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 CO_2 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.[1)] 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.[2)] 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.[3)] 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

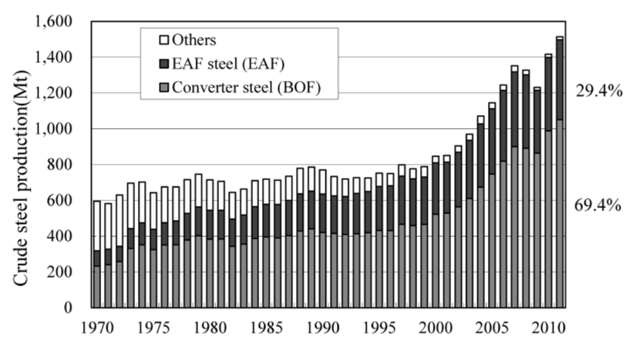

Fig. 1 Changes in world crude steel production [1)]

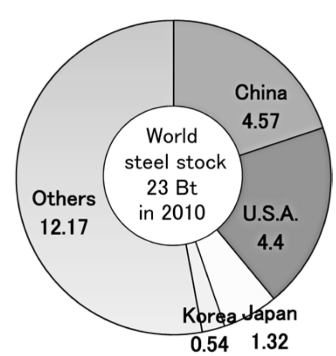

Fig. 2 World steel stock in 2010 [2)]

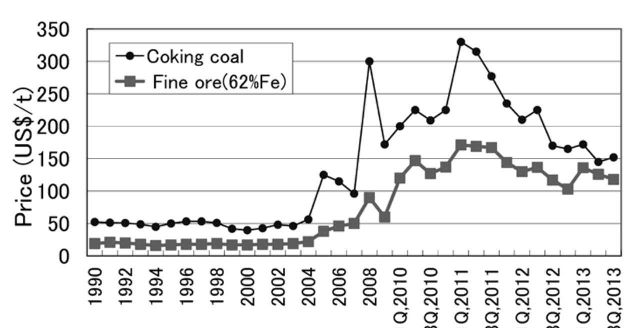

Fig. 3 Price changes in iron ore and coking coal [3)]

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.[4] Accordingly, the price of electricity for industrial use is expected to see a further decrease from its 2011 price of 7 ¢ /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.[5]

Table 1 [6] 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**.[7] Approximately 80% of HBI is currently produced by the MIDREX® [note 1] 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** [5] 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,

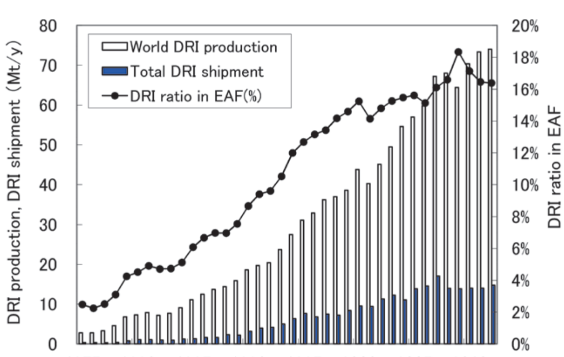

Fig. 4 Changes in world DRI production and DRI shipments by year [5]

Table1 Characteristics of DRI and HBI [6]

	DRI	HBI
T.Fe(%)	90～94	←
M.Fe(%)	83～89	←
Metallization(%)	92～95	←
Carbon(%)	1.0～3.5	←
Gangue (%)	2.8～6.0	←
Bulk Density(t/m^3)	1.6～1.9	←
Apparent Density(t/m^3)	3.4～3.6	5.0～5.6

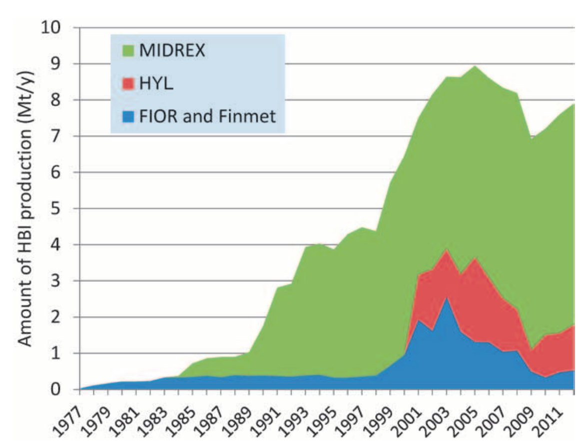

Fig. 5 Yearly HBI production by process [7]

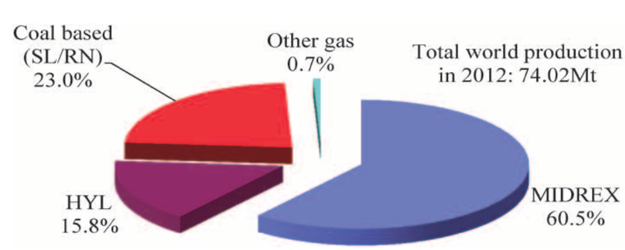

Fig. 6 World DRI production processes in 2012 [5]

note 1) "MIDREX" is a registered trademark of Kobe Steel.

