Utilizing Reduced-Iron Manufacturing Technology to Contribute to Green Society

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Abstract

Efforts to reduce greenhouse gases are accelerating worldwide. The steel industry is one of the sectors that emit the greatest amount of carbon dioxide, a type of greenhouse gas, making its decarbonization highly desirable. Currently, the primary method of steel production is through blast furnaces, which rely on coke and coal as the main heat source and reducing agent, resulting in significant carbon dioxide emissions. Kobe Steel, in pursuit of decarbonization, is steadily implementing initiatives to reduce carbon dioxide emissions by lowering the ratio of reductant and incorporating more direct-reduced iron in the blast furnaces. Furthermore, by combining the company's expertise and fundamental technologies developed through reduced-iron manufacturing, raw material pellet plant operation, and engineering projects, Kobe Steel aims at contributing to the carbon neutrality of the steel industry.

Introduction

Amidst the acceleration of global efforts to reduce greenhouse gases (GHG), Japan has declared that it will be carbon neutral (CN) by 2050. Kobe Steel is part of the steel industry, which accounts for a large proportion of GHG emissions within the industrial sector. This is why contributing to a green society is one of the company's key challenges, and why it is working toward the goal of carbon neutrality (CN) in the ironmaking process by 2050.

Iron production begins with the removal of oxygen from iron oxide (reduction reaction) in iron ore, which can be in the form of lump or powder. This process generally takes place inside a blast furnace; Kobe Steel operates one at Kakogawa Works. Often regarded as the heart of steel production, blast furnaces enable economical mass production. However, they generate carbon dioxide (CO_2), a GHG, because coke and coal are used as the main heat source and reducing agent. This makes the steel industry one of the largest producers of GHG, accounting for approximately 7-11% of total emissions,[1)] so decarbonization within the industry is critical. Two options for achieving CN ironmaking are a lower reducing agent ratio in the blast furnace coupled with CO_2 recovery technology, and replacement of the blast furnace with a CN process. The ironmaking industry has other pressing challenges to solve as well, such as the established issue of the declining quality of iron ore.

Aside from ironmaking, Kobe Steel also provides plant engineering services for reduced iron plants and iron ore pelletizing plants. To meet customer needs, we have commercialized a variety of reduced iron processes and pelletizing processes, such as MIDREX® [Note 1)], FASTMET® [Note 2)], ITmk3® [Note 3)], and the KOBELCO Pelletizing System. Kobe Steel has developed multiple technologies to evaluate and improve furnace response in the reduced iron process, which varies with the properties of the ore, furnace temperature, and gas composition. This paper outlines the technologies that support Kobe Steel's ironmaking process initiatives, including those pertaining to reduced iron. Introduced as well are the company's efforts toward implementing its unique CN ironmaking process using these technologies.

1. Features and technological challenges of Kobe Steel's ironmaking process

Kobe Steel operates an integrated steel plant that processes iron ore into pig iron, steel ingot, and finished steel products. The company continuously promotes efforts to reduce CO_2 emissions from these processes.

Specifically, we have been working to reduce CO_2 emissions by charging reduced iron into blast furnaces using furnace ventilation control technology developed through blast furnace operation (see "Core Technologies Supporting KOBELCO Group's Contributions to Green Society" on p.5 of this issue) and improving the reducibility of raw materials in our pelletizing plants and other facilities.

We are also pursuing advancements in the MIDREX® Process, which has lower CO_2 emissions than blast furnaces, thereby reducing CO_2 emissions in the ironmaking process.

The MIDREX® Process has been taking on an

Note 1) MIDREX® is a trademark of Kobe Steel.
Note 2) FASTMET® is a trademark of Kobe Steel.
Note 3) ITmk3® is a trademark of Kobe Steel.

increasing share of reduced iron production for electric furnaces. This stable process boasts a 60% share in the production of reduced iron. Under development for further CO_2 emissions reduction are MIDREX Flex™ Note 4), designed for use with natural gas and hydrogen blends of any ratio, and MIDREX H_2™ Note 5), designed for use with 100% hydrogen.

The blast furnace and MIDREX® Process involve a reduction reaction that removes oxygen from iron ore. The final state of a chemical reaction (equilibrium state) is based on the specific compound, pressure, and temperature. Therefore, it is typically unnecessary to consider the reaction mechanism or rate occurring along the way to the equilibrium state. However, the reaction mechanism and rate do affect quality in ironmaking, as the product is often recovered before the equilibrium state.

