ITmk3® Process

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The ITmk3 process, which produces high-quality iron (ITmk3 iron nuggets) from ore fines and coal fines, was developed based on a unique concept of iron ore and carbon composite technology. The development started in 1996, followed by test operations at a pilot plant and large-scale pilot plant. The first commercial plant was constructed in the U.S. and has started producing iron nuggets. This article outlines the history of the development, the features of the process, the product, and the future outlook.

Introduction

ITmk3 (pronounced as "[ai ti:] mark three") is a rapid ironmaking process that includes reducing ore, carburizing & melting iron and separating slag, all at relatively low temperatures.

Referring to generation classes of ironmaking processes, the first generation would be the blast furnace (BF) process, which is the current mainstream. The second is the direct reduction ironmaking (DRI) process as typified by the MIDREX process. ITmk3 (Ironmaking Technology Mark 3) falls in the third generation category; it is a process based on a concept totally different from those of the earlier generations. In the ITmk3 process, a series of reactions occur within about 10 minutes. The reactions occur much faster in this process than in BF and DRI processes. In a typical BF process, raw materials dwell in a furnace for about 8 hours, while in the MIDREX process, the materials stay in a shaft furnace for 6 hours.

1. Developmental background

Blast furnace processes require pretreatments such as producing coke from coking coal and preparing sinter from iron ore. Thus, an integrated steel mill with a blast furnace must have a capacity greater than 10,000 tonnes/day to be feasible. This limits the types of resources, such as raw materials, that can be used. The production may also lack in flexibility. Direct reduction ironmaking processes using natural gas, on the other hand, are limited as to plant locations. DRI plants can be built only in areas where natural gas is produced at a low cost.

Thus, the industry has focused on new processes that utilize the abundant reserves of fine ore and fuel coal. In the 1980s, various attempts were made to develop a new process, including the smelting reduction process. With this background, Kobe Steel and its US subsidary, MIDREX Technologies, Inc., developed a process called FASTMET, which produces reduced iron by heating agglomerates consisting of fine ore and coal.

In 1995, when developing the FASTMET process, the companies found that metallic iron can be separated from slag within ten minutes of heating. This reaction principle was adapted for a new ironmaking process, ITmk3. This paper describes the details of the new process.

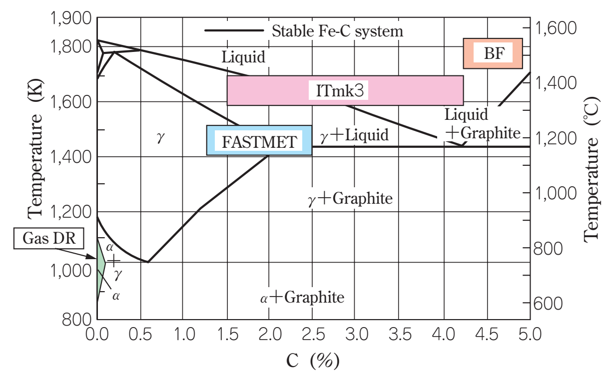


Fig. 1 Operational region of ironmaking processes

Fig. 1 is the iron-carbon phase diagram, which compares the operational regions of ironmaking processes, including ITmk3. The blast furnace (BF) process produces pig-iron saturated with carbon at a temperature around 1,500℃, while ITmk3 produces metallic iron with higher purity at a temperature lower than that required for BF.

2. Basic research

Kobe Steel began to study a new ironmaking process in 1996. Using a tube furnace installed at the Iron & Steel Research Center (Kakogawa Works, Kobe Steel), the company found that metallic iron grows rapidly, being separated from slag, at a relatively low temperature. **Fig. 2** shows this phenomenon occurring in the tube furnace. After this result was reported and became the subject of repeated discussions among researchers, domestic and overseas, the conclusion was reached that this was an unprecedented phenomenon. The new ironmaking process was called ITmk3.

