

KOBELCO TECHNOLOGY REVIEW

No. **44** Jul. 2026

Feature- I : KOBELCO Machinery-Stay Close to Customers' Value Creation
Feature- II: KOBELCO's Materials and Solutions for Architecture and Civil Engineering

Contents

Feature- I KOBELCO Machinery-Stay Close to Customers' Value Creation

Kobe Steel's Efforts to Meet the Growing Market Need for Larger Turbo Compressors	1
Yuichi KONDO • Tsukasa SHIGA • Yoshihiro TOYODA	
New Large Resin Mixer, LCM-620IM	7
Kazuo YAMAGUCHI	
Hydrogen Utilization in Boilers and Industrial Furnaces Using Hybrid-type Hydrogen Gas Supply System	11
Hiroshi IMAYO • Koji TANAKA • Kiminobu KAGAWA • Dr. Akira MATSUOKA • Kazuki MURAKAMI • Dr. Akitoshi FUJISAWA	
Demonstration Tests of Three Types of Liquid Hydrogen (LH ₂) Vaporizers	22
Yasutake MIWA • Tomohiro SUZUKI • Shinji EGASHIRA • Masataka AZUMA • Yoshihiko TSURU • Takumi NISHIMURA	
Compressor for LNG Carriers	30
Yoshiharu IKEGAMI • Satoshi TEZUKA	
Integrally-gearred Centrifugal Compressor for Carbon Capture and Storage (CCS) and Long Duration Energy Storage (LDES) Applications	35
Komei FUJIOKA	
High-temperature, High-pressure Warm Isostatic Pressing Equipment for All-solid-state Battery Manufacturing Process	43
Hiroyuki ITO • Kazushi HAYASHI • Natnapin PONGCHASIRIKUL	
Characteristic of AlCrN Hard Coatings Deposited with New AIP Evaporation Source and Evaluation on Actual Mold	48
Shinichi TANIFUJI • Masaru NAKAMURA • Susumu KUJIME • Dr. Takeshi ISHIKAWA	

Feature- II KOBELCO's Materials and Solutions for Architecture and Civil Engineering

KOBELCO's Materials and Solutions for Architecture and Civil Engineering	56
Dr. Takeshi TAKADA	
Development of 780 N/mm ² -Class Structural Steel for Building Structures Suitable for High Heat Input Welding	66
Ryota MIYATA • Tetsuo YAMAGUCHI • Akito TABATA • Takahiro YAMAMOTO • Ryohei KURIYAMA	
Corrosion Resisting Steel Eco-view Plus™, a Repaint Term Extension under High Humid Environment	71
Takuto MATSUBAYASHI • Dr. Yusuke TAKAHASHI • Dr. Fumio YUSE • Masahiro MATSUSHITA • Akito TABATA • Tetsuo YAMAGUCHI	
Kobelco Group's Welding Technologies for Architectural Steel Frames	78
Dr. Reiichi SUZUKI	
Latest Trends and Lineup of Welding Consumables for Structural Steel	86
Takahiro YAMAMOTO • Hang YU • Yuto INOUE • Masaharu KOMURA	
Stealth Brace for Traditional Wooden Architecture	95
Yuto HASHIDA	
Introducing New Automation System and CAD-Linked Software for Architectural Steel Frame Beam Welding	102
Yuki SHIKA • Taisei FUJIMOTO • Ryo ASANO • Atsushi ARAI • Nobuaki TANAKA	
Compact Portable Welding Robot System with Vision Sensor	107
Junichi KAWATA • Keito ISHIZAKI • Kohei MATSUSHIMA • Kohei KOMUKAI • Dr. Tatsuya YOSHIMOTO	

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Published by

**Technical Development Group
Kobe Steel, Ltd.**

5-5, Takatsukadai 1-chome,
Nishi-ku, Kobe, HYOGO 651-2271, JAPAN
<https://www.kobelco.co.jp>

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Kobe Steel's Efforts to Meet the Growing Market Need for Larger Turbo Compressors

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Abstract

In recent years, as various plants have grown in size, there has also been a demand for larger compressors and other key equipment. Kobe Steel has been working to meet the needs of customers who are looking for more extensive and more efficient compressors in oil and petrochemical plants, such as EO/EG (ethylene oxide/ethylene glycol) and PDH (propane dehydrogenation), as well as air separation, which has traditionally been the main application of turbo compressors. This paper discusses the details of these efforts.

Introduction

Alongside overall growth in the global population, a further trend impacting industry is that many developing nations are experiencing increased economic strength and higher standards of living. This is increasing the demand for raw materials essential to industry and everyday life, including petrochemicals as well as industrial gases such as oxygen, nitrogen, and argon. To meet market demand, plants that produce these gases are expanding their operations and striving to improve efficiency and reduce costs. Expanded operations in turn necessitate larger compressors, which are the heart of such operations. This paper details our progress in developing the larger Kobe Steel centrifugal compressors (DH and VG series) typically used for ethylene glycol, propylene, and air separation applications.

1. Developments in ethylene glycol and propylene production applications

1.1 Role of Kobe Steel compressors in these applications

EO/EG process technology is used to produce ethylene oxide (EO) and one of the compounds for which it serves as a raw material, ethylene glycol (EG). EG is used in products such as antifreeze for automotive cooling, textile fibers, and PET bottles. The current mainstream technologies are licensed by three companies: Scientific Design LLC, The Dow Chemical Company, and Shell plc. EO is a

product of the catalytic reaction between ethylene and oxygen in a tubular catalytic reactor. Kobe Steel DH-series compressors play a key role in improving the efficiency of this reaction. Specifically, these single-stage overhung centrifugal compressors serve as cycle gas compressors, which return unreacted gas to the reactor.

A related industry process is PDH (propane dehydrogenation), which produces propylene for the manufacture of plastics, textiles, solvents, and medical products. Unlike EO/EG, this process is licensed by many engineering companies, with leading technologies comprising Oleflex technology, the CATOFIN process, and the STAR process. Some of these processes use a compressor as a heat pump, and similar to EO/EG applications, Kobe Steel's DH-series compressors can compress and heat the propylene that overflows from the splitter or separator. The heat from the compressed propylene is used to reboil propane, improving the overall energy efficiency of the process. The demand for this compressor is expected to increase due to its capacity to further the global trend toward decarbonization.

1.2 Compressor specifications

Typical compressor specifications for EO/EG applications include a suction pressure of slightly less than 2 MPaA, suction temperature equal to ambient temperature, and a compression ratio (ratio of absolute suction pressure to absolute discharge pressure) of about 1.2. Large-scale systems for these applications have a flow rate of at least 150,000 m³/h and large compressors with an impeller diameter of greater than 1 m and a shaft power of at least 10,000 kW.

Typical compressor specifications for PDH applications are a suction pressure of slightly less than 1.5 MPaA, a suction temperature near the saturation temperature of propylene, and a compression ratio of about 1.8. Large-scale plants for these applications have a flow rate of about 100,000 m³/h and large compressors with an impeller diameter of greater than 1 m and a shaft power of at least 20,000 kW.

1.3 Compressor structure

Kobe Steel's DH-series compressors are single-stage centrifugal compressors suitable for low compression ratios and high flow rates. Fig. 1 shows the operating range of the DH series. The boxed range of high flow rates corresponds to the range required for EO/EG and PDH applications. Fig. 2 shows a cross-section of a DH-series compressor. The shaft seal, a tandem dry gas seal on the back of the impeller, prevents process gas from leaking out of the machine. With this shaft seal as the reference point, the impeller side is the side in contact with the process gas, and the journal bearing side is the side exposed to atmosphere. Two journal bearings support the rotor, which consists of the impeller and shaft. Between the journal bearings is a thrust bearing that accepts the thrust generated in the axial direction by the pressure differential between the process gas and atmospheric pressure, as described above. The impeller overhangs past the two journal bearings at the shaft end.

An inlet guide vane (IGV) serves as a flow regulator to support the turndown operation required for PDH applications. A high-head impeller supports the compression ratio necessary for

PDH applications, which is higher than that of the polyethylene/propylene process (traditionally the main application of the DH series).

1.4 Challenges of larger equipment, and solutions

Market demands now require a larger casing for both applications described to accommodate a larger gas flow channel for higher flow rates. However, using conventional design principles for the new casing would be problematic because they prioritize performance optimization. While this would secure the superiority of Kobe Steel compressors, it would result in excessively large casings, increasing cost and introducing constraints in casting production. Therefore, we mitigated the increase in casing size by using a lower value than typical for the diffuser ratio, which is the ratio of the diffuser outlet diameter (D_5) to the impeller diameter (D_2), or D_5/D_2 . We predicted that an excessively small casing would affect gas flow in the casing channel in a way that would reduce performance. As such, the challenge was to determine the casing size that would keep performance within market requirements. We used computational fluid dynamics (CFD) to predict how various diffuser

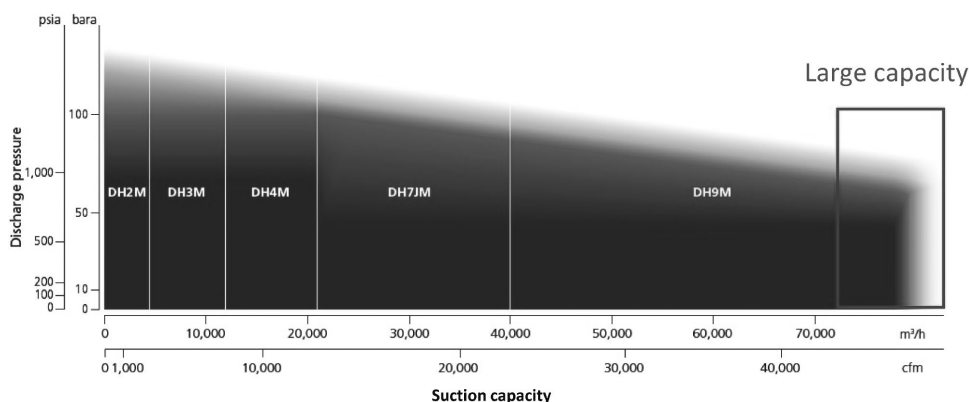


Fig. 1 Standard range chart for DH series

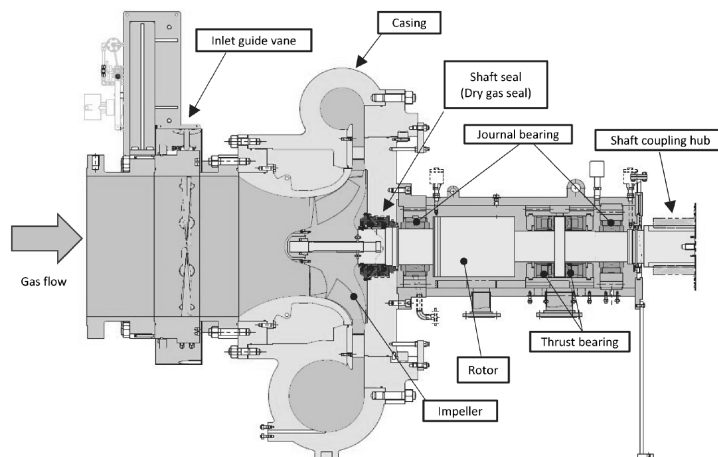


Fig. 2 Typical sectional drawing of DH series

ratio specifications would impact performance in EO/EG and PDH processes. We also produced physical prototypes of each scaled-down model and measured their performance. **Fig. 3** shows the test facility and the casing of a scaled-down model. Testing confirmed that the performance values of the scaled-down models were within range; therefore, we adopted the more scaled-down specifications. Furthermore, the error between the measured efficiency and the calculated CFD efficiency was less than ± 1 point, which constitutes high accuracy.

As a result, we mitigated the weight increase of the casing by about 30% compared with the design based on conventional methodology, yet maintained the performance required of the market. Moreover, we satisfied the customer's need for expanding plant capabilities. **Fig. 4** shows a comparison of casing size between the conventional method and the more compact model.

We confirmed numerous design parameters

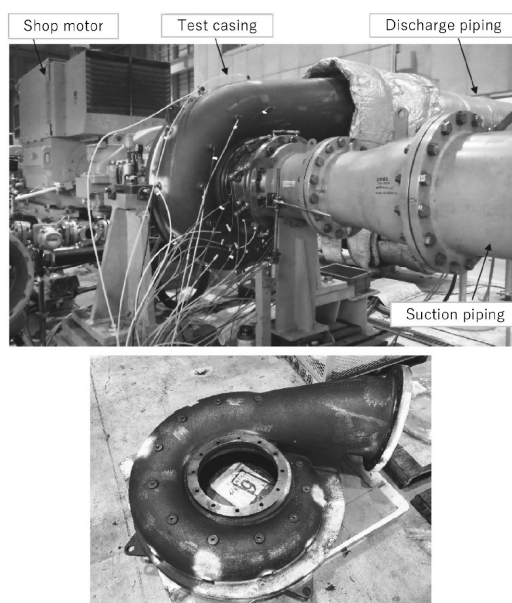


Fig. 3 Overview of test facility and scaled-down casing

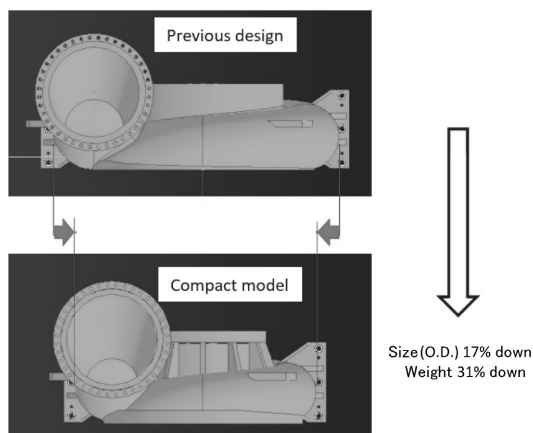


Fig. 4 Comparison of compressor casing size

of each component even aside from the casing to ensure suitability for the increased power accompanying an increased flow rate. For instance, we confirmed sufficient strength of the joint between the shaft and impeller to transmit more torque, and sufficient strength of the larger-diameter impeller and shaft. We also considered that a larger shaft diameter increases the diameter of the dry gas seal, increasing the thrust of the process gas on the compressor rotor. Particularly when the customer needs the compressor to start up from a pressurized state, the effect of process gas thrust on starting torque during startup dictates the specification of the drive.

Extensive working hours go toward maintaining large machines. As such, the structure of the DH series enables the compressor rotor assembly, which includes the shaft seal and bearing box (requiring particularly frequent maintenance), to be removed as a unit from the coupling side of the compressor. We adopted this same structure for the compressor with a scaled-down casing as designed for this application. Accordingly, it is possible to service the main parts of the compressor without removing the large-diameter suction and discharge piping (diameter ≥ 40 inches) connected to the compressor casing.

Additionally, larger impellers are heavier, shifting the rotor assembly's center of gravity toward the impeller. To prevent the rotor from tipping when supported independently for maintenance, we designed the shape of the rotor such that the center of gravity is between the bearings.

A further challenge presented by PDH processes is the need for high flow rates as well as gases with high relative density, which increase the stress on the IGV and the force required to move it. The pneumatic actuator that operates the IGV is selected such that it can exert the force required for operation under the minimum instrument air pressure in the customer's system.

Figs. 5 and 6 show external photographs of the compressors supplied for EO/EG and PDH applications.



Fig. 5 Centrifugal compressor for EO/EG application



Fig. 6 Centrifugal compressor for PDH application

2. Developments in air separation technology

2.1 Role of Kobe Steel compressors in these applications

Air separators separate and extract the main components of air: oxygen, nitrogen, and argon. One air separation process is cryogenic distillation, in which air is cooled to a very low temperature, liquefied, and then separated into its constituents by distillation. The first step requires a main air compressor (MAC) to compress air, a role filled by Kobe Steel's VG series integrally geared centrifugal compressors. Although we have previously developed a larger compressor,¹⁾ we made the casing and impeller smaller and more efficient to optimize price and efficiency and thus secure our position within this highly competitive market.

2.2 Compressor specifications

Typical MAC specifications require an increase in air pressure from atmospheric pressure to 0.5 MPaG. Flow rates depend on the size of the air separator. However, among the suitable range of VG-series compressors as indicated in Fig. 7, large models

with suction flow rates of 300,000 Nm³/h to 400,000 Nm³/h (indicated by the rectangle) demonstrate the benefits of a compact and highly efficient casing and impeller particularly well. Fig. 8 illustrates the need for these high-capacity machines, as the flow rate of compressors Kobe Steel has provided for air separation units has increased over the years.

2.3 Compressor structure

Integrally geared centrifugal compressors have conventionally been used to conserve energy and space. Fig. 9 shows a cross-section of this type of compressor. Connected directly to the input shaft is a low-speed bull gear. Surrounding this bull gear are high-speed pinion shafts, which have impellers at one or both ends. This design enables each impeller to rotate at the optimal speed. Additionally, each impeller has a dedicated casing. This makes it possible to install a gas cooler in the discharge section of each casing for interstage cooling, which increases efficiency. A further feature of this single-

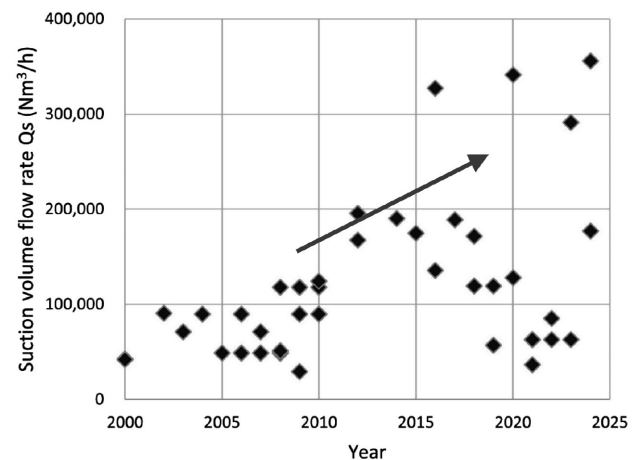


Fig. 8 Trend of flow rate of VG series for ASU application

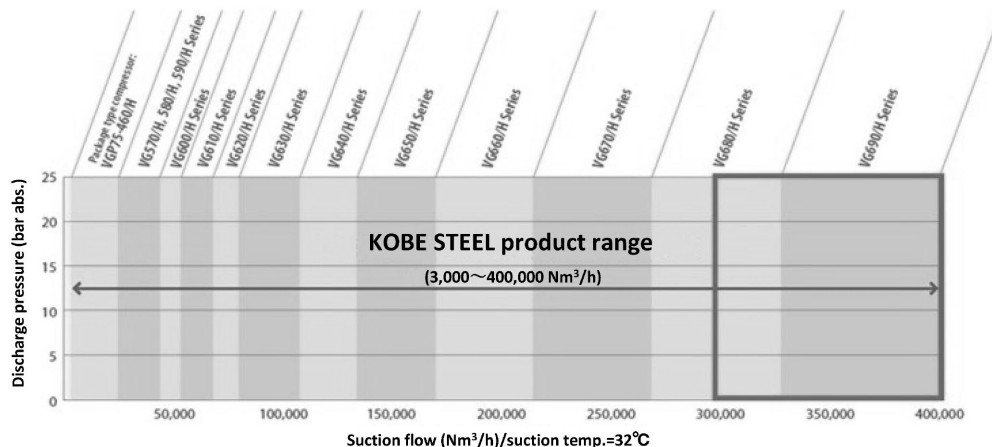


Fig. 7 Standard range chart for VG series

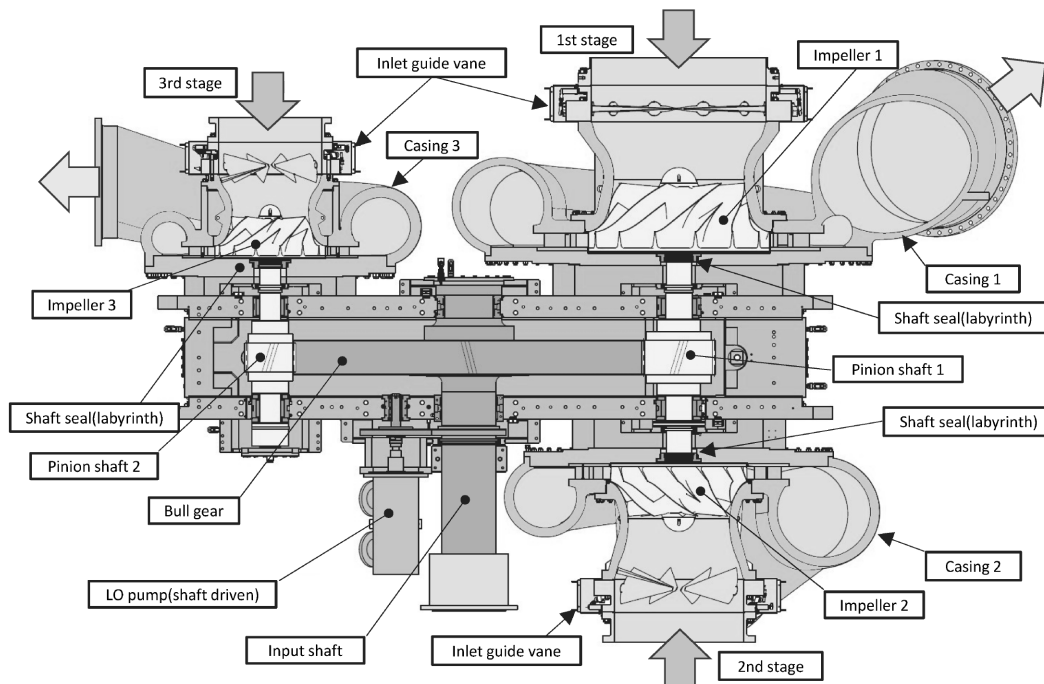


Fig. 9 Sectional drawing of VG series

shaft, multi-stage centrifugal compressor is the integral gearbox, which saves space compared with the conventional external gearbox design.

2.4 Challenges of larger equipment, and solutions

As with EO/EG and PDH processes as described above, larger casings pose challenges in terms of production and cost. Distance between the shaft centers of an integrally geared compressor separates the multiple casings connected directly to the gearbox. Therefore, reducing the diameters of the casings in turn reduces the size of the gearbox. This is notable for air separation equipment because the power consumption of the MAC has a major impact on the plant's overall power consumption, causing efficiency to be a critical evaluation point in MAC selection by the customer. Larger equipment increases power consumption, so MAC efficiency is particularly crucial. As such, Kobe Steel has taken actions such as improving upon conventional impeller design to ensure competitiveness as plants continue to increase in size. **Fig.10** shows an external photograph of the improved impeller. Alongside reducing impeller size by 10%, our redesign improves efficiency by up to 3 points in the low-flow range (the range often used in actual operation) compared with the conventional impeller¹⁾ designed for the same flow rate and head ratio (see **Fig.11**). **Fig.12** shows a photograph of the compressor manufactured with the improved impeller.

A further challenge is that as compressors



Fig.10 Improved impeller

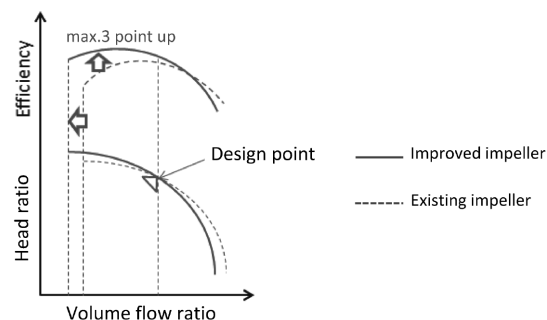


Fig.11 Comparison of efficiency/head between existing and improved impeller

become larger, the size of ancillary equipment such as integral gearboxes, gas coolers, and lubricating oil units must also increase. In turn, there is a need for cost reduction of these components. Because these components are essential to any compressor system, it is critical to secure suppliers that can guarantee supply and satisfy our and our customers'

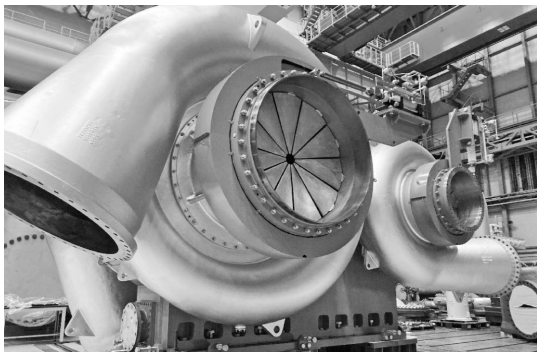


Fig.12 VG series with improved impeller

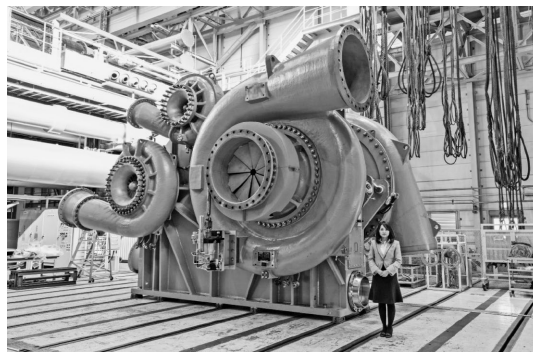


Fig.13 Compressor for blast furnace gas application

requirements in quality, cost, and delivery. For this reason, Kobe Steel actively engages new suppliers from various regions capable of manufacturing the ancillary components. The company also furthers the capabilities of these suppliers by providing training in design, manufacturing, and quality control.

