Resources Trend and Use of Direct Reduced Iron in Steelmaking Process

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Expectations are rising for new ironmaking processes that can utilize a wide variety of materials and fuels and also are environmentally friendly. The direct reduction (DR) process is one such ironmaking process that can substitute for blast-furnace (BF) ironmaking. This new process can utilize inexpensive shale gas, which enables its plants to be built at various locations. The DR process may be adapted for coal-based processing, which will contribute to the stable supply of direct reduced iron (DRI). This paper outlines the DR technologies developed by Kobe Steel and includes a survey on the contribution of DRI as a substitute for scrap used in electric arc furnaces (EAFs) and as a burden material in BFs.

Introduction

It was believed that the blast furnace (BF) ironmaking process would continue to predominate for some time in the future. However, the process seems to be reaching a turning point due to various problems: e.g., i) the soaring prices of iron ore and coking coal, resulting from the rapid growth of crude steel production in China, ii) the service life issues of coke ovens, and iii) environmental issues such as CO₂ reduction.

On the other hand, shale gas has grabbed much attention. In the U.S., it is not only influencing energy security, but affecting a number of industries, including iron and steel.

This paper focuses on steelmaking processes that utilize direct reduced iron (hereinafter referred to as "DRI"), taking up the aspects of environmental protection and resource depletion. It reviews the present status of the direct reduction (hereinafter referred to as "DR") technology at Kobe Steel and examines the role played by DRI in achieving a paradigm shift in the iron and steel industry.

1. Resources trend surrounding iron and steel industry

As shown in Fig. 1, world crude steel production exceeded 1.5 billion tonnes in 2011 owing to the increasing production of crude steel in China, and this value is steadily increasing. Almost 70% of the crude steel was produced by blast furnace / basic oxygen furnace (BF/BOF) process.

In the meantime, as shown in Fig. 2, the world steel stock exceeded 23 billion tonnes as a result of the crude steel production in the past and, accordingly, the amount of scrap generated is increasing steadily year by year. In other words, a so-called "urban mine" has emerged, providing the source of iron for, and promoting the use of, electric-arc-furnace (EAF) processes.

This rapid increase in crude steel production has also resulted in significant increases, as shown in Fig. 3, in the prices of iron ore and coking coal, the principal raw materials of iron and steel. There are some background factors: e.g., i) the current BF process relies heavily on high-grade ore mined in Brazil and Australia and on special coking coal with small reserves, and ii) several suppliers of the raw
materials have merged and become oligopolistic.

On the other hand, thanks to the beginning of commercial production of shale gas in North America, the price of natural gas dropped from 11.5 $/mmBTU in 2008 to 3.7 $/mmBTU in 2012. Accordingly, the price of electricity for industrial use is expected to see a further decrease from its 2011 price of 7 c/kwh.

2. Status of world DRI production

Direct reduction is a process for reducing iron ore in the solid state. It requires much less capital investment than the BF process and requires no coke. Therefore, DR plants have been built mainly in oil and natural gas producing countries to supply raw iron for EAF processes. Particularly in the Middle East, where only a limited amount of scrap is generated, DRI is used as the principal raw material to produce steel in EAFs.

Fig. 4 shows the transition of world DRI production. The DRI production has increased by a factor of almost 100, from approximately 0.8 million tonnes in the 1970s to approximately 74 million tonnes in 2012. Currently, DRI accounts for 16% of the raw material charged into EAFs. Recently, the demand for DRI has also been increasing in developed countries, and the amount of DRI carried by sea reached 14.7 million tonnes in 2012.

Table 1 summarizes the typical characteristics of DRI. DRI has many pores left after the oxygen is removed by reduction reaction and can easily be re-oxidized. Therefore, DRI has a risk of generating heat and igniting, making its maritime transport difficult. For this reason, DRI was originally consumed solely within ironworks. It was against this background that production technology was developed for hot briquetted iron (hereinafter referred to as "HBI"); the technology involves the hot compacting of DRI to increase its apparent density and thus prevent re-oxidation. This technology has facilitated marine transport and enabled the raw iron to be supplied to the global market.

