Steel production requires iron ore and coal, and accompanies greenhouse gas emissions. The annual production of the world crude steel increased from 0.9 to 1.3 billion tonnes since 2002, and is anticipated to increase due to the continuous economic growth in developing countries especially in Asia.

About two thirds of the crude steel is produced by BF–BOF route whose ratio in the total crude steel production has gradually been increasing. The BF–BOF process is an excellent process in terms of productivity and energy efficiency, the process, however requires high grade iron ore and coal, and the large steel production by the BF–BOF route will accelerate the exhaustion of the high grade raw materials. The CO$_2$ emissions are also anticipated to increase as does the steel production, since approximately 2 tonnes of CO$_2$ is generated per tonne of steel by the BF–BOF process.

On the other hand, world in-use steel stock has been increasing year by year due to the continuous large steel production, and will be recycled as a large amount of scrap to the market in the future.

Steelmaking by feeding Iron Nuggets to EAF together with the scrap can significantly decrease the CO$_2$ emissions while satisfying the steel quality by diluting the impurities containing in the scrap, as well as conserving the natural resources of high grade iron ore and coal. Steel production by using the direct reduction processes together with the scrap is a suitable and reasonable solution for a sustainable iron and steel making.

KEY WORDS: iron nugget; DRI; scrap; natural resources; global warming; CO$_2$; direct reduction; steelmaking model; rotary hearth furnace; iTmk3; Midrex; EAF; iron ore fines; non-coking coal; natural gas.

1. Introduction

Global warming has been a major environmental issue worldwide for the last few decades. Kyoto Protocol has put great pressure on industrialised countries to reduce greenhouse gas emissions. Under the protocol, those countries pledged to reduce their collective emissions of the greenhouse gases at least by 5% in 2008–2012 compared to 1990 levels. The world greenhouse gas emissions in 2007, however, have increased by 38% mainly due to large increase of emissions from developing countries especially in Asia, though efforts have been made for the emission reduction in various industries in developed countries.

Approximately 2 tonnes of CO$_2$ are generated per tonne of steel by BF–BOF route which is a major iron and steelmaking process. Due to the enormous volume of the steel production, the CO$_2$ emissions from the steel industry have a large impact on the world CO$_2$ emissions. Consumption of the raw materials in the steel industry has also increased as the increase of the steel production. Trading iron ore from overseas where high grade iron ores are reserved such as Australia and Brazil has also increased. In 2008 the traded iron ore became over 800 million tonnes, which is more than a double compared to a decade ago. Since the world steel production is forecasted to increase further due to strong demand especially in China and India, the requirements for technologies to mitigate the CO$_2$ emissions will become stronger together with to conserve the natural resources of high grade iron ores and coals.

In this article a direction of the future steel industry is proposed for a sustainable steelmaking.

2. Global Trend and Fundamental Conditions in Steel Industry

Mitigation of the CO$_2$ emissions has been a major environmental issue, since CO$_2$ is a major greenhouse gas and more than 90% of the global warming is due to the CO$_2$ emissions. The world CO$_2$ emissions have consistently been increasing as shown in Fig. 1. Comparing steelmaking processes between EAF and BOF from 2000 to 2007, the annual production by the EAF increased from 288 to 419 million tonnes, on the other hand the production by the BOF increased from 496 to 890 million tonnes, and the increase of the steel production by the BOF was approximately three times larger than that by the EAF as shown in Fig. 2. Since the CO$_2$ emissions from the BF–BOF are approximately 2 tonnes per tonne of steel, which is much larger than those
from the EAF,\textsuperscript{5} it is thought that the increase of the CO$_2$ emissions from the world steel industry during the years was remarkably large.