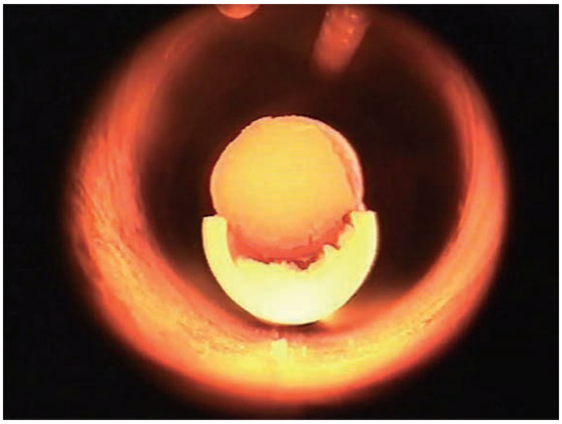


Fig. 2 Inside view of tube furnace

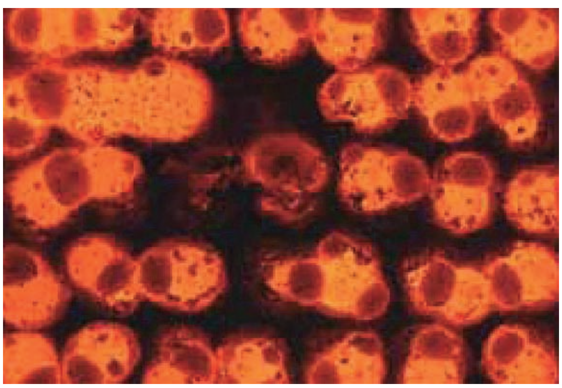


Fig. 3 Hot samples of box-type furnace test

The company initiated collaborative research involving universities and institutes, domestic and overseas, and installed a box-type furnace at the Iron & Steel Research Center to conduct experiments on a larger scale. **Fig. 3** shows hot samples discharged from the box furnace. Metallic iron has a bright orange color, while slag appears in dark orange, showing they are clearly separated from each other. Tohoku University and Tokyo Institute of Technology conducted research to elucidate the reaction mechanism of this new ironmaking phenomenon[1), 2)]. University of Surrey, in the UK, conducted research on heating methods, using a large multi-stage box furnace newly installed at their site (**Fig. 4**). Max Planck Institute in Germany studied the equation modeling of the reactions[3)].

The reaction between iron ore and coal remains the same as that for general ironmaking and is expressed as follows:

$$Fe_xO_y + yCO = xFe + yCO_2 \quad \cdots\cdots (1)$$

$$CO_2 + C = 2CO \quad \cdots\cdots (2)$$

$$C(s) = C\ (\text{carburized}) \quad \cdots\cdots (3)$$

$$Fe(s) = Fe(l)\ (\text{melt}) \quad \cdots\cdots (4)$$

Reactions (1) and (2) occur in the FASTMET process. In the ITmk3 process, there are the additional reactions (3) and (4), which separate metallic iron from slag.

Fig. 4 Test furnace at Surrey University

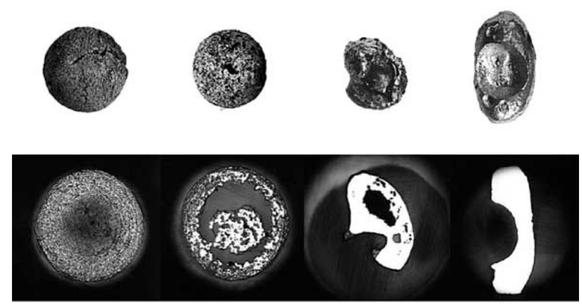


Fig. 5 ITmk3 reaction mechanism

In this new ironmaking process, particles of iron ore and coal exist next to each other in each agglomerate. This is in contrast with the BF and DRI processes, which use bulky materials such as iron ore and coke, and may explain the fast reaction of the new process to some extent. However, this does not fully explain the rapidity of the reactions.

Another series of experiments, conducted at the Kobe Steel Iron & Steel Research Center, confirmed a similar phenomenon. In these experiments, typical ores and coals, four types each, were combined and were heated in a box furnace. A study was conducted to clarify the effect of raw materials, temperature and furnace atmosphere on the reactions. Another study was conducted to elucidate the reaction mechanism. This study involved investigating the cross sections of agglomerates in the stages of reducing, melting and slag-separating, respectively. **Fig. 5** shows sample results of the cross-sectional study. During the first three minutes, the agglomerate, consisting of fine ore and coal, did not exhibit any significant change in appearance, despite the reduction reaction that should have occurred inside. After five minutes, the metallic iron and slag started to partially melt and became separated. In about six minutes, the entire agglomerate started to melt rapidly, with metallic iron being separated from the slag. After nine minutes, they had separated completely. University of Surrey conducted experiments to optimize this process reaction by separately controlling the reduction and melting. Separable control is a feature of their multi-stage box furnace.

