CHAPTER II
LITERATURE REVIEW

2.1 Iron

Iron (Latin: ferrum, Fe) is the most common element in the whole planet Earth. Iron metal has been used since ancient times. Pure iron is soft. Crude iron, known as iron ore, is reduced by coke to cast iron. Further refinement with oxygen reduces the carbon content which makes steel.

2.2 Iron Ore

Iron ore is a rock with minerals from which metallic iron can be economically extracted. It is usually rich in iron oxides and exists in many colors from dark grey, bright yellow, deep purple, to rusty red (shown in Figure 2.1).

Figure 2.1 Hematite: the main iron ore.

Iron ore can be found in many types such as Magnetite (Fe_3O_4), Hematite (Fe_2O_3), Goethite ($FeO(OH)$), Limonite ($FeO(OH).n(H_2O)$) and Siderite ($FeCO_3$). Hematite is known as "natural ore" and containing up to 66% iron. Iron ore is the raw materials, which makes a pig iron, which is used to produce steel.

2.2.1 Grade of Iron Ore (Ranawat, 2008)

Iron ore can be classified into 3 grades:

1. High grade is containing iron more than 65%
2. Medium grade is containing iron between 62% to 65%

3. Low grade is containing iron less than 62%

2.3 Ironmaking Technology (Rutherford, 2009, Negami, 2001)

The coal-based reduction technology has been developed the method of making iron from iron ore into 3 generations namely:

2.3.1 Ironmaking Technology Mark 1, ITmk1

ITmk1 is the first generation known as the "Heatfast" using a blast furnace, as developed and tested by National Steel Corp. In a blast furnace, a fuel and an iron ore are supplied from the top of the furnace, while hot air is blown into the bottom of the chamber, the chemical reaction takes place which produces a molten metal and a slag, the latter is tapped from the bottom, and flue gases exit from the top of the furnace.

2.3.2 Ironmaking Technology Mark 2, ITmk2

ITmk2 is the second generation known as gas-based direct reduction. Direct-reduced iron, also called sponge iron, is produced from the direct reduction of iron ore by a reducing gas, with a majority of Hydrogen (H_2) and Carbon Monoxide (CO), which are produced from a natural gas producing coal. The process reduces the iron ore in a solid form and produces sponge iron as the product.

2.3.3 Ironmaking Technology Mark 3, ITmk3

ITmk3 is the third generation of ironmaking developed by Kobe Steel and Midrex. ITmk3 is a unique process technology since it ventures into a new area in the Fe-C diagram (shown in Figure 2.2). Carbon composite pellets are reduced and melted at a relatively low temperature around 1,350°C and the hot metal is easily separated from the slag. The ITmk3 reaction can be found in the solid/liquid co-existence phase. Melting occurs after the reduction, and the residual FeO is less than 2%. Therefore, there is no FeO damage to the refractory (Negami, 2001).