In the steel industry, various technologies have been developed to improve the energy efficiency. \textbf{Figure 4}\textsuperscript{6} shows diffusions of the major energy efficient technologies in the BF–BOF process. Continuous efforts should be made to reduce the CO$_2$ emissions by diffusing these technologies to steel works with low energy efficiency. The crude steel production is, however, forecasted to increase further in the near future due to strong demand especially in China and India, the CO$_2$ emissions accompanied by the steel production is also anticipated to increase. It is reported that the CO$_2$ emissions from the steel industry at the base line conditions where no special countermeasures are taken will be 4.8 – 5.2 billion tonnes in 2050, which is approximately a double as much as 2.6 billion tonnes we had in 2006 as shown in \textbf{Table 1}\textsuperscript{7}

Carbon Capture and Storage from the blast furnace top gas and iron ore reduction by feeding the reducing gas containing hydrogen are proposed to mitigate the CO$_2$ emissions for the blast furnace operations.\textsuperscript{5} Considering the large increase of the steel demand being expected in the future, however, it is hardly to say that it is sufficient to achieve the aimed CO$_2$ mitigation keeping the scenario that improvements will be made only in the BF–BOF process. \textbf{Table 2} shows annual productions and proved reserves of iron ore and coal. Although the reserve life time of the both materials is over 100 years at present, it is anticipated that the quality of the materials will gradually be lowered in the future.\textsuperscript{9} As was described above, the crude steel production will also increase to be doubled in 2050, and if we keep relying on the BF–BOF route, which requires high grade iron ore and coking coal, the exhaustion of the high grade raw materials will be accelerated.
Major duties which the steel industry is given can be summarised as follows:-

- Stabilised supply of steel products to meet the continuous strong demand especially in Asian countries
- Development and distribution of technologies to handle low grade iron ore and coal since it will be more difficult to obtain high grade raw materials in the future
- Taking countermeasures for decreasing the CO₂ emissions to prevent the global warming

3. Solutions for Future Steelmaking

The followings are proposed solutions for the sustainable steel industry.

- To adopt ironmaking technologies which can handle low grade raw materials
- To adopt ironmaking technologies which use the reductant with less carbon than coal
- To adopt steelmaking process which can use a large amount of scrap
- To develop a steelmaking model with a suitable combination of processes of ironmaking and steelmaking, considering locations suitable for ironmaking including mining sites of raw materials and steel users to satisfy the raw material flexibility and the CO₂ mitigation

### Table 1. Forecasted crude steel production and CO₂ emissions from steel industry at base line conditions in 2050.

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2050 low</th>
<th>2050 high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude steel</td>
<td>1.2</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>CO₂ emissions</td>
<td>2.6</td>
<td>4.8</td>
<td>5.3</td>
</tr>
</tbody>
</table>

### Table 2. Life of iron ore and coal.

<table>
<thead>
<tr>
<th></th>
<th>Iron Ore</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Million t</td>
<td>15 700</td>
<td>6 781</td>
</tr>
<tr>
<td>Proved Reserve Million t</td>
<td>350 000</td>
<td>826 001</td>
</tr>
<tr>
<td>Life year</td>
<td>159</td>
<td>122</td>
</tr>
</tbody>
</table>

### Table 3. Comparison of CO₂ emissions from ITmk3 with BF.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>1 995</td>
<td>14</td>
<td>–51</td>
<td>1 957</td>
<td>ITmk3</td>
<td>1 627</td>
<td>16</td>
<td>–20</td>
<td>1 623</td>
<td>–17%</td>
</tr>
<tr>
<td>Canada</td>
<td>1 995</td>
<td>33</td>
<td>–122</td>
<td>1 906</td>
<td>BF</td>
<td>1 627</td>
<td>38</td>
<td>–47</td>
<td>1 618</td>
<td>–15%</td>
</tr>
<tr>
<td>Japan</td>
<td>1 995</td>
<td>67</td>
<td>–250</td>
<td>1 812</td>
<td>ITmk3</td>
<td>1 627</td>
<td>78</td>
<td>–98</td>
<td>1 608</td>
<td>–11%</td>
</tr>
<tr>
<td>Italy</td>
<td>1 995</td>
<td>75</td>
<td>–282</td>
<td>1 788</td>
<td>BF</td>
<td>1 627</td>
<td>88</td>
<td>–110</td>
<td>1 605</td>
<td>–10%</td>
</tr>
<tr>
<td>UK</td>
<td>1 995</td>
<td>86</td>
<td>–320</td>
<td>1 760</td>
<td>ITmk3</td>
<td>1 627</td>
<td>100</td>
<td>–125</td>
<td>1 602</td>
<td>–9%</td>
</tr>
<tr>
<td>German</td>
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<td>93</td>
<td>–346</td>
<td>1 742</td>
<td>BF</td>
<td>1 627</td>
<td>108</td>
<td>–135</td>
<td>1 600</td>
<td>–8%</td>
</tr>
<tr>
<td>USA</td>
<td>1 995</td>
<td>96</td>
<td>–358</td>
<td>1 732</td>
<td>ITmk3</td>
<td>1 627</td>
<td>112</td>
<td>–140</td>
<td>1 599</td>
<td>–8%</td>
</tr>
</tbody>
</table>

