Carbon Resource Conversion and Application Technology Contributing to Realization of Carbon-neutral Society

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Abstract

To achieve carbon neutrality, it is essential not only to reduce CO_2 emissions and sequester CO_2, but also to recycle carbon resources such as coal and biomass. The Kobelco Group is actively developing technologies to convert these carbon resources into easily recyclable forms, such as fuel products and functional carbon materials, as well as technologies to safely use them as environmentally friendly products required for a sustainable society. This paper introduces an overview of carbon resource conversion and application technology of these carbon resources and provides application examples. It also discusses the future prospects of technology development aimed at realizing a carbon-neutral society.

Introduction

The KOBELCO Group has set goals of reducing CO_2 emissions from production by 30-40% by 2030 and of becoming carbon neutral (CN) by 2050. The company will support the SDGs (Sustainable Development Goals) and a sustainable society by promoting initiatives for a low-carbon, recycling-oriented society.

These goals require multiple approaches: renewable energy (solar, wind, geothermal, biomass, etc.) and non-fossil fuels (hydrogen, ammonia, etc.) to reduce CO_2 emissions; carbon dioxide capture and storage (CCS) to separate and recover CO_2 and confine it in a designated space; and carbon resource recycling and use to recycle the carbon resources necessary for everyday life and reduce the need to mine fossil fuels.

Kobe Steel's core technology of carbon resource conversion and application technology supports the use of carbon resources such as coal, biomass (wood, sewage sludge, food waste, agricultural residues, etc.), and industrial waste (plastics, tires, etc.) as functional carbon materials (carbon fiber, electrodes, etc.).

This paper introduces an overview of carbon resource conversion and application technology of these carbon resources and provides application examples. It also discusses the future prospects of technology development aimed at achieving a sustainable society.

1. History of Coal technology development at Kobe Steel

In support of energy security in Japan, Kobe Steel has been working since the 1980s on a process to upgrade unutilized low-grade resources and use them as a substitute for metallurgical coal or as fuel (**Fig. 1**). The technologies we have developed in these endeavors forms the foundation for our carbon resource conversion and application technology. This section covers Kobe Steel's history in coal technology development, including the characteristics of each technology.

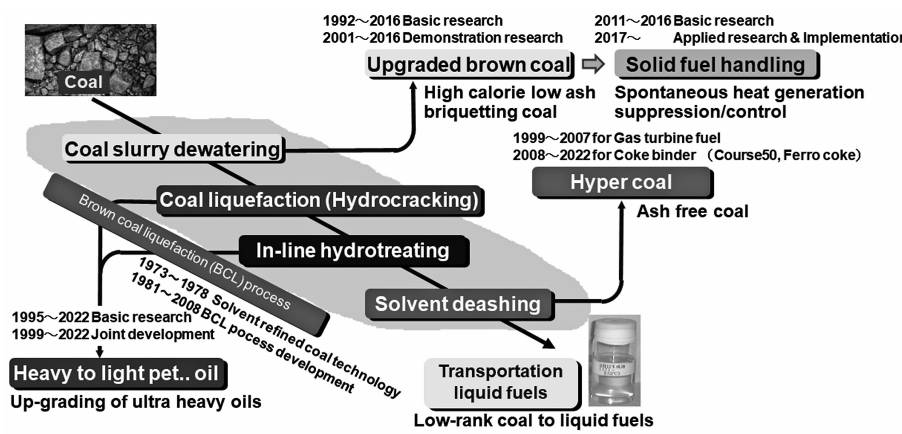

Fig. 1 Background of coal technology development

Brown coal liquefaction (BCL)

The second oil crisis (1979) spurred the development of fuels that could serve as alternatives to petroleum. It was during this period that Kobe Steel developed its solvent-refined coal (SRC) production technology to use brown coal from Victoria, Australia. The purpose of this countermeasure was to support BCL in response to the shortage and soaring cost of metallurgical coal for coke production.