Kobe Steel, which has blast furnace processes, reduced iron processes (e.g., the MIDREX® Process), and pelletizing plants, has optimized processes to ensure they are conducive to the reduction and melting of raw materials with various compositions and properties. This has led us to develop technologies for analyzing reaction mechanisms, reaction rates, and the properties of raw materials that affect reaction mechanisms and rates. Section 2 describes technologies for micro- and macro-analysis of raw materials and reduced iron properties; Section 3 describes process analysis and control technologies.

2. Analysis technologies for micro- and macro-analysis of raw materials and products

2.1 Evaluation technologies for mineral phases and properties of raw materials and products

Raw iron ore is available in lump or powder form. While lump ore can be charged directly into the furnace, direct charging of powder ore into the furnace reduces gas permeability and thus reduces operational stability. For this reason, pre-processing (agglomeration) is carried out to turn the raw material, including auxiliary constituents, into lumps through processes such as sintering. During sintering, some of the auxiliary materials and iron ore react to form a composite oxide. It is critical to control the quantities and compositions of these products, as they affect the strength of the agglomerate as well as the reduction and melting processes. This is why we have developed technologies to evaluate these parameters.

One of our unique technological developments is our equipment for automatic identification of composite oxides throughout a sample (MLA, mineral liberation analysis). It acquires the EDX (energy-dispersive X-ray) spectrum of each microscopic element on screen and identifies mineral phases through comparison against a database. The output is an image identifying the minerals present (**Fig. 1**).

Combining this analysis with experimental data make it possible to quickly investigate the optimal raw material recipe. Data collection and analysis using this equipment have led to significant cost improvements through optimization of raw material recipes for sintered ore, the raw material used in blast furnace charging.

Because raw ore grain size and the types and amounts of trace constituents change during reduction and melting, we also analyze constituents and properties during the reaction process. **Fig. 2** shows the results of research into the micro- and macro-scale properties and composition of the

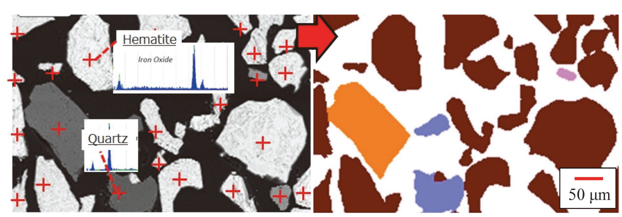

Fig. 1 Example of MLA analysis

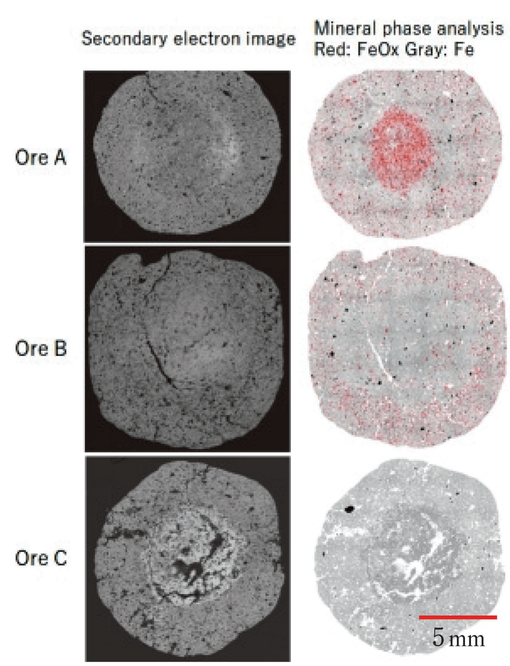

Fig. 2 Examples of DRI analysis by MLA

Note 4) MIDREX Flex™ is a trademark of Kobe Steel.
Note 5) MIDREX H_2™ is a trademark of Kobe Steel.

unreacted parts of direct reduced iron (DRI), a product of the MIDREX® Process, when different brands of iron ore pellets are reduced under the same conditions. The analysis shows that the parameters of the raw material affect the characteristics of the iron oxide after reduction.

Performing the same analysis on different brands of DRI during the reaction process reveals the reaction mechanism of each brand. This information is useful when evaluating reactions in the reduction shaft furnace where the MIDREX® Process occurs and when creating models and establishing parameters for reaction analysis (described later).