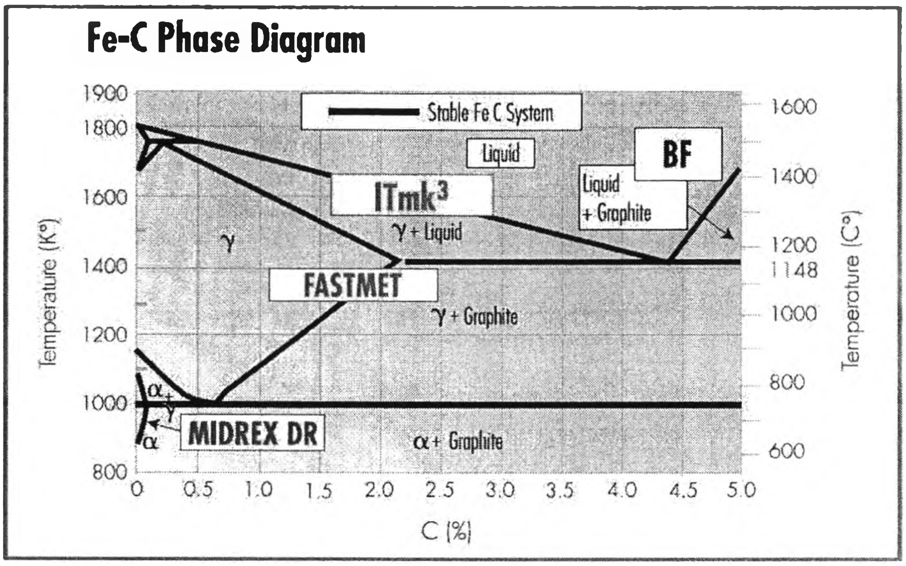

Figure 2.2 Fe-C Phase Diagram (Negami, 2001).

2.4 Reactions in ITmk3 Process

The final goal of ITmk3 is to produce a molten iron directly from a fine ore and a coal through a one-step process. In the reduction stage, two reactions take place inside the pellet

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \quad (1)$$

$$CO_2 + C \rightarrow 2CO \quad (2)$$

Reaction (2) is endothermic, activated at temperatures over 1,000°C. While reduction is most active over 1,000°C, the required reaction heat balances the heating rate from the furnace, so that the pellet temperature is kept constant. When the reduction degree reaches 95 percent, a temperature drop in the iron is observed. Using this reaction mechanism and a FASTMET-type RHF reactor with a carbon composite iron ore pellet as the raw material, ITmk3 produces an iron nugget product in a solid form which is similar to a pig iron (Negami, 2001).

2.5 ITmk3 Process Features

ITmk3 use iron ore fines and a non-coking coal, thus avoiding the need for oxide pellets or a sintering and a coke. It is simple, performing the reduction and the melting functions within one vessel, the rotary hearth furnace, RHF (shown in Figure 2.3).

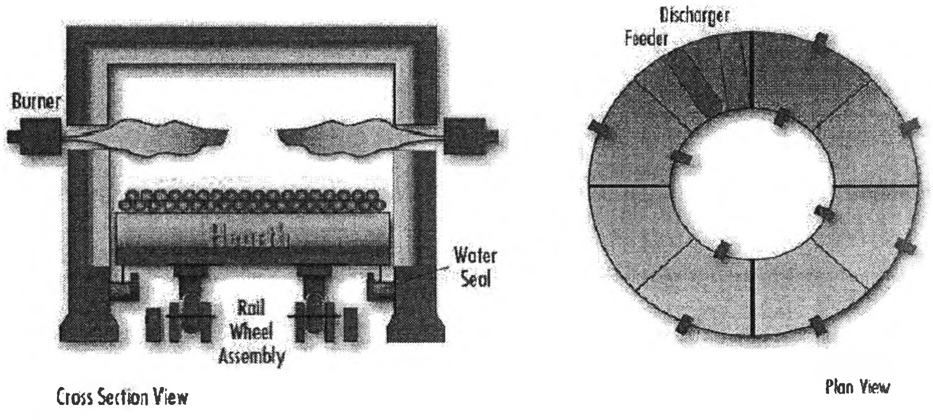

Figure 2.3 Rotary heart furnace (RHF) details.

Figure 2.3 shows the RHF. The hearth is essentially a large turntable that rotates within a toroidal enclosure. The feed pellets are charged to the hearth, one to two layers deep, and as they move on the hearth they are heated by burners firing above the hearth and by combustion of gases liberated from the pellets. The pellets are melted in the last zone of the hearth to produce a high quality pig iron product, plus slag.