In BCL, brown coal is heated and dewatered in an organic solvent, converted to liquefied crude oil using an iron-based catalyst and hydrogen, and further lightened and refined to obtain gasoline and kerosene. Through demonstrations associated with the Brown Coal Liquefaction Project in Australia, we have developed technologies in areas such as high-temperature, high-pressure slurry handling, dewatering, hydrocracking, hydrotreating, and solvent de-ashing. Additionally, we have been developing new processes for the application of these fundamental technologies since the 1990s.[1)]

Upgraded brown coal (UBC)

The rise of emerging economies in the 2000s led to significant increases in energy supply and demand, in turn causing the price of thermal coal (bituminous coal) used in coal-fired thermal power plants to skyrocket.

This drove Kobe Steel to develop a process for upgrading low-rank coals such as brown coal and subbituminous coal, increasing their calorific value and stability to levels comparable to those of bituminous coal.[2)]

We also conducted a large-scale demonstration (600 tons of product per day) in Indonesia to support an economical and stable supply of coal. Through this demonstration, we refined technologies for self-heat recuperation dewatering, powder handling (pulverizing, conveying, briquetting etc.), solid fuel analysis, and coal upgrading process design and control.[3)]

Hyper-coal (HPC)

In the mid-2000s, an increase in global crude steel production caused a jump in the price of metallurgical coal alongside concern that high-quality metallurgical coal resources could be depleted in the medium to long term. This revealed needs including reducing the consumption of metallurgical coal and making effective use of low-grade coal, conventionally considered difficult to use in coking. Kobe Steel focused on HPC, which is ashless and has superior softening and melting properties. The company turned its focus away from developing power generation fuel for gas turbines and toward developing coke binder.

HPC is ashless coal obtained by heating and extracting coal in a solvent (partially dissolving the coal), separating the soluble organic component from the insoluble inorganic component to isolate the precipitate, and removing the solvent from the soluble organic component.[4)] Through small-scale laboratory tests and demonstration of continuous operation at a bench-scale plant, we have enhanced our technologies for high-temperature, high-pressure slurry handling, solvent heating and extraction, and precipitate separation.

Solid fuel handling technology

Coals with strong oxidation properties such as low-rank coals, with their high O/C ratio (oxygen-to-carbon ratio) and high specific surface area, are more susceptible to spontaneous combustion than bituminous coal. To address the challenge of suppressing the spontaneous build-up of heat in low-rank coal, Kobe Steel has developed aging technology (low-temperature oxidation) to reduce coal reactivity based on the mechanism of heat generation, stockpile simulation technology to estimate the temperature of stockpiled coal,[5)] and technology to evaluate spontaneous heat generation characteristics.[6)] We have used our technologies as a springboard to develop a simulation model that can predict heat generation behavior in the coal silos at Kobe Steel's coal-fired thermal power plants. Using this model at other sites helps determine whether to introduce new brands of coal and helps propose operating methods.

Test infrastructure to support process development

Kobe Steel has various testing facilities (**Fig. 2**)

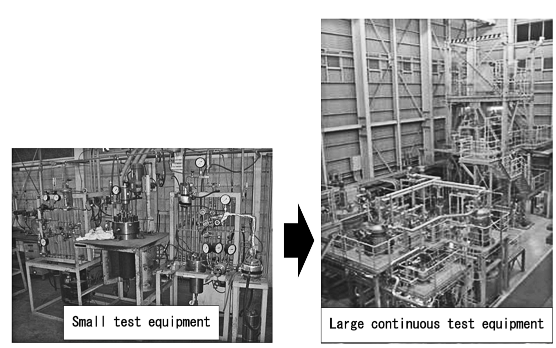

Fig. 2 High-temperature, high-pressure test facility (example of test infrastructure)

designed for high-temperature, high-pressure tests as well as operators specially trained to operate this equipment. Our process development method begins with theoretical research and laboratory-scale testing. We then scale up to the demonstration level (bench/pilot facility). This method supports overall process optimization and research into plant design theory. We have also constructed testing infrastructure with equipment for evaluating pulverizing capacity, thermal analysis, and physical analysis. This infrastructure can be used for everything from process development (production technology) to the evaluation of product properties and is currently being used as a foundation for carbon resource conversion and application technology.

2. Carbon resource conversion and application technologies

Fossil-based resources such as coal and petroleum are used not only for energy, but also as raw materials in a variety of industries and products including adsorbents, plastics, synthetic fibers, synthetic rubber, and paints. However, while some of these substances are recycled, they are ultimately incinerated, generating CO_2 emissions. Therefore, achieving a sustainable society requires the decarbonization not only of energy and fuel resources, but also of the raw materials for the industries and products that use them.