2.5 Expanding the application range of large integrally geared compressors

To curtail energy consumption and carbon emissions, steel plants are transitioning to combined cycle power generation equipment that uses gas turbines (GT) fueled by natural gas or byproduct gases with a lower heating value, such as blast furnace gas (BFG) and coke oven gas (COG). Traditionally, single-shaft centrifugal compressors have filled the role of byproduct gas compressors in the supply of byproduct gas to gas turbines. However, to support improved efficiency in such operations, Kobe Steel is building upon experience in gas applications to expand the scope of use of large integrally geared compressors with optimized impeller speed functionality and interstage cooling (see Section 2.3).

Typical compressor specifications for this application are suction pressure equal to atmospheric pressure, suction temperature near ambient temperature, and a compression ratio of about 25. Flow rates of such compressors depend on the requirements of the gas turbine but are around 150,000 Nm³/h. These large six-stage compressors feature interstage cooling, an individual impeller diameter of greater than 1 m, and a shaft power of at least 20,000 kW.

Byproduct gas contains corrosive and combustible constituents. Hence, the compressor casing is made of cast stainless steel, or carbon steel with a corrosion-resistant coating on the inner surface. In the latter case, the rotating parts including the impeller have the same coating. The shaft seal, which prevents the leakage of process

gas from the compressor casing to the atmosphere, is a dry gas seal or carbon seal. Gas turbine applications have various key process requirements such as behavior upon emergency shutdown and restrictions on fluctuation in compressor discharge pressure. Such parameters depend on the operating conditions on both the gas turbine and generator sides. Therefore, we perform dynamic simulation of the system including the compressor to determine the control valve specifications, with an end goal of validating and optimizing operating settings.²⁾

Fig.13 shows a photograph of the compressor we supplied for this application.

Conclusions

Recent years have seen increased demand for larger plants for EO/EG, PDH, air separation, and byproduct gas (e.g., blast furnace gas) applications. In support of this trend, Kobe Steel is solving the challenges associated with manufacturing and optimizing the efficiency of the larger compressors required for these market needs. Kobe Steel continues to develop state-of-the-art compressors to foster technological innovation and greater efficiency in this field.

One of Kobe Steel's most important tasks is to understand the precise needs of the market to ensure we provide compressors that meet our customers' needs. We understand that the key to close partnerships with our customers is to put their trust and satisfaction first while constantly striving toward innovation and evolution.

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New Large Resin Mixer, LCM-620IM

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Abstract

The largest-ever LCM-620IM continuous mixer for polyethylene resins has been developed, and the first unit was shipped in 2024. This machine has a production capacity of over 100 tonnes per hour, improving production efficiency. By applying intermeshing rotor technology to a commercial mixer for the first time, this mixer achieves the same or better mixing performance with 12% less energy consumption compared with our company's conventional machines. In response to the increasing volume of polyolefin production, improving the mixing performance and production capacity will contribute to reducing CO₂ emissions and achieving a carbon-neutral society. A customer has also placed an order for the LCM-560IM and its intermeshing rotor technology is highly regarded in the industry.

Introduction

The annual global production of commodity polyolefins such as polypropylene and polyethylene has increased year over year. As such, in pursuit of improved production efficiency, production plants have increased the capacity per production line year on year. Kobe Steel manufactures the LCM™ series of large continuous mixing and pelletizing systems that are the nucleus of these production lines. We have developed and shipped the first unit of the LCM-620IM, the largest in the series with a nominal mixing shaft diameter of 620 mm, to meet the needs for larger production lines.

The LCM-620IM is not only the largest of its kind, but also the first commercial machine in the series with intermeshing rotor technology. This innovation reduces energy consumption in polyethylene production, furthering progress toward a carbon-neutral society. This paper introduces the LCM-620IM large continuous mixer.

1. Mixer size specifications

Equipment throughput has increased in recent years in support of more economical polyolefin pellet production. Annual per-plant throughput has increased from 400,000 metric tons/year in the 2010s to a range of 500,000 to 650,000 metric tons/year in the 2020s. Plans are underway to increase this figure to more than 800,000 metric tons/year in the future.

In the 1980s, Kobe Steel introduced the LCM™ series of large continuous mixers with combined gear pump in the size designation of 380 (LCM-380G), indicating a nominal mixing shaft diameter of 380 mm. Ever since, we have developed larger mixers roughly every 10 years to meet market needs: the 450 in the 1990s (LCM-450H), the 500 in the 2000s (LCM-500H), and the 560 in 2013 (LCM-560H). We released the 620 (LCM-620IM) in 2022 and shipped the first unit in 2024. **Fig. 1** shows the LCM™ pelletizer system. **Fig. 2** shows the change in production rate per unit of the LCM™ series over time. The launch of the LCM-380G spurred an accelerated pace of increases in capacity, owing to the pressure boosting technology of a gear pump downstream of the mixer. This development greatly increased the efficiency of polyolefin production worldwide.

Fig. 3 shows an external photograph of the LCM-620IM. Intermeshing biaxial mixing rotors turn in opposite directions in the chamber of the LCM™ to efficiently melt and mix polyethylene powder.

Over the past 30 years, each model in the LCM™ series has incorporated design improvements

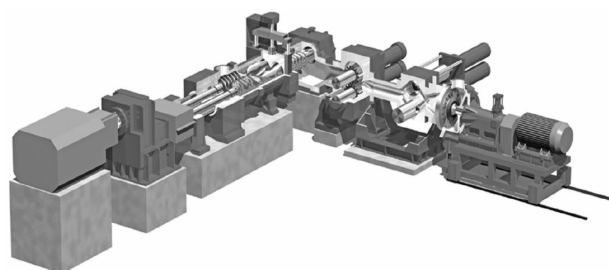


Fig. 1 LCM pelletizer unit overview

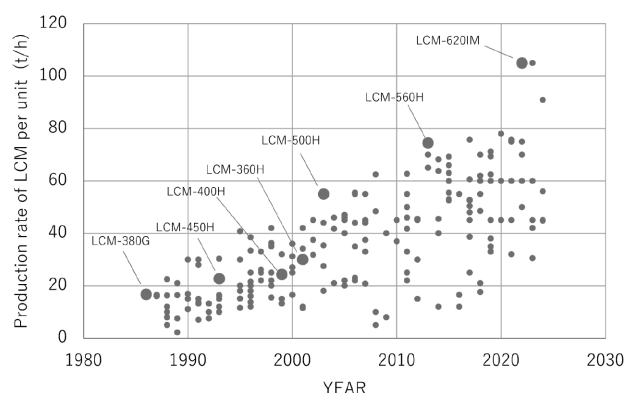


Fig. 2 Transitions of LCM production rate per unit

to accompany an increase in size. The LCM-G series had twin mixing rotors at a 45-degree angle, the LCM-H series featured horizontally aligned twin rotors alongside increased motor power and shaft torque, and the LCM-IM series introduced intermeshing rotors for increased power and improved mixing performance.

The LCM-620IM large continuous mixer is the largest ever of the series with its 620 size rotor shaft, which is about 10% larger than the 560 rotor that previously held this title. **Table 1** shows the specifications of each size class of LCM. The 10-meter mixing rotor makes the LCM-620 the world's largest continuous mixer. With a 13% increase in power over the LCM-560's rating of 23 MW, the 26 MW rating of the 620 results in an increased production capacity that can yield 100 metric tons or more of high-density polyethylene (HDPE) pellets per hour.

There was initial hesitation before the first customer agreed to purchase the largest continuous mixer ever. However, they were at ease after recognizing not only the machine's mixing performance, but also Kobe Steel's track record of reliable equipment and strong customer service as well as our machine production and operating record of around 300 units of 560 and smaller models.

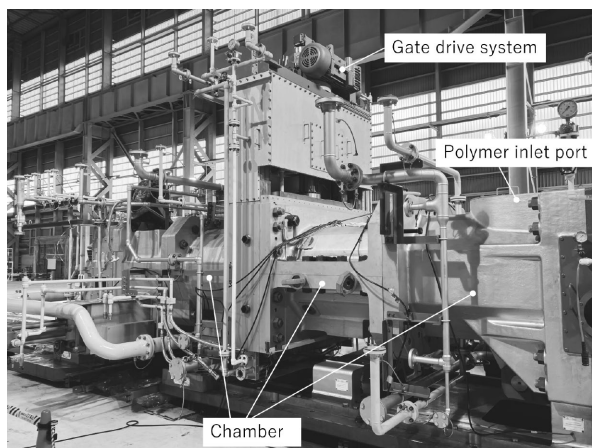


Fig. 3 LCM-620IM overview

Table 1 Main specifications of LCM

Model No.	Power (kW)	Rotor speed (rpm)	Rotor diameter (approx. mm)	Rotor length (approx. mm)	Typical production rate (ton/hour)
LCM-360	9,600	550	360	5,800	48
LCM-400	11,800	500	400	6,300	59
LCM-450	15,000	440	450	7,100	75
LCM-500	18,000	400	500	7,800	90
LCM-560	23,100	360	560	9,100	116
LCM-620	26,300	320	620	10,000	132

2. Mixer performance

One of the main components of the resin manufacturing process is the reactor, which produces resin powder. The large continuous mixer downstream of the reactor then begins the pelletizing process by melting and mixing resin powder, homogenizing the polymer with a specific molecular weight distribution. The equipment in this process is also sometimes responsible for uniformly mixing in additives.

Recent years have seen an increase in the development and production of bimodal HDPE resin, owing to its good formability alongside its superior durability and strength that yield a long service life. However, some grades of high-performance HDPE resin present greater challenges in homogenization and mixing compared with conventional materials. This is because the constituents of their raw powders do not easily compound into a homogeneous mixture. Such grades have peaks in the high and low ranges of the molecular weight distribution. As a result, clumps of high-molecular-weight PE are dispersed throughout a matrix of low-molecular-weight PE. The force of mechanical mixing does not readily transmit to the high-molecular-weight PE, inhibiting the dispersion of the high-molecular-weight components. More energy is then generally needed during mixing to achieve sufficient dispersion.

To produce these mix-resistant materials with less energy, our newly developed mixer has the intermeshing rotor technology with optimized geometry as detailed in an earlier issue of the Kobe Steel Engineering Report.¹⁾ **Fig. 4** shows the rotor configurations described next. In contrast to the conventional LCM-H series, the LCM-IM series features a larger rotor diameter in the downstream second mixing zone (D_2). This yields the relationships ($D_1 < D_2$) and (rotor diameter > shaft center distance) and thus a dimensional

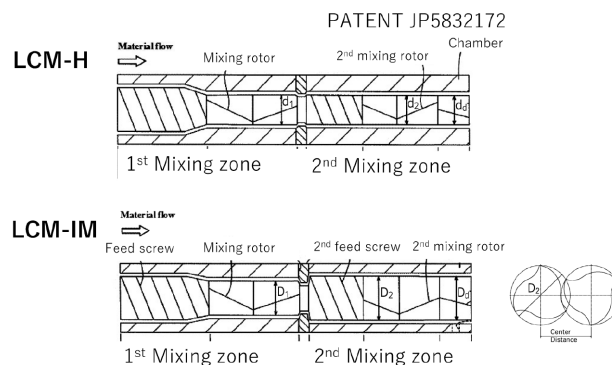


Fig. 4 Rotor configurations of LCM-H and LCM-IM

relationship in which the rotor lobes of the two abutting shafts intermesh with each other.

When we received the order for the first 620, we ran laboratory-scale testing of the new intermeshing rotor technology for the first time, with the customer present. The machine passed the mixing performance test and performed very well in terms of energy efficiency in particular.

One step in the process of melting and mixing HDPE resin powder is to disperse the non-dispersed polymer clumps (hereafter, “gel”) to the required level. However, the specific energy input (SEI), or energy consumption, of the mixing process must be low. In developing the geometry of the intermeshing rotor, we used mixing performance evaluation technology based on Kobe Steel’s proprietary flow dynamics simulation software.^{2), 3)}

We conducted basic mixing tests to analyze the factors affecting gel dispersion and energy consumption of the LCM™ in detail. Furthermore, we ran simulations to find the rotor geometry that optimizes both gel dispersion and energy conservation.

Fig. 5 shows an example of a simulation used to evaluate mixing performance. The contour color (grayscale in this paper) indicates the stress level. We tuned the parameters of the rotor geometry to yield a stress distribution with larger areas of high stress, corresponding to high gel dispersion efficiency, and smaller areas of low stress, corresponding to low gel dispersion efficiency.

Fig. 6 shows the results of the mixing performance test using the simulated material in the lab-scale mixer. The simulated material was a blend of general-purpose polyethylene and ultra-high-molecular-weight polyethylene. The results confirm that the dispersion of ultra-high-molecular-weight polyethylene in general-purpose polyethylene during mixing correlates with the dispersion of the high-molecular-weight component in bimodal polyethylene. We evaluated the degree of dispersion based on the amount of white spots (hereafter, WSA: white spot area ratio), regarded as incomplete dispersion, when carbon was added and dispersed. A lower WSA (%) indicates higher quality. **Fig. 6** shows the relationship between mixing quality and SEI for the conventional rotor and the intermeshing rotor, with SEI on the horizontal axis and WSA on the vertical axis. While the conventional LCM™ mixing rotor consumes 0.33 kWh/kg to achieve a WSA of 1%, the LCM-IM-series intermeshing rotor consumes only 0.29 kWh/kg for the same WSA, indicating a 12% reduction in SEI.

Lab-scale mixing performance testing using the customer’s polyethylene also confirmed that

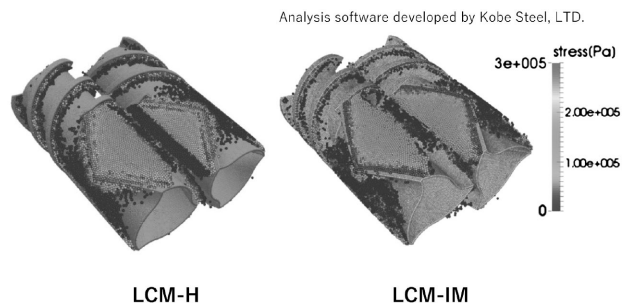


Fig. 5 Mixing stress contour by flow dynamics simulation

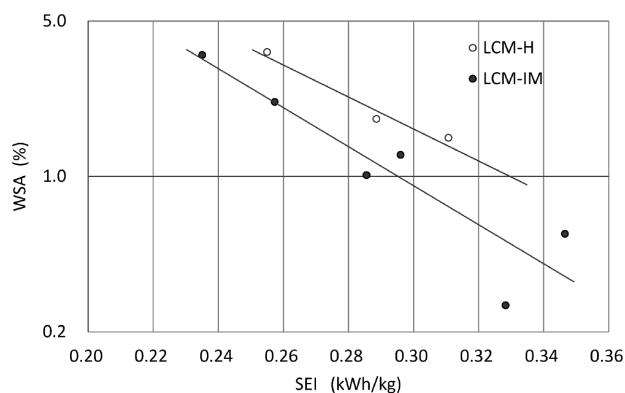


Fig. 6 WSA depending on SEI by LCM-H mixing and LCM-IM mixing

the intermeshing rotor technology required a significantly lower SEI for gel dispersion than did the conventional LCM™ mixing rotors. This was the deciding factor in securing the order.

The customer anticipates reduced SEI in the pellet production process after LCM-620IM installation. Assuming an annual resin production of 300,000 metric tons/year, an SEI reduction of 0.040 kWh/kg yields the calculation 300,000 metric tons/year × 0.040 kWh/kg = 12,000 MWh/year of energy savings. This amounts to a substantial reduction in energy, cost, and carbon emissions. The enhanced mixing performance and reduced SEI described are expected to be validated after operation begins in 2026.

3. Manufacture of the machine

The challenge in manufacturing the largest continuous mixer is the size itself. It is necessary to use technology for manufacturing large cast and forged parts with high quality. The largest machining and polishing equipment available must be used, and in inventive ways. Furthermore, the assembly and testing of such massive equipment require advanced manufacturing techniques and expertise. The success of producing the first of these large machines was built upon involving manufacturing engineering in the design phase

and thoroughly reviewing each production step in advance.

4. Vibration analysis

Numerous technical aspects must be considered when designing the largest continuous mixer to ensure reliability, including component strength, the heating and cooling performance of the mixer, pressure loss in the flow channels for molten material, and each part's sealing performance. This section covers the particularly critical concern of mechanical vibration.

Large mixers experience extreme levels of vibration. When the mixing lobes of the rotor mix highly viscous polyethylene, the frequency of the reaction force is a multiple of the number of lobes, causing fluctuations in the mixing load. Since there was concern that the new larger machine would experience more vibration, we conducted vibration analysis during the machine design phase to ensure vibration would not exceed the permissible value.

We used laboratory equipment to measure the mixing load generated at the rotor. Specifically, we measured the load, the magnitude of fluctuations in load, and the frequency at which the fluctuations occurred. For the vibration analysis, we scaled up the mixing load of the lab-scale experiment to the mixing load of the production machine, accurately simulating the excitation frequency and the phase of the mixing load as generated by the two rotors. The analysis software used was Abaqus.

The simulation confirmed that the vibration level is permissible for the 620-size mixer. **Fig. 7** shows the mesh model used for vibration simulation via FEM analysis. **Fig. 8** shows an example of the program output from an analysis of equipment deformation caused by vibration due to the reaction force of mixing resin. We extracted the necessary information from depictions of deformation such as

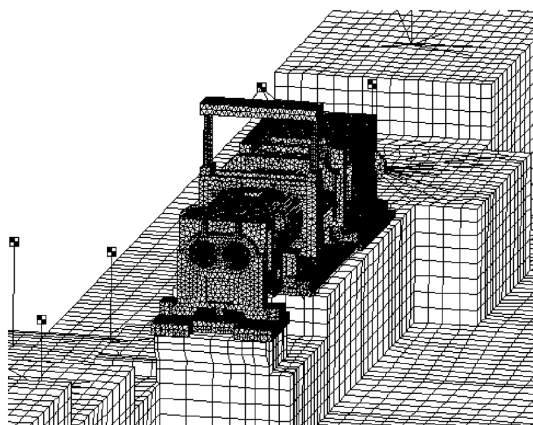


Fig. 7 LCM-IM chamber vibration analysis model

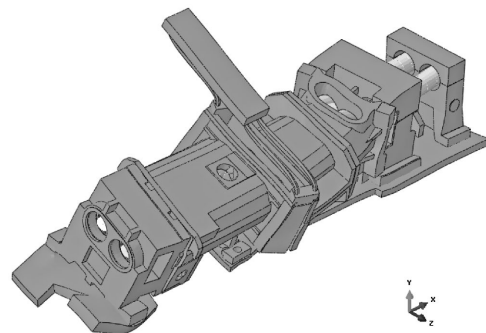


Fig. 8 LCM-IM chamber vibration analysis result

these for each vibration mode to increase component rigidity in areas with a high degree of deformation. As a result, we were able to suppress the overall vibration level.

Conclusions

Kobe Steel launched and delivered the LCM-620IM, the company's largest-ever mixing and pelletizing system, in response to market needs for improved efficiency, energy conservation, and dispersion in polyethylene production. This machine has the new intermeshing rotor technology, which enables economical production of polyethylene pellets by consuming less energy than the conventional LCM™. Around the time of this development, another customer ordered an LCM-560IM with the same intermeshing rotor technology, validating the energy-saving capacity of Kobe Steel's intermeshing rotor technology. We anticipate the wide adoption of this technology.

We will continue the timely development and delivery of large continuous mixers with improved energy efficiency and dispersion performance for new high-performance materials developed by polyolefin producers. In this way, we will help reduce carbon emissions from the production and disposal of plastics, thereby fostering progress toward a carbon-neutral society.

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Hydrogen Utilization in Boilers and Industrial Furnaces Using Hybrid-type Hydrogen Gas Supply System

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Abstract

CO₂-free hydrogen is attracting attention as a decarbonization measure. In transitioning to a hydrogen society, the use of hydrogen in a local production for local consumption model, utilizing electricity derived from renewable sources for on-site production and utilization of hydrogen, is a realistic solution until a large-scale hydrogen supply infrastructure is established. However, electricity derived from renewable sources faces the challenge of ensuring a stable hydrogen supply. To counter this, Kobe Steel is developing and demonstrating a hybrid hydrogen gas supply system that combines two hydrogen supply sources: hydrogen derived from renewable energy sources and stored liquid hydrogen. In addition, it is more realistic for facilities that use hydrogen to convert fuel while making the most of existing equipment rather than undergoing large-scale modifications or renovations. Therefore, in transitioning to a hydrogen society, it is important to consider how to start a realistic hydrogen supply and utilization system from the perspectives of both hydrogen suppliers and users. Kobe Steel's Takasago Works strives to realize a hydrogen society by demonstrating a series of steps, from hydrogen production and supply to hydrogen use in boilers and heating furnaces.

Introduction

In October 2020, the Ministry of Economy, Trade and Industry (METI, an agency of the Japanese government) declared a goal of achieving carbon neutrality by 2050 by reducing greenhouse gas emissions to net zero. METI then released the Basic Hydrogen Strategy in June 2023 to provide direction on accelerating the transition to a hydrogen-based society and on strengthening the competitiveness of the hydrogen industry.¹⁾ This Strategy also sets targets for hydrogen supply costs at 30 JPY/Nm³ by 2030 and 20 JPY/Nm³ by 2050. As part of these efforts, advancements are being made in hydrogen production in Australia. For instance, the country completed the world's first large-scale maritime transport of liquid hydrogen to Japan via liquefied hydrogen carrier in February 2022.

Currently, about 90% of primary energy supplied in Japan comes from fossil fuels, with about 40% consumed as thermal energy. Furthermore, roughly 40% of this thermal energy is used in the industrial sector. The decarbonization of not only electric power, but also thermal energy, is thus a key challenge in achieving carbon neutrality. Switching to CO₂-free fuels is one means of decarbonizing thermal energy. This paper focuses on hydrogen, regarded as a promising CO₂-free fuel. Section 1 explains the justification for this area of focus. CO₂-free hydrogen includes green hydrogen and blue hydrogen. Green hydrogen is produced using electricity from renewable energy sources via water electrolysis equipment (hereafter, electrolyzers). Blue hydrogen describes the capture and subsequent storage or reuse of by-product CO₂ produced when fossil fuels are reformed, which reduces carbon emissions. One challenge in achieving the aforementioned goal lies in securing green hydrogen. Electric power from renewable energy is not yet widely available in Japan, making procurement difficult. Furthermore, green hydrogen is significantly more expensive than the typical fuels such as city gas. Efforts such as those described above in Australia should make it possible to economically import blue hydrogen into Japan as liquid hydrogen, although this is not expected to come to fruition until the 2030s or later. Because the industrial sector needs a stable energy supply, it cannot easily switch to CO₂-free hydrogen fuel yet, as the supply infrastructure is not in place.

This paper proposes a hybrid-type hydrogen gas supply system (Section 2) as a concrete strategy for gradually expanding hydrogen supply and utilization. The system starts with the production of green hydrogen derived from renewable energy using an on-site electrolyzer (Fig. 1). Once the stable supply of economical liquid hydrogen is established, green or blue hydrogen will be incorporated as an input to the system.

Kobe Steel's Takasago Works in Takasago City, Hyogo Prefecture, is a production base for materials business divisions (e.g., cast and forged steel, titanium, iron powder) and machinery

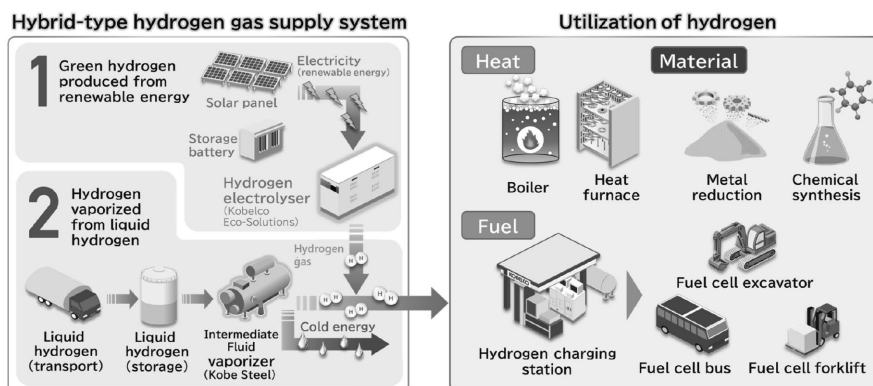


Fig. 1 Hybrid-type hydrogen gas supply system

business divisions (e.g., energy-related equipment). Therefore, we must switch from fossil fuels to CO₂-free fuels in our numerous boilers and heating furnaces alongside providing products and technologies that contribute to our customers' decarbonization efforts. Kobe Steel is combining the technologies and products of Kobelco Eco-Solutions Co., Ltd. and Kobelco E&M Co., Ltd. to conduct studies and demonstration tests on hydrogen utilization in a way that involves collaboration between the users of hydrogen and the producers of hydrogen.²⁾

1. Hydrogen utilization potential at Takasago Works

Many companies have initiated CO₂ reduction efforts. For instance, Power Purchase Agreements (PPAs) are gaining attention as a means to advance carbon-neutral electricity through the use of renewable energy. PPAs set the conditions for an arrangement in which a third-party power provider installs renewable energy equipment (e.g., solar panels) on the customer's premises and the customer pays the provider for the electricity consumed. However, electrification is difficult for industrial furnaces operating in the high-temperature range of 800 to 900°C and above. One challenge associated with such equipment is the thermal resistance of recirculation fans. As such, one measure of decarbonization to advance carbon-neutral thermal energy is to switch to CO₂-free fuels such as hydrogen or ammonia.