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.[8) 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):

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O : \varDelta H^0 = 72.82\text{kJ} \quad \cdots\cdots \quad (1)$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3{+}CO_2 : \varDelta H^0 = -42.98\text{kJ} \quad \cdots \quad (2)$$

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 CO_2 compared with the BF process with coal reductant.[8)

The main feature of the MIDREX process lies in the composition of its reductant gas. In this process, the CO_2 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).

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

As a result, the concentration ratio of H_2/CO in the reductant gas becomes 1.5, which is much richer in CO gas than that of the HYL process with H_2/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.[5) **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

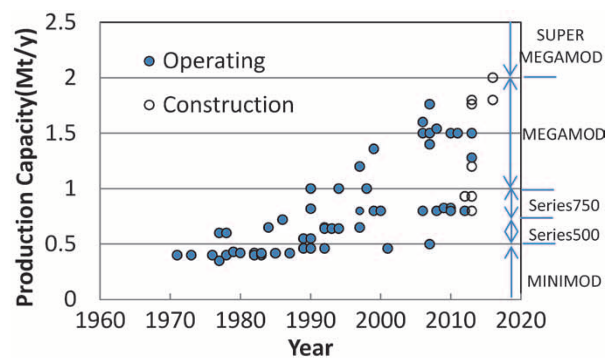

Fig. 8 Rated capacities of MIDREX plant by year

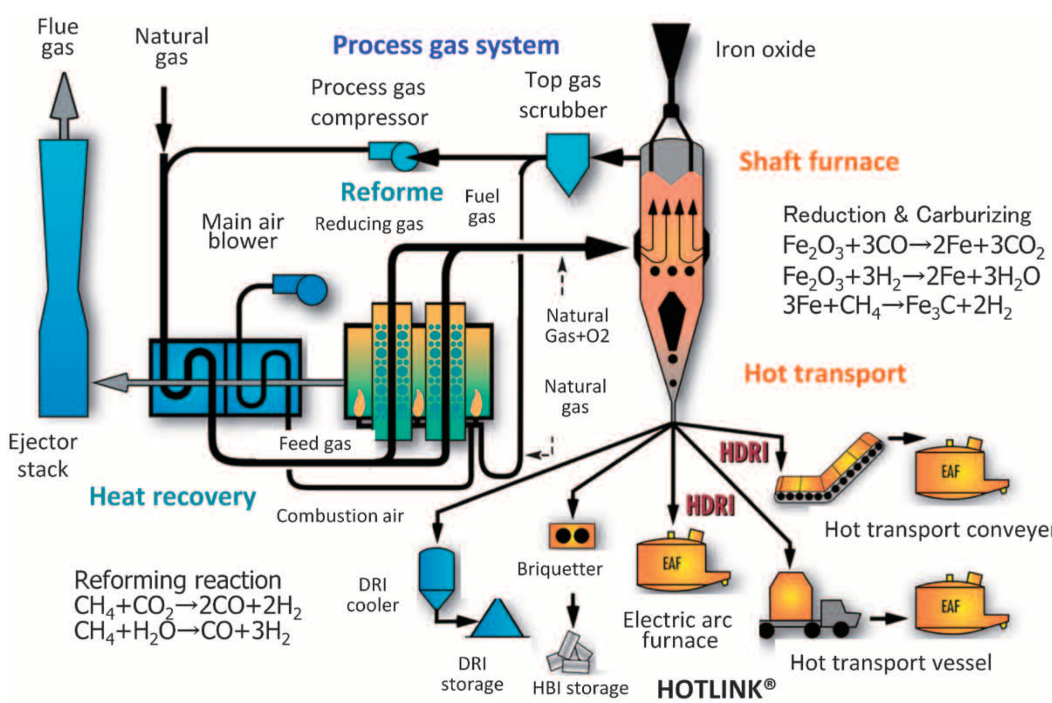

Fig. 7 MIDREX process flow sheet [8)

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 H_2 and CH_4. 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 CO_2 emissions, but also increases productivity by 30%, according to a report.[12]