* CO₂ emissions by consumed coal, fuel and additives, considering CO₂ credit by recovered chemicals.

** It was assumed that all of surplus by-product gas and generated steam are used for power generation with 35% efficiency.

3.1. ITmk3® Process

ITmk3 is an ironmaking process to produce “Iron Nuggets” which are equivalent to pig iron in terms of chemical compositions. Iron ore fines are mixed with coal fines, agglomerated into green pellets and processed in a RHF (rotary hearth furnace) to produce the iron nuggets. Figure 5 shows the process flow of the ITmk3 process.

Since high strength is not required for processing in the RHF, coke ovens are not required and non-coking coal can be used as the reductant. Sinter plants to increase the strength of the iron oxide are not required, either. The plant shut-down and start-up can easily be made, as the retention time in the RHF is only about 10 minutes. Nearly all of the combustible gases generated by the reactions are burnt within the RHF as a fuel gas, and no surplus gas is exported from the system.

Table 3 shows the CO₂ emissions to produce cold pig iron both from the ITmk3 and the BF processes in various countries, which have different carbon emission factors for the electric power generation (CO₂ emissions per kWh) as shown in Table 4. The CO₂ emissions from the BF include those from the coke oven and the sinter plant. The CO₂ emissions from the ITmk3 are less than those from the BF in all of the countries by 8–17%. Considering that the product capacity of the ITmk3 is 500 000 tonnes per annum in the calculations, which is much smaller than that of the BF in a typical iron and steelmaking complex in Japan referred for the calculations, it is comprehended that the ITmk3 process is superior in energy efficiency and environmental friendliness.

The ITmk3 can take more advantages over the BF, as the
carbon emission factor of the electric power is lower. Recently, especially in advanced countries like in Europe, the power generation processes emitting less CO₂ by using nuclear power or renewable energy are preferred due to the CO₂ issue. As this trend spreads worldwide and such processes replace existing coal or gas fired power plants, the average unit CO₂ emissions per kWh will decrease. It is supposed that the CO₂ emissions from the ITmk3 will even become lower than the BF as this happens all over the world in the future.

3.2. Gas Based DR Process

Gas based DR process uses natural gas as a source of reductant instead of coal. Figure 6 shows a standard process flow of Midrex® process which is the most distributed natural gas based DR process in the world.

Iron ore, in pellet or lump form, is introduced to a shaft furnace. As the iron ore descends through the furnace, the iron ore is heated and the oxygen is removed from the iron ore by reducing gas that has a high H₂ and CO content. The reducing gas reacts with the Fe₂O₃ in the iron ore and converts it to metallic iron called DRI, leaving H₂O and CO₂ as off-gas. The off-gas from the shaft furnace is recycled and blended with fresh natural gas. This gas is fed to the reformer where the gas is heated and reformed to the reducing gas, and then fed to the shaft furnace. The DRI is discharged by being cooled in the lower portion of the shaft furnace to be a cold DRI. The DRI can also be discharged hot and fed to a briquetting machine for production of HBI, or fed hot, as hot DRI to an EAF.