In the reaction mechanism, the rapid carburizing phenomenon could not be explained by the conventional theories of gas carburization or solid carburization. Much time was devoted to elucidating the new carburizing phenomenon. Unlike the shaft furnaces used for DRI plants, the contribution of gas carburization is considered to be small. A recent study by Tohoku University found carburization via liquid slag[2)], which appears to contribute to the rapid carburization along with solid carburization.

Using the box furnace at the Iron & Steel Research Center, Kobe Steel tested over a hundred types of raw materials, which verified the versatility of the raw materials that can be used for the ITmk3 process. The tests included applicability tests on low grade materials, such as iron ore containing a large amount of crystal water, oil coke and upgraded brown coal (UBC). They confirmed the applicability of these low grade materials.

3. Application of new ironmaking method

3.1 Pilot plant

In parallel with the basic research, application studies were conducted on the new ironmaking process based on this unique carburization phenomenon. Among the various processes deliberated, granular ironmaking was chosen as the most feasible approach. Designing of a pilot plant began in 1998. Unlike box furnaces, in which reactions occur under ideal conditions, the pilot plant had many issues to be addressed. Process development was conducted to resolve these issues. **Fig. 6** shows the process flow of granular ironmaking. The process comprises

1) agglomerating iron-ore and coal (blue),
2) reducing and melting the agglomerates (red),
3) separating metallic iron from slag (green), and
4) treating exhaust and recovering heat (yellow).

The pilot plant employs a rotary hearth furnace, which facilitates radiation heating, to exploit the rapid reaction feature of ITmk3. In a smelting reduction process, melting occurs before reduction, during which FeO may corrode furnace refractory. To avoid this, reduction and smelting technology was adopted in which melting occurs after reduction is completed.

In a rotary hearth furnace (RHF), the heating combustion gas from a burner may adversely affect the reductive atmosphere in the furnace. To resolve this issue, the Mechanical Research Laboratory at Kobe Steel conducted a simulation study based on the computational fluid dynamics (CFD) to optimize the RHF, in the designing stage, for gas characteristics such as temperature distribution and flow (**Fig. 7**).

There are many technical challenges in continuously producing metallic iron by melting raw materials on the hearth of a furnace. Once melted and separated from slag, the metallic iron is cooled, solidified and discharged out of the furnace. This subjects the furnace hearth to repetitive thermal stress in short cycles. The furnace hearth must also resist corrosion caused by the slag