Which CO₂-free fuel will prevail remains to be seen, but four factors point to the conversion to hydrogen fuel as promising for the industrial sector. 1: There have been advances in hydrogen burner technology, and there are already hydrogen boilers on the market. 2: Hydrogen has various uses outside of fuel. 3: Hydrogen can support energy security owing to its multiple procurement

avenues (production via electrolysis using regionally sourced renewable energy, blue or green hydrogen from overseas, and regional by-product hydrogen). 4: Ammonia is a toxic gas. Therefore, while it can be used where people can be distanced from a leak (e.g., power plants in coastal areas), the danger associated with leakage is high for inland plants. Further, the dehydrogenation of MCH (methylcyclohexane) is highly energy intensive.

Kobe Steel's Takasago Works operates over 100 boilers and heating furnaces across multiple material and machinery production sites. These pieces of equipment have varying combustion capacities and operating patterns (continuous, intermittent, load fluctuations during operation, etc.). As such, our research examines hydrogen supply and utilization models suitable for multiple locations and a wide variety of hydrogen utilization points. These studies thus have value not only in our own transition to carbon neutrality, but also in this transition among production sites across various industries throughout Japan. Therefore, we assessed the potential for using CO₂-free hydrogen (including various hydrogen carriers such as ammonia and MCH) at each of our sites based on the energy demand of our boilers, heating furnaces, metal reduction equipment, industrial vehicles, etc. We also established a comprehensive model for the procurement, storage, supply, and utilization of CO₂-free hydrogen and calculated the applicable costs. Furthermore, we identified challenges to expanding hydrogen utilization and researched solutions to these challenges.³⁾

Calculations show ammonia as the most economical option in terms of both hydrogen carrier procurement and consumer receiving terminals, and thus the most economical option within the hydrogen utilization model. However, as mentioned earlier, ammonia poses risks for inland plants. The technological readiness level of liquid hydrogen for transport and storage is lower than that of ammonia.

However, the significant potential for the costs associated with liquid hydrogen to decline could shrink the difference in cost between ammonia and liquid hydrogen. Selecting the optimal hydrogen carrier also depends highly on the regional import policies for hydrogen carriers applicable to the plant location. Kobe Steel's Takasago Works is in the Kobe/Kansai region, where there is ongoing discussion regarding the establishment of a hydrogen supply chain. In anticipation of growth in the hydrogen supply chain, we are investigating converting to hydrogen for thermal energy in our plants.

2. Producing hydrogen

The method of hydrogen delivery must be based on demand patterns and levels and on the progress of fuel conversion. For example, while racks of hydrogen cylinders are an adequate means of supplying hydrogen to a few fuel cell forklifts, this method would be unsuitable for supplying hydrogen as fuel to boilers or heating furnaces. Such cases necessitate plumbed hydrogen gas or large-scale supply facilities, such as liquid hydrogen satellite bases (facilities that store liquid hydrogen and supply it to plants as needed). However, in the early stage of transitioning to hydrogen, high hydrogen prices and inadequate supply infrastructure will likely mean that only a limited number of plants will use hydrogen. This period of low hydrogen demand will see little progress in the construction of large-scale hydrogen production and supply facilities. As such, cost reduction for the supply infrastructure will stagnate, potentially in turn stagnating the conversion to hydrogen for fuel. Therefore, in establishing the hydrogen supply chain, hydrogen demand must grow in tandem with the construction of hydrogen supply infrastructure. The stepwise expansion of hydrogen demand will promote the fuel transition over the medium to long term.

The only liquid hydrogen currently available in Japan is gray hydrogen produced by reforming LNG, and the import of inexpensive CO₂-free hydrogen is not expected to reach full-scale operation until the 2030s or later. It will likely be even later before the hydrogen supply chain is sufficiently developed to support inland utilization. Until that point, the most realistic option during the introduction phase of the transition to hydrogen is to produce and use hydrogen locally. This model uses local renewable energy from sources such as electrolysis and solar power to produce and use green hydrogen on site. On-site hydrogen production equipment can convert

surplus renewable energy into hydrogen for storage and utilization. This is a promising solution for coordinating the supply and demand of renewable energy in conjunction with fluctuations related to both location and time.

As hydrogen utilization increases over time, hydrogen derived from renewable energy alone will likely be insufficient to meet demand, necessitating supplementation with liquid hydrogen. Even if it becomes possible to import CO₂-free liquid hydrogen, it would be exceptionally costly for every plant to have its own facility for liquid hydrogen storage, regasification, and supply, inhibiting widespread adoption. Therefore, liquid hydrogen facilities shared by multiple plants or industrial parks should reduce the burden on individual companies and facilitate the expansion of hydrogen utilization.

As described above, the expansion of demand and the construction of supply facilities must occur in tandem for a successful hydrogen supply chain. A promising hydrogen introduction plan begins with supporting hydrogen utilization by using regional renewable electricity for on-site hydrogen production via electrolysis. Hydrogen shortages will be supplemented with domestic gray hydrogen or other liquid hydrogen. The switch to domestic and imported green hydrogen for liquid hydrogen will occur in a later phase. The next section provides an overview of the hybrid-type hydrogen gas supply system, which is designed around the early stage of the hydrogen supply chain, and details the system's products and technologies.

2.1 Overview of the hybrid-type hydrogen gas supply system

Kobe Steel has begun technological development and demonstration tests on its hybrid-type hydrogen gas supply system⁴⁾, which is a combination of two supply systems: a hydrogen production process that uses electrolysis powered by renewable electricity, and a regasification process for stored liquid hydrogen. An operation management system connects the two supply systems for optimized control. This system supports a hydrogen supply process that addresses both the initial phase of hydrogen utilization (introduction phase) and the subsequent phase when hydrogen utilization expands (expansion phase). The explanation that follows illustrates how Kobe Steel envisions the model for the hydrogen supply process.

In the introduction phase, there is not yet a stable and economical supply of CO₂-free liquid hydrogen. Therefore, hydrogen comes from electrolyzers

capable of producing CO₂-free hydrogen using renewable electricity. Since stable plant operation is the top priority, the reliability and ease of operation of the electrolyzers are particularly critical during this phase. On-site renewable electricity is unstable because it is weather dependent, presenting a challenge to ensuring sufficient electricity for an electrolyzer. Therefore, it is important to charge the battery when renewable electricity exceeds demand and to draw power from the grid (e.g., by using renewable energy certificates or electricity during cheaper time periods) when renewable electricity is insufficient. This is why we developed an operation management system, which provides power control functions to ensure stable and economical power while maximizing the electrolyzer's utilization of renewable energy. Section 2.1.3 details this system.

During the expansion phase, since the supply of CO₂-free liquid hydrogen will be established, the hydrogen supply system will be upgraded to use both liquid hydrogen and hydrogen from electrolyzers to accommodate the increase in hydrogen utilization by the plants. Using stored liquid hydrogen to adjust supply rates is a simple solution for overcoming the instability of CO₂-free hydrogen produced by electrolyzers. In addition, the cold energy generated during liquid hydrogen regasification can be used for cooling production plant equipment, air conditioning systems, heat pumps, and similar applications to improve process efficiency and reduce energy consumption. In addition, the combined use of hydrogen from electrolyzers and liquid hydrogen makes it possible to capitalize on liquid hydrogen procured from overseas alongside hydrogen from electrolyzers that are located domestically and are powered by domestically produced energy. This strengthens our local energy security.

When using both hydrogen from electrolyzers and liquid hydrogen, balancing the supply of each

with overall hydrogen gas demand is crucial. This is why our operation management system will have control functionality to selectively minimize running costs or CO₂ emissions according to customer needs. This function will account for CO₂ emissions intensity, the unit price of grid electricity for powering the electrolyzer, and the unit price of liquid hydrogen.

In March 2023, we completed construction of a demonstration facility for the hybrid-type hydrogen gas supply system, where demonstration tests are underway. **Fig. 2** shows the facility, and **Fig. 3** shows its flow diagram. The HHOG[®] (detailed in Section 2.1.1), manufactured by Kobelco Eco-Solutions Co., Ltd., is the electrolyzer. Kobe Steel's Intermediate Fluid Vaporizer (detailed in Section 2.1.2) serves as the liquid hydrogen vaporizer. The facility's renewable energy power generation system comprises a photovoltaic system (detailed in Section 2.1.1) and a battery bank. The EPC (engineering, procurement, and construction) of this facility was handled by Kobelco E&M Co., Ltd., which has amassed expertise in all types of hydrogen-related technology through its abundant experience in constructing hydrogen stations. The following sections detail the facility's main equipment and operation management system.

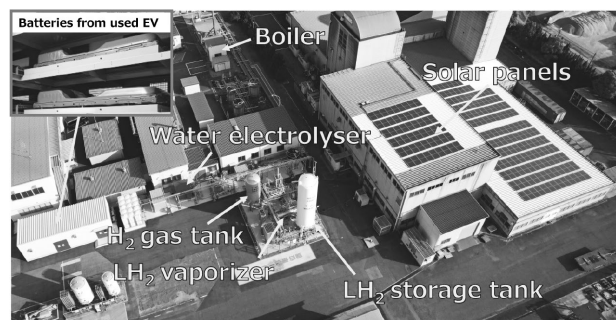


Fig. 2 Hybrid-type hydrogen gas supply system demonstration facility (Takasago Works)

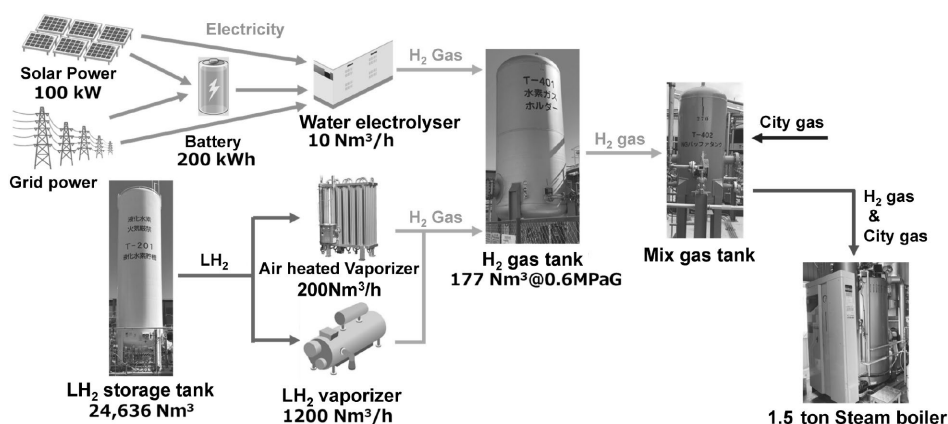


Fig. 3 Overview of demonstration facility

2. 1. 1 Electrolyzer powered by renewable energy

Kobelco Eco-Solutions Co., Ltd. has been working on the technological development of the HHOG® (High-purity Hydrogen and Oxygen Generator) electrolyzer, which uses a polymer electrolyte membrane.

While we have primarily supplied industrial process gases for production in industries such as electronics and metalworking, the use of hydrogen produced using renewable energy sources (e.g., solar and wind-power generation) has recently gained attention as a means of achieving carbon neutrality. As a result, hydrogen now sees widespread use in energy applications such as hydrogen stations, fuel cells, and hydrogen boilers.

Electrolyzers require several utilities including municipal water, electricity, nitrogen gas, coolant, and compressed air for instrumentation. When these utilities are not available near the operating site, customers face the challenge of setting up utilities in addition to the electrolyzer itself. This led us to release the “all-in-plan” unit in March 2023, which eliminates the need for all utility connections except water and electricity.

The demonstration unit of the all-in-plan unit completed standalone trial operation before being relocated to Kobe Steel’s Takasago Works for the demonstration test of the hybrid-type hydrogen gas supply system. Long-term demonstration testing will validate its reliability during the summer and winter seasons and provide a means for potential customers to observe the system operating under solar power before introducing it in their operation.

The nominal maximum output of the demonstration facility’s photovoltaic system is 105 kW, which is approximately twice the demonstration electrolyzer’s full-load power consumption of 50 kW. Solar power systems generate a highly variable amount of power during the day based on how the panels are installed, sunlight intensity, and the position of the sun. **Fig. 4** shows a sample of the variation in solar power production over time during the demonstration. Overcast conditions and nighttime hours limit power generation, whereas peak output is extremely high in clear daytime weather. Therefore, ensuring the full-load power consumption of the electrolyzer is less than the maximum output of the photovoltaic system increases the proportion of renewable energy used even during periods of low generation.

Specifically, the power generated on sunny days exceeds the demand of the electrolyzer, resulting in the generation of surplus power, whereas on cloudy days, power generation decreases significantly

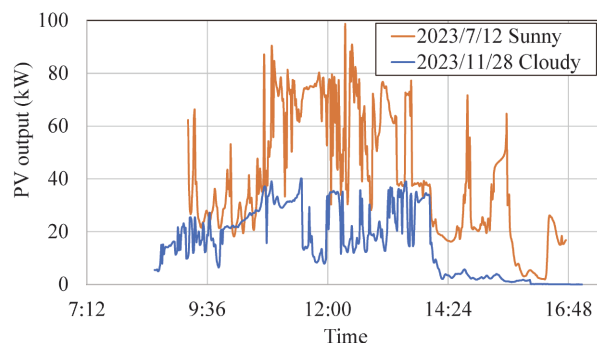


Fig. 4 Typical examples of solar power production

and may fall below the demand of the electrolyzer. Furthermore, there is an overall decrease in power generation in the winter because of the low position of the sun, which results in a poor angle of incidence on solar panels. Thus, solar power is highly prone to seasonal and weather variation, making it an unstable power source for electrolyzers. This again illustrates the importance of establishing a reliable, economical supply of low-carbon hydrogen by combining unstable solar power with municipal and battery power as backups based on the weather and time of day alongside liquid hydrogen regasification. Our operation management system, covered in Section 2.1.3, is the control system that satisfies this need.

2. 1. 2 Cryogenic intermediate liquid hydrogen vaporizer

The “Large-scale Hydrogen Supply Chain Establishment” project, which is part of the Green Innovation Fund Projects, is examining the import of CO₂-free hydrogen from overseas. Hydrogen is unsuitable for transport in gaseous form because of its extremely low density. Therefore, research into the maritime transport of hydrogen in liquid form is underway. In this state, hydrogen is cooled to -253°C and reduced to 1/800 of its gaseous volume. Imported liquid hydrogen is stored in vacuum-insulated cryogenic double-wall tanks and then vaporized as needed for supply. Liquefying hydrogen gas is highly energy intensive. Recovering and utilizing cold energy given off during regasification conserves energy and reduces CO₂ emissions. If hydrogen is used in large quantities for purposes such as hydrogen power generation, the recovery and utilization of cold energy from liquid hydrogen will be essential.

Kobe Steel is a leading manufacturer of liquefied natural gas (LNG) vaporizers, with a strong track record of supplying this equipment all over the world. Our lineup includes the Intermediate Fluid Vaporizer (IFV), which is well suited for recovering

cold energy during regasification.

We used the technology cultivated in developing LNG vaporizers to develop an IFV-type liquid hydrogen vaporizer under a grant from the New Energy and Industrial Technology Development Organization (NEDO).⁵⁾ For details, see “Demonstration Tests of Three Types of Liquid Hydrogen (LH₂) Vaporizers” on p.22 of this issue.

2. 1. 3 Operation management system for monitoring and controlling hydrogen production and utilization

The operation management system balances the supply of hydrogen gas between vaporized liquid hydrogen and hydrogen produced by an electrolyzer with three power sources (solar, battery, grid power). Managing the power source of the electrolyzer curtails carbon emissions and hydrogen supply costs. Thus, this system ensures a stable supply of hydrogen gas by controlling two hydrogen supply sources such that they complement each other based on hydrogen demand. Our system performs automatic operation, control, and monitoring based on a pre-established supply plan. Inputs to the supply plan include the following day's projected demand, weather factors, consumption rate, and operating mode. Parameters managed by the system include the balance of the electrolyzer's power supply sources as well as the amounts of hydrogen produced and vaporized. Described next are the results of the system's demonstration and plans for system enhancements.

We conducted a demonstration of our system that balances the power source of the electrolyzer based on a supply plan. **Fig. 5** shows the electrolyzer's operating data from this demonstration. As described in Section 2.1.1, the full-load power consumption of the electrolyzer (50 kW) is less than the maximum output of the solar power generation system (105 kW). Therefore, we

configured the demonstration facility such that the battery stores surplus power when solar power generation exceeds electrolyzer demand; the battery is discharged as a backup power source when solar power generation is insufficient; and power is supplied from the grid if there is still a deficit. Thus, the battery and power grid compensate for the instability of renewable energy to ensure stability of the power supply to the electrolyzer. The system also includes functionality to manually prioritize the electrolyzer's power sources (solar power, battery, grid power). Although the default settings prioritize renewable energy for maximum reduction of carbon emissions, it is possible to prioritize grid power during periods of low electricity costs for economy. As shown in Fig. 5, periods of surplus power generation are characterized by the storage of power in the battery, and periods when solar power alone is insufficient for the electrolyzer are characterized by power discharging from the battery as second priority. If the battery level falls below the lower limit, power is drawn from the grid as the third-priority source, ensuring stable operation of the electrolyzer at rated power.

The demonstration facility also has a screen enabling real-time monitoring of hydrogen production, storage, and supply as shown in **Fig. 6** as part of an operation monitoring system. The system calculates the cost and carbon emissions of the hydrogen supplied and can output this data as daily and monthly reports. This simplifies the monitoring of carbon emissions from hydrogen supply plants. It also enables data-driven decision-making for capital investments in electrolyzers, liquid hydrogen equipment, renewable energy equipment, and similar technologies in conjunction with the expansion of hydrogen use by elucidating the cost structure (e.g., costs for grid power and liquid hydrogen).

At a later time, we will demonstrate the supply planning function we are developing. This function

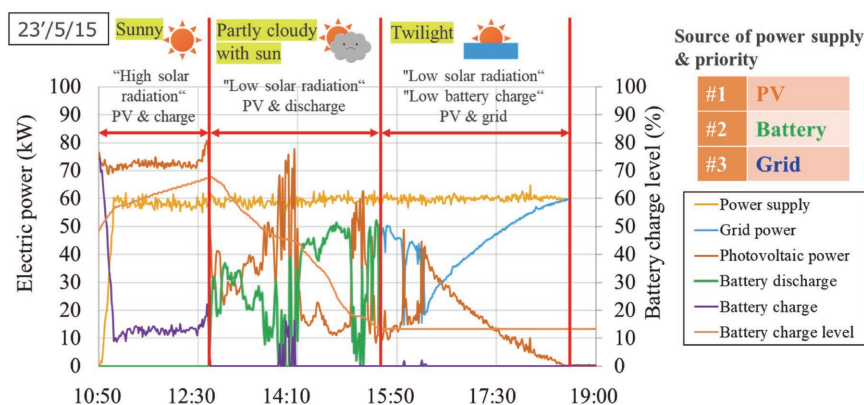


Fig. 5 Examples of power supply to electrolyzer

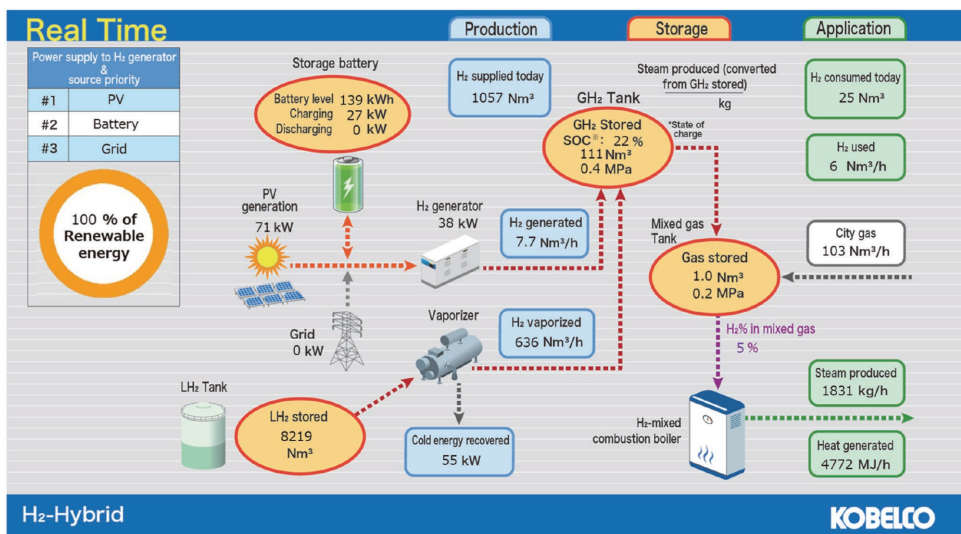


Fig. 6 Real-time monitor of operation management system

automatically produces a hydrogen supply plan based on hydrogen demand values entered in advance and controls hydrogen supply equipment based on the mode selected (CO₂ reduction priority or cost priority). The hydrogen supply planning function plans battery charging and discharging operations based on solar power generation prediction technology that uses sunlight intensity forecast data. This ensures sufficient storage capacity for when the predicted sunlight intensity is high, minimizing excess solar power generation. Furthermore, by predicting the daytime draw from the power grid, this function minimizes consumption during the day by discharging only the necessary amount of inexpensive electricity stored during nighttime hours. Additionally, the system has a function to calculate the balance daytime storage capacity with nighttime storage amount to preferentially minimize either carbon emissions or costs.

3. Hydrogen utilization

Recent years have seen the commercialization of pure hydrogen boilers and hydrogen co-firing boilers for hydrogen utilization as well as progress in the development of hydrogen burners for industrial furnaces. However, promoting the transition to hydrogen for fuel is difficult because the industrial sector prioritizes stable operation and cost reduction. Problematically, the early stage of adoption is characterized by an unstable hydrogen supply chain and significant costs. To overcome this challenge, it is important to leverage existing facilities to gradually expand hydrogen utilization and thereby reduce capital investment requirements. Following are our proposed strategies

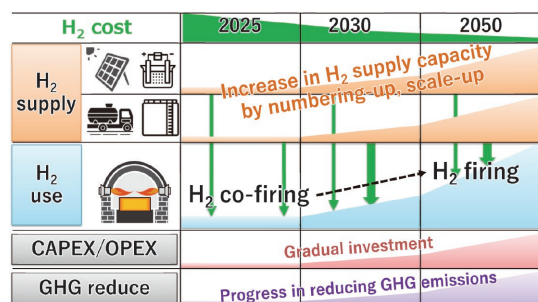


Fig. 7 Overview of phased fuel conversion scenarios

for transitioning existing facilities to hydrogen fuel in support of hydrogen utilization.

Municipal gas in Japan is assigned a designation based on its specifications. “City gas 13A,” a common type of municipal gas, has a different heat value, maximum combustion potential, and flame temperature than hydrogen. Therefore, completely switching from city gas 13A to hydrogen renders current equipment obsolete because it must be replaced by burners and other components capable of hydrogen combustion. Therefore, as shown in Fig. 7, co-firing city gas 13A with hydrogen could be a realistic option for a phased fuel conversion during the introduction phase of hydrogen. A blending ratio of hydrogen in city gas 13A of about 20 vol% maintains the standard combustion characteristics range for city gas 13A⁶⁾, in which case hydrogen co-firing is considered feasible even in combustion equipment with burners designed for city gas 13A.

Hydrogen co-firing with existing combustion equipment enables operations to revert to city gas if the hydrogen supply becomes unstable, thereby maintaining production activities. This is an effective means of hydrogen utilization for the introduction phase.

During the subsequent hydrogen expansion

phase, it is realistic to gradually introduce combustion equipment with hydrogen burners. In this case too, plants can hedge their operational risk by keeping their current equipment while using the new equipment designed for use with hydrogen. However, many plants will likely not have sufficient footprint for multiple sets of equipment, necessitating a fuel transition plan that accounts for equipment swap-out.