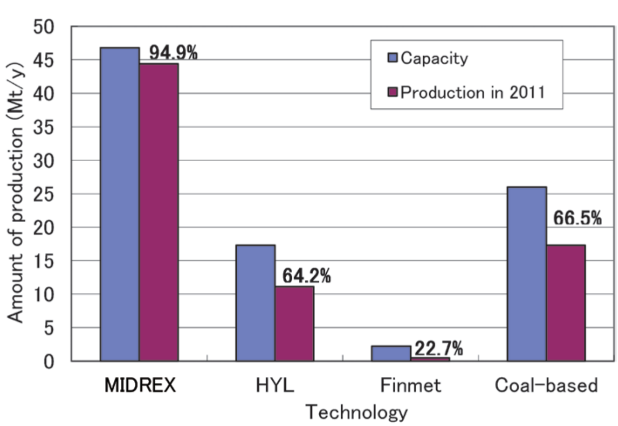

Fig. 9 World DRI capacity and production per technology in 2011 [10]

Table 2 MIDREX process energy source flexibility [11]

	Energy source	Reducing gas H_2/CO	MIDREX plant reference	Start-up
COREX/MIDREX plant	COREX offgas	0.3–0.4	Arcelor Mittal South	1999
		0.5–0.6	JSW Projects Limited	Construction
MIDREX NG Plant	Natural gas	1.5–1.7	Numerous (60 modules operation)	Since 1969
MXCOL Plant	Coal gasifier	2.0	JSPL Angul	Construction

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]

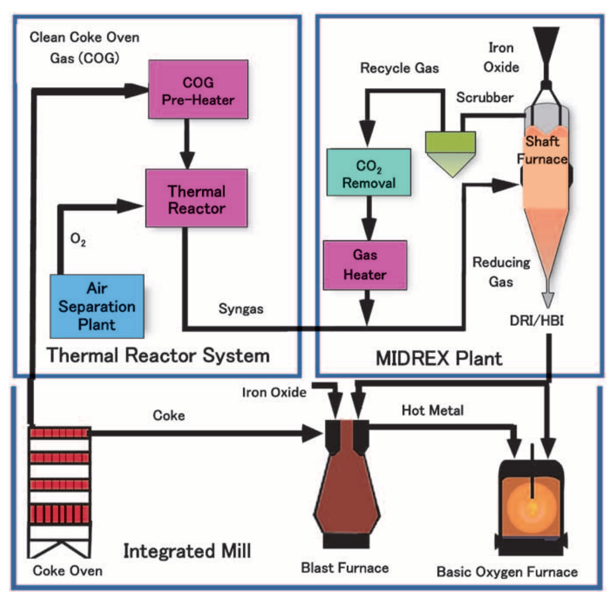

Fig.10 Using COG for MIDREX process [12]

Table 3 FASTMET commercial plants [15]

Company	Location	Dust (t/y)	Start up
NSSMC	Hirohata No.1	190,000	April. 2000
	Hirohata No.2	190,000	Feb. 2005
	Hirohata No.3	190,000	Dec. 2008
	Hirohata No.4	220,000	Oct. 2011
JFE	Nishinihon	190,000	Apr. 2009
KSL	Kakogawa	14,000	April 2001

note 2) "FASTMET" is a registered trademark of Kobe Steel.

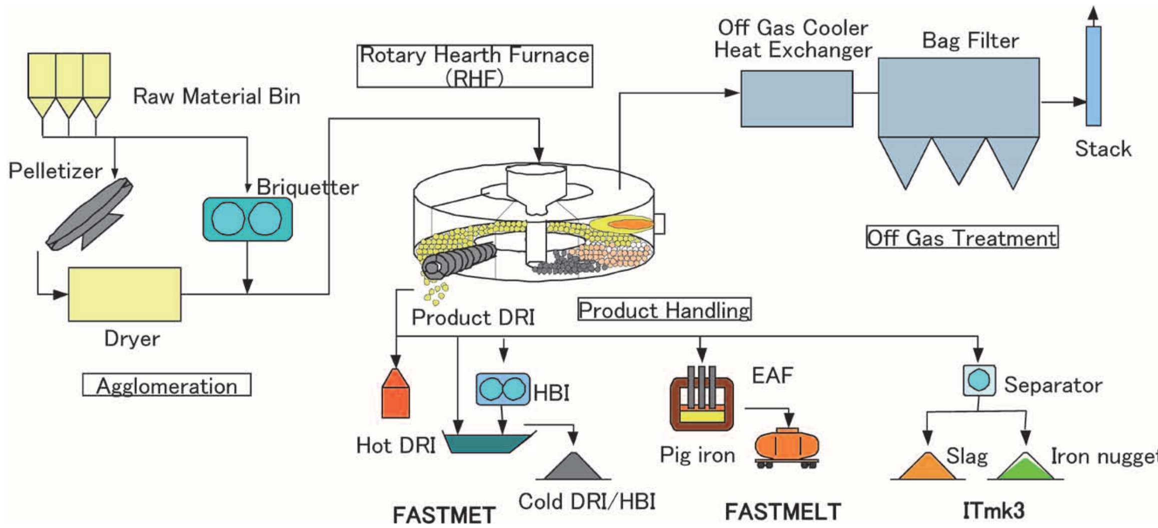

Fig.11 Flow sheet of Kobe's coal-based direct reduction process

This technology has led to the development of a next-generation ironmaking process, ITmk3® note 3) ([ai ti:] mark three). 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