Since no excess gas is generated from the process, the plant can be built as a dedicated stand alone plant. The operation of the plant is therefore flexible, and the plant can be an ironmaking section in an iron and steel mill complex, or an independent DRI production mill.

Basic compound of natural gas is CH₄ whereas coal consists of aromatic compounds which have higher proportions of carbon to hydrogen than the natural gas. Since almost all the carbon and hydrogen used in iron and steelmaking are eventually converted to CO₂ and H₂O, the natural gas produces much less CO₂ than does the coal. Table 5 shows the CO₂ emission rates for combusting methane versus two types of coal.

The natural gas emits only about one-half of the CO₂ per unit of energy compared to the coal, which is a characteristic that makes the natural gas an ideal energy source for steel-making. The natural gas can also be used to produce electricity required for the EAF. The combination of the gas based DR process and the EAF can lower the CO₂ emissions per tonne of steel significantly, when compared with the BF–BOF process.

Figure 7 shows the energy requirements and CO₂ emissions to produce one tonne of liquid steel for comparing the Gas DR–EAF steelmaking route with the BF–BOF route. The CO₂ emissions by the Gas DR–EAF using 80% cold DRI and 20% scrap are 1,140 kg per tonne of steel, which is significantly smaller than 1,959 kg per tonne of steel by the BF–BOF route. The hot DRI feed to the EAF can even lower the CO₂ emissions. The CO₂ emissions by using 80% hot DRI with 20% scrap is 1,033 kg per tonne of steel.

3.3. Expected Scrap Supply

Steel scrap is an important iron source, since steel products can easily be recycled as the scrap, and new steel products can essentially be reproduced by only melting the scrap without reduction. Hayata et al.15,16) showed the outlook of the world steel cycle until 2050 by using dynamic material flow analysis, forecasting the stock and flow of three end users i.e. civil engineering, building and vehicles, which covers 70% of the current in-use steel stock.

Strong steel demand is continuously expected in China for the first decade followed by India, and the world steel production is forecasted to increase until 2025 and will be stayed with a small change after 2025, according to the analysis.
The steel products are once in a stock in society and then discharged as the scrap after the product life time which is dependent on the type of the products. The amount of the discharge scrap is, therefore, related to the amount of the steel stock and the type of the steel products.

The in-use steel stock will consistently increase while the steel production is over the steel discarding. The analysis estimated that the steel stock in 2050 will be about six times larger than that in 2005, and the discharging scrap from the three end users will be 1.5 billion tonnes per annum in 2050 which is a large increase compared to just over 0.1 billion tonnes per annum in 2005 as shown in Fig. 8.

Figure 9 shows an image of the steel production changes by different iron sources between the raw materials and the scrap from 2005 to 2050, which can be comprehended from the analysis. The steel production will need to rely on raw materials during the first few decades from 2005, since the amount of the discharge scrap will not be so large compared to the steel demand. The discharge scrap will increase as does the in-use steel stock, and will be a major iron source in the long term.

It is certain that the steel industry will have to have a steelmaking process to utilise the large discharging scrap in the market before we have this situation. It is envisaged that research and development to improve quality of steel products when using the scrap as the main iron source will be one of the most important themes in the long term.

On the other hand, since the consumptions of the iron ores and coals are anticipated to be very large for the first few decades from now, it will become more difficult to obtain high grade raw materials, and the request for ironmaking to use lower grade iron ores will be stronger. The production by using ironmaking processes such as the ITmk3 and the gas based DR is highly recommended for the increase demand instead of by the BF.

3.4. Steelmaking Process to Utilise Steel Scrap

The steel scrap normally contains impurities such as Cu, Sn, Pb, etc. which often limit its usage to satisfy the product quality. The iron nuggets and the DRI are pure iron sources and can be used not only for satisfying the quantity demand but also improving the steel quality. The usage ratio of the iron nuggets can vary depending on the target product quality and the available scrap quality at the EAF as well as the availability of the scrap. Figure 10 shows tonnes of various steel products both from the EAF and the BOF routes in the USA where it should be noted that most of the products including hot and cold rolled are produced by the EAF route by selecting higher quality feed including the DRI. The typical usage ratio of the iron nuggets is in the range of 20–40% as pure iron unit and the rest is the scrap (80–60%), although the scrap ratio can change from 0 to 100% at the EAF operations.