The change in the production volume of HBI by processes is shown in Fig. 5. Approximately 80% of HBI is currently produced by the MIDREX® process. As will be described later, the MIDREX process, thanks to its unique reductant gas composition, can discharge DRI at a higher temperature than the HYL process, which mainly relies on hydrogen reduction. Thus the MIDREX process is more suitable for producing HBI.

DR processes roughly fall into two classes depending on the reductant used: namely, natural gas based and coal based. Fig. 6 shows the world production volume of DRI in 2012 and the ratio of DRI produced by each process. The MIDREX process and HYL process, both using natural gas as the reductant, account for approximately 75% of the total production. The remainder is produced by other processes using coal. Midrex Technologies,
Inc., the leading company in DR processing, is a wholly-owned subsidiary of Kobe Steel.

3. Direct Reduction Technology

3.1 Kobe Steel’s natural-gas-based DR process

Fig. 7 depicts the flow of the MIDREX process. Either pellets or ore lumps are charged into a shaft furnace from the furnace top, reduced inside the furnace and discharged from the bottom as DRI. Conventionally, the DRI was discharged after cooling; however, it is now being discharged hot and then transferred to the steelmaking process downstream so as to improve the energy consumption rate and productivity of the EAFs.

The reduction reaction of the iron oxide occurring inside the shaft furnace is expressed by (1) and (2):

\[
\begin{align*}
\text{Fe}_2\text{O}_3 + 3\text{H}_2 & \rightarrow 2\text{Fe} + 3\text{H}_2\text{O} : \Delta H^0 = 72.82 \text{kJ} \quad (1) \\
\text{Fe}_2\text{O}_3 + 3\text{CO} & \rightarrow 2\text{Fe} + 3\text{CO}_2 : \Delta H^0 = -42.98 \text{kJ} \quad (2)
\end{align*}
\]

Equation (1) represents the reduction reaction by hydrogen and is highly endothermic, while Equation (2) represents the reduction reaction by CO gas and, conversely, is exothermic. Thus the temperature distribution in the furnace varies depending on the ratio of the reduction reactions (1) and (2) occurring in it. It should be noted that the DR process that uses natural gas as reductant exploits the contribution of hydrogen to the reduction, as expressed by Equation (1), and is reported to emit significantly less CO₂ compared with the BF process with coal reductant.

The main feature of the MIDREX process lies in the composition of its reductant gas. In this process, the CO₂ in the exhaust gas of the reduction reaction, emitted from the furnace top, is effectively utilized as a reforming agent of natural gas, as expressed by Equation (3).

\[
\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2 \quad \cdots \cdots \cdots \cdots \cdots (3)
\]

As a result, the concentration ratio of H₂/CO in the reductant gas becomes 1.5, which is much richer in CO gas than that of the HYL process with H₂/CO of 3 to 5. This distinguishes the MIDREX process from others by its feature of easily being able to maintain a higher temperature inside the furnace.

The MIDREX plants have been operated mainly in oil producing regions with abundant natural gas. There were 63 plants in operation as of 2012. Fig. 8 shows the rated production capacities of the MIDREX plants built so far. Currently, work is in progress to develop the SUPER MEGAMOD, a further scale-up of the shaft furnace with a projected
capacity of 2 million tonnes per year. A DR plant with 2 million tonne capacity is to be launched in Texas in the U.S. in 2016. The plant capacities are becoming larger year by year.9)

Fig. 9 compares the processes in their 2011 capacities and production volumes.10) As is evident from this chart, the MIDREX process has achieved a production volume that is close to its capacity, which indicates that it has a more stable operation than other processes. This is one of the reasons for its world share of 60%.