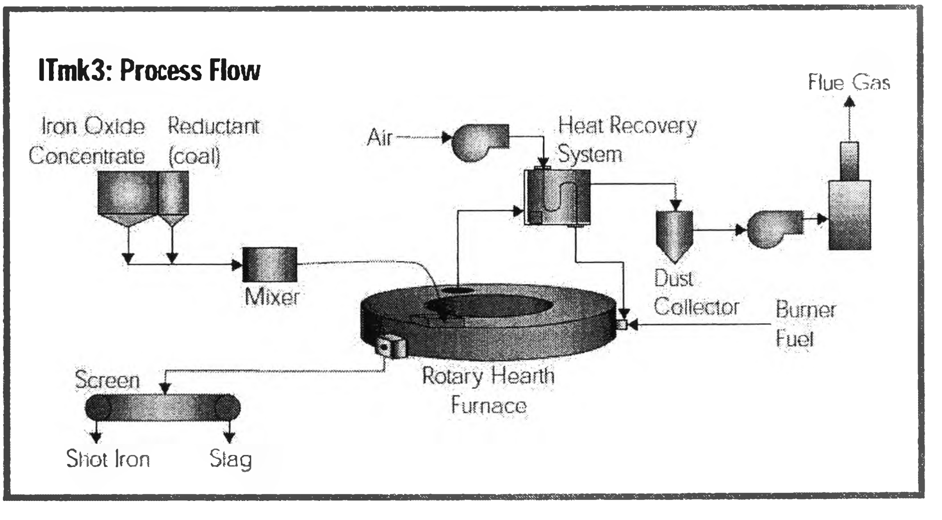

Figure 2.4 ITmk3 process flowsheet.

Figure 2.4 shows the flowsheet of the ITmk3 process. The process begins with mixing of an iron ore concentrate and a fine coal. They are pelletized, dried, and fed into the RHF. The pellets are reduced and melted in less than ten minutes. The final step is the separation of the iron nuggets and the slag. During the reduction, volatiles from the coal and CO produced from the reduction evolve into the gas space above the hearth and are combusted with air. The heat thus generated, plus the heat from the burners, provide the energy required for the reduction and the melting (Negami, 2001, Rutherford, 2009, MIDREX, 2009).

2.6 Product Features

ITmk3 nuggets are an ideal steelmaking feed material. They are essentially all iron and carbon, with almost no gangue (slag) and have low levels of metal residuals. The nuggets are a premium grade pig iron product with superior shipping and handling characteristics. They can be shipped in bulk inland or on oceangoing vessels, railcars, or trucks, and stored outside with no special precautions. They can be handled as a bulk commodity using conventional magnets, conveyors, bucket loaders, clams, and shovels. Charging to an EAF, BOF, or foundry furnace can be batch or continuous (Rutherford, 2009).

2.7 Environmental Advantages

ITmk3 also has environmental advantages versus the blast furnace, including lower energy consumption and reduced emissions of CO_2, other gases, and particulates. CO_2 emissions are 20 percent less than traditional ironmaking methods and 30 percent less per ton of iron product shipped (Negami, 2001).

2.8 Iron Nugget Production

Anameric and Kawatra (2004) studied the production and the properties of pig iron nuggets. Pig iron nuggets were produced in a laboratory scale furnace at Michigan Technological University. These nuggets were produced from pellets consisting of a mixture of iron oxide, coal, flux, and a binder, which are heated to 1450°C. These pellets then self-reduced to produce a solid, high-density, highly metallized (96.5% Fe) pig iron. During the nugget production process, a separate slag phase formed that cleanly separated from the metal. The physical and chemical properties of the pig iron nuggets are similar to the pig iron produced by blast furnaces, which is distinct from the Direct Reduced Iron (DRI).

Kobayashi, Tanigaki and Uragami (2010) studied a new process to produce iron directly from an ore and a coal. An innovative ironmaking process, which can produce iron nuggets directly from a fine ore and a coal. The key feature was the separation of the metal and the slag with a rapid reaction rate and at a relatively lower operation temperature such as 1,350°C. The reaction mechanism was investigated in details by the laboratory experimental furnace and the mass behavior was examined using the box furnace which has two heating chambers. In order to confirm the process concept and to industrialize the technology, a pilot plant of the type of rotary hearth furnace was constructed. The pilot plant was operated through 6 months and iron nuggets were successfully produced.