Kobe Steel's Takasago Works has approximately 100 boilers and industrial furnaces with varying combustion capacities that serve as hydrogen utilization points. We are conducting demonstration tests to verify the feasibility of using hydrogen in existing city gas boilers and industrial furnaces, as well as heating characteristics and the effects of hydrogen on heated materials when switching to hydrogen combustion.⁷⁾

3.1 Hydrogen utilization in combustion boilers

Small once-through boilers are widely used in factories. Although they are already available in pure hydrogen-fueled models, securing a reliable supply of hydrogen will be a challenge in the early stages of their adoption. For example, operating one pure hydrogen boiler with an evaporation rate of 2 tons/h at rated capacity requires approximately 400 Nm³/h of hydrogen. Until there is a stable and economical supply of CO₂-free liquid hydrogen, CO₂-free hydrogen must be produced on site. Specifically, a large electrolyzer capable of producing 400 Nm³/h of hydrogen is required, and thus renewable power equipment within the 2-MW class (based on an electrolyzer power consumption of 5 kW/Nm³). The solar park capable of this demand requires a footprint of approximately 10,000 m² (roughly the size of the playing field inside the Tokyo Dome), which most plants would find difficult to secure. Even if solar panels could be installed, their average annual operating rate is only about 15%. To produce a stable supply of hydrogen for the boiler, renewable electricity must be procured from the grid. Plants controlling multiple small once-through boilers would need even more additional equipment. Consequently, there is likely a limited number of plants capable of introducing pure hydrogen boilers.

While securing a stable supply of hydrogen presents challenges, as mentioned earlier, even plants without a guaranteed supply of hydrogen from renewable energy can reduce carbon emissions through hydrogen co-firing in existing city gas boilers. Therefore, it is necessary to clarify the challenges involved in hydrogen co-firing with city

gas boilers. This spurred the execution of hydrogen co-firing tests using existing small, city gas-fired once-through boilers.⁸⁾

Fig. 8 shows the layout of the hybrid-type hydrogen gas supply system demonstration facility and the boiler at Kobe Steel's Takasago Works. The system mixes city gas and hydrogen at a set ratio and supplies the mixture to the boiler. The boiler used is a Samson Co., Ltd. NFBS-1500PN, a small, city gas-fired once-through boiler with an equivalent evaporation of 1.5 ton/h. The operating load of the boiler is controlled using a three-position control system: high-combustion mode, low-combustion mode, and stop. The boiler has a nozzle-mix burner, meaning fuel and air are supplied separately and mix at the burner tip for combustion.

City gas and propane are supplied to consumers at a consistent composition by gas retailers. By contrast, with hydrogen co-firing, the consumer is responsible for the mixture of city gas and hydrogen in the system the boiler is part of. A hydrogen mixing ratio that fluctuates during boiler operation can cause a deviation from optimal combustion conditions, potentially leading to issues such as incomplete combustion or increased NO_x emissions. Therefore, it is critical to maintain a constant hydrogen mixing ratio.

Fig. 9 shows an overview of the hydrogen mixing system in this demonstration facility. The system uses cascade control, meaning the flow rates of hydrogen gas and city gas into the tanks vary based on the difference between the actual and setpoint pressures of the mixed gas tank (city gas/hydrogen). Setpoints for the hydrogen gas flow sensor (QH) and city gas flow sensor (QC) are configured to constantly maintain a predetermined mixing ratio α of city gas to hydrogen. Since city gas and hydrogen have different heat values per unit volume, the mixing ratio can be calculated from the heat value of the mixed gas. The tank outlet has a calorimeter to monitor the hydrogen mixing ratio.

Fig.10 shows the time-dependent change in mixed gas flow rate and heat value during operation

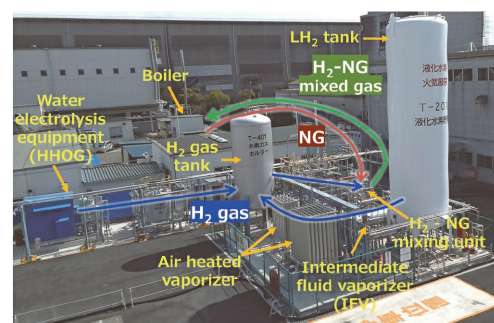


Fig. 8 Demonstration facility and small once-through boiler

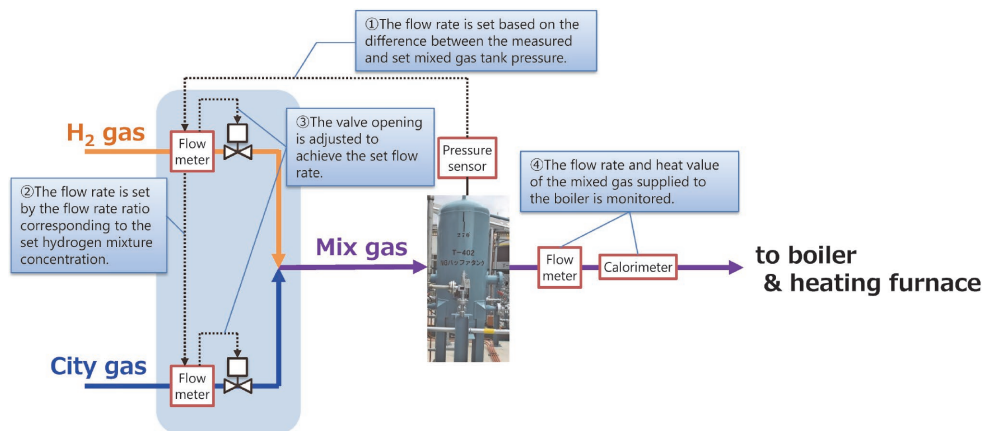


Fig. 9 Overview of hydrogen mixing system

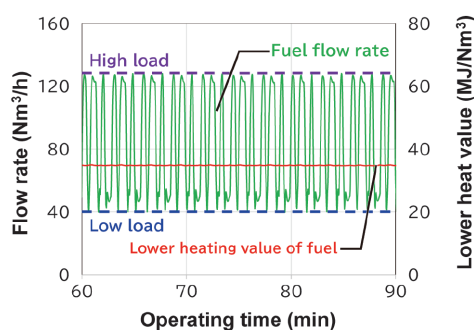


Fig.10 Evaluation of supply stability of 30 vol% H₂ mixed gas

with a 30 vol% hydrogen mixture and fluctuating boiler load. Although the flow rate of the mixed gas fluctuates in response to changes in boiler load, its heat value remains constant. We confirmed that our hydrogen mixing system can supply mixed gas at a constant ratio of city gas to hydrogen even when boiler load and fuel gas consumption vary.

Table 1 shows boiler performance during rated load operation for hydrogen concentrations from 0 to 30 vol%. At all hydrogen concentrations, boiler efficiency was equivalent to that of pure city gas combustion. The exhaust gas characteristics, including NO_x and O₂ concentrations, were also comparable. The maximum NO_x concentration in this boiler remained below the limit of 60 ppm (equivalent to 5% O₂ concentration) stipulated in the agreement with the municipality.

This demonstration confirmed that hydrogen co-firing up to 30 vol% is feasible even in city gas boilers. However, the effects of increased flame temperature due to hydrogen co-firing and the potential for long-term deterioration of components such as burners and boiler shells requires further testing. Furthermore, these results are based on tests conducted using a specific manufacturer's boiler. It is necessary to confirm with each boiler manufacturer whether their boilers are capable of hydrogen co-firing. Ongoing discussions with major once-through

Table 1 Comparison of boiler performance at various H₂ conc.

H ₂ conc.	0%	10%	20%	30%
Boiler efficiency [%]	91.3	90.3	90.7	90.5
Exhaust gas NO _x conc. [ppm, 5%-O ₂]	48.5	46.2	47.9	47.0
Exhaust gas O ₂ conc. [vol%]	3.8	3.3	3.7	3.6

boiler manufacturers reveal differing opinions regarding the feasibility of hydrogen co-firing in city gas boilers. However, boiler manufacturers are working to accommodate hydrogen co-firing, such as by developing hydrogen co-firing boilers⁹⁾ and producing components for retrofitting to enable hydrogen co-firing in city gas boilers.¹⁰⁾ We will continue corresponding with boiler manufacturers to explore reasonable methods for initiating and expanding hydrogen utilization from both the supply and usage perspectives.

3.2 Hydrogen utilization in heating furnaces

Fig.11 shows the distribution of heating furnace capacities at Kobe Steel's Takasago Works. Most heating furnaces at this facility have a combustion capacity of 1 – 3 MW, which is likely representative of heating furnaces in Japan in general. Therefore, we are first investigating a fuel conversion to hydrogen in 2-MW-class heating furnaces and are conducting demonstration tests using existing Kobe Steel furnaces and new test furnaces. The two types of demonstration tests are described next.

Section 2 presented a phased fuel conversion scenario. However, since it will take time to secure a stable and economical supply of hydrogen, it is crucial to begin hydrogen utilization in the early stages of fuel conversion by using existing furnaces through hydrogen co-firing rather than pursuing replacement with pure hydrogen furnaces at the outset. Achieving a combustion capacity of 2 MW using pure hydrogen requires a hydrogen supply of 667 Nm³/h (based on hydrogen's lower heating

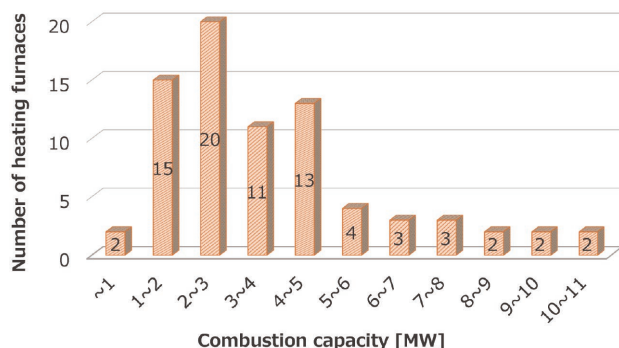


Fig.11 Distribution of combustion capacity of heating furnaces



Fig.12 Heating furnace scheduled for modification

value of 10.8 MJ/Nm³). Given the lack of a stable and economical supply of hydrogen in the early stage of the transition, stable operation will likely be difficult. Additionally, the use of existing heating furnaces makes it possible to continue furnace operation by reverting to city gas upon hydrogen supply insecurity. Therefore, we are conducting hydrogen co-firing and pure hydrogen combustion tests at Kobe Steel's Takasago Works using an existing heating furnace that has been in operation for nearly 50 years (Fig.12). The objective of this test series is to determine what hydrogen co-firing ratio is feasible without modifications and what modifications are necessary for pure hydrogen combustion.

Hydrogen will differ greatly from a given heating furnace's current fossil fuel (e.g., city gas) in terms of the combustion characteristics (maximum combustion potential, flame temperature) and the composition of the combustion atmosphere (e.g., vapor pressure of water), a critical consideration when converting the fuel in a heating furnace to hydrogen. Particularly in direct-fired furnaces, in which the product (the item being heated) is exposed to a high-temperature hydrogen combustion atmosphere, it is essential to thoroughly investigate the effect on the product's quality (scaling, decarburization, hydrogen content) and thermal characteristics (heat transfer rate/temperature distribution). As such, we installed a new 2-MW-class hydrogen demonstration furnace at Kobe Steel's Takasago Works for detailed data analysis into combustion characteristics, thermal characteristics, and the effect on product quality during hydrogen co-firing and pure hydrogen firing.

Kobe Steel has more than 500 heating furnaces across all sites, including Takasago Works. These furnaces cover a broad spectrum of specification sets because they have varying combinations of processing temperatures, heating methods, and types of metal heated. Therefore, although our demonstration tests target 2-MW-class direct-fired furnaces, we are pursuing technological

development that applies to a multitude of conditions (e.g., by developing combustion simulations and material evaluation technologies).

By conducting demonstrations from both the hydrogen supply and utilization perspectives, we are revealing and overcoming technological development challenges shared by both sides. This includes accumulating expertise on the responsiveness of the supply side (vaporizers, electrolyzers) to fluctuations in hydrogen demand on the utilization side (heating furnaces) and the effects of start-up and shutdown operations.

In addition to demonstration testing for fuel conversion using existing heating furnaces, demonstration testing for hydrogen co-firing and pure hydrogen firing in new test furnaces will yield insights into fuel conversion practices suitable for both the introduction phase and the expansion phase of hydrogen utilization. This should drive more widespread use of hydrogen in heating furnaces.

Conclusions

Achieving carbon neutrality requires the hydrogen supply side and the hydrogen utilization side to work in lockstep to build the hydrogen supply chain. Kobe Steel's Takasago Works operates boilers and industrial furnaces of various sizes. Therefore, identifying the challenges of fuel conversion to hydrogen and conducting studies and demonstrations to address these challenges contributes to our own carbon neutrality while revealing valuable insights and achievements supporting decarbonization in other industrial sectors that use thermal energy.

The KOBELCO Group's current Mid-Term Management Plan (FY2024 – 2026) delineates seven "X initiatives," collectively called "KOBELCO-X," as the transformations our Group must bring to fruition to evolve into an appealing enterprise. The hydrogen utilization efforts introduced in this paper are examples of AX and GX.

■AX (Ambidexterity: enhancing earning power and pursuing growth)

The machinery & engineering divisions (development of hybrid-type hydrogen gas supply system) and the materials divisions (hydrogen utilization in high-temperature furnaces) are collaborating to accelerate the demonstration of hydrogen utilization.

■GX (Green transformation : taking on the challenge of realizing carbon neutrality)

This transformation promotes decarbonization by advancing CO₂-free hydrogen supply technologies and promoting hydrogen utilization as thermal energy.

Finally, some of our results were obtained through the project “Development of Technologies for Realizing a Hydrogen Society” (JPNP14026), a grant program of the New Energy and Industrial Technology Development Organization (NEDO). We express our gratitude here.

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Demonstration Tests of Three Types of Liquid Hydrogen (LH₂) Vaporizers

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Abstract

Kobe Steel owns multiple types of liquefied natural gas (LNG) vaporizers to suit various applications and is developing liquid hydrogen (LH₂) vaporizers based on the design and manufacturing techniques the company has cultivated over many years. Liquid hydrogen is stored at -253°C and must be processed at a temperature approximately 100°C lower than LNG, posing great technical challenges for a heat exchanger. Therefore, reliability should be secured by conducting actual liquid demonstration tests to back up performance and thermal stress calculations. To this end, a small demonstration machine has been prototyped to conduct demonstration tests using liquid hydrogen. This paper describes the current status of demonstration tests of three types of vaporizers with different characteristics: an intermediate-medium vaporizer (IFV), an open rack vaporizer (ORV), and a microchannel heat exchanger (DCHE).

Introduction

Kobe Steel has supplied many LNG (liquefied natural gas) vaporizers, a market in which we are

a leading manufacturer, of various types and for various applications all around the world. Amidst this, plans have emerged in recent years to import and utilize liquid hydrogen (LH₂) as part of industry efforts to achieve net-zero carbon emissions by 2050.

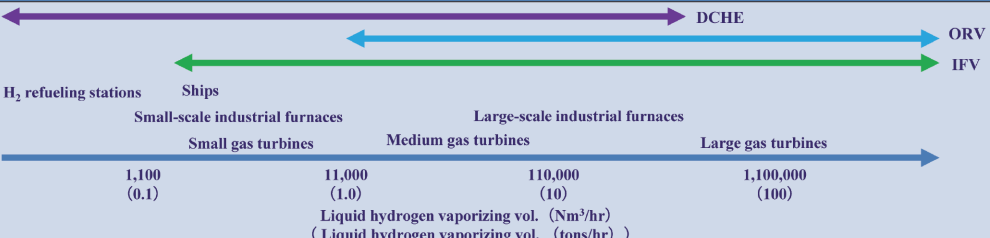
LH₂ is stored at -253°C and has a processing temperature that is approximately 100°C lower than that of LNG, posing great technical challenges for the heat exchanger. Therefore, it is necessary to create a small LH₂ vaporizer demonstration unit as a prototype, conduct demonstration tests using LH₂ to collect heat transfer performance and mechanical data on the vaporizer, and lay the foundation for scaling up.

Table 1 shows the features, intended applications, and demonstration test schedule overview for each of three types of LH₂ vaporizers: intermediate fluid vaporizer (IFV), open rack vaporizer (ORV), and microchannel heat exchanger (diffusion-bonded compact heat exchanger, DCHE).

This paper outlines the results of demonstration testing for these three types of vaporizers and future development plans.

Table 1 Liquid hydrogen vaporizer product lineup

Liquid hydrogen vaporizer product lineup			
Type	(1) IFV	(2) ORV	(3) DCHE
Appearance			
Features	Material: Stainless steel, titanium (for seawater) ● Eliminates the risk of freezing seawater and industrial water by using propane as an intermediate fluid. Suitable for mid- to large-scale vaporizers. ● Enables the use of exhaust heat from nearby facilities. ● Enables the use of cold energy through the secondary use of heating medium (wide temp. range)	Material: Aluminum alloy + thermal spray ● Uses seawater as heating medium, making it an economic solution for mid- to large-scale vaporizers ● Seawater is an open system, making it difficult to use cold energy ● Allows for the transition of an LNG power plant to a hydrogen co-firing plant using existing seawater intake/outlet facilities as is	Material: Stainless steel ● Enables downsizing while maintaining high thermal fatigue strength. ● Uses brine as heating medium. ● Enables the use of cold energy through the secondary use of heating medium (narrow temp. range)
Demo. schedule	Completed in March 2023	Planned to begin in March 2025	Completed in March 2024

Vaporizing volume by application			
			
1,100 (0.1) 11,000 (1.0) 110,000 (10) 1,100,000 (100) Liquid hydrogen vaporizing vol. (Nm ³ /hr) (Liquid hydrogen vaporizing vol. (tons/hr))			

1. Developing a large-capacity liquid hydrogen vaporizer (IFV), which supports the use of cold energy

1.1 Choosing the large-capacity (IFV), which supports the use of cold energy

Plans are in place to conduct demonstration tests of hydrogen co-firing and pure hydrogen firing in gas turbines. These tests, which will foster the commercialization of hydrogen power generation by 2030, require LH₂ vaporizers with a capacity of approximately 30,000 to 50,000 Nm³/hr. Furthermore, improving energy efficiency is critical for the stable supply of hydrogen. Utilizing the cold energy from LH₂ for purposes such as increasing gas turbine efficiency through intake air cooling could contribute to this objective.^{1), 2)} The IFV is the optimal choice for this purpose given its proven track record among LNG vaporizers and its capacity to support large-scale, continuous, and stable vaporization for cold energy utilization.

1.2 Structure and vaporization process of the IFV

The IFV uses a heat source such as seawater and an intermediate fluid such as propane to vaporize cryogenic liquids.

Fig. 1 shows a conceptual diagram of the IFV. LH₂ enters the heat transfer tubes of the LH₂ vaporizer (E-2). It then undergoes heat transfer with the intermediate gas in the upper part of the intermediate fluid vaporizer (E-1) shell. Nearly all the LH₂ vaporizes and travels to the shell side of the H₂ heater (E-3) via connecting piping. Here, heat transfer with seawater flowing through the heat transfer tubes heats the hydrogen gas for discharge at ambient temperature. Meanwhile, the intermediate fluid condenses on the outside of the heat transfer tubes of the E-2 due to heat

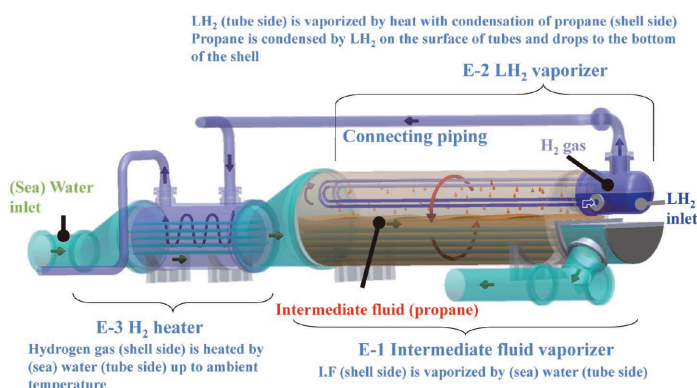


Fig. 1 Schematic of IFV

transfer with LH₂ and falls to the lower part of the E-1 shell. The seawater flowing inside the E-1 heat transfer tubes transfers heat to the intermediate liquid, causing the gas to vaporize again and then vaporize the LH₂ in the heat transfer tubes of the E-2. Unlike ORVs, in which the heat source is vented to atmosphere during vaporization, IFVs can circulate the heat source in a closed loop. This enables effective extraction of cold energy using the cooled intermediate fluid or heat source fluid.³⁾

1.3 Challenges of using IFVs for LH₂

Because no company had pursued LH₂ vaporization in IFVs, the associated practical challenges were not yet known. Therefore, we created a small cold energy recovery-type LH₂ vaporizer demonstration unit as a prototype and conducted demonstration tests to collect heat transfer performance and mechanical data, laying the foundation for scaling up the vaporizer.

Fig. 2 shows the demonstration IFV. The E-3 heat exchanger is mounted on top of the E-1 shell to save space. The E-1 shell has a sight glass for checking the status of the intermediate fluid. The outside of the E-2 has a strain gauge and a thermocouple. We constructed dedicated equipment for the IFV at Kobe Steel's Takasago Works for the demonstration of LH₂ vaporization. **Fig. 3** shows the process flow of this facility. The heat source is circulating water. An electric heater was used as a simulated load for temperature control during testing. **Fig. 4** shows a photo of the entire facility.

This demonstration unit was designed for a performance rating of 0.1 ton/h (1,200 Nm³/h) to correspond to the smallest size at which heat transfer performance could be verified. The mechanical design of the unit conforms to the Designated Equipment Inspection requirements of the High Pressure Gas Safety Act. After undergoing the



Fig. 2 Outside view of IFV for LH₂ vaporization demonstration

inspections prescribed by The High Pressure Gas Safety Institute of Japan, it received a passing test certificate.

The four points below were confirmed or investigated during the demonstration of LH₂ vaporization.

- (1) Even during continuous operation, the temperature of the vaporized gas at the outlet does not decrease, allowing for stable vaporization of LH₂.
- (2) Even when LH₂ flows through inside the heat transfer tubes, the intermediate fluid (propane) outside the heat transfer tubes does not freeze.
- (3) It is possible to extract stable cold energy for utilization.
- (4) The stress and strain during actual operation were measured and compared with the results of thermal stress analysis.

1.4 Results of the demonstration test of LH₂ vaporization using the IFV

Table 2 shows the test conditions.

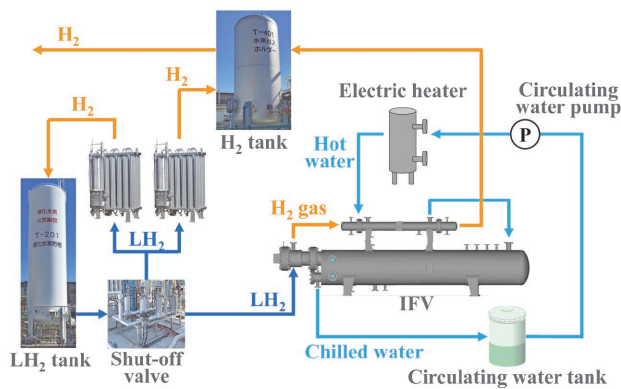


Fig. 3 Schematic flow of LH₂ vaporization demonstration facility



Fig. 4 Outside view of LH₂ vaporization demonstration facility

1.4.1 Confirming stable vaporization

The sample data in Fig. 5 from the demonstration shows the trend in hydrogen outlet temperature and flow rate. Vaporized gas temperatures were stable for over one hour, demonstrating that LH₂ can undergo stable vaporization without a decrease in the temperature of the vaporized gas at the outlet even during continuous operation.

1.4.2 Testing for freezing of the intermediate fluid

The temperature of the LH₂ is below the freezing point of the intermediate fluid (propane). Therefore, there was concern that the intermediate fluid might freeze on the heat transfer tubes when LH₂ flows through them. However, visual inspection via the sight glass (Fig. 6) and the operating data confirm that even when LH₂ flows through inside the heat transfer tubes, the intermediate fluid (propane) outside the tubes does not freeze.

Table 2 Test conditions of IFV for LH₂ vaporization demonstration

Condition	Case 1	Case 2	Case 3	Case 4	Case 5
H ₂ flow rate (Nm ³ /h)	1,200	1,200	1,200	1,200	1,300
H ₂ Press. (MPaG)	0.70	0.70	0.70	0.40	0.70
CW flow rate (m ³ /h)	8.0	6.8	4.5	8.0	8.0
CW inlet Temp. (°C)	20	20	30	20	20
CW temp. Difference (°C)	Above 10	Above 15	Above 20	Above 10	Above 10

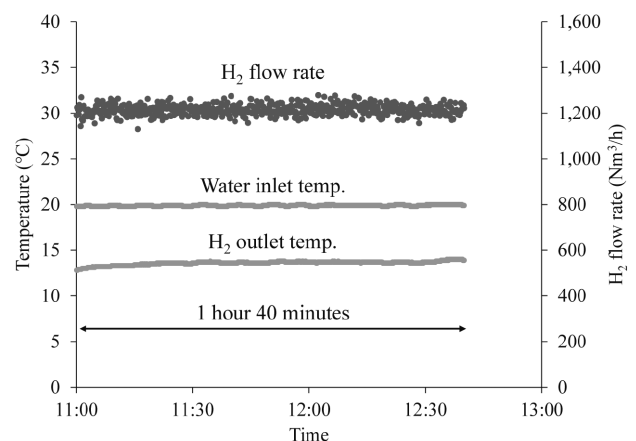


Fig. 5 Example of H₂ outlet temp. and H₂ flow rate trend during demonstration test

1.4.3 Confirming stable cold energy extraction

Fig. 7 shows the trend of the circulating water inlet and outlet temperatures upon fluctuation of the hydrogen flow rate. The circulating water is cooled via heat transfer with hydrogen gas and an intermediate fluid. It must be supplied at a stable temperature to ensure efficient cold energy utilization even during fluctuations in cooling load. This demonstration test confirmed that even with fluctuations in the hydrogen flow rate, it is possible to have a stable supply of chilled water at approximately 7°C, which is more than 10°C cooler than the inlet water temperature of 20°C. This demonstrates that a stable supply of cold energy is possible.