The MIDREX process used to be operated at limited locations. To alleviate this restriction, attempts have been made to diversify fuels as shown in Table 2.11) This includes the use of reductants such as the off-gas from the COREX process and synthesis gas produced by a coal gasifier. In particular, a DR plant with a capacity of 1.8 million t/y is gathering attention. The order for this plant was placed by Jindal Steel & Power Limited, an Indian steel manufacturer, at the end of 2009. This plant is worthy of attention because it utilizes synthesis gas produced by a coal gasifier as its reductant and enables the use of Indian coal with high ash content for the production of DRI.

Coke oven gas (hereinafter "COG") can also be used for the production of DRI, since it contains chemical energy in the form of highly concentrated H₂ and CH₄. A new partial-oxidation system as shown in Fig. 10 may be introduced to convert COG into synthesis gas suitable for the MIDREX process and to produce DRI in a shaft furnace. The DRI thus produced can be used in BFs and in BOFs, which not only reduces CO₂ emissions, but also increases productivity by 30%, according to a report.12)

3.2 Kobe Steel’s Coal-based DR process

The rotary kiln process has been used for a long time as a DR process based on coal. This process, however, has the disadvantages of being relatively small in scale, suffering from long downtime due to the formation of kiln rings, and consuming a large amount of coal. This has limited the plant locations, to India, for example.13)

As another DR process using coal, the reduction of carbon composite agglomerates began to attract attention in the 1990s. It was found that, when iron oxide and carbon are closely placed in agglomerates, the reduction reaction occurs at lower temperatures and at higher rates.14) These carbon composite agglomerates, however, are fragile. To compensate for the reduction in physical strength, a new process, FASTMET note 2), was developed; it involves a rotary hearth furnace (hereinafter "RHF") that allows the reduction reaction to occur statically. This process is promising as a DR process allowing the use of inexpensive coal, and it is being put to practical use to treat steel mill dust, as shown in Table 3.15)

![Fig. 9 World DRI capacity and production per technology in 2011](image)

![Table 2 MIDREX process energy source flexibility](table)

<table>
<thead>
<tr>
<th>Technology</th>
<th>MIDREX</th>
<th>HYL</th>
<th>Finmix</th>
<th>Coal-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>94.9%</td>
<td>64.2%</td>
<td>48.7%</td>
<td>66.5%</td>
</tr>
<tr>
<td>Production</td>
<td>50</td>
<td>45.5</td>
<td>33.5%</td>
<td>40%</td>
</tr>
</tbody>
</table>

![Fig. 10 Using COG for MIDREX process](image)

![Table 3 FASTMET commercial plants](table)

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Dust (t/y)</th>
<th>Start up</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSSMC</td>
<td>Hirohata No.1</td>
<td>190,000</td>
<td>April, 2000</td>
</tr>
<tr>
<td></td>
<td>Hirohata No.2</td>
<td>190,000</td>
<td>Feb, 2005</td>
</tr>
<tr>
<td></td>
<td>Hirohata No.3</td>
<td>190,000</td>
<td>Dec, 2008</td>
</tr>
<tr>
<td></td>
<td>Hirohata No.4</td>
<td>220,000</td>
<td>Oct, 2011</td>
</tr>
<tr>
<td>JFE</td>
<td>Nishinomihon</td>
<td>190,000</td>
<td>Apr, 2009</td>
</tr>
<tr>
<td>KSL</td>
<td>Kakogawa</td>
<td>14,000</td>
<td>April, 2001</td>
</tr>
</tbody>
</table>

(note 2) "FASTMET" is a registered trademark of Kobe Steel.
This technology has led to the development of a next-generation ironmaking process, ITmk3 \(^\text{\textregistered}}\) (note 3). This process is attractive, since it can produce iron nuggets, the equivalent of pig iron, in one step in a rotary hearth furnace. A first commercial plant with an annual capacity of 500 thousand tonnes was inaugurated in Minnesota, U.S., in January 2010.\(^{16}\)  