Anameric, Rundman, and Kawatra (2005) studied the carburization effects on pig iron nugget making. The iron nugget process is a single step and environmentally friendly cokeless process. Residence time and dependent process requirements for the production of pig iron nuggets at a fixed furnace temperature 1425°C were investigated. Three chemically and physically different products were produced after the complete reduction to iron, depending on the residence time in the furnace. These products were a direct reduced iron (DRI), transition direct reduced iron (TDRI), and pig iron nuggets (PIN). The increase in the carbon content of the system as a function of residence time was detected by the optical microscopy and the microhardness measurements. Sufficient carbon dissolution for the production of pig iron nuggets was obtained after 40 minutes of the residence time. The pig iron nuggets produced had chemical and physical properties similar to the blast furnace pig iron. They were liquid state products and slag was completely separated from the metal.

Iwasaki, Lalich, Beaudin, Kiesel, Lindgren, and Bleifuss (2006) studied the method and the system for producing metallic iron nuggets. The method included providing a reducible mixture (e.g., reducible micro-agglomerates; reducing material and reducible iron bearing material; reducible mixture including additives such as a fluxing agent; compacts, etc.) on at least a portion of a hearth material layer. In one embodiment, a plurality of channel openings extended at least partially through a layer of the reducible mixture to define a plurality of nugget forming reducible material regions. Such channel openings may be at least partially filled with nugget separation fill material (e.g., carbonaceous material). Thermally treating the layer of reducible mixture resulted in the formation of one or more metallic iron nuggets. In other embodiments, various compositions of the reducible mixture and the formation of the reducible mixture provided one or more beneficial characteristics.

Anameric and Kawatra (2007) studied on conditions for making a direct reduced iron, transition direct reduced iron and pig iron nuggets in a laboratory furnace. The pig iron nugget process is gaining its importance as an alternative to the traditional blast furnace route. Throughout the process, self-reducing–fluxing dried greenballs composed of an iron ore concentrate, a reducing-carburizing agent (coal), a flux (limestone) and, a binder (bentonite) were heat-treated. During the heat treatment, dried greenballs were first transformed into the direct reduced iron (DRI), then to the transition direct reduced iron (TDRI), and finally to the pig iron nuggets. The furnace temperature and/or residence time and the corresponding levels of the carburization, the reduction and the metallization dictated these transformations. This study involved the determination of threshold furnace temperatures and residence times for completion of all of the transformation reactions and pig iron nugget production. The experiments involved the heat treatment of self-reducing–fluxing dried greenballs at various furnace temperatures and residence times. The products of the heat treatments were identified by utilizing the optical microscopy, the apparent density and the microhardness measurements.

Mohapatra and Patra (2009) studied the reduction behavior of iron ore lumps. Studies on chemical and physical properties, and the reduction behavior (in coal) of hematite iron ores, as procured from ten different mines of Orissa, were undertaken to provide information to the iron and steel industries (sponge iron plants in particular). Majority of the iron ores were found to have high iron and low alumina and silica contents. All these iron ores were free from the deleterious elements (S, P, As, Pb, alkalies, etc.). The results indicated lower values of shatter and abrasion indices, and higher values of tumbler index in all the iron ore lumps except Serazuddin (previous) and KhandaBandha OMC Ltd.. For all the fired iron ore pellets, the degree of reduction in coal was more intense in the first 30 minutes after which it became small. Slow heating led to a higher degree of reduction in fired pellets than rapid heating. All the iron ores exhibited more than 90% reduction in their fired pellets in 2 hours' time interval at a temperature of 900°C. Iron ore lumps showed a lower a degree of reduction than the corresponding fired pellets.

Anameric and Kawatra (2007) studied the microstructure of the pig iron nuggets. The pig iron nugget process (referred to as the Iron Technology Mark 3, or ITmk3, process by Kobe Steel) was developed as an alternative to the traditional blast furnace process. Throughout this process of self reducing– fluxing dried greenballs were reduced and smelted in to nuggets of metal. The objective of this research was to produce pig iron nuggets at a laboratory scale, then to characterize and to compare them with the blast furnace pig iron. Pig iron nuggets were characterized utilizing the apparent density measurement, the optical microscopy, the scanning electron microscopy with energy dispersive spectroscopy, and the bulk chemical analysis. It was determined that pig iron nuggets had a high apparent density (6.7–7 g/cm3); had a high iron content (95–97%); and exhibited microstructures similar to white cast iron, which is essentially the same as pig iron from a blast furnace.