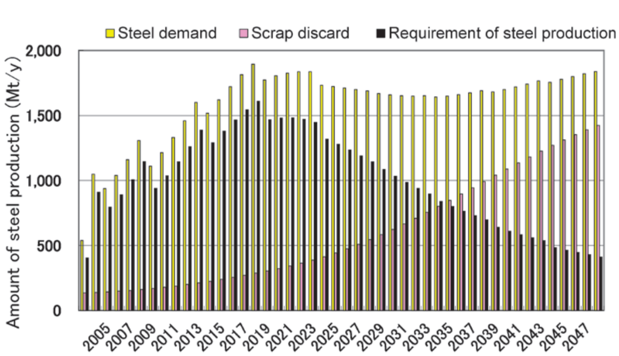

Fig.12 Necessary amount of steel production forecasted from steel demand and scrap discard [19)]

note 3) "ITmk3" is a registered trademark of Kobe Steel.

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. Comparison was made with the BF/BOF process.[8)] 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

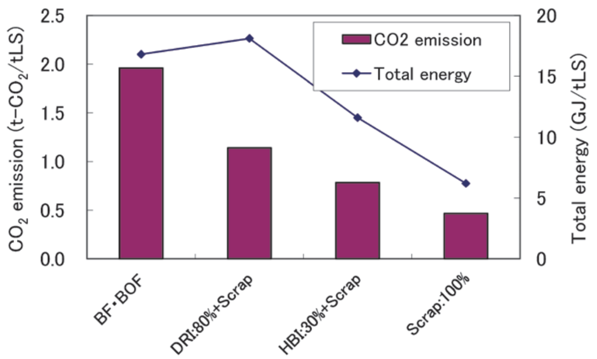

Fig.13 Energy consumption and carbon emissions for steelmaking routes [8)]

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.[1)] 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**).[22)] 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.[23)]

Table 4 Status of gas-based DRI projects in North America [22)]

Company	Location	Capacity (kt)	Status	Start-up
Nucor	Louisiana	2,500	Confirmed	2013
Nucor	Louisiana	2,500	Permitted- not approved	2015+
Voestalpine	Texas	2,000	Confirmed- needs permitting	2016
Bluescope	Ohio	1,000	Under consideration	2016+
Essar Steel	Minnesota	2,500	Permitted- not approved	2016+
Severstal NA	Mississippi & Trinidad	n/a	1.5 tpy project rejected	
US Steel	Minnesota	n/a	Under consideration	2016+
Total		10,500		

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 reductant ratio, a decrease in agglomerates and reduction of CO_2.[24)] A laboratory study has shown that the upper limit of DRI that can be charged into a BF may be as high as 100%.[25)] 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 [26)], 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

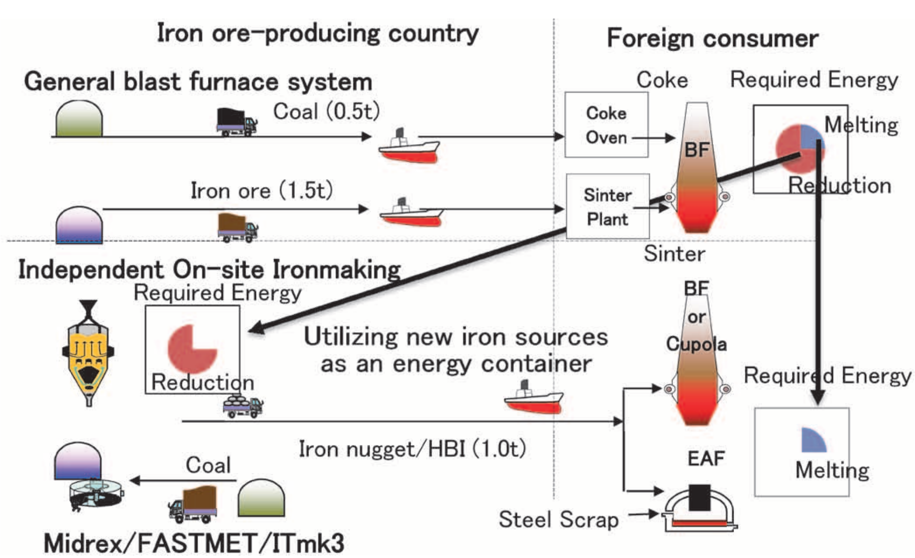

Fig.14 General blast furnace system and future independent on-site ironmaking model

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.

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