**Fig.11** depicts the flow of Kobe Steel’s coal-based DR process using an RHF.

### 4. Future perspective

#### 4.1 Expansion of ironmaking process using iron scrap

**Fig.12** combines and shows the forecasted world steel demand and the forecasted scrap generation.\(^{17,18}\) These forecasts are made on the basis of construction, civil engineering and transportation, the sectors that account for 70% of the total amount. The gap between these two forecasts (black column) indicates the insufficient quantity of iron, which cannot be compensated for by scrap alone. In order to fill this gap, iron must be newly made from iron ore. As for the future, this deficiency of iron is forecasted to increase, reaching 1.6 billion tonnes around 2020, and to decrease thereafter.\(^{19}\) This is a forecast and the actual time may vary, but it will happen sooner or later. In other words, the increasing scrap generation implies that ironmaking processes using iron scrap as their principal raw material will possibly play an important role.

Scrap iron usually contains tramp elements such as Cu and Sn. An increase in their content adversely affects the processing quality in the downstream processes including continuous casting and rolling. This is the reason why EAFs, using scrap as their principal raw material, have been applied primarily to steel grades for construction with relaxed quality requirements. These tramp elements are difficult to remove by treating hot metal and/or molten steel. Thus, in order to control their content, clean scrap must be selected for the raw material, or the scrap must be diluted by clean raw iron such as DRI or pig iron. In the U.S., clean raw iron is added in the amount of 65 to 70% to dilute the scrap melted in EAFs. This process can even produce high-grade steel that compares with the steel produced by BOFs.\(^{20}\) Another advantage is that the carbon in the clean raw iron resolves the issue of nitrogen, a problem intrinsic to EAFs.\(^{21}\)

**Fig.13** shows the energy consumption and CO\(_2\) emissions of EAF processes that use scrap and DRI. The energy consumption and CO\(_2\) emissions become minimal when 100% scrap is used, which reduces CO\(_2\) emission to a quarter. If scrap and DRI are combined, a common practice in the US, a significant CO\(_2\) reduction is expected in comparison with the BF/BOF process because natural gas is used to...
produce the DRI charged.

In the US, the volume of crude steel produced by EAFs has been exceeding that produced by the BF/BOF process since 2002. There, EAF integrated mini-mills are prevailing. These EAF integrated mini-mills use scrap and DRI as a source for their iron and produce thin sheets. In 2011, approximately 60% of the crude steel was produced by the EAF process. Therefore, a stable supply of DRI for diluting degraded scrap is important for the sustainable growth of EAF processes in the future.

4.2 Expansion of DRI production in North America

Recently, the gas-based DR process has been scaled up (to greater than 2 million t/y/unit). In North America, where the emergence of shale gas has made electric power and natural gas readily available at lower cost, a number of projects are being actively pursued to implement upstream ironmaking based on this process (Table 4). The reason for the introduction of the process is said to be that, when compared with the BF process of the same scale, the DR process emits 1/3 amount of carbon and the DRI facilities require only half the investment.

As described above, as a result of increased scrap generation and the reduced price for natural gas in the U.S., the DR process is being revisited as an ironmaking process with less environmental burden. The amount of DRI production in North America is expected to grow sharply in the future.

4.3 Use of DRI as energy container

The past records indicate that charging DRI into a BF is expected to bring about positive effects such as increased production, a decreased reducant ratio, a decrease in agglomerates and reduction of CO₂. A laboratory study has shown that the upper limit of DRI that can be charged into a BF may be as high as 100%. In actual operation at the AK Steel Corporation, the amount of DRI recorded as charged into their BF reached a monthly average of 227 kg/t, indicating that up to approximately 20% can be charged without causing any problem.

