONS

Direct reduced iron production from EAF slag under different duration, temperature and reductant stoichiometry parameters in a fixed type bed furnace. Samples that were obtained from the furnace experiments subjected to chemical analysis to calculate metallic and total iron amount in the samples. Chemical analysis results were supported with XRF analysis. In order to define the phases in the samples, XRD studies were performed on each sample. To be able to examine the distribution of metallic iron, the samples were cut into two pieces and observed under optical microscope. Depending on the analysis results effect of experiment parameter on direct reduction conditions were observed which are summarized below.

1. 40% iron oxide containing EAF slag was used in production of DRI with carbo-thermic reduction reactions in fixed type bed furnace were observed and it was seen that high degree of metallization can be achieved.

2. The experiment parameters were defined as follows: 1050°C, 1100°C and 1150°C as temperature, 5, 10, 15, 30, 60, 90 and 120 minutes duration steps and 1,5 and 2,0 times of stoichiometrically required coke. These parameters were combined for each sample by keeping the two of the variables dependent and one independent to be able to observe how the each parameter affects the reduction.

3. The temperature studies on metallization of iron oxide in EAF slag was indicated that increasing temperature has a positive effect. For each samples with different duration and stoichiometry, the positive effect of temperature was clearly observed. The increase in reduction with increasing temperature was a result of achieving faster chemical reactions and diffusion.

4. Effect of stoichiometry increase on metallization observed as when the coke stoichiometry changed from 1,5 to 2,0 times than the metallization efficiency increased significantly.

5. Duration trials showed that longer time durations have an effect on increasing metallization degree. While 5, 10 and 15 minute steps were not enough for a feasible metallization at different temperature and stoichiometry, after 30 minute step a significant change in metallization was examined. The best metallization result for the experiment was observed at
the 90th minute step and after that a decrease was occurred due to lack of carbon environment since the experiment was not performed in a fully isolated furnace set.

6. The best metallization result obtained from the sample that was prepared with 2.0 times stoichiometrically required coke and subjected to 1150°C for 90 minute. The result of this experiment set was 90% metallization in the sample.

7. The XRD analysis results demonstrated the iron containing phase chance from oxide to metallic iron. When the XRD results compared to chemical analysis results, the obtained metallic and total iron from chemical analysis verified each other.

8. Magnetic separation of metallic and non-metallic parts and evaluation of both of them is suggested for the further studies.

9. It is expected to achieve high metallization efficiency at lower amount of carbon addition with rotary furnace experiments under controlled atmosphere.
7. REFERENCES


6. EUROSLAG, The European Association Representing Metallurgical Slag Producers and Processors, 2010


34. http://healthyhay.vt.tuwien.ac.at/division/project.php?project_id=43

35. http://ietd.iipnetwork.org/content/slrn-process


8. APPENDICES

Table A.1. Chemical analysis results of samples prepared with 2.0 times stoichiometrically coke addition at 1150°C

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**Table A.3.** Chemical analysis results of samples prepared with 2,0 times stoichiometrically coke addition at 1100°C

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**TABLE A.4.** Chemical analysis results of samples prepared with 1,5 times stoichiometrically coke addition at 1100°C

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