On the other hand, it is known that the applicable scrap usage ratio at the BF–BOF is 20% at the highest, because of the limitations of the excess heat available at the BOF.

Figure 11 shows the comparison between the CO₂ emissions from ITmk3-EAF and those from the BF–BOF, where
the applicable range of the scrap usage ratio is 0–20% for the BF–BOF and 60–80% for the ITmk3-EAF. It shows the CO2 emissions from the ITmk3-EAF are around 50% of those from the BF–BOF due to the benefits by utilising the scrap for steelmaking. Similar tendency is observed regardless of the plant location or the carbon emission factor of the electric power generation.

Steelmaking by feeding either the iron nuggets or the DRI to the EAF together with the scrap can significantly decrease the CO2 emissions while satisfying the steel quality by diluting the impurities containing in the scrap.

4. Expected Future Model for Steelmaking

As was mentioned in section 1 and 2, the exhaustion of the high grade iron ores and coals will become a more serious problem as well as the global warming in the near future. Lower grade raw materials are, on the other hand, distributed widely in the world and the requirements to utilise local materials in spite of the lower grade are expected to be stronger. The ITmk3 can contribute to these problems, since the ITmk3 process uses iron ore fines and non-cooking coal as the raw materials, and can produce steel with less CO2 emissions by utilising the scrap as well.

Expected future steelmaking model is to build and operate the plant near mining sites, and provide the iron nuggets or the DRI as iron products to the market where steelmaking users procure the iron products together with the scrap to produce steel products as shown in Fig. 12. In this model, the iron nuggets and the DRI can be regarded as energy containers, since the required energy can significantly be decreased at the consumer sites by using the iron nuggets as well as the CO2 emissions. Although the CO2 emissions increase at the mining sites to the contrary, the overall emissions can be mitigated from global point of view.

In case of the ITmk3 process, moisture, carbon and oxygen containing in the iron ore and the coal are removed, and only iron and some carbon which are necessary to make steel are delivered from the mining site to the steel mills, which can neglect the waste energy and the CO2 emissions accompanied by transferring these unnecessary materials to the downstream processes.

There are some opinions among tech-scientists in academies saying that mining sites should also share the responsibilities of the CO2 emissions for steelmaking, and this steelmaking model can be a practical solution to share the responsibilities between the mining sites and the steelmaking sites. This model can also make it useful to solve the elemental environmental problem due to the dust emissions from the raw material preparations and the ironmaking processes included in the present iron and steel mill complex where residential areas are nearly located.

5. Conclusions

It is expected that the requirements for decreasing the CO2 emissions will be stronger to prevent the global warming. It is also expected that a strong demand for high grade iron ores and coals will continue due to industrial development in developing countries such as China and India. Requirements for steelmaking processes which are environmentally friendly, but also can utilise local ores and coals instead of imported raw materials have been increasing for sustainable steelmaking.

Both of the ITmk3 and the gas based DR are the processes to produce iron units which are advantageous in terms of the CO2 emissions as well as the raw material friendliness over the conventional BF based process.

Considering the increase of the scrap supply to the steel market being expected as a result of a large accumulation of steel products during the last few decades in the world especially in China, the process which can efficiently utilise the scrap is highly required.

Feed of the scrap with the iron nuggets and/or the DRI is
expected to be effective and practical solutions for these problems, since the CO2 emissions are reduced by mixing the scrap, while most of the steel products including the hot rolled and the cold rolled can be produced by proper quality controls with the DRI or the iron nuggets.

It is therefore proposed that a new business model should produce the iron nuggets and/or the DRI by utilising the local natural resources near the mining sites and transfer these products to consumer sites where the scrap is mixed with them to produce the steel products.

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7) Energy Technology Transitions for industry 2009 (IEA), Figure 2.3.
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