2.2 Nondestructive testing (NDT) technology for structural analysis (X-ray CT)

The physical properties of sintered ore/pellets (particle size, pore channels, etc.) also have a major impact on the reaction. Observation of the cross-section is a common method for examining the internal structure. However, this method only provides two-dimensional information, neglecting to reveal the three-dimensional structure of particles and voids. This is why we use X-ray CT analysis, which enables nondestructive, three-dimensional evaluation of lump structure. As an example, **Fig. 3** shows sintered ore and coke processed to separate into regions bounded by cracks. Image analysis technology (described later) processes these three-dimensional images to quantify physical properties such as particle diameter and pore channel distribution. This information can be used to eliminate bottlenecks.

2.3 Image analysis technology

This section presents image analysis technology that quantitatively evaluates the images from the process described above in conjunction with the three-dimensional information obtained from superimposing the images. Image analysis technology evaluates differences in color and shape within an image to identify characteristic particle groups and quantitatively analyze positional relationships and structures. This is how it evaluates, for example, the size and distribution of grains such as iron oxide, impurities, and voids in pellets. **Fig. 4** shows an example of pellet analysis using this technology. White areas in the upper-left image of Fig. 4, obtained via SEM, are iron oxide. These areas were converted to black and extracted to produce the upper-right image of Fig. 4. Although the iron oxide particles are sintered and connected here, there are localized small (thin) and large (thick) particles. The proportion of large grains is one factor that affects the reduction rate. Basic image analysis is insufficient for evaluating this parameter. This is because such technologies regard an individual group of connected pixels as a single particle.

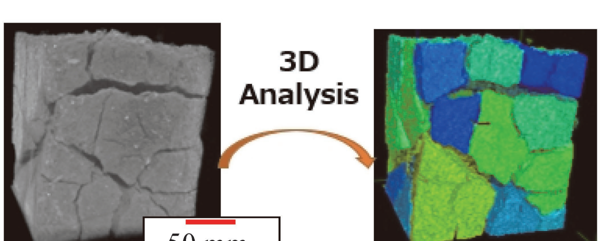

Fig. 3 Example of X-ray CT analysis

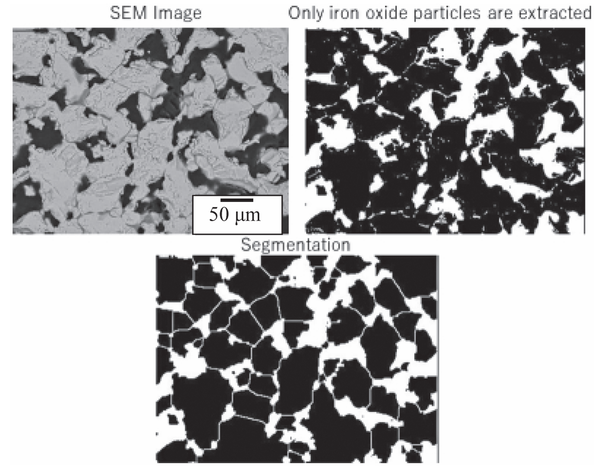

Fig. 4 Examples of image analysis of iron oxide pellets

Therefore, we processed the image using the neck of the particle as the starting point of the boundary to separate particles for effective analysis. This generated the image at the bottom of Fig. 4, which we analyzed to determine grain size distribution. These methods fostered simultaneous analysis of iron oxide and voids to quantitatively evaluate the physical characteristics of each brand of raw material. We compared these data with an expansive repository of data from actual machines to link raw material characteristics with product quality. In this way, it is possible to predict product quality in the plant based on the physical characteristics of the raw materials.

3. Process analysis and control technologies

3.1 Control technologies for raw material agglomeration

In the agglomeration process of pellet production, powdered ore is mixed with auxiliary materials as needed, rolled to form lumps, and then sintered. Moisture in the ore creates challenges such as sudden evaporation and rupture during sintering. We are developing technologies based on the properties of raw materials[2)] in response to these challenges. We are also working on grain size control[3)] and the addition of auxiliary material (dolomite) to improve the reducibility of pellets in blast furnaces after sintering. We have also developed a number of other technologies, such as for reducing SOx in exhaust gas for the use of high-sulfur-content ore.[4)] We will continue developing technologies that enable full use of iron ore, which is expected to decrease in quality, alongside control technologies for pellet characteristics as well as the raw material evaluation technology described in Section 2.