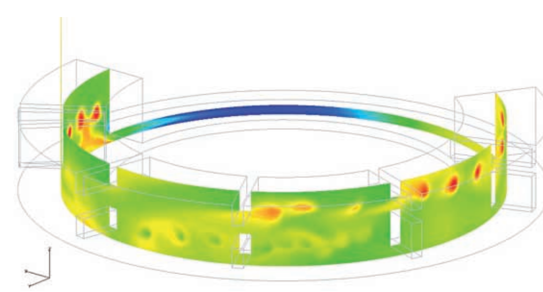


Fig. 7 CFD analysis result for rotary hearth furnace

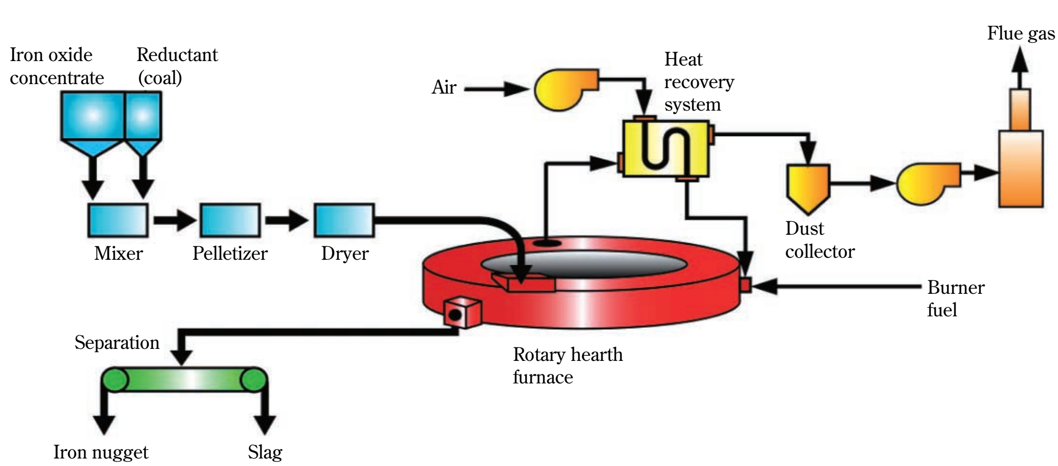


Fig. 6 Process flow

reacting on the hearth. Several tens of types of refractories were tested in order to identify the one best suited for the purpose. Repetitive thermal stress, involving rapid heating and cooling, was applied using an experimental furnace owned by a refractory manufacturer. A box furnace was used to clarify the corrosion behavior of slag. The hearth refractory was determined based on these experiments.

Although important, the selection of the hearth refractory does not resolve all the issues associated with the continuous production of granular iron. The key to the process is to maintain the hearth in good condition during the entire process, including the charging and discharging of materials to/from the furnace. Studies using the box furnace made such a technology available for the pilot plant.

A major difficulty was to design an apparatus for retrieving granular iron from an RHF. Although cooled and solidified, the granular iron is still at an elevated temperature. Several methods were contemplated. Having expertise in equipment for handling hot iron, specialists at Kobe Steel's Machinery and Engineering Company (currently, Machinary Business) designed the discharging apparatus. The Materials Research Laboratory of Kobe Steel collaborated in the selection of materials used for the apparatus.

Fig. 8 Small pilot plant in Kakogawa Works

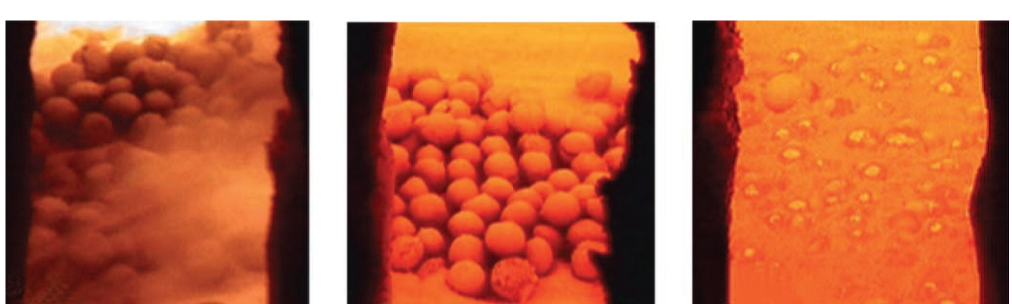
In June 1999, within one year of the beginning of process development and designing, Kobe Steel started the construction of a small pilot plant, with a capacity of 3,000 tonnes/year, at its Kakogawa Works (**Fig. 8**). Experimental operation began at the end of August 1999. In September, the operation began to produce reduced iron. The plant was confirmed as producing iron reduced over 90% as originally planned. Then, the operating temperature was raised to successfully produce granular iron for the first time. In the beginning, operation continued for about six hours a day, during which various adjustments were made to the raw material mixture, heat pattern, furnace atmosphere and retention time. Improvements were also pursued for productivity and the quality of the granular iron. During these continuous operations, each lasting for about six hours, there were no problems with the hearth—a major concern—nor was there any significant mechanical failure. Experiments continued at a good pace (**Fig. 9**).

In late November, when the company started continuous operations lasting for an extended period of time, a pool of molten iron began to form on the hearth and grew larger and larger. It was not possible to cool and solidify this large pool of molten iron, a problem that necessitated the development of a new technology.

In April 2000, a new technology for maintaining the hearth was developed through observing the changes that occur on the hearth, completing the first campaign of the pilot plant.

The second campaign operation began in the latter part of 2000 with a view to receiving visits from potential collaboration partners and operating for an extended period of time.

This campaign succeeded in conducting a stable operation that continued for the target number of days, the result of a modified hearth maintenance technology. The hearth was repaired periodically while producing granular iron, which enabled continuous operation. This approach has no theoretical limits on continuity and advanced the



Feed zone Reduction zone Melting zone

Fig. 9 Inside views of RHF at small pilot plant in Kakogawa Works application. During the campaign, data were collected for the design and operation of a large pilot plant that followed.