1.4.4 Comparison of thermal stress analysis with stress-strain measurements during operation

High stresses are expected near the tube sheet of the E-2 because of the temperature differentials. As such, we compared finite element analysis (FEA) results from this region with the temperatures and stresses generated during rated operation. While this paper does not include detailed comparisons, the research by Egashira et al.⁴⁾ shows that the stress-strain results correspond to the thermal stress analysis results qualitatively, validating the analysis method.

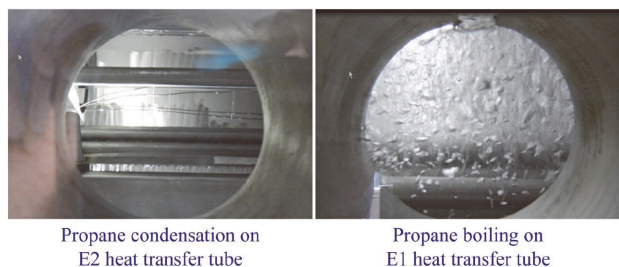


Fig. 6 Photo of propane boiling and condensing behavior from sight glass

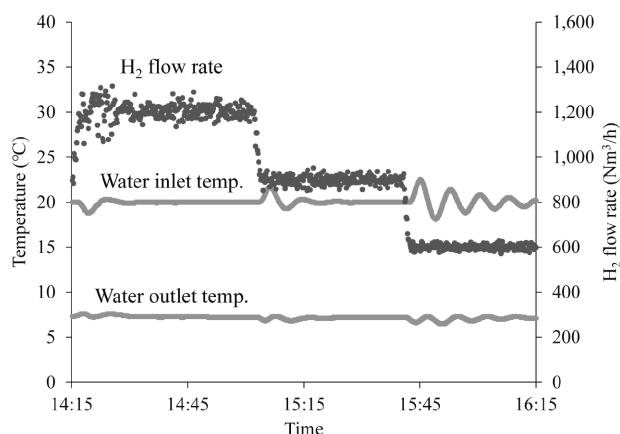


Fig. 7 Trend of water inlet and outlet temp. during H₂ flow rate fluctuation

1.5 Plan for demonstrating high-pressure LH₂ vaporization using IFV in hydrogen cogeneration system (CGS) of Kobe's Port Island

We collected operating data below the critical pressure of hydrogen during the demonstration test described in Section 1.4. The next step is to investigate the heat transfer behavior of the IFV at pressures above the critical pressure. Comparing this data with the data from below the critical pressure in the previous demonstration will reveal challenges across a wide range of operating pressures. For this operational demonstration, we incorporated the actual equipment into the hydrogen fuel supply system of the Kobe hydrogen CGS demonstration facility. The New Energy and Industrial Technology Development Organization (NEDO) selected this demonstration as a grant project in June 2023 to “improve the efficiency and performance of the hydrogen fuel supply system in a hydrogen CGS regional model.” Demonstration testing commenced in fiscal year 2025.

2. Progress in large-capacity LH₂ vaporizers (ORVs)

2.1 ORVs, the most widely used large-capacity LNG vaporizer

ORV heat exchangers usually use seawater as a heat source to heat LNG from -160°C to a temperature above 0°C. The ORV is a high-flow LNG vaporizer that uses economical, readily available seawater. As such, it is superior in terms of both operating and construction costs. Consequently, it is widely adopted as the large-capacity vaporizer at LNG terminals all over the world.

2.2 Structure and vaporization process of the ORV

Fig. 8 (left) shows the structure of the ORV and an overview of its process. This counterflow heat exchanger is characterized by a simple vaporization process and structure. Its heat transfer tubes are

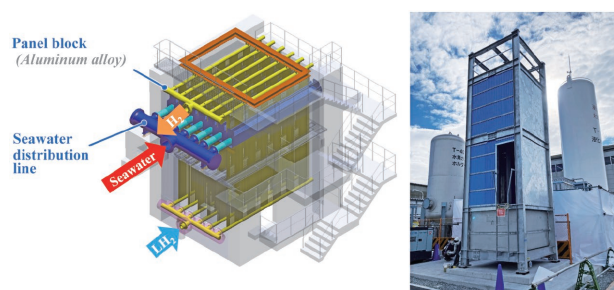


Fig. 8 The structure of ORV and outside view of ORV for LH₂ vaporization demonstration

arranged vertically. A low-temperature fluid (LNG) flows inside the tubes and a heating fluid (seawater or industrial water) flows from the outside. The heat transfer tubes are made of an aluminum alloy with excellent low-temperature toughness and heat transfer performance. Since corrosion by seawater is a concern for aluminum alloys, a material serving as a sacrificial anode is applied to the heat transfer tubes via thermal spraying.

2.3 Challenges of using ORVs for LH₂

The logic behind developing our new LH₂ vaporizer based on the structure of LNG ORVs was twofold. First, LH₂ vaporizers are expected to support large-scale, continuous, and stable operation; and second, we frequently receive inquiries regarding ORVs because they are a familiar technology. Kobe Steel had no empirical data on LH₂ vaporization in ORVs at the start of development, so there was uncertainty regarding the practical challenges. Therefore, we created a small demonstration unit as a prototype and conducted demonstration tests to collect heat transfer performance and mechanical data, laying the foundation for scaling up the vaporizer.

2.3.1 Heat transfer performance with LH₂

Vaporizing LH₂ requires the transfer of approximately five times more heat per unit mass than for LNG. Consequently, the same mass flow rate as LNG cannot be vaporized. Furthermore, if the heat transfer coefficient inside the tubes is the same as for LNG, a 100°C decrease in operating temperature could promote ice formation and degrade performance. To apply the performance simulation used for LNG to LH₂, the actual heat transfer performance data of LH₂ as determined through testing must be incorporated into the simulation.

2.3.2 Thermal stress analysis for using LH₂

The operating temperature of LH₂ is around -250°C, which is about 100°C colder than LNG's operating temperature of about -150°C. Managing the resulting increase in thermal stress is a key challenge, requiring cryogenic thermal stress analysis. Kobe Steel has many years of experience conducting thermal stress analysis for LNG vaporizers, including ORVs, and draws on this expertise to advance the development of ORVs for use with LH₂.

2.4 Plans for the demonstration test of LH₂ vaporization using the ORV

Kobe Steel already has a comprehensive facility for evaluating LH₂ vaporizer performance as part of our hybrid-type hydrogen gas supply system and has completed demonstration tests for IFVs below critical pressure. In fiscal year 2024, we expanded the facility to include a demonstration setup for an ORV for LH₂ (Fig. 8, right).

Starting in March 2025, we conducted demonstration tests using actual liquid hydrogen to collect data to perform thermal stress analysis and determine heat transfer performance, providing information critical to the challenges of ORV design. We then began working toward commercializing the LH₂ vaporizer.

This demonstration unit was designed for a performance rating of 0.1 ton/h (1,200 Nm³/h) to correspond to the smallest size at which heat transfer performance could be verified. As with the IFV described above, this unit also received a passing test certificate for the Designated Equipment Inspection required by The High Pressure Gas Safety Institute of Japan.

The objective of demonstrating LH₂ vaporization is to confirm the two points below.

- (1) Even during continuous operation, the level of the ice buildup outside the tubes stabilizes within an assumed standard range, and LH₂ vaporization remains stable without a decline in the outlet vaporized gas temperature.
- (2) Thermal stress analysis based on the temperature distribution in the lower area of the ORV confirms sufficient thermal fatigue life.

3. Progress in small-capacity LH₂ vaporizers (DCHEs) for offshore applications

3.1 DCHEs, a compact and highly pressure-resistant vaporizer

The DCHE features a compact design and excellent pressure resistance, yielding a wide scope of application in space-constrained environments such as floating production storage and offloading systems (FPSO) and floating LNG (FLNG) production systems. Its application range has also expanded to LNG vaporizers for vessel fuel gas supply systems (FGSS). Kobe Steel has established technology to prevent the freezing of the heat transfer fluid using LNG and is deploying it for shipboard and land-based applications.

3.2 Structure and vaporization process of the DCHE

The DCHE is a compact heat exchanger whose main manufacturing processes include etching as well as diffusion bonding to simultaneously join the plates. Fig. 9 (left) shows its structure.

The etching process involves dissolving metal using the corrosive action of chemicals such as etching solutions. This technique is applied to stainless steel plates to form millimeter-sized flow channels through which fluid passes.

Diffusion bonding involves stacking the processed plates and bonding them via diffusion at the atomic level at the joint interface. Since the base materials bond directly, the strength of the

joint is equivalent to that of the base metal. The etching plates are stacked in a specific ratio, with some plates carrying LNG and others carrying a heat transfer fluid such as an ethylene glycol/water mixture, enabling direct heat transfer through the plates between adjacent flow channels. LNG and the ethylene glycol/water mixture are distributed to each plate in the stack via a header, which is downstream of a nozzle.

3.3 Challenges of using DCHEs for LH₂

LH₂ is used at cryogenic temperatures far below the freezing point of the ethylene glycol/water mixture, the heat source. As such, a critical challenge is to prevent freezing in the flow channels of the heat exchanger. Although over 50 years of plate-fin heat exchanger design technology ensure solid heat transfer design, there are no calculations that can predict freezing phenomena. Therefore, we identified the conditions related to freezing under various operating states through experiments using LNG, liquid nitrogen (LN₂), water, and an ethylene glycol/water mixture. This led to the development and patenting of two unique anti-freezing technologies. Figs.10 and 11 summarize the patents ("1 cold:3 hot design" and "2-zone design,"

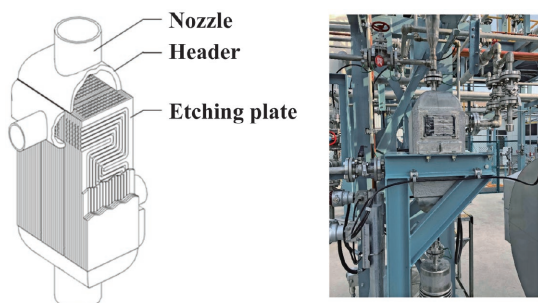


Fig. 9 Schematic structure of DCHE

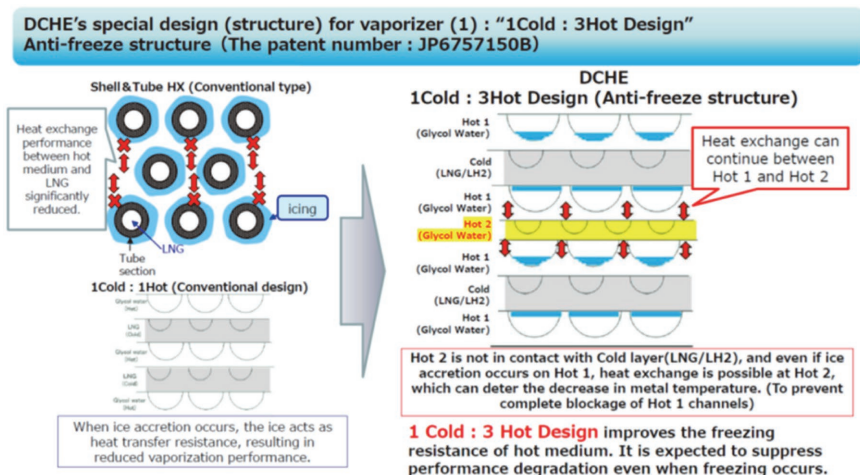


Fig.10 Anti-freeze structure (1 cold : 3 hot design)

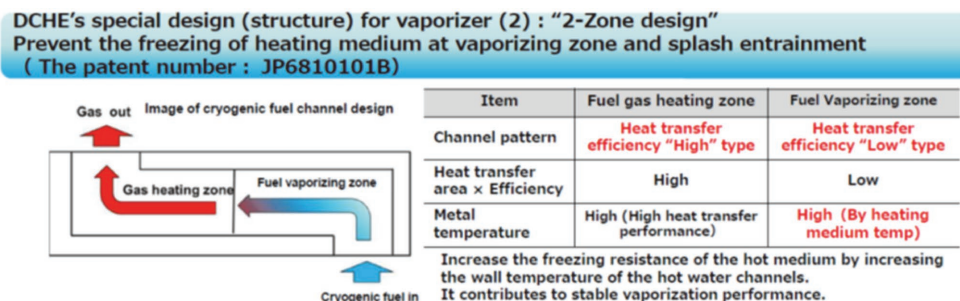


Fig.11 Anti-freeze structure (2 -zone design)

respectively).

Kobe Steel supplies LNG vaporizers for satellite bases, LNG fuel vaporizers for marine use, and high-pressure LH₂ vaporizers, which validates our design methodology and anti-freezing technology.

We needed to first confirm that the established technical standard applies at LH₂ temperatures (-253°C) below the critical pressure at which boiling phenomena occur. Therefore, we conducted a demonstration test using a prototype unit that simulated the size of the product to be delivered.

We used LH₂ for testing and installed the test unit in parallel with the IFV in the hybrid-type hydrogen gas supply system. **Table 3** and Fig. 9 (right) show the design specifications of the test unit, the test conditions, and a photo of the test unit. This test unit also received a passing test certificate for the Designated Equipment Inspection. The LH₂ vaporization demonstration confirmed the two points below.

- (1) The heat transfer fluid does not freeze, and vaporization performance is stable.
- (2) Heat transfer performance meets design specifications.

3.4 Results of the demonstration of LH₂ vaporization using the DCHE

3.4.1 Confirming heat transfer fluid freezing behavior and stable vaporization performance

If the heat transfer fluid freezes, the flow channels of the heat transfer fluid will gradually become obstructed, causing the pressure drop to gradually increase. Therefore, we ran the system in continuous operation at the design point (LH₂ flow rate 18.9 kg/h) for one hour to observe the change in pressure drop of the heat transfer fluid as an indicator of whether the heat transfer fluid froze.

Fig.12 shows that the pressure drop of the heat transfer fluid remained stable and did not trend upward, confirming that the heat transfer fluid did

not freeze at the design point.

Specifically, **Fig. 12** shows the time-dependent changes in the flow rate of hydrogen, pressure drop of the heat transfer fluid (scale values not shown), and hydrogen gas outlet temperature.

The hydrogen gas outlet temperature was essentially constant over the one hour of continuous operation shown in **Fig. 12**, indicating stable vaporization performance.

3.4.2 Evaluating heat transfer performance

The following equation expresses the heat transfer rate Q of the heat exchanger.

$$Q = UA\Delta T$$

Where

Q : Heat transfer rate (kW)

U : Overall heat transfer coefficient (kW/(m²·°C))

A : Heat transfer area (m²)

ΔT : Logarithmic mean temperature difference (°C)

In this equation, when fluid properties and flow rates are similar, the overall heat transfer coefficient U is nearly the same. Furthermore, since the heat transfer area A is constant, UA indicates the performance of the heat exchanger. **Table 4** compares the UA calculated from the Q (heat transfer rate, kW) and ΔT (logarithmic mean temperature difference, °C) measured

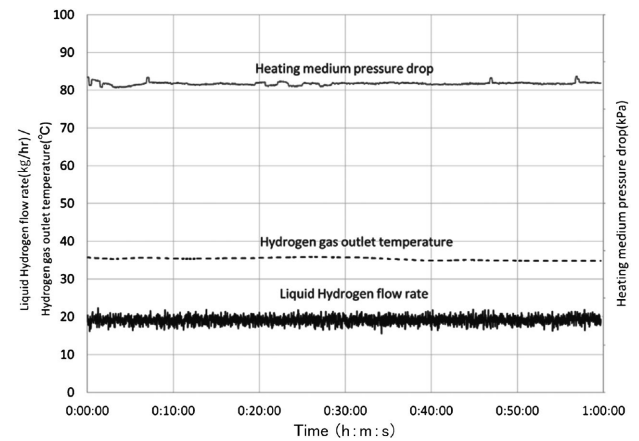


Fig.12 H₂ outlet temp., H₂ flow rate and heating medium pressure drop trend during performance test at design point

Table 3 DCHE specifications for hydrogen vaporization performance test

Basic specifications	Vaporization capacity (liquid hydrogen)	18.9 kg/h
	Type	Micro channel heat exchanger
	Material	Stainless steel type 316 L
Design specifications (path A) Fluid: liquid hydrogen	Inlet temp. (°C)	-253
	Outlet temp. (°C)	30
	Operating press. (MPaG)	0.3
Design specifications (path B) Fluid: ethylene glycol water	Inlet temp. (°C)	40
	Outlet temp. (°C)	35

Table 4 Comparison of UA calculated from design value and actual test value

Item	Design	Actual measurements
Heat duty (kW)	23.0	25.3
Logarithmic mean temperature difference (°C)	69.5	40.2
UA (kW/°C)(*)	1	Over 1.5

(*) It is defined as 1 at the design point.

during performance testing with that of the design point. Since the UA calculated based on testing at the design point is at least 100% of the design value, testing confirms that the heat transfer performance meets the design specifications. These results demonstrate that the design of our LH_2 vaporizer, which uses the design criteria and patented technologies established for LNG vaporizers, is sound and that there is potential for commercialization.

Conclusions

This paper introduced the results and plans of demonstration tests conducted using the LH_2 supply facilities from the project “development of intermediate fluid vaporizer for liquid hydrogen that enables use of liquid hydrogen cold energy.” This project, which received grant assistance from the New Energy and Industrial Technology Development Organization (NEDO), was completed at the end of March 2023. Upon completion of all demonstrations introduced in this paper, we will be able to offer an LH_2 vaporizer comparable to LNG vaporizers in our product lineup.

This research was made possible in part by the project “Development of Technologies for Realizing a Hydrogen Society” (JPNP14026), a grant program of the New Energy and Industrial Technology Development Organization (NEDO). We express our gratitude to NEDO and all involved.

Kobe Steel is advancing the societal implementation of hydrogen energy by supplying vaporizers capable of handling liquid hydrogen in various environments, from land-based to shipboard applications.

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Compressor for LNG Carriers

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Abstract

Due to the need to comply with environmental regulations for ships, dual-fuel engines that can use natural gas in addition to heavy fuel oil have been adopted in nearly all newly-built LNG carriers in recent years. While there are two types of propulsion engines, low pressure (X-DF) and high pressure (ME-GI), our company offers the optimal compressors for fuel gas supply for each type. This paper outlines the fuel gas supply system for propulsion engines that uses boil-off gas (BOG) generated from the LNG tank of LNG carrier, including the re-liquefaction of excess BOG while also explaining the characteristics of oil-flooded screw compressors and reciprocating compressors for this application. Furthermore, it discusses the prospects of technological development for other environmental vessels, such as liquefied hydrogen carriers.

Introduction

Tighter environmental regulations imposed by the International Maritime Organization (IMO) have caused the shipping industry to focus on low-speed, dual-fuel engines capable of burning both heavy fuel oil and natural gas. Nearly all LNG (liquefied natural gas) carriers built in recent years have these types of propulsion engines. Examples include MAN Energy Solutions' electronically controlled gas injection diesel engine (hereafter, ME-GI) and WinGD's dual-fuel engine (hereafter, X-DF), which employs a low-pressure gas injection system for premixed, lean-burn fuel. Both require a compressor to supply natural gas as fuel. The projected rate of LNG carrier construction is anticipated to be around 30 per year around the world, meaning there will be continuous demand for compressors for propulsion engines. Kobe Steel has a strong track record in providing fuel gas supply compressors (screw compressors and reciprocating compressors) for this application. This paper discusses compressors for LNG carriers and the prospects for their application to liquefied hydrogen carriers, which have seen progress toward commercialization in recent years.

1. Gas supply system for LNG carriers

LNG carriers have systems that use the boil-off gas (BOG) generated by the LNG tank during

navigation. BOG is used as fuel for the propulsion engine. In most systems, when the engine is stopped or operating at low load, surplus BOG is recovered by a re-liquefaction system, liquefied, and returned to the LNG tank. This section provides an overview of representative gas supply systems and key compressor specifications.

1.1 Gas supply system of ME-GI

Fig. 1 depicts the gas supply system of an LNG carrier with an ME-GI. The amount of BOG generated depends on the tank and its insulation capacity and ranges from 3.0 to 5.0 t/h. A reciprocating compressor boosts the pressure of the BOG to around 30 MPa for supply to the ME-GI. Some BOG is pressurized to around 1 MPa and sent to the dual-fuel diesel engine (DFDE) for shipboard power. Surplus BOG is pressurized to around 15 MPa and sent to the re-liquefaction system, where it is liquefied and returned to the tank to improve LNG transport efficiency.

1.2 Gas supply system of X-DF

Fig. 2 depicts the gas supply system of an LNG carrier with an X-DF. A screw compressor boosts the pressure of the BOG generated for supply to the X-DF at around 1.3 MPa. Some BOG is diverted and reduced to a pressure of about 1 MPa for supply to the DFDE. The reciprocating compressor further pressurizes surplus BOG to around 15 MPa and

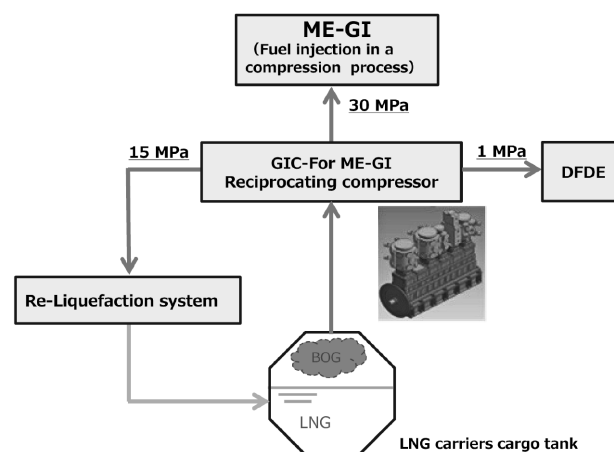


Fig. 1 Gas supply system of LNGC ME-GI

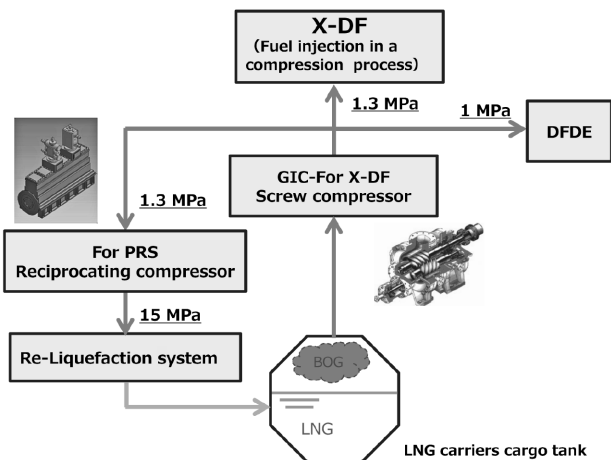


Fig. 2 Gas supply system of LNGC X-DF

sends it to the re-liquefaction system, where it is liquefied and returned to the tank to improve LNG transport efficiency. There are at least two other valid system setups. One is to use a refrigeration unit to reliquefy gas at the supply pressure of the screw compressor (around 1.3 MPa) instead of using a reciprocating compressor to boost pressure. Another is to install a re-liquefaction system with a refrigeration unit directly on the LNG tank to minimize BOG generated by the tank.

2. Screw compressor for LNG carriers

2.1 Structure and basic system

Kobe Steel's X-DF gas supply systems use oil-flooded screw compressors. Screw compressors combine the characteristics of positive displacement and rotary compressors to feature high efficiency, compactness, and long-term operating capacity. Oil-flooded screw compressors, which inject oil into the compressed gas, can achieve high discharge pressure and compression ratios in a single stage.¹⁾ Figs. 3 and 4, respectively, show Kobe Steel's screw compressor for LNG carriers and its system configuration.

Gas at around atmospheric pressure is brought to the appropriate temperature using a pre-heater. It then passes through a filter and a check valve before being compressed to about 1.3 MPa. In an oil-flooded screw compressor, oil is injected into the gas stream for multiple purposes, including lubricating the rotors and bearings and removing heat from compression. This oil must be separated and removed from the gas to meet the permissible oil content limits of the X-DF and the re-liquefaction system.