Kobe Steel's expertise in pellet production supports effective engineering services in the field of pellet production equipment (pelletizers). Kobe Steel's pelletizers are grate-kiln systems that heat pellets during the rolling process. This method heats all pellets as uniformly as possible and enables easy temperature modification. The uniform, high-quality pellets produced by the system serve as proof of concept.[3)] We also created a system for the drafting of proposals optimally suited to customer needs and ore characteristics. Pellet quality verification is an integral element of process design and is secured through sample testing using a variety of equipment.[5)]

3.2 Reaction evaluation analysis technology

In the MIDREX® Process, solid pellets are charged into a shaft furnace and are reduced by carbon monoxide and hydrogen derived from natural gas. Production volume in this process is based on the volume of the shaft furnace and the dwell time of the pellets in the furnace. Therefore, reducing the dwell time - in other words, speeding up the reduction reaction - increases productivity. The characteristics of the raw pellet affect reduction behavior. Therefore, we used the test apparatus depicted in **Fig. 5** to evaluate changes in the reaction rate over time to drive improvements. The apparatus provides web-based gravimetric measurements to reproduce gas parameters and temperature in the MIDREX® furnace, revealing changes in the reaction over time. In this way, the apparatus enables the collection of reaction rate data under 100% H_2 conditions, as one application example, making it possible to establish the appropriate operating conditions for actual machines.

Reaction rate analysis is also performed to reveal the mechanisms behind changes in the reaction rate by raw material brand and to perform comprehensive computations related to reactions in operating furnaces. As an example, **Fig. 6** compares the experimental reduction curve for the MIDREX® reduction reaction based on gas temperature and composition with calculations based on reaction rate analysis. Although the details behind the analytical model and reaction formulas are omitted, we also used the raw material evaluation technologies described in Section 2.1 to confirm the phenomena occurring during the reaction process and to establish reaction models and parameters based on the phenomena. We have reproduced our experimental results over a wide range of temperatures and gas compositions, even under complex conditions involving gradual changes in gas composition and temperature, as occurs in an actual furnace.