While conducting this experimental operation, Kobe Steel was visited by potential partners, who were given tours of the site. Among the visitors, the most interested were those in the consortium organized by Iron Range Resources, Cleveland-Cliffs Inc. (currently, Cliffs Natural Resources), the largest mining company in North America, and Steel Dynamics, Inc., the second largest EAF based steel manufacturer. Iron Range Resources and Cleveland-Cliffs Inc. had attempted to revitalize the mining industry, while Steel Dynamics, Inc. had been searching for a stable supply of iron source. Their aims coinciding, they were in search of a partner for collaborative development.

In March 2002, the decision was made to construct a large pilot plant in the beneficiation and pelletizing facility of Northshore Mining, Minnesota, owned by Cleveland-Cliffs. Different roles were allotted for the collaboration: Kobe Steel to provide technology and to design the pilot plant, Cleveland-Cliffs to supply iron ore and to provide operators, Steel Dynamics to receive and evaluate the product granular iron, and Iron Range Resources to finance the project. Later, the U.S. Department of Energy also provided financing, recognizing the project as the development of a new ironmaking technology with excellent energy efficiency.

3.2 Large pilot plant

In 2002, designing began for the large pilot plant. MIDREX Technologies, Inc. collaborated in designing the details. An RHF was the heart of the pilot plant. There were many rotary hearth furnaces for heating, with sizes up to 50m (diameter)×7m (hearth width), delivered to the market. A goal was set for the first commercial plant to have a size close to that described above (50m×7m). This would make the target capacity of the commercial plant about 500 thousand tonnes/year, judging from the productivity achieved by the small pilot plant.

The larger the pilot plant, the smaller the risk in upsizing it to a commercial scale; however, developing a large pilot plant may become too costly. Therefore, care must be taken in deciding the size of the pilot plant.

The following describes two factors emphasized in determining the size of the rotary hearth furnace used for the large pilot plant.

1) In the ITmk3 process, the secondary combustion of the carbon monoxide generated in carbon

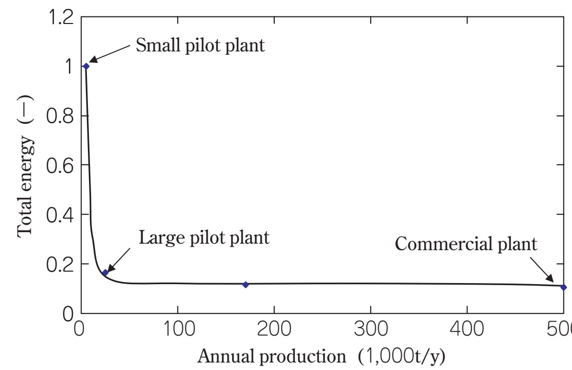


Fig.10 Production size vs. energy consumption

composite agglomerates significantly affects energy efficiency and the reductive atmosphere in the furnace. The energy input (furnace gas volume) for producing a tonne of granular iron was correlated to the production amount (**Fig.10**). The capacity of the large pilot plant was determined to be 25,000 tonnes/year, which is at the folding point of the correlation curve.

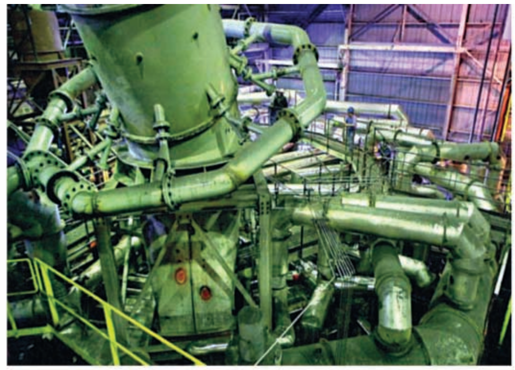
2) The key to this process is the maintenance technology for the furnace hearth, and the hearth width is an important factor. Considering the hearth width of 7m for the commercial plant, a conservative scale-up factor, from the pilot to commercial, was considered to be a factor of 3 or 4. Assuming a similar scale-up factor for the small pilot plant in Kakogawa, the hearth width for the large pilot plant was determined to be 2m.

The furnace profile was determined using the CFD model, which was further optimized by feedback data from the operation of the small pilot plant.