The carbon resource conversion and application technology that Kobe Steel has refined over the years supports the conversion of non-fossil-based carbon resources such as biomass into coking materials, fuel for power generation, and functional carbon materials (**Fig. 3**). This section introduces examples of developments we have underway.

2.1 Carbon fiber

There are two main types of carbon fiber, which is fiber made of carbon atoms: PAN-based (derived from acrylic fibers) and pitch-based (derived from coal and petroleum). Compared with iron, carbon fiber is about 1/4 the specific gravity, 10 times the tenacity, and 7 times the specific elastic modulus. Moreover, it can reduce CO_2 emissions through lightweight aircraft and vehicle design and by extending the driving range of electric vehicles.

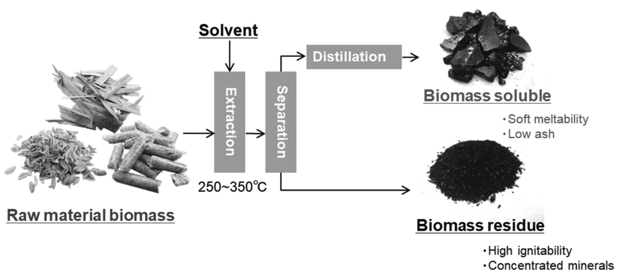

Fig. 3 Example of elemental technology for carbon resource conversion and application technology

Coal pitch-based carbon fiber is made from coal pitch obtained during coke production (carbonization of coal) that is then refined and modified into an intermediate substance between a liquid and a solid. The fibers are then carbonized in a melt spinning process. Challenges associated with this type of fiber and process are low recyclability and high cost.

Kobe Steel participated in the initiative "Development of Clean and Efficient Utilization of Low Rank Coals and Biomass by Solvent Treatment" in Thailand. Kyoto University led the project as part of the Science and Technology Research Partnership for Sustainable Development (SATREPS) program run by the Japan Science and Technology Agency (JST). Kobe Steel's contribution comprised researching how to apply the HPC process to biomass feedstock. We were able to obtain the desired solvent extract by heat treating low-rank coal and biomass waste (rice straw) from Thailand in a process tuned to the properties of the raw material. Further, using the native distillate (liquid from the pyrolysis process) as the extraction solvent improved the extraction rate, confirming that this technology can be applied to biomass.

Kyoto University also confirmed that the solvent extracts from current carbon fiber production methods can produce carbon fiber with a strength and surface area comparable to commercially available carbon fiber.[7] Biomass-derived solvent extract obtained this way can be used as raw material for carbon fiber. The next section covers how such fibers are being developed for use as electrode materials.

2.2 Electric double-layer capacitors (EDLCs)

EDLCs are energy storage devices in which an electrical double layer forms at the interface between the electrolyte and electrode during charging and discharging. It is anticipated that EDLCs will be used for applications such as load leveling for renewable energies such as solar- and wind-power generation. Although EDLCs have a lower energy density than lithium-ion batteries, they have desirable features such as a long service life and short charge and discharge times. Electrode materials must have a high specific surface area and high electrical conductivity because these characteristics greatly support the capacitance of an EDLC.

Kobe Steel collaborated with Oita University to develop a technique for obtaining porous carbon with a structure rich in nanopores of a few nanometers from HPC (**Fig. 4**). First, HPC is dissolved in an organic solvent (e.g., pyridine). This HPC solution is then added to water, which has poor HPC solubility (weak solvent). Carbon precursors instantaneously precipitate, become infusible, and carbonize (**Fig. 5**). A key feature of this method is that it does not require chemical activation. We fabricated a prototype EDLC electrode material using this porous carbon powder and evaluated its charge-discharge characteristics. It has a higher capacity than the currently available products (activated carbon), confirming the potential of using porous carbon powder in EDLC electrodes.[8)]

We are researching the use of this porous carbon powder in gas separation materials (carbon molecular sieves) to take advantage of its high specific surface area and abundance of nanopores. Processing conditions could be controlled to manage pore size for the selective separation of gas species. Biomass resources with a low degree of carbonization and high oxygen content yield porous carbon powder with a higher specific surface area, which we are working to develop into a recyclable material with high adsorption capacity.