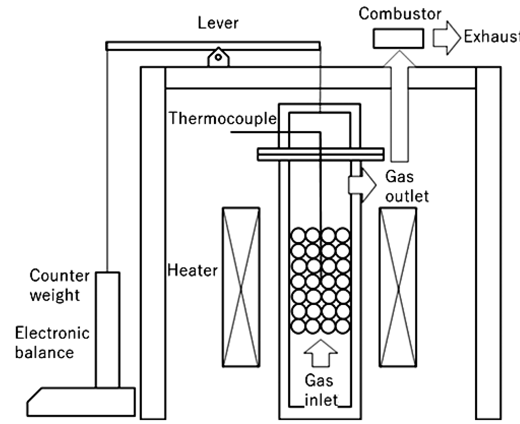

Fig. 5 MIDREX basic test furnace

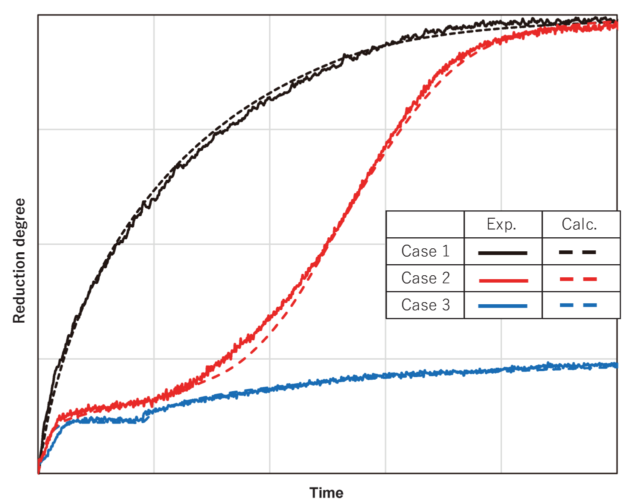

Fig. 6 Example of reaction rate analysis

3.3 Comprehensive analysis technology for reactions in actual furnaces

Understanding the reaction conditions in a furnace is essential for improving quality and productivity. As one tool for this purpose, we are developing a comprehensive computational technique applicable to furnace conditions. In furnaces, gas and temperature changes caused by a reaction in a given moment affect the reaction in the next moment by changing the gas composition and temperature through diffusion as well as modes of heat transfer such as convection. To evaluate the effects of these phenomena and analyze reactions throughout the furnace, the reaction analysis technique described in the previous section must be combined with thermal and fluid analysis technologies. For example, it is possible to reproduce the conditions in the shaft furnace of the MIDREX® Process by combining thermal and fluid analysis related to conditions inside the furnace with chemical reaction analysis using CFD (computational fluid dynamics). First, we compared the results of this analysis with actual furnace data. We then used the reaction analysis technology described in the previous section to optimize parameters through iterative verification. This method resulted in the highly accurate reproduction of parameters in actual furnaces such as reaction rates (e.g., reduction and carburization) and measured values (e.g., temperature) (see "Thermal and Fluid Dynamics Control Technology Supporting Production Processes and Products to Realize Green Society," p.84 of this issue). This comprehensive in-furnace analysis simulation technology identifies challenges related to reactions in various plants and presents operating conditions to optimize the reactions.

4. Kobe Steel's approach to CN in the ironmaking process

The current mainstream ironmaking process is the blast furnace method, which is a highly sophisticated, energy-efficient process capable of economical mass production of iron. However, the use of coal and other carbon sources as reductants generates CO_2, a GHG. Since most of the CO_2 generated in the steel industry comes from the reduction process, Kobe Steel is taking steps to reduce the blast furnace reductant ratio through reduced iron charging and through improvements to the reducibility of raw materials. Another way to foster CN is by promoting carbon capture, utilization, and storage (CCUS). This section covers the KOBELCO Group's CO_2 reduction solutions involving the MIDREX® Process.

As described Section 3.2, the MIDREX® Process uses carbon monoxide and hydrogen produced by reforming natural gas as reducing agents. It is possible to almost fully eliminate CO_2 emissions by replacing all reducing gas with hydrogen (MIDREX H_2™ Process) and using renewable electricity and green hydrogen.

Replacing the gas in the MIDREX® Process with 100% hydrogen presents several challenges, such as an increase in endothermic reactions in the furnace compared with conventional processes, altering the temperature balance. However, we overcame this challenge by combining the existing MIDREX plant operational data and expertise with predicted data regarding future conditions of the actual furnace using the basic technologies described above. Laboratory testing and comprehensive in-furnace analysis simulations confirmed that it is possible to produce DRI using 100% hydrogen without a significant redesign of the shaft furnace.[6), 7)]

In addition, combining the MIDREX H_2™ Process with an electric furnace reduces CO_2 emissions by more than 80% compared with the current blast furnace-converter process for producing crude steel, although the amount of reduction varies based on CO_2 emissions from the electricity used.[6)]

The transition to a hydrogen society is expected to continue progressing. We introduced the MIDREX Flex™ Process, which can switch between natural gas and hydrogen operation, to support the transition. The KOBELCO Group has received orders for the MIDREX H_2™ Process from H2 Green Steel of Sweden and the MIDREX Flex™ Process from Thyssenkrupp of Germany. We will use operational data from these plants to refine our fundamental technologies, further our operational expertise, and supply CN iron sources alongside plants capable of producing them.

Conclusions

Kobe Steel not only manages integrated steel production operations with in-house-pelletizing plants in Japan, but also provides reduced iron production systems such as the MIDREX® Process, which has a strong track record. We have developed numerous technologies that can consistently evaluate and optimize the entire process from the raw material to the reduced iron, including microscopic analysis of raw materials, experiment-based technologies centering around individual grains of raw material, and chemical reaction rate analysis techniques. We have also developed comprehensive analysis and simulation techniques for actual furnaces that incorporate microscopic and macroscopic reactions. Kobe Steel's unique strength, backed by this group of technologies, is its ability to respond swiftly to changing conditions such as the shift to a hydrogen society and changes in the grade of raw materials. This strength enables us to promote the MIDREX H_2™ and MIDREX Flex™ processes as methods to significantly reduce CO_2 emissions compared with the current blast furnace process. Furthermore, by supplying the low-carbon iron source made possible by these processes, Kobe Steel is furthering the transition of the ironmaking process and the entire iron and steel industry to carbon neutrality.

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