Anameric and Kawatra (2007) studied the transformation mechanisms of self-reducing fluxing dried greenballs into pig iron nuggets. Pig iron nuggets, which have similar chemical and physical properties with the blast furnace pig iron, were produced by a single step heat treatment of self-reducing – fluxing dried greenballs. During this single step heat treatment, the transformation of self-reducing fluxing dried greenballs into pig iron nuggets did not take place instantaneously. Rather, it was composed of three transformation stages: (1) transformation of self-reducing – fluxing dried greenballs into direct reduced iron (DRI): (2) transformation of DRI into transition direct reduced iron (TDRI): and (3) transformation of TDRI into pig iron nuggets. Thus, the objective of this research was to investigate these transformation mechanisms by analyzing the transformation stage products. The transformation stage products were produced at a constant furnace temperature of 1425°C and various furnace residence times. They were characterized according to their microstructures, the microhardness and the apparent density. The changes in the product's physical and chemical properties with furnace residence time were utilized in understanding the transformation behavior, the chemical events that took place and the controlling mechanisms. It was determined that the transformations were dictated by the changes in the slag viscosity and wetting properties, and by carbon diffusion into metallized areas.

2.9 Direct Reduction

Kikuchi, Tokuda, and Kobayashi (2004) studied the production method of metallic iron. A method producing metallic iron by reducing raw materials including an iron-oxide containing material and a carbonaceous reducing agent under heating. which can minimize the re-oxidation of the metallic iron and can efficiently produce metallic iron having a high metallization ratio and high iron purity at high yield. The method produced a metallic iron, by heating raw materials including a carbonaceous reducing agent and an iron-oxide containing material in a reduction melting furnace of the moving hearth type, and reducing and melting iron oxides in the raw materials. The reduction melting furnace is partitioned into at least three zones in a hearth moving direction. One partitioned zone upstream in the hearth moving direction is a solid-state reducing zone, one downstream partitioned zone is a carburization melting zone, where a reduction aging zone is between the solid-state reducing zone and the carburization melting zone.

Seki, Tanaka (2008) developed an iron and steel making technique by applying coal based processes: FASTMELT and ITmk3.Raw material prices, such as iron ore, scrap and pig iron are currently high and climbing steadily. A construction of an integrated iron and steel complex generally takes a long lead time for the preparation and needs a huge investment cost. Further, such kind of mass production model may not work as it used to be, under the present iron ore and cokes market situation. On the other hand, though mini/small-blast furnace seems to be competitive in the initial investment cost, it is not an efficient system for the operation from the long term view point and for the sustainable development of the iron and steel industry considering the environmental impacts. Two RHF based processes, namely ITmk3 and FASTMELT, are outstanding technologies which may give solutions to the South East Asian region by considering the indigenous characters of each country.

Kim, Lee, and Sasaki (2010) studied on enhancement of iron melting rate under the co-existence of graphite and Wustite. Carburization and melting processes of solid Fe under the co-existence of Graphite and Wustite were investigated based on a confocal laser scanning microscope "*in-situ*" observation of the movement of the interface between Fe–C melt and solid Fe at 1523 K. In the experiments, strong stirring flow at the surface of the Fe–C melt is observed. This flow was found to be Marangoni flow and was introduced by the surface tension gradient due to the difference of oxygen concentration between the Fe–C melt interface with graphite and solid iron. The velocity of the Marangoni flow was measured from the moving velocities of bubbles at the molten Fe–C surface. The melting rate of Fe was analyzed by computational fluid flow simulations of the Fe–C melt. Based on these results, it was confirmed that the carburization and the melting rate of solid Fe can be enhanced by allowing Fe–C melt to come into contact with Wustite and Graphite simultaneously.