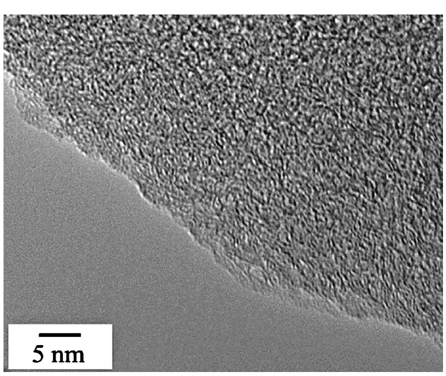

Fig. 4 TEM image (transmission electron microscopy) of precipitated porous carbon

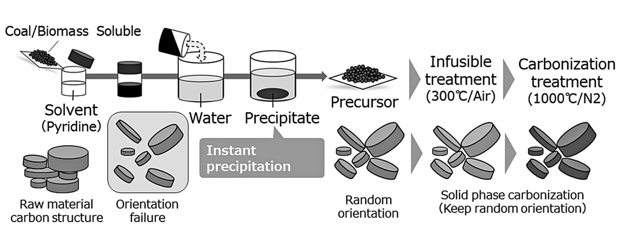

Fig. 5 Porous carbon production method by precipitation method

2.3 Binder for blast furnace coke

Carbon recycling via the functional carbon materials described above is just one pathway to achieving a sustainable society. Also important is the reduction of CO_2 emissions in the current ironmaking process to achieve CN. Next, we present a case study related to developing high-strength coke for operation with a low reducing agent ratio.

Iron ore and coke are charged into a blast furnace in alternating layers, after which iron ore is reduced to produce pig iron. In addition to its function as a heat source and reducing agent for iron ore, coke serves as a spacer to ensure permeability in the blast furnace. Operating with a low reducing agent ratio is particularly important to improve pig iron production efficiency and reduce CO_2 emissions. As such, it is important to use high-strength coke that can ensure sufficient permeability in the furnace even with a reduced coke charging rate.

Blast furnace coke comes from a blend of raw coals, ranging from metallurgical coals with strong caking properties to thermal coals with weak caking properties. High-strength coke requires a blend containing a high proportion of metallurgical coals, which have excellent caking properties and carbonization characteristics. However, because metallurgical coals are costly and are a limited resource, the challenge is to increase the proportion of inferior coals such as thermal coals while maintaining the required strength.

The HPC Kobe Steel develops is an aggregate of carbon compounds (molecular weight 300-1000) as shown in **Fig. 6**.[9)] Since it is a solvent-extracted product, its molecular bonds are weak, yielding excellent softening and melting properties. Adding HPC improves the fluidity of the blended coal, producing coke that has sufficient strength for practical use while incorporating a certain amount of thermal coal. A key project in this development was COURSE50,[10)] commissioned by NEDO (New

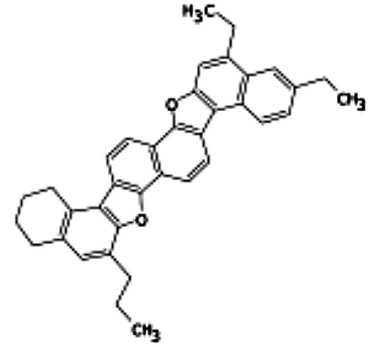

Fig. 6 Estimated molecular structure of soluble fraction of HPC

Energy and Industrial Technology Development Organization) as a collaboration between four Japanese companies involved in the steel industry. The result was a low-reactivity, high-strength coke production technique using HPC as a coke binder, supporting the hydrogen reduction of iron ore in a blast furnace. Production testing and performance validations in an actual coke oven achieved the target coke strength.[11)]

Potential methods to reduce CO_2 emissions in the coke production process include reducing the carbonization temperature of the coke oven and using coke made from a blend of biomass and metallurgical coal. In either case, however, one of the key challenges is to maintain coke strength. Our endeavors to overcome this challenge include designing blends that account for compatibility between coal and biomass varieties (including biochar), pre-processing materials (pulverizing, removing alkali, etc.), and using solvent extracts obtained from biomass as a coke binder.