As it involves the development of a process, the project must minimize the risk to equipment. Because of this, the large pilot plant had to adopt industrially proven equipment as much as possible. Another prerequisite was that the equipment could be used for the commercial plant. In the end, the only apparatuses especially designed for this process were the charging and discharging units for the RHF. The rest were chosen from among those that had been industrially proven.

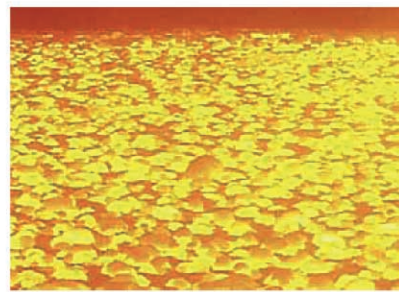
The process flow for the large pilot plant is basically the same as that for the small pilot plant, except that, for separating iron from slag, the small pilot plant adopts a batch-type process, while the large pilot plant adopts a continuous process.

The construction of the large pilot plant began in June 2002. The plant was completed and blown-in in May 2003. The first day was spent in producing reduced iron with a high metallic ratio, as in the



(a) Outside view of RHF

(b) Inside views of RHF (reduction zone)



(c) Inside views of RHF (cooling zone)

Fig.11 Rotary hearth furnace at large pilot plant

case of the small pilot plant. The production of granular iron succeeded on the second day. The large-scale demonstration followed and continued for 15 months until August 2004 (**Fig. 11**).

The following four campaigns were conducted during the demonstration operation:

1) optimizing the hearth maintenance technology
2) improving productivity and granular iron quality
3) improving the unit consumption of fuel (optimizing the secondary combustion)
4) testing performance

Various improvements were made during these campaigns. The demonstration by the prototype plant went smoothly for an extended period of time with an equipment utilization of 91 to 94%. A minor issue was the failure of a ceiling refractory caused by the insufficient firing of support anchor tiles by a refractory manufacturer.

Official environmental measurements, conducted twice during these campaigns, confirmed the process to be more environmentally friendly with higher energy efficiency than conventional ironmaking processes. The advantage was also confirmed by the Minnesota Pollution Control Agency[4] and the U.S. Department of Energy.

The following summarizes the features of the ITmk3 process.

- The process is simple.
- It allows the direct use of low grade materials (e.g., fine ore and fuel coal with neither sintering nor coking).
- It is highly energy efficient.
- It has a low environmental load.
- It facilitates the adjustment of production by starting and stopping.
- The facility cost is low.
- Most of the equipment involved in the process has been industrially proven with high reliability.
- The plant is easy to operate, without a need for handling molten iron, which is unprecedented in ironmaking processes; so operators with mining companies can run the plant in the same manner as they run a pelletizing plant.

Fig.12 Iron nugget product

The granular iron produced by the large pilot plant (**Fig. 12**) was received well by large EAF based steel makers in the U.S. and was used as a raw material for their steel products, such as sheet, plate and special rods. The granular iron, with its ease of melting in EAFs, increased the furnace productivity by 5 to 8% compared with conventionally used pig-iron. Thus the ITmk3 was demonstrated to be superior, not only in its ironmaking process, but also in its product, granular iron. The granular iron, which is to be continuously charged into EAFs, will further increase the productivity and energy consumption of the steelmaking process.

The following are the features of granular iron.

- It has a 2 - 4% carbon content.
- It is a clean iron with no impurities such as copper and nickel, which adversely affect the steelmaking process.
- It has a large specific gravity.
- It is easy to melt with a low melting point and high thermal conductivity.
- It is of an appropriate size for charging continuously into steelmaking furnaces.
- It has a size that is easy to handle.
- Unlike other reduced iron and hot briquette iron (HBI), the iron is completely reduced.
- Unlike other reduced iron and hot briquette iron (HBI), it does not reoxidize and ignite a fire.
- Unlike other reduced iron and hot briquette iron (HBI), it does not contain a gangue constituent.

In the U.S., granular iron is referred to as "iron nuggets," after gold nuggets.