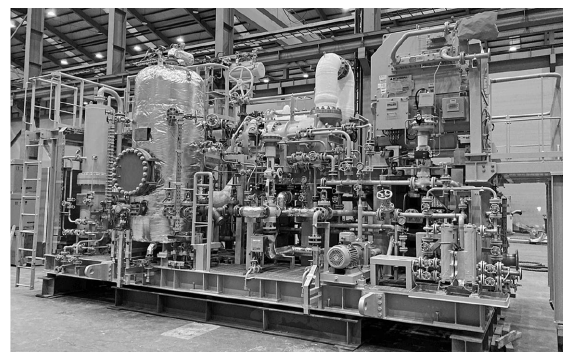


Fig. 3 Appearance of oil-flooded screw compressor for X-DF

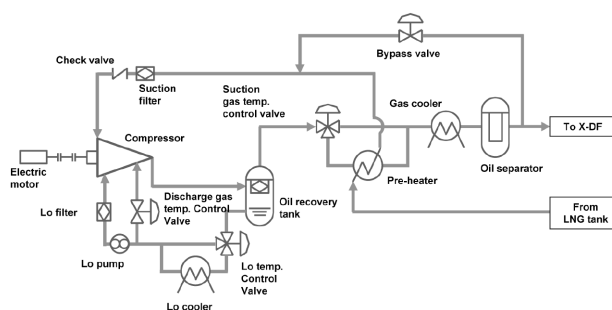


Fig. 4 System flow of oil-flooded screw compressor for X-DF

2.2 Features of the compressor system

2.2.1 Preheating system

BOG generated by the LNG tank is in the cryogenic temperature range (around -160°C). The pre-heater (Fig. 4) uses the heat of compression from the compressor to heat the BOG to around -90°C as a suitable suction temperature for the oil-flooded screw compressor ("Compressor" in Fig. 4). The discharge gas temperature control valve (Fig. 4) controls how much oil is sent to the compressor, ensuring appropriate removal of the heat of compression and holding constant the temperature of the compressed gas discharged from the compressor. The suction gas temperature control valve (Fig. 4) maintains the appropriate temperature of the gas supplied to the oil-flooded screw compressor by controlling the flow of compressed gas to the pre-heater.

2.2.2 Oil separation system

Oil in the compressed gas undergoes primary separation in the oil recovery tank (Fig. 4). The separated oil is then sent back to the compressor via the oil cooler ("Lo cooler" in Fig. 4). The secondary separator ("Oil separator" in Fig. 4) separates and removes oil remaining in the compressed gas

after primary separation. The secondary separator uses a special fine-fiber filter (coalescing filter), the same type used in helium gas liquefaction applications with strict oil removal standards. Adding an activated carbon adsorber downstream as needed provides further oil separation and removal.

2.2.3 Coordinated control of screw compressors and reciprocating compressors

In one example of an X-DF gas supply system, the screw compressor supplies gas not only to the X-DF and DFDE, but also the reciprocating compressor and re-liquefaction system. In such a system, pressure must remain stable even upon fluctuations in the gas demand of each load. Kobe Steel is the only manufacturer with a proven track record of supplying both screw compressors and reciprocating compressors for this application. Hence, we have the ability to implement coordinated control that accurately reflects the control and flow characteristics of both types of compressors. This makes it possible to maintain a constant screw compressor discharge pressure (i.e., gas supply pressure) even upon the large fluctuations in gas flow rate typical of reciprocating compressor startup. In turn, it is possible to ensure stable operation during normal operation and upon fluctuations in load.

3. Reciprocating compressors for LNG carriers

3.1 Reciprocating compressor for ME-GI gas supply

3.1.1 Structure and basic system

Reciprocating compressors used for shipboard applications must generally be vertical reciprocating compressors because of space constraints. Kobe Steel uses a six-stage reciprocating compressor for the ME-GI gas supply system, with stages one through five having non-lubricated cylinders and stage six having an oil-lubricated cylinder. The system flow of these sections is shown in **Fig. 5** (non-lubricated) and **Fig. 6** (lubricated). This six-stage reciprocating compressor pressurizes the BOG generated by the LNG tank from approximately atmospheric pressure to 30 MPa. Reciprocating compressors have various sliding components made of resin, including piston rings, rider rings, and piston rod packings. To enhance the durability and reliability of these components and thus enable long-term continuous operation, lubricating oil is fed into the sixth-stage cylinder, where friction is highest. However, the oil content of the gas must be reduced to a permissible

level for the ME-GI. As such, there is an oil separator (Fig. 6) with a high-performance filter downstream of the discharge of the compressor's sixth stage to separate and remove lubricating oil entrained in the gas.²⁾

3.1.2 Features

The reciprocating compressor in this system supplies gas not only to the ME-GI, but also to the DFDE and to the re-liquefaction system for surplus BOG. The system adjusts the processing volume of each stage based on the demand of the ME-GI and DFDE. Furthermore, the stringent oil contamination requirements for the 15 MPa gas sent to the re-liquefaction system are met. These requirements are necessary because of heat transfer with the cryogenic BOG generated by the LNG tank and the return of re-liquefied LNG to the LNG tank. Hence, the cylinders of stages 1 to 5, which boost the pressure to 15 MPa, are non-lubricated. When gas in the system backflows during shutdown, oil-laden gas may flow from the high-pressure lubricated line (stage 6) to the low-pressure non-lubricated line (stage 5). Therefore, there is a check valve (Fig. 6) to prevent backflow and a coalescing filter (Fig. 6) to collect oil contained in the leaking gas between stages 5 and 6.

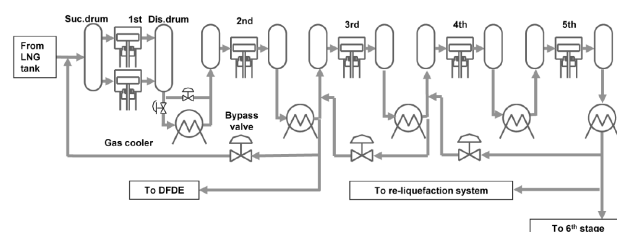


Fig. 5 System flow of reciprocating compressor for ME-GI (Non-lubrication line)

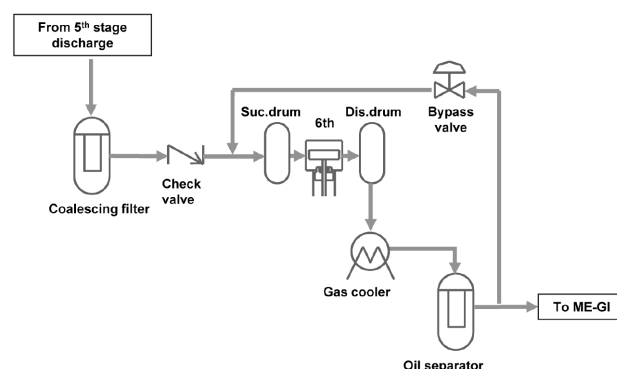


Fig. 6 System flow of reciprocating compressor for ME-GI (Lubrication line)

3.2 Reciprocating compressor for surplus gas re-liquefaction system of X-DF

3.2.1 Structure and basic system

Fig. 7 shows the system containing the reciprocating compressor that re-liquefies surplus gas for the X-DF, and Fig. 8 shows the unit itself. The preceding oil-flooded screw compressor boosts the BOG generated by the LNG tank from atmospheric pressure to about 1.3 MPa. The reciprocating compressor then further boosts the BOG to about 15 MPa. To maximize re-liquefaction efficiency, gas undergoes heat transfer with the cryogenic BOG generated by the LNG tank. Its pressure is then reduced to around 0.1 to 0.3 MPa before re-liquefaction. Because there are strict limits on the oil content of gas in the re-liquefaction system, Kobe Steel offers a three-stage reciprocating compressor that can boost pressure from 1.3 MPa to 15 MPa without lubrication. The flow rate as well as the pressure range of the third, fourth, and fifth stages are the same as for the aforementioned ME-GI reciprocating compressor. Standardizing the cylinder design with that of the ME-GI reciprocating compressor minimizes variety in consumable parts, thereby minimizing maintenance costs.

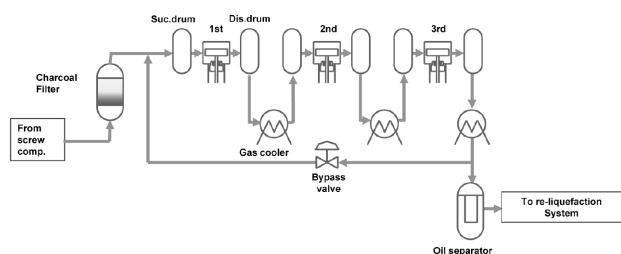


Fig. 7 System flow of reciprocating compressor for re-liquefying surplus gas of X-DF

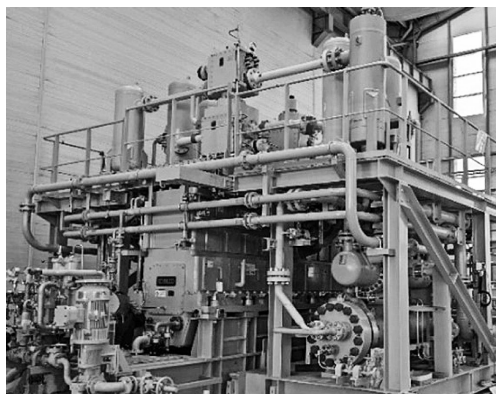


Fig. 8 Appearance of reciprocating compressor for re-liquefying surplus gas of X-DF

3.2.2 Features

In non-lubricated cylinders, the sliding action between resin components (piston rings, piston rod packings) and their mating parts (cylinder liners, piston rods) causes resin to adhere to the mating parts and form a transfer film. This extends service life by reducing wear between the surfaces. However, an extremely small amount of oil (on the order of ppmwt) in the gas will inhibit the formation of the transfer film on the mating surface and lead to abnormal wear. The oil separator on the screw compressor side can reduce the oil content to below 0.5 ppmwt. However, sudden failure of the oil separator would lead to oil dispersion into the reciprocating compressor or the re-liquefaction system. An activated charcoal filter (Fig. 7) upstream of the reciprocating compressor mitigates this risk and thus enhances reliability. There is also an oil separator (Fig. 7) downstream of the reciprocating compressor to separate oil carryover and enable the detection of oil accumulating at the low point. This separator also prevents other foreign matter aside from oil from entering the re-liquefaction system, further increasing reliability.

4. Expansion into liquid hydrogen transport

The forthcoming hydrogen supply chain is undergoing technological development in support of a carbon-neutral society. The liquid hydrogen transport sector is working on foundational designs and plans for constructing liquefied hydrogen carriers. To transport liquid hydrogen, it must be stored at a lower temperature than that required for LNG. Specifically, it is transported near the cryogenic temperature of -253°C . Therefore, as with LNG transport, the carrier must have a system for utilizing the BOG generated by the tank during navigation. There is progress in the development of diesel engines fueled by hydrogen gas, and these engines also require compressors for the supply of hydrogen gas as fuel. Hydrogen BOG generated by the tank is near atmospheric pressure. Boosting this to the pressure required for the engine (around 1 MPa) generally necessitates a compressor with a high compression ratio. This is a challenging requirement to meet because hydrogen gas leaks easily due to its low molecular weight. Hence, multi-stage compressor systems are often used for this application.

Oil-flooded screw compressors suppress the increase in temperature of the compressed gas and reduce gas leakage between the rotors by injecting lubricating oil into the rotor chamber during

compression. This design yields a high compression ratio in a single stage even for hydrogen, with its low molecular weight. Kobe Steel's proprietary tandem compressor (rotors for single-stage and two-stage compression in a single unit) enables a space-saving design that eliminates the connecting piping and interstage cooler normally required in two-stage compression systems.¹⁾

Reciprocating compressors can efficiently boost the pressure of hydrogen despite its low molecular weight. Technology for LNG BOG applications with gas intake temperatures around the cryogenic temperature of -160°C can be used to minimize the heating of cryogenic gas in hydrogen BOG applications. This enables the intake of hydrogen gas while maintaining a high gas density, offering the advantages of a compact compressor size and reduced power consumption.

Kobe Steel has extensive operational experience with both screw compressors and reciprocating compressors in the onshore hydrogen gas sector. We have combined considerations for maritime use with the cryogenic BOG preheating systems used in LNG carrier applications to support the specification and supply of compressors suitable for liquefied hydrogen carriers. This will contribute significantly to the development of the hydrogen supply chain.

Conclusions

Stricter environmental regulations have led to the mainstream use of dual-fuel engines in LNG carriers. This paper describes typical gas supply systems for LNG carriers and the screw compressors and reciprocating compressors used in these applications. Kobe Steel will continue to play a role in ensuring stable, large-scale LNG transport through our operational track record and technical reliability. Furthermore, we will provide suitable compressors for emerging fields such as liquid hydrogen transport by leveraging the technologies we have cultivated for LNG carrier applications. Our focus on efforts such as these will help solve current and future energy and environmental challenges.

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Integrally-gearred Centrifugal Compressor for Carbon Capture and Storage (CCS) and Long Duration Energy Storage (LDES) Applications

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Abstract

In recent years, as environmental awareness in society has increased, Carbon Capture and Storage (CCS) has been implemented to reduce greenhouse gas emissions. Kobe Steel has developed a high-pressure CO₂ compressor for injecting captured CO₂ into underground reservoirs and conducted pressure tests in a supercritical state using CO₂ gas in its factory. Meanwhile, the charging compressor for the mechanical battery system in Long Duration Energy Storage (LDES), which is expected to undergo technological advancement, faces technical challenges in handling high-temperature gas and operating conditions that require daily start and stop. Kobe Steel is addressing these challenges by combining its own technologies and know-how the company has cultivated to date. This article explains Kobe Steel's product development and approach to technical issues for centrifugal compressors to support its customers by creating a better environment.

Introduction

Carbon capture and storage (CCS) contributes greatly to advancing not only carbon neutrality but also the supply of energy via blue hydrogen and blue ammonia. As such, recent years have seen a surge in efforts toward related plant planning and operations, particularly in the United States and Europe. Additionally, Japan declared a goal in 2020 of achieving carbon neutrality by 2050. Consequently, the Act on Carbon Dioxide Storage Projects (CCS Business Act) was enacted in 2024, with a target for commencement of no later than 2030. It can thus be surmised that CCS projects will become a familiar presence in Japan as well in the near future.

In CCS applications, compressors are primarily used for transport and storage, specifically to pressurize CO₂ to transport it from an emission source via a vessel or pipeline, and to inject it into a reservoir. The equipment and operational costs associated with CCS generally reduce the overall economic efficiency of a plant. Therefore, the compressors in such systems must be not only mechanically reliable, but also economical and highly efficient.

The increasing prevalence of renewable energies such as solar and wind-power generation have placed increased attention on long-duration energy storage (LDES) as a means of storing surplus energy over extended periods. Several processes have been developed since the 2020s, some of which have been marketed commercially. One type of system is mechanical energy storage that uses compressors to store the pressure and thermal energy of gases. Advantages of mechanical systems over battery systems (e.g., lithium-ion batteries) include a high availability of materials for components, longer service life, and greater storage capacity. However, these systems have different considerations from machinery typically used in continuous operation, such as high-temperature gases and frequent start-stop cycles.

This paper first introduces the development details and key technological aspects of Kobe Steel's high-pressure CO₂ compressor designed for injecting CO₂ captured as part of CCS into underground reservoirs. It then covers the technical requirements and challenges for high-temperature compressors used in LDES, along with Kobe Steel's efforts to address them.

1. High-pressure CO₂ compressor for CCS

In Kobe Steel's flagship product, the integrally geared centrifugal compressor (hereafter, integrally geared compressor), the pinion rotors have impellers at the ends and a small gear in the center. The speed of the gear is increased via a large gear (bull gear), as shown in the compressor cutaway model in Fig. 1. Thus, the impeller's rotational speed can be adjusted per each pinion rotor by changing the gear ratio. As shown in Fig. 2, the efficiency of a centrifugal compressor is characterized based on the specific speed (n_s), which indicates how similar the impellers are in shape.¹⁾ Adapting the impeller diameter and rotational speed for the required head and volumetric flow rate sets an appropriate specific speed, thus optimizing efficiency. Specific speed is defined by rotational speed, volumetric flow rate, head, and gravitational acceleration per Equation (1).

$$n_s = 2\pi N Q^{\frac{1}{2}} / (gH)^{\frac{3}{4}} \dots\dots\dots (1)$$

Here, N = rotational speed (1/s)
 Q = volumetric flow rate (m^3/s)
 g = gravitational acceleration (m/s^2)
 H = head (m)

Furthermore, because the integrally geared compressor has independent stages, it is easy to incorporate interstage cooling between stages. This brings operation closer to isothermal compression, reducing power consumption. However, the rotor of this design tends to have a decrease in rigidity because it rotates at high speeds and has impellers at both ends of the shaft. Therefore, a challenge arises if efficiency is prioritized such that very high rotational speeds result, as it becomes difficult to ensure stability against rotor vibration.

Using an integrally geared compressor with these characteristics for high-pressure CO_2 compression in CCS applications presents the following technical challenges:

- i) Ensuring accurate prediction of aerodynamic performance accounting for changes in CO_2 properties at high pressure

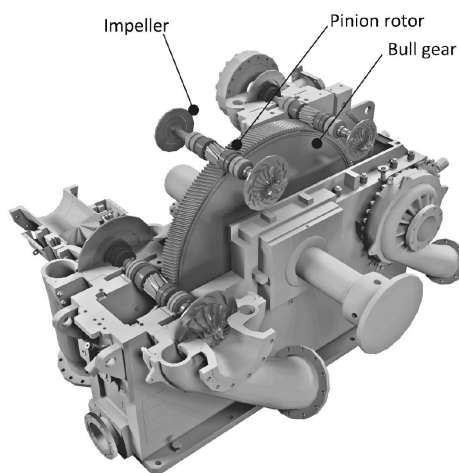


Fig. 1 Section model of integrally geared centrifugal compressor

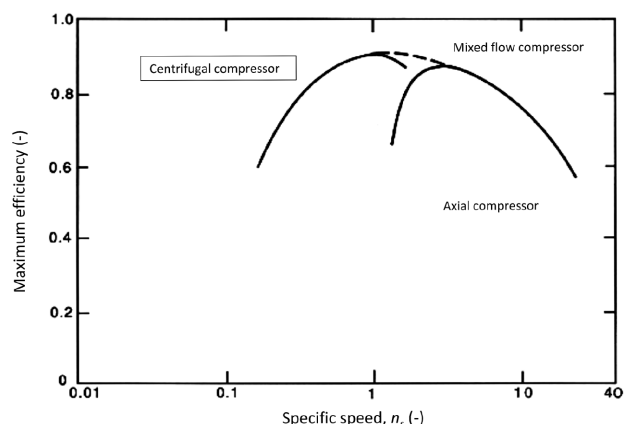


Fig. 2 Specific speed vs maximum efficiency ¹⁾

- ii) Ensuring vibrational stability of the rotor and vibrational strength of the impeller blades, which are subjected to fluid forces from high-pressure, high-density CO_2
- iii) Ensuring seal performance sufficient to inhibit the leakage of high-pressure CO_2 gas
- iv) Reducing life cycle costs

To validate the solutions for overcoming these challenges, Kobe Steel designed and manufactured a prototype compressor and conducted in-plant pressure testing using CO_2 gas.²⁾ **Table 1** shows the target specifications for the prototype CO_2 compressor. **Fig. 3** shows the CO_2 compressor and associated equipment in the test facility. The next section describes the results of pressure testing as well as the key technologies of the high-pressure CO_2 compressor (hereafter, prototype unit) that address the aforementioned technical challenges.²⁾

Table 1 Specification of development target for high-pressure CO_2 compressor

Application	Prototype
Type	Integrally geared
No. of stage	8 stages
Gas handled	CO_2
Capacity	140,000 kg/h (72,500 m^3/h)
Suction / discharge pressure	0.01 / 20 MPaG
Shaft power	16,600 kW
Driver	Motor (18,500kW)

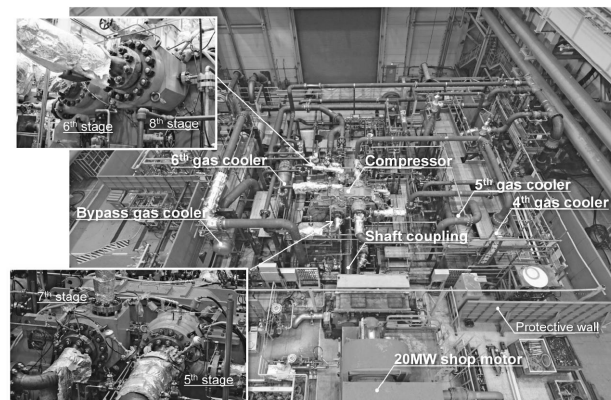


Fig. 3 Overview of high-pressure CO_2 prototype compressor and test facility

1.1 Aerodynamic design and results of performance testing

Key components that define compressor performance include the impeller, which imparts kinetic energy to the gas, and the diffuser, which converts this kinetic energy into an increase in static pressure. The physical properties of CO₂ gas change significantly in the high-pressure supercritical region. Regarding it as an ideal gas can result in a compression ratio that differs greatly from calculated values. Accounting for these changes in the physical properties of the gas in the aerodynamic design yields an impeller design that more accurately achieves target specifications.

Fig. 4 shows the aerodynamic performance test results from pressure testing of the prototype unit. At the specified flow rate ($\phi/\phi_{\text{design}} = 1$), the discharge pressure of the final stage (eighth stage) reaches 20 MPaG, validating the aerodynamic design.

1.2 Evaluating rotor design and stability

Hydrodynamic forces generated by the impellers and seals in the rotor package act as destabilizing forces. The stability of the rotor must be sufficient to overcome the resulting unstable vibration. Stability is generally evaluated in terms of the logarithmic decrement of the rotor system, which consists of the rotor and bearings. A positive log decrement indicates a stable rotor system, a negative log decrement an unstable system. **Fig. 5** shows the stability analysis results for the seventh-to-eighth stage rotor of the prototype unit. The horizontal axis shows the destabilizing force (cross coupling) as specified in the widely adopted centrifugal compressor standard API 617.³⁾ The vertical axis shows the log decrement. As gas pressure increases,

power and density also increase, in turn increasing the destabilizing forces acting on the impeller and seals. API 617 requires a design log decrement of 0.1 or greater. However, calculations show that achieving this value is difficult for tilting pad journal bearings (TPJB) because of excessive destabilizing forces. Hence, the labyrinth seal at the impeller suction has a swirl brake with a large number of ribs to suppress swirling flow and thereby suppress destabilizing forces. Additionally, the ISFD (integral squeeze film damper) bearing imparts excellent damping characteristics to the rotor, resulting in a highly stable rotor design.

We conducted excitation tests to measure the rotor's vibration characteristics. **Fig. 6** depicts Kobe Steel's test method for exciting the rotor to evaluate rotor stability. We arranged four electromagnets in the circumferential direction on the front of the impeller. Electromagnetic force during compressor operation applied a bending moment to the rotor via the impeller, inducing excitation perpendicular to the shaft. This setup enabled us to obtain precise data regarding the rotor's damping characteristics. The horizontal axis in **Fig. 7** shows the discharge pressure of the last stage. The vertical axis shows the natural frequency and log decrement of the rotor's first forward rotation mode (1st FW) and second forward rotation mode (2nd FW) measured during the excitation test. The excitation test results confirm

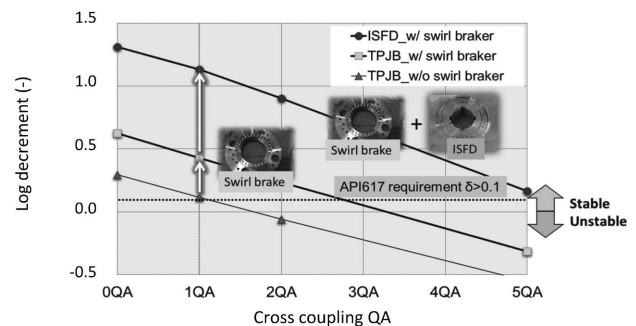


Fig. 5 Result of rotor stability analysis

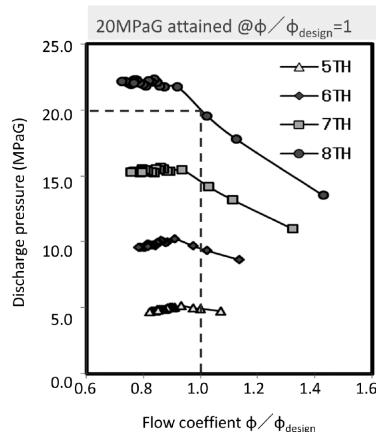


Fig. 4 Discharge pressure of each stage

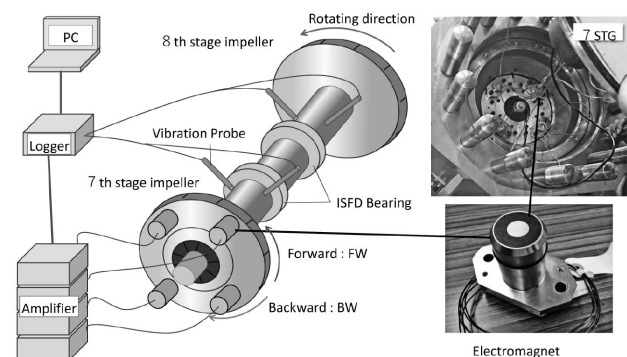


Fig. 6 Developed magnetic excitation system

that the rotor's stability exceeds the log decrement specified in API 617 even under high-pressure conditions.