3. Future prospects for technological development toward a sustainable society

This section introduces some of our latest initiatives involving the industrial process design infrastructure (facilities, operators, process design and evaluation methods, etc.) acquired or enhanced through the technological developments described in Sections 1 and 2.

3.1 Supporting the shift to CN for a sustainable society

The Ministry of Economy, Trade and Industry's Carbon Recycling Roadmap (June 2023 release) declares that technologies using minerals (concrete, carbonate, etc.) do not require hydrogen and aims to prioritize the commercialization of such technologies by 2030.[12)]

Steelmaking slag, a byproduct of the ironmaking process, contains a large amount of alkaline components such as Ca, which is necessary to remove impurities (P, S, etc.) from steel materials. These alkaline components react readily with CO_2, making them useful in CO_2 fixation. As such, the KOBELCO Group is developing CO_2 fixation technology that uses steelmaking slag (slag carbonation technology) as a technology that contributes to CN in the NEDO-commissioned research project "Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation." Slag carbonation technology (**Fig. 7**) begins with the extraction of Ca from steelmaking slag into a solvent. CO_2 is blown into the Ca-containing solvent, fixing CO_2 as calcium carbonate ($CaCO_3$).[13)] The products of this process are $CaCO_3$ and Ca-extracted slag.

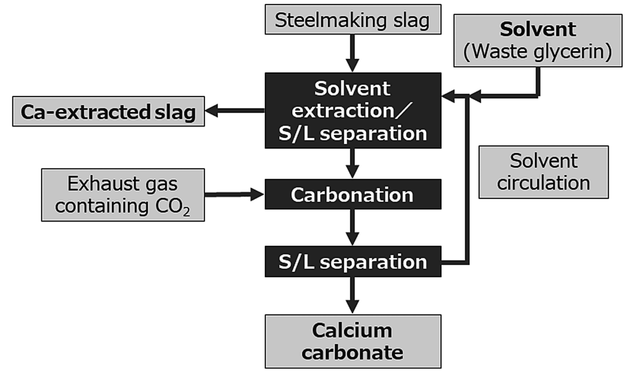

Fig. 7 Block flow diagram of CO_2 fixation technology for steel slag[13)]

We are running tests on 100-kg batches of slag to collect data relevant to scaling this technique up and to explore applications for product samples. The market demand for $CaCO_3$ in Japan is 4.8 million tons, and its main fields of application are in the production of paper, resins, paints, and construction materials. The $CaCO_3$ obtained in this process is a CO_2-free product that can be used as a raw material to create products associated with low CO_2 emissions. The Ca-extracted slag is best suited for use in existing applications such as roadbed material.

3.2 Resource recycling to achieve a sustainable society

Carbon resource recycling is being driven through initiatives specific to various sectors. In the plastics industry, the Act on Promotion of Resource Circulation for Plastics was made effective by the Ministry of the Environment in April 2022.[14)] As for the aviation industry, the Ministry of Land, Infrastructure, Transport and Tourism set a goal of replacing 10% of the fuel used by Japanese airlines with sustainable aviation fuel (SAF).

Kobe Steel is taking part in this trend using our proprietary technologies in hydrocracking/hydrotreating and in Heat Extraction and filtration. Specifically, we are advancing the monomerization of polymers through precise pyrolytic control of waste plastics and waste tires, the switch to basic substances, biomass gasification (wood, agricultural residues, etc.), and SAF production technologies that use hydro-processing and Fischer-Tropsch (FT) synthesis.

Furthermore, we have gained great expertise in techniques to obtain fuel from spent coffee grounds as well as semi-carbonized and hydrothermally carbonized palm empty fruit bunches (EFB). This knowledge feeds our research on the conversion of biomass resources into solvent extracts and carbides for use in the ironmaking process. Specifically, these materials could be used as carburizer in the reduced iron production process or as recarburizer in an electric furnace. We will use renewable solid carbon resources in Kobe Steel's ironmaking process to reduce CO_2 emissions and achieve CN.

Conclusions

Kobe Steel will foster a sustainable society through efforts to convert carbon resources such as coal and biomass into functional carbon materials and to use such materials. Our core technology of carbon resource conversion and application technology is a prime mover in achieving these goals.

Furthermore, Kobe Steel will create new approaches to carbon resource recycling in support of a sustainable society through the industrial process design infrastructure the company has cultivated.

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