Fig.13 Location of commercial plant

Fig.14 Commercial plant at Hoyt Lakes

3.3 Construction of commercial plants

The success of the large pilot plant immediately led to planning the construction of the first commercial plant. The Mesabi Iron Range, the largest ore mine in North America, lies from east to west, about 100km north of Lake Superior. There are many beneficiation/ pelletizing plants in this area. One of them is the plant run by LTV Mine, which closed in 2002 due to the steel recession. With this prospective site in mind, we have begun to work toward obtaining an environmental permit to construct a commercial plant (**Fig. 13**).

In 2007, stimulated by the recovering demand for steel, Steel Dynamics, Inc. decided to construct its first commercial plant with a capacity of 500 thousand tonnes/year of granular iron to secure a clean iron source. This project was co-financed with Kobe Steel. Kobe Steel's role included the provision of the process under license, engineering, major equipment and instructors. Steel Dynamics, Inc. agreed to accept all the granular iron produced and use it for their own EAFs. The construction of the commercial plant began in June 2007, and production started in 2010 (**Fig. 14**).

The construction of another commercial plant in Michigan, in the U.S., is being planned in collaboration with Cleveland-Cliffs Inc. (currently, Cliffs Natural Resources), one of the partners in collaborative development. Efforts to obtain an environmental permit are underway. Commercial plants are also being planned in many other countries, including Kazakhstan, India and Ukraine.

4. Business model

Granular iron manufacturing is a process suitable for locations adjacent to ore mines. The process converts iron ore, the major raw material, into value additive granular iron. The operation is similar to the conventional pelletization. The process also removes unwanted oxygen and gangue minerals contained in iron ore and pellets, allowing the shipment to steel mills of a product consisting essentially of iron. Unnecessary oxygen and gangue minerals account for about 40% of ore weight. Thus the new process decreases the shipping weight and significantly reduces CO_2 emissions during shipment. The steel mills that receive the granular iron can enjoy the benefit of granular iron that generates no slag and decreases the cost associated with the treatment of slag.

In the U.S., EAFs account for 63% of steelmaking, significantly exceeding the amount made by the blast furnace - converter method. However, the quality of scrap, the major raw material for EAFs, has become more degraded year by year, and securing clean iron source has become a major concern for EAF based steel makers. Clean iron source such as pig-iron and HBI, on the other hand, is almost totally dependent on imports from other countries, such as Venezuela, Brazil, Ukraine and Russia. Thus, US EAF makers are subject to supply instability and large price variations. These issues in the U.S. can be resolved by the prevalence of granular ironmaking plants.

In the U.S., most ore mines are found in the Mesabi Iron Range, to the north of the Great Lakes. Therefore, many steel makers are located in the area around the Great Lakes. They also import about ten million tonnes of clean iron source every year. The iron source is landed at New Orleans in the south and transferred upstream on the Mississippi River at a high transportation cost. The prevalence of ITmk3 plants around the Mesabi Iron Range, in the area around the Great Lakes, is expected to replace imported iron source, including scrap, with granular iron.

The following are the advantages to each sector of the industry that have been brought about by granular iron and granular ironmaking plants.

1) Mining sector
- Mining companies can make granular iron, which is much more value additive than conventional iron ore and pellets.
- Mining companies can expand their customer bases to EAF based steel mills in addition to blast furnace based integrated steel mills.
- Allowing the use of low grade ore will extend the lives of mines.
- The new process is feasible even for small scale mines.

2) EAF based steel manufacturers
- Use of granular iron improves the productivity and energy efficiency of the steelmaking process.
- The manufacturers can secure the source for clean iron.
- Granular iron allows conversion to higher end steel products.
- Installing granular ironmaking plants in steel mills allows the use of hot granular iron, which further increases energy efficiency.

3) Blast furnace based steel manufacturers
- The new process does not require equipment with a high environmental load, such as coke ovens and sinter plants.
- The new process allows the use of low grade materials.
- Ironmaking by the new process requires a small capital investment.
- The new process facilitates production adjustment.
- Granular iron production overseas enables the offsetting of CO_2.
- Granular iron decreases the cost and CO_2 emissions associated with transportation, compared with iron ore and pellets.
- Granular iron generates less slag than do iron ore and pellets.

Conclusions

The application of ITmk3 has just begun. In the same manner as blast furnaces have evolved for over a hundred years, ITmk3 is expected to expand its applicability from granular ironmaking to, for example, molten ironmaking and low temperature ironmaking. Kobe Steel will continue its efforts in the research and development of these new processes.

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