1.3 Measuring impeller blade vibration and evaluating strength

High-density gas exerts significant forces on the blades of open impellers because they are cantilevered. Increased vibration can cause excessive dynamic stress and potentially lead to failure. Therefore, we performed strength testing by measuring blade vibration in the fifth- and sixth-stage impellers of the prototype unit.

Fig. 8 shows a conceptual diagram of the blade vibration measurement system. An optical displacement sensor on the casing opposite the impeller measures the frequency at which the blades pass the sensor during vibration (dashed

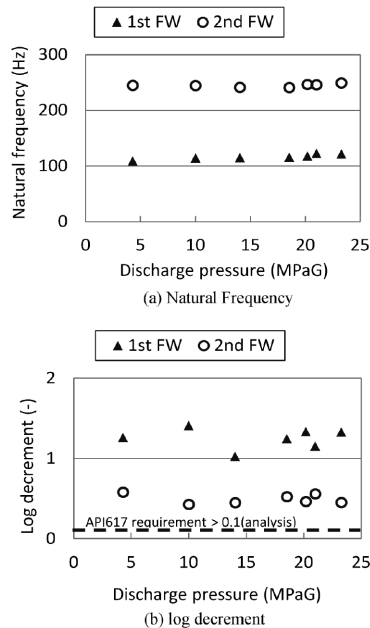


Fig. 7 Measured dynamic characteristics of rotor vs discharge pressure (ISFD bearing)

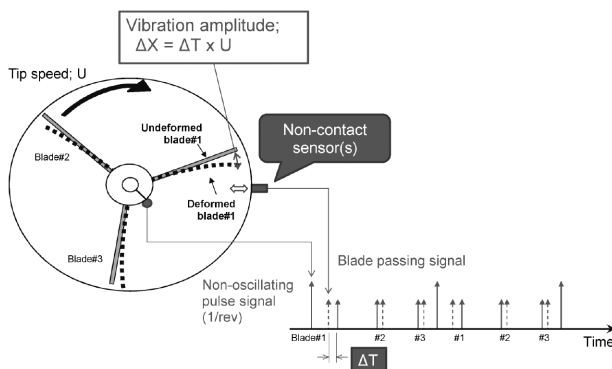


Fig. 8 Schematic of blade vibration measurement system

line). Analyzing the difference in time (ΔT) as compared with the non-vibrating blades (solid line) indicates the impeller's vibration amplitude (ΔX) and vibration frequency. **Fig. 9** shows the blade amplitude of the impeller at each operating point, with the ratio of the flow rate to the design flow rate on the horizontal axis and the discharge pressure of the sixth stage on the vertical axis. The size of the circle at each point represents the magnitude of the blade amplitude. We used finite element analysis to calculate dynamic stress based on the acquired amplitude. **Fig.10** shows the resulting modified Goodman diagram, with normalized mean stress on the horizontal axis and normalized dynamic stress on the vertical axis. Alongside vibration in the normal operating range, we also calculated surge point stresses, confirming that stress is below the fatigue limit of the impeller material at all operating points and that the load on the impeller is sufficiently low. This validation demonstrates

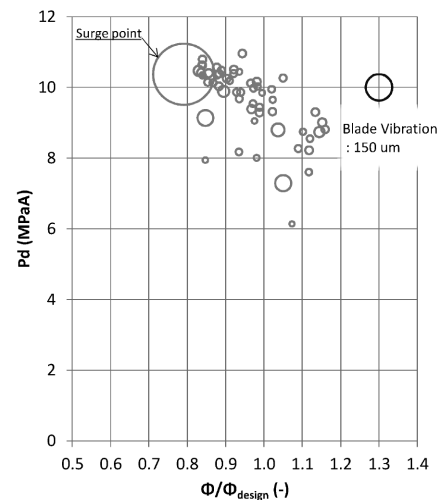


Fig. 9 Blade vibration of 6th stage open impeller at each operation point

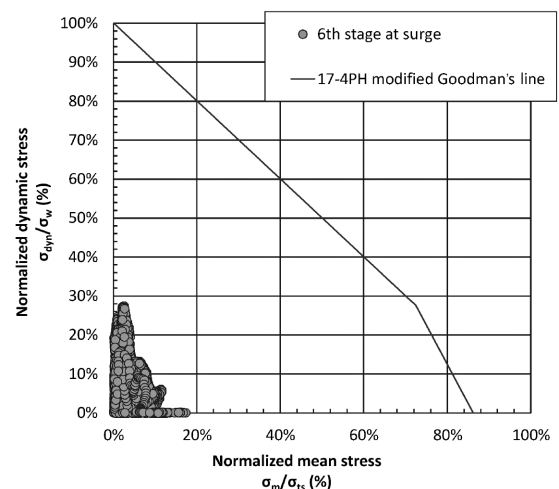
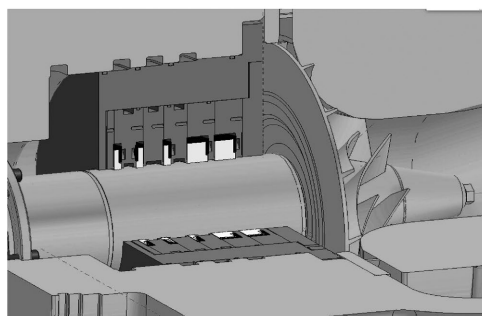


Fig.10 Modified Goodman diagram of open impeller

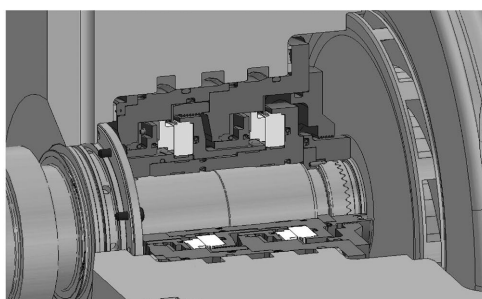
that by expanding the application of open impellers, which can operate at higher rotational speeds than closed impellers, it is possible to reduce the number of stages and achieve a more compact compressor.

1.4 Selecting shaft seals and performing leak testing

Fig.11 shows a carbon ring seal and a dry gas seal, which are commonly used in CO₂ compressors. Low system pressures are near atmospheric pressure. Therefore, carbon ring seals are used because they are inexpensive and provide adequate protection against leakage. Carbon ring seals are a type of annular non-contacting seal. They reduce leakage to atmosphere because the difference between the coefficient of liner thermal expansion between the shaft material and the carbon causes the gap in the sealing area to close during operation. When sealing pressure is high, the number or thickness of the carbon rings must be increased. For integrally geared compressors with impellers at both ends, this leads to longer overhang, generally reducing rotor rigidity and stability. Therefore, dry gas seals are used for high-pressure conditions, as their sealing width is constant regardless of pressure and they inhibit leakage better than carbon ring seals. Dry gas seals are non-contacting radial flow seals that exploit the dynamic pressure generated by gas trapped between the sealing surfaces during equipment rotation. This dynamic pressure causes the sealing surfaces to lift a distance on the order of microns.



(a) Carbon ring seal



(b) Dry gas seal

Fig.11 Gas seal

We used a dry gas seal as the shaft seal for the prototype unit. We measured leakage at a discharge pressure of 20 MPaG and verified the high reliability and low leakage of the dry gas seal. Fig.12 shows the discharge pressure (horizontal axis) and the leakage of the dry gas seal (vertical axis) of the last stage (eighth stage).

The temperature of the barrier gas must be controlled because dry gas seals generally require a dry environment. Measures are taken to prevent the liquefaction of gas due to the Joule-Thomson effect when diverting discharge gas from the high-pressure stage to purge the low-pressure stage with barrier gas.

Compressor shaft seals used in CCS are specified to optimize leakage characteristics, cost, and mechanical reliability at the respective pressure levels for separation, capture, transport, and storage.

1.5 Skid-mounted compressor packages

One means of reducing compressor footprint and installation time is to use a package, which contains the system in a two-level steel frame structure (hereafter, skid) to achieve a compact, integrated compressor unit. The first level usually

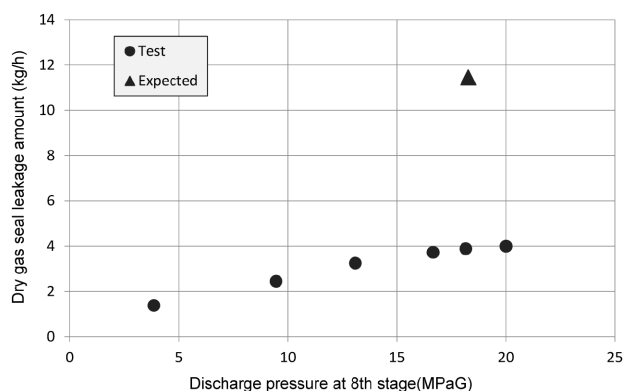


Fig.12 Dry gas seal leakage amount of 8th stage

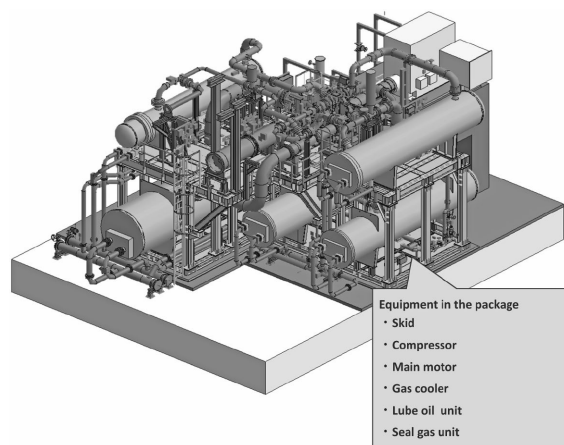


Fig.13 Overview of compressor package

contains the lubricating oil unit, barrier gas unit, and interstage cooler for the low-pressure stage; the second level usually contains the compressor, motor, and interstage cooler for the high-pressure stage. **Fig.13** shows the structure of the skid-mounted compressor package.

The two-level structure of this compressor package reduces the floor space required for the compressor and auxiliary equipment. Furthermore, since the compressor package is fully assembled including final piping connections before leaving the factory, there is no need for on-site pipe welding or pressure and leak testing. On-site assembly is relatively easy because components are installed in the same sequence as at the factory. This reduction in on-site working hours helps lessen the burden of labor costs, which have recently been on the rise. However, special considerations are required for maintenance: The compressor and auxiliary equipment must be able to be rigged and lowered easily, workers must be able to access equipment easily, and special safety considerations such as handrails must be in place. Furthermore, methods such as eigenvalue analysis must be used during design to ensure resonance will not occur between the natural frequency of the skid and the operating frequency since the compressor package is a two-level structure. Additionally, the foundation material and the size of the bolts used in the structure must be validated as capable of withstanding the dynamic loads generated by rotating machinery. Kobe Steel provides highly reliable compressor units through these technical approaches.

2. High-temperature compressor for LDES

Recent years have seen an increase in studies and demonstration projects for systems for long-term storage of renewable energy.⁴⁾ Mechanical charging systems combine a heat exchanger, a pressure and heat storage system, and a power generation turbine to perform charging and power generation. Specifically, these systems separate and store the

pressure energy and thermal energy imparted to high-temperature gas by a centrifugal compressor. Advantages of mechanical energy storage systems over batteries (e.g., lithium-ion batteries) include the elimination of procurement constraints for materials, no degradation in charge/discharge efficiency over time, and lower operating costs as charge/discharge capacity increases.

Fig.14 shows the schematic of one type of mechanical energy storage system, a CO₂ battery.⁵⁾ During the charging phase, CO₂ gas is drawn from a large-capacity CO₂ gas holder, called a dome, and sent to a compressor that increases its pressure and temperature. The thermal energy is stored in a heat exchanger called a TES (thermal energy storage unit). CO₂ is then liquefied and stored under high pressure. During discharge, the TES vaporizes the stored CO₂. The heated gas expands to drive a turbine and generate electricity. **Fig.15** shows the compressor of a CO₂ battery for this application.

Fig.16 shows the schematic of an LAES (liquid air energy storage) system, which uses air to charge a cryogenic liquefaction system.⁶⁾ Two major technical challenges for compressors used in these systems are high operating temperatures and frequent start-stop cycles. The following subsections explain each challenge and Kobe Steel's solutions.

2.1 High temperature and thermal insulation design

Increased temperatures cause a decrease in the strength of the materials of the impeller in a centrifugal compressor. Therefore, the material and rotational speed are specified such that the stress of the impeller remains below the permissible value at operating temperature. The rear of the impeller in particular is exposed to high temperatures due to the impeller outlet temperature. Furthermore, the interior and rear of the impeller experience constant, high stress during operation due to the centrifugal loads from the rotation of the impeller itself. Strength analysis using finite element analysis is necessary to account for creep rupture

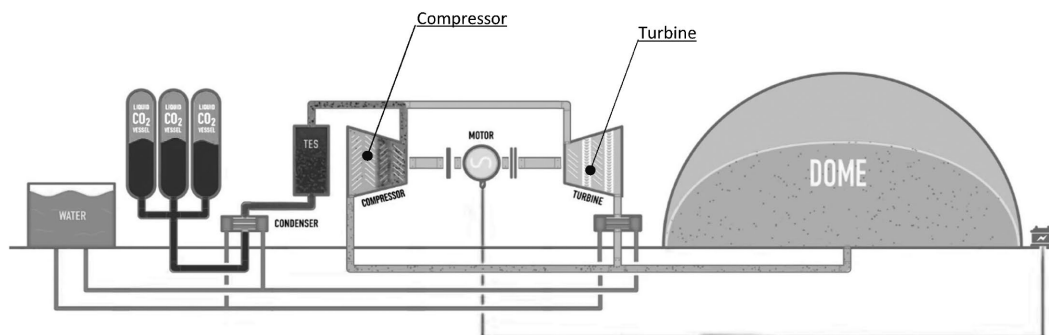


Fig.14 System schematic of CO₂ battery

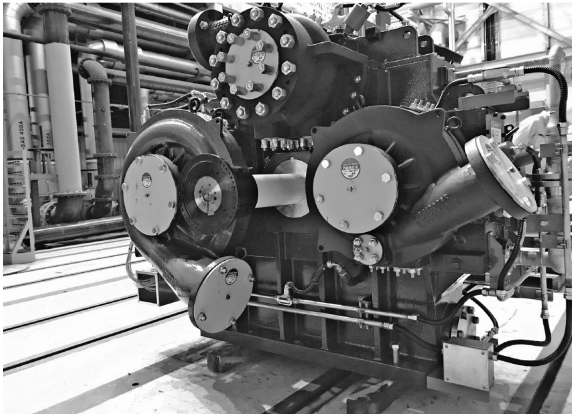


Fig.15 Centrifugal compressor for CO₂ battery

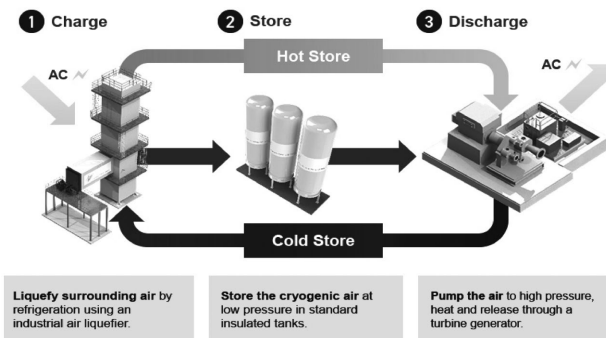


Fig.16 System schematic of LAES

life and ensure that permissible stresses are not exceeded. Kobe Steel addresses high temperatures by specifying heat-resistant steel for the impeller and surrounding components based on design temperature.

The pinion rotor also becomes hot due to thermal conduction from the impeller and heat transfer with the gas. This component is heat treated to increase its gear strength, so the operating temperature must stay below the tempering temperature of the material. It is also critical to evaluate the strength of the shaft end, which is the area of torque transmission, and to prevent heat transfer to the shaft area. To address this challenge, Kobe Steel incorporated a sleeve made of heat-resistant steel axially between the impeller and pinion rotor to increase the distance between these components, thereby suppressing heat input to the rotor.⁷⁾

Additionally, excessive heat transfer from the compressor casing to the gear case causes thermal deformation in the gear case. This in turn causes misalignment of the bearing section, potentially leading to contact between rotating and stationary parts. For this reason, the gear case must be thermally insulated. Thermal insulation between the compressor casing and gear case suppresses heat input to the gear case and thus minimizes the effects of thermal deformation.

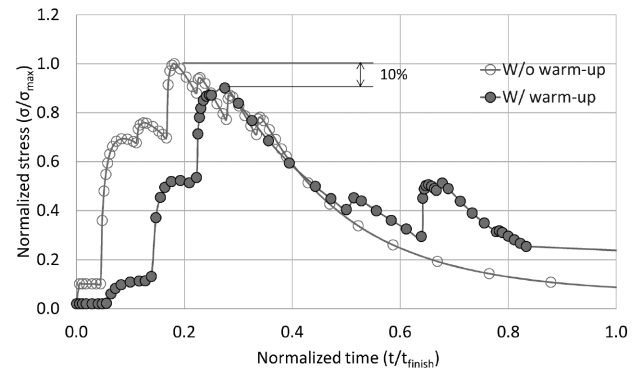


Fig.17 Stress at root of impeller blade during start-up

2.2 Thermal stress and frequent start-stop cycles

A large temperature difference between the stopped and operating states can lead to very large loads and moments on the pipe nozzles due to thermal expansion. In this case, the nozzles must be supported, or the loads must be reduced. We investigated support plans to relieve external forces on piping and support piping loads using expansion joints and bent pipes.

Furthermore, for this application, curtailing start-up time is important to minimize energy loss. However, rapid temperature shifts during start-up and shutdown cause thermal stresses, necessitating an understanding of when and where high-stress conditions occur. We calculated thermal stresses by combining transient thermal analysis, fluid analysis to determine the temperature distribution of parts in contact with gas, and structural analysis. **Fig.17** shows a comparison of the change in stress during start-up with and without a warm-up operation. On the horizontal axis is the time, normalized by the time it takes for the compressor to reach rated speed, and on the vertical axis is the stress generated in the impeller, normalized by its maximum value. We optimized the temperature and duration of the warm-up to reduce the stress level ratio at the root of the impeller blade by 10%, which should extend impeller service life.

LDES systems are charged using surplus electricity and serve to balancing power supply sources. Because they undergo frequent start-stop cycles, the number of daily start and stop cycles (DSS) must be considered during the design phase. The aforementioned thermal stresses are iteratively applied with each start-stop cycle, meaning that the fatigue design must account for the number of cycles. Furthermore, the starting torque of the shafts and couplings that transmit torque is several times greater than the rated torque. Therefore, design strength must account for both the starting torque

and the number of starts and stops.

When the time between shutdown and the next startup is relatively short, the compressor's internal components do not cool uniformly. This uneven temperature distribution can cause the rotor to warp. Thermal distortion causes imbalances, leading to increased vibration during startup and potentially preventing the equipment from reaching rated speed. Applicable countermeasures are necessary, particularly with large units where the effects of thermal distortion are significant. Instead of completely stopping the rotor after operation, a turning device turns the rotor at low speed to equalize its temperature, enabling a smooth subsequent start-up.

Conclusions

This paper describes the technical challenges and their countermeasures for high-pressure CO₂ compressors used in CCS and high-temperature compressors for LDES. These technologies are

critical for a carbon-neutral, sustainable society. Kobe Steel will continue tackling new demands and advancing high-efficiency, high-end, reliable compressor technologies and products to support customers' manufacturing needs.

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High-temperature, High-pressure Warm Isostatic Pressing Equipment for All-solid-state Battery Manufacturing Process

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Abstract

In the manufacturing process of all-solid-state batteries, pressure treatment is performed to form the interface between the electrode active material and the electrolyte. Warm isostatic pressing (WIP) technology has potential application in the pressure treatment process because it can isostatically pressurize target materials at high temperatures and pressures. However, the optimal processing pressure and temperature remain unclear for all-solid-state batteries. Accordingly, Kobe Steel has been researching the densification of all-solid-state battery electrodes using WIP technology, aiming to adopt it in the all-solid-state battery manufacturing process. The company is also developing equipment to perform WIP treatment at higher temperatures. This study demonstrates that a good electrode interface can be obtained by performing WIP treatment at a high temperature and pressure. Furthermore, heating the pressure medium inside the high-pressure piping of the WIP equipment improves the temperature distribution inside the pressure vessel. This is expected to reduce temperature variations during the processing of all-solid-state batteries, thereby improving battery quality when performing WIP treatment at high temperatures. This paper discusses the results of this research and equipment development.

Introduction

Warm isostatic pressing (WIP) simultaneously applies high temperature and high pressure to workpieces, using a liquid heated to a high temperature as the pressure medium. WIP technology has been utilized in various applications, including the pressure bonding of multilayer ceramic capacitors, and Kobe Steel has long history of providing WIP equipment in many applications.

Recent research has shown the possibility that WIP technology can be applied to the manufacturing process of all-solid-state lithium-ion batteries. All-solid-state batteries are composed entirely of solid materials; therefore, pressure treatment is performed to eliminate voids between the electrode active material (AM) and solid electrolyte (SE) and to improve adhesion. Research on pressure treatment has reported that simultaneous heating

and pressurizing enhances the fluidity of the SE and is effective for forming a good interface.¹⁾ Therefore, WIP technology is thought to be suitable as a pressurization method for manufacturing all-solid-state batteries.

However, all-solid-state batteries are still under development, including their manufacturing process, and the optimal processing pressure and processing temperature have not yet been determined. Accordingly, Kobe Steel is advancing research on how WIP processing temperature and pressure affect the structure and characteristics of all-solid-state batteries, with the aim of adopting this technology in their manufacturing process, developing higher processing temperature capability for WIP equipment, and reducing temperature variation inside the pressure vessel.

1. Challenges of pressurization technology in all-solid-state battery manufacturing process

Eliminating voids between the electrode AM and the SE and improving adhesion are important for enhancing charge and discharge capacity and energy density for an all-solid-state battery. Uniaxial pressurization methods such as roll pressing and single-action pressing are commonly used to eliminate these voids and improve adhesion. However, microscopic irregularities on the surfaces of the electrode AM layer and SE layer prevent uniform pressurization, making it difficult to sufficiently improve the adhesion between the electrode AM layer and SE layer.²⁾ By contrast, WIP technology can apply isotropic pressurization to a workpiece; therefore, it is considered possible to obtain an all-solid-state battery with superior adhesion between the electrode AM layer and SE layer by adopting WIP technology.

All-solid-state batteries are still under development, including their manufacturing process, and optimal processing pressure and temperature are not yet clear. However, it is possible that high temperatures, up to 200°C may be required as the processing temperature. Research has reported that pressurization at a high temperature of 190°C using WIP technology increases electrolyte

fluidity and enables the formation of an interface with higher adhesion.³⁾

Kobe Steel aims to develop large-size WIP equipment for the stable mass production of all-solid-state batteries. For this purpose, it is necessary to solve issues related to increasing processing temperature and reducing temperature variation in the pressure vessel in intensifier-type WIP equipment. This paper describes the development results of intensifier-type WIP equipment compatible with 200°C that can be applied to production machines.

2. Current status of the WIP equipment

2.1 Overview of Kobe Steel's WIP equipment

Our WIP equipment is composed of the following components:

- 1) Pressure vessel and top and bottom closure that retain high pressure internally
- 2) Press frame that supports the axial force inside the pressure vessel
- 3) Hydraulic pressurizing system(intensifier or piston)
- 4) High-pressure valves that hold and release pressure medium
- 5) Jacket and heating equipment that heat the pressure vessel

With these components, the pressure vessel is filled with the pressure medium and heated; then, the workpiece is inserted and pressure is increased using the pressurization mechanism. This process creates a high-temperature, high-pressure state inside the pressure vessel, thereby applying isostatic pressure to the workpiece.

2.2 Advantages and challenges of pressurizing system for WIP equipment

WIP equipment is classified as intensifier or piston type depending on the pressurization method. **Fig. 1** compares each pressurization method in WIP equipment, and the characteristics, advantages, and challenges of each method are listed in **Table 1**. The intensifier type is a method in which the pressure medium is fed into the pressure vessel by an intensifier to increase pressure, and it is mainly adopted in medium to large machines with processing pressures of 600 MPa or less. By contrast, the piston type is a method in which the pressure medium is directly compressed by pushing a piston into the pressure vessel and is mainly adopted in small machines with processing pressures exceeding 600 MPa. The intensifier type is more suitable for increasing the diameter of the pressure vessel compared to the piston type, but the temperature of the pressure medium supplied to the intensifier

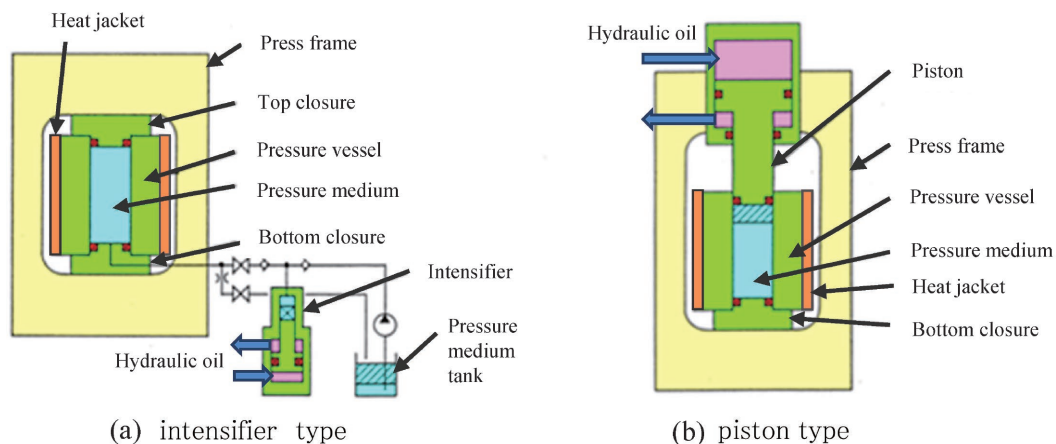


Fig. 1 Comparison of pressurizing system for WIP: (a) intensifier type and (b) piston type

Table 1 Advantages, and challenges of each pressurizing system for WIP

Pressurizing system	Intensifier type	Piston type
Inner diameter	Medium to large	Small
Pressure level	Low (600 MPa or under)	High (over 600 MPa)
Advantage	Suitable for large scale (diameter) WIP	Easy to achieve high temperature and high pressure in pressure vessel
Challenge	Difficult to achieve high temperature and prevent occurring temperature distribution	Not suitable for large scale (diameter) WIP

is limited to 80°C depending on the heat resistance temperature of the intensifier high-pressure seal. As a result, even if the pressure medium inside the pressure vessel is heated before pressurization, low-temperature pressure medium flows into the pressure vessel, causing temperature differences inside the pressure vessel after pressurization. When temperature differences occur inside the pressure vessel, variation in processing temperature arises in the workpiece inside the pressure vessel. Furthermore, even if an attempt is made to increase the processing temperature inside the pressure vessel, the temperature of the pressure medium supplied to the intensifier cannot be raised, leading to increased temperature differences inside the pressure vessel during pressurization.

2.3 Development strategy

Kobe Steel's development strategy is to develop intensifier-type WIP equipment, which is more suitable for larger diameter, with future mass production of all-solid-state batteries. And furthermore, the strategy is to develop technology that increases processing temperature and reduces variation in processing temperature inside the pressure vessel.

3. Verifying application of WIP through trial densification of cathode for all-solid-state batteries

First, an attempt was made to verify whether densification of the cathode for an all-solid-state battery is possible using WIP technology. In all-solid-state batteries, the AM has a structure in which it is mixed with the SE and additives. In this study, $\text{Li}(\text{Ni}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3})\text{O}_2$ (NMC) with a surface coating of LiNbO_3 was used as the AM, and $\text{Li}_6\text{PS}_5\text{Cl}$ was used as the SE. The AM, SE, and conductive additive (AB) were mixed at a ratio of 74 : 23 : 3 (wt%), made into a slurry by adding binder and solvent, coated onto Al current collector foil, and dried to form the electrode. Finally, it was sealed in an aluminum laminate film to prevent contact with the atmosphere. The piston type was used for WIP treatment. The processing pressure was set to 600 MPa, processing temperature to 190°C, and processing time to 1 min. Synchrotron X-ray-Computed-Tomography (CT) was used to nondestructively evaluate the three-dimensional structure of the obtained electrode. X-ray CT measurements were conducted at SPring-8 BL16B2 (proposal numbers 2021A5320, 2021B5320, and 2022A5320). The incident X-ray energy was 30 keV. Xsight Micron LC was used to acquire X-ray

CT data. The voxel size of the X-ray CT data was 1.3 μm or 0.65 μm . The sample was sealed in a glass capillary inside a glove box under an Ar atmosphere. Threshold values were determined based on the CT values of each component, and the obtained CT images were classified into three regions (AM, SE, and voids/AB/binder) to evaluate structural differences.

Fig. 2 shows CT images inside the electrode and analysis results by three-value segmentation before WIP treatment and after WIP treatment (room temperature (Approximately 20°C) or 190°C). From Fig. 2, it was confirmed that voids, AB, and binder (black) present within the electrode SE (red) decreased due to WIP treatment. This result shows that WIP treatment at a processing pressure of 600 MPa and processing temperature of 190°C is effective for the densification of the electrode with the mixing ratio used in this study.

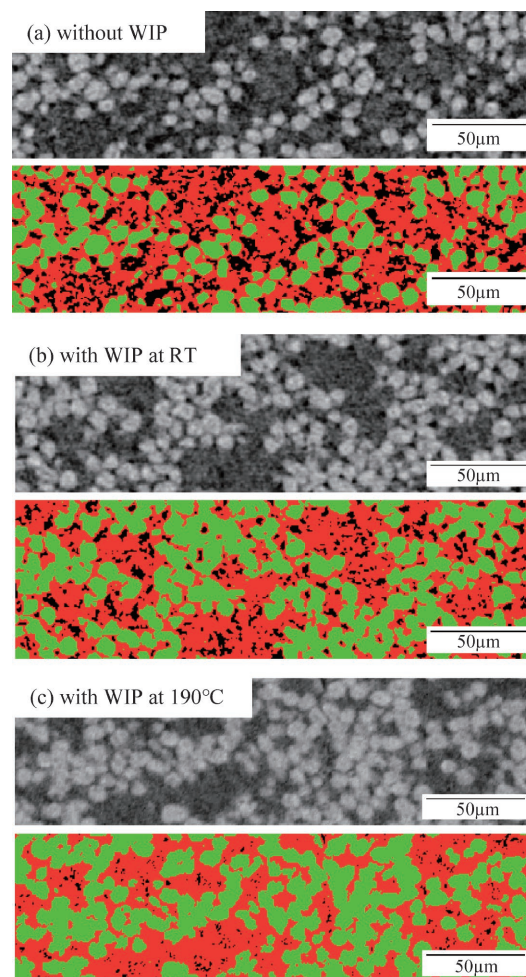


Fig. 2 CT (upper) and the categorized (lower) images of the composite electrodes. (a) without WIP, (b) with WIP at room temperature (RT), and (c) with WIP at 190°C. (NMC: green, SE: red, and voids/carbon/binder: black) The samples of (b) and (c) were pressed at 600 MPa for 1 min.

4. Study of methods for increasing temperature and reducing temperature variation using intensifier-type WIP equipment

4.1 Challenges and solutions in intensifier-type WIP equipment

As described above, in intensifier-type WIP equipment, low-temperature pressure medium flows into the pressure vessel during pressurization, which causes the inhibition of temperature increase and generation of temperature variation. This issue was addressed by applying heat exchange technology to high-pressure piping (“high-pressure heat exchange technology”). A system diagram adopting high-pressure heat exchange technology is shown in Fig. 3.

In this technology, the pressure medium inside the high-pressure piping is heated, enabling high-temperature pressure medium to flow into the pressure vessel. This approach in turn maintains a high-temperature state inside the pressure vessel after pressurization and reduces temperature variation.

4.2 Confirmation of effect of high-pressure heat exchange technology

4.2.1 Experimental details

Operating conditions were set such that the pressure inside the pressure vessel was 600 MPa and the pressure medium temperature was 200°C, and pressurization operation was carried out while changing the heat exchange system temperature conditions to confirm the effect of high-pressure heat exchange technology. The specifications of the test equipment used in this experiment are

given in Table 2, and the experimental conditions are shown in Table 3. The heat exchange system temperature was set to 60 (Case 1) and 200°C (Case 2), and temperatures at different height position during pressurization operation were measured using thermocouples installed at the lower, middle, and upper parts inside the pressure vessel. The thermocouples were installed at positions not in contact with the inner surface of the pressure vessel.

4.2.2 Experimental results

The pressurization operation charts obtained in these experiments are shown in Fig. 4. In Case 1, the temperature from the lower to upper regions inside the pressure vessel at 600 MPa ranged from 172 to 204°C (temperature variation of 32°C), whereas in

Table 2 Specifications of WIP equipment with a high-pressure heat exchange

Maximum operating pressure	600MPa
Maximum operating temperature	200°C
Pressure medium	Hydraulic oil of high flash point
Diameter of working zone	120mm
Height of working zone	500mm
Thermocouple height (Thermocouple is inner work zone)	Upper / +450mm Middle / +300mm Lower / +150mm

Table 3 Experimental conditions of high-pressure heat exchange

	Case1	Case2
Operating pressure (MPa)	600	600
Temperature of pressure medium inner pressure vessel (before pressurizing) (°C)	160	160
Heating temperature of high-pressure piping by heat exchange system (°C)	60	200

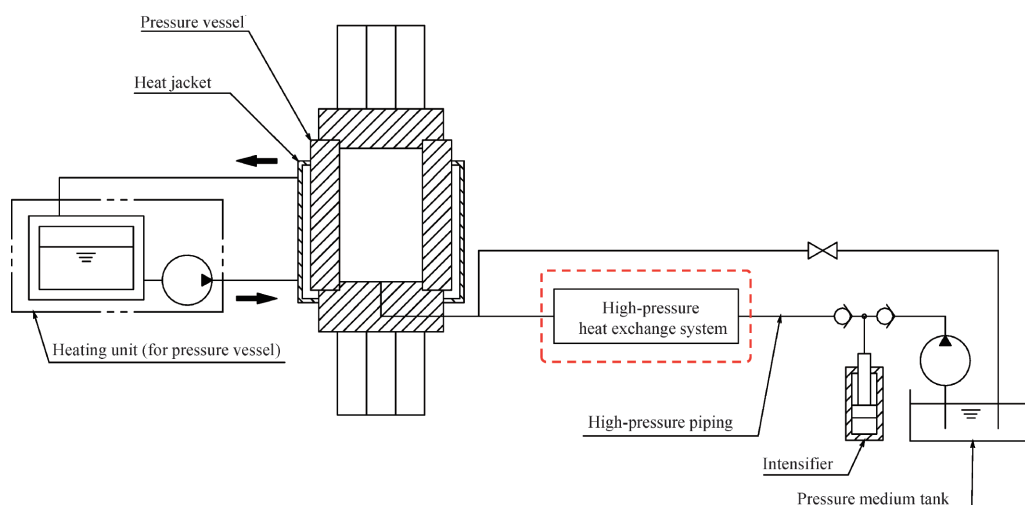


Fig. 3 System diagram of high-pressure heat exchange technology

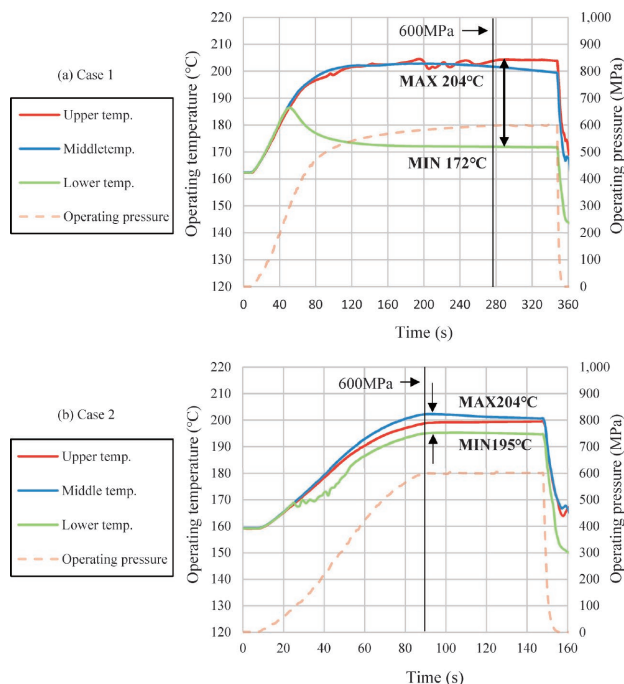


Fig. 4 Operation chart of high-pressure heat exchange for (a) Case 1 (heating temperature of high-pressure piping 60°C) and (b) Case 2 (heating temperature of high-pressure piping 200°C)

Case 2, the temperature from the lower to upper regions inside the pressure vessel ranged from 195 to 204°C (temperature variation of 9°C), resulting in an improvement of 23°C in temperature variation.

4.2.3 Discussion

In both cases 1 and 2, the temperatures at the upper and middle regions inside the pressure vessel remained within 195–205°C when 600 MPa was reached. Meanwhile, in Case 1, a significant temperature drop was observed at the lower region inside the pressure vessel. These results suggested that the upper and middle regions inside the pressure vessel were not affected by the temperature of the pressure medium flowing

in during pressurization and instead increase in temperature due to compression heat. By contrast, the lower region inside the pressure vessel were affected to a larger extent by the temperature of the pressure medium flowing in during pressurization.

Further improvements are necessary, such as by enhancing the heat exchange efficiency and forming a flow path for the pressure medium inside the pressure vessel to distribute the inflowing pressure medium to the upper part.

Conclusions

This paper described the development strategy and results of Kobe Steel's WIP equipment. Future studies should prototype large-scale WIP equipment, verify the effectiveness of high-pressure heat exchange technology, and connect this to commercialization and expansion while advancing the design of a uniform temperature structure inside the pressure vessel.

Production capacity must be improved by scaling up WIP equipment so that WIP equipment can be applied to the manufacturing process of all-solid-state batteries. We will steadily scale up WIP equipment, continue to support test processing, and conduct needs surveys for customers such as automobile and battery manufacturers to enable the adoption of WIP equipment in the manufacturing process of all-solid-state batteries.

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Characteristic of AlCrN Hard Coatings Deposited with New AIP Evaporation Source and Evaluation on Actual Mold

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Abstract

Due to the growing concern about environmental issues, the use of oilless and cold working process is increasing in mold processing, and the operating environment is becoming more challenging each year. In order to extend the service life of molds, their surfaces are coated with metal nitride using the AIP (cathodic arc deposition) method, and AlCrN coatings are often used due to the requirement for high hardness. Additionally, the properties of the coating are greatly influenced by the properties of the evaporation source used for the deposition process. This paper evaluates the properties of AlCrN coatings deposited by varying the deposition conditions and Al content using a new evaporation source (hereinafter referred to as μ -ARC) while also assessing carbide punches coated with this coating and subjected to cold forging. AlCrN coatings deposited by μ -ARC demonstrated excellent durability due to the formation of a cubic structure with a high Al content and exceptional smoothness. In addition, reciprocating sliding tests were conducted, and the mold processing test results were examined from viewpoint of tribology.

Introduction

Physical vapor deposition (PVD) is a method in which a solid metal (hereafter, target) evaporates or sublimates in a vacuum and adheres to a substrate in the same vacuum chamber as a thin-film coating. PVD has been used as a surface treatment method to impart wear resistance to products such as cutting tools and dies since the 1980s. In 1986, Kobe Steel brought the foundational technology for cathodic arc deposition (arc ion plating, AIP), a type of PVD method, from the United States to Japan, initiating the production and sale of this equipment in Japan. The AIP method begins with an arc discharge in a vacuum chamber in which the target is the cathode. An arc spot, which has a diameter on the order of micrometers, forms on the surface of the target. Energy from the arc current concentrates at the arc spot, causing the target to evaporate and ionize and form a coating on the surface of the substrate. Introducing process gases such as nitrogen into the chamber during the

process enables the formation of compound coatings (e.g., nitrides). A key characteristic of the AIP method is the extremely high ionization rate of the evaporated target material. A negative bias voltage applied to the surface of the substrate controls the ionization energy and enables the formation of a dense coating with excellent bonding properties.¹⁾ Since entering the PVD equipment market, Kobe Steel has focused not only on producing equipment but also improving and developing coatings to provide hard coatings suitable for cutting tools and dies. This paper introduces one of our developments in coatings for cold forging dies.

The operating environment for dies such as cold forging dies is becoming increasingly adverse. Metal nitride coatings applied via AIP are used to extend die life. These coatings must exhibit high hardness, wear resistance, and toughness alongside excellent frictional and anti-seizing properties. AlCrN coatings constitute one coating with these properties. The basic structure of AlCrN is the rock-salt cubic structure (B1) of CrN, with a mixture of CrN with Al substituted for Cr, and the cubic structure (B1) of AlN. Intrinsically, the stable phase of AlN is the hexagonal diamond structure (B4) of wurtzite, with the cubic structure being reported only under high-pressure conditions.^{2), 3)} Therefore, AlCrN coatings are achieved by forming a solid solution of metastable cubic AlN within the cubic lattice of CrN. The hardness of an AlCrN coating increases approximately in proportion to the Al content. However, theoretical band parameters indicate the maximum solid solubility of AlN in the cubic structure of AlCrN to be 77 at%.⁴⁾ Additionally, coating properties depend on the characteristics of the plasma generated by the AIP evaporation source. A challenge with conventional AIP evaporation sources is that when the Al content in AlCrN exceeds 70 at%, hexagonal AlN precipitates, reducing the hardness of the coating.⁵⁾ As explained previously, the arc discharge in AIP causes the formation of an electron emission point called an arc spot, which is several micrometers in diameter, on the surface of the target. A current on the order of dozens of amperes (at a discharge voltage of about 30 V) flows through the arc spot, instantaneously

delivering a high energy input of 10^9 W/cm². This instantaneously ionizes the metal and causes some of the target to be ejected as molten droplets, which adhere to the substrate as metal particles (hereafter, macroparticles). Herein lies one of the challenges associated with AIP, as these droplets increase the surface roughness of the coating. To solve this issue, Kobe Steel developed a new AIP evaporation source, μ -ARC, in 2022. We confirmed that it can form AlCrN coatings that exhibit high hardness even with an Al content above 70 at% and that have fewer macroparticles than coatings produced by conventional AIP evaporation sources.⁶⁾ This paper reports on our findings from investigating the effects of Al content and coating conditions on the properties of AlCrN coatings applied using μ -ARC. We produced AlCrN-coated cold forging dies based on our findings and compared performance with coatings applied using a conventional AIP evaporation source. We also evaluated the dies in terms of reciprocating sliding friction tests conducted under conditions simulating the actual environment in which the dies are used.

1. Experimental method

1.1 Coating method

AlCrN coatings were applied using an AlCr target produced by powder metallurgy. **Table 1** shows the test conditions. **Figs. 1** and **2**, respectively, show diagrams of the coating process using the conventional AIP evaporation source Super Fine Cathode 2 (hereafter, SFC2) and the new AIP evaporation source μ -ARC. With the conventional AIP evaporation source SFC2, when the target metal evaporates and ionized particles are deposited onto the substrate, macroparticles emitted from the target also adhere to the substrate. The μ -ARC source, however, has a cylindrical neck between the target and substrate and an electromagnetic coil encircling this neck. With this design, the neutral macroparticles are captured before entering the neck, so only ionized particles are directed to the substrate by the magnetic field.

1.2 Analysis of coating composition

We measured the average composition of the metal elements in the AlCrN coating using an energy-dispersive X-ray spectrometer (EDS) (detector: C3400 x-act, Oxford Instruments; analysis software: INCA) on a scanning electron microscope (SEM) (S-3400N, Hitachi High-Tech Corporation), with an electron beam accelerating voltage of 15 kV.

Table 1 Coating conditions

Evaporation source	New model (μ -ARC) Conventional model (SFC2)
Target composition	Al70at%-Cr30at% Al75at%-Cr25at% Al80at%-Cr20at%
Arc discharge current (A)	150
Process gas	Nitrogen
Gas pressure (Pa)	4
Substrate bias voltage (-V)	75, 100, 125, 150
Substrate temperature (°C)	500
Substrate	Solid carbide coupon
Coating thickness (μ m)	4

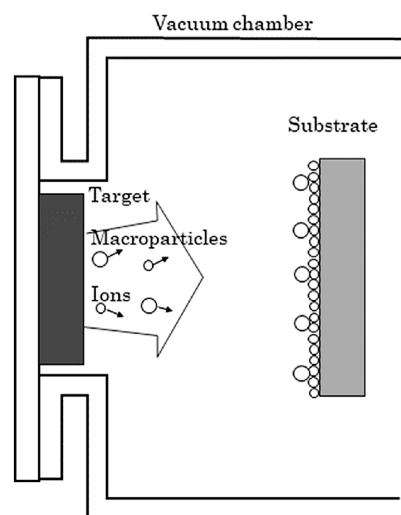


Fig. 1 Schematic diagram of coating process by SFC2

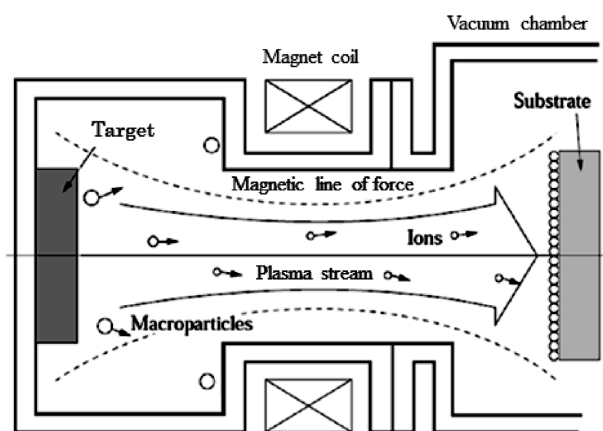


Fig. 2 Schematic diagram of coating process by μ -ARC

1.3 Surface roughness of the coating

We measured surface roughness using a combination surface roughness and contour measuring machine (Surfcom NEX, Tokyo Seimitsu Co., Ltd.) in accordance with JIS B 0601 (2001).

1.4 Hardness and Young's modulus of the coating

We measured hardness and Young's modulus using a nanoindentation tester (ENT-1100b, Elionix

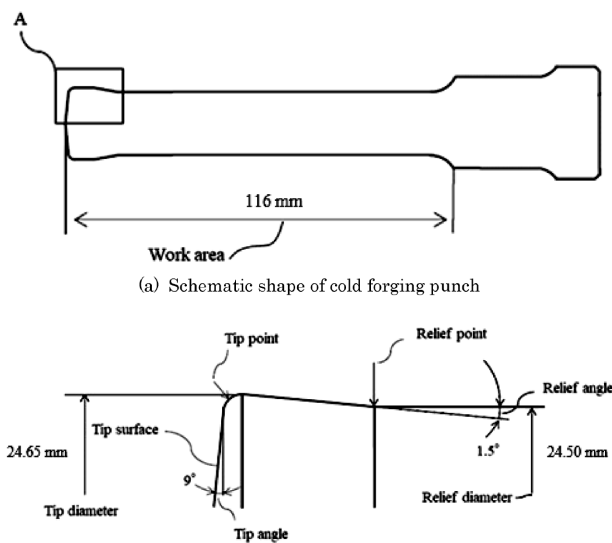
Inc.). Measurements were performed using a Berkovich indenter at a loading rate of 1 mN/s and a maximum load of 10 mN. Fused quartz was used as the standard sample, and analysis was performed with indenter tip correction using the Oliver-Pharr method.⁷⁾

1.5 Analysis of the crystalline structure via X-ray diffraction (XRD)

We analyzed the crystalline structure of the coating using an X-ray diffractometer (SmartLab, Rigaku Holdings Corporation). Measurements were conducted using a Cu K α source at an output of 40 kV, 40 mA, with a $2\theta/\theta$ scanning axis and a sampling width of 0.01°.

1.6 Testing the cold forging dies

The punches for the dies were made of cemented carbide equivalent to VC30 per the CIS standard (CIS019D classification). The cemented carbide was ground and cut to yield the test punch shape shown in Fig. 3. After machining, the surface of the functional section (“Work area” in Fig. 3(a)) was mirror-polished to achieve surface roughness values of Ra of 0.03 μm or less and Rz of 0.3 μm or less.



(b) Details of “A” in (a)
Fig. 3 Cold forging punch

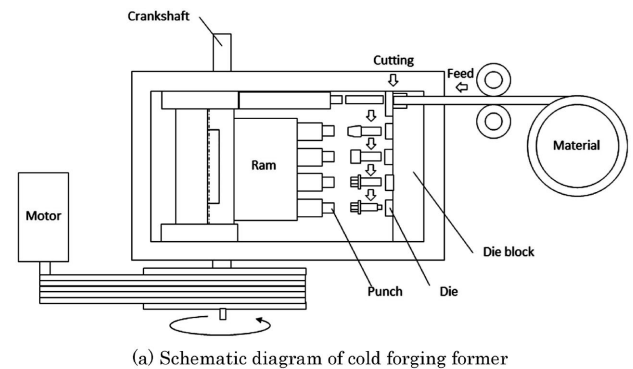
Table 2 Cold forging test conditions

Cold forging former	BPF-680SSL (Six-stage former)
Stage	Second stage
Forging method	Forward extrusion process
Drawing depth (mm)	110
Reduction of area (%)	50 to 65
Work material	SCM440
Lubricant	Forging oil
Shot number	7,000