Fig.14 compares the current ironmaking with future small-scale, independent on-site ironmaking. This independent on-site ironmaking offers a new business model in which the energy of the reduction reaction, which accounts for three-fourths of the energy consumption and carbon emissions for steelmaking routes.

Table 4 Status of gas-based DRI projects in North America

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Capacity (kt)</th>
<th>Status</th>
<th>Start-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucor</td>
<td>Louisiana</td>
<td>2,900</td>
<td>Confirmed</td>
<td>2012</td>
</tr>
<tr>
<td>Nucor</td>
<td>Louisiana</td>
<td>2,500</td>
<td>Permission not approved</td>
<td>2015+</td>
</tr>
<tr>
<td>Voestalpine</td>
<td>Texas</td>
<td>2,000</td>
<td>Confirmed; needs permitting</td>
<td>2016</td>
</tr>
<tr>
<td>Risslesteel</td>
<td>Ohio</td>
<td>1,000</td>
<td>Under consideration</td>
<td>2016+</td>
</tr>
<tr>
<td>Kears Steel</td>
<td>Minnesota</td>
<td>2,500</td>
<td>Permission not approved</td>
<td>2016+</td>
</tr>
<tr>
<td>Severstal NA</td>
<td>Mississippi &amp; Trinidad</td>
<td>n/a</td>
<td>1.5 tpy project expected</td>
<td></td>
</tr>
<tr>
<td>US Steel</td>
<td>Minnesota</td>
<td>n/a</td>
<td>Under consideration</td>
<td>2016+</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>10,500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig.14 General blast furnace system and future independent on-site ironmaking model
energy used for ironmaking, is shifted to a third country to exploit DRI as an energy container, while halving the transported amount of the raw materials required for ironmaking. One example is the MIDREX plant with 2 million t/y capacity that a European company, voestalpine AG, announced to build in Texas, U.S.\(^9\) In this project, iron ore pellets produced in Brazil will be transferred to Texas to be reduced by inexpensive shale gas, and the product HBI will be shipped to Austria to be used by ironworks there. This project thus will reduce CO\(_2\) emissions. Kobe Steel’s MIDREX process, which can produce HBI with ease, is more advantageous in exploiting DRI as an energy container.

There are future concerns including CO\(_2\) reduction, the service life of coke ovens, the environmental issues of sintering plants and the elasticity of BF production. Against this background, the use of inexpensively produced DRI in integrated ironworks may be promoted further, depending on the price trends of iron ore and coking coal governing the cost of pig iron made by BFs.

**Conclusions**

The U.S. iron and steel industry, the precursor of the Japanese iron and steel industry, passed the period of its maturity in the 1950s and saw the decline of BFs in the 2000s. In place of these BFs, Nucor-type mini-mills using scrap have emerged. Equipped with state-of-the-art technologies including the continuous casting of thin slabs, they are continuing their highly efficient production on a small scale. As evident from the history of the iron and steel industry in the U.S., the time is approaching when the industry will rely on scrap as its raw iron, which will be generated in large quantities.

On the other hand, the lower price of natural gas resulting from the commercial production of shale gas in North America is promoting the gas-based DR process. In addition, the development of the coal-based DR process that exploits the ubiquitous energy of coal has relaxed the restrictions on the locations of DR plants, which, in the past, could be built only in natural gas producing countries. This is expected to facilitate a stable supply of clean raw iron. As a result, DRI can be combined with scrap, adding versatility in the production of high-grade steel by EAFs, and can also be used for BF etc. as an energy container, an effective way of suppressing CO\(_2\) emissions. Kobe Steel will strive to contribute to problem solving in the iron and steel industry through its own DR process.

**References**

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10) MIDREX Technology Inc. 2011 WORLD DIRECT REDUCTION STATISTICS.
19) T. Harada et al. METEC InSteelCon ECIC 2011, Session 10.

\(^{Note}\) The names of companies and products cited herein may be trademarks or the registered trademarks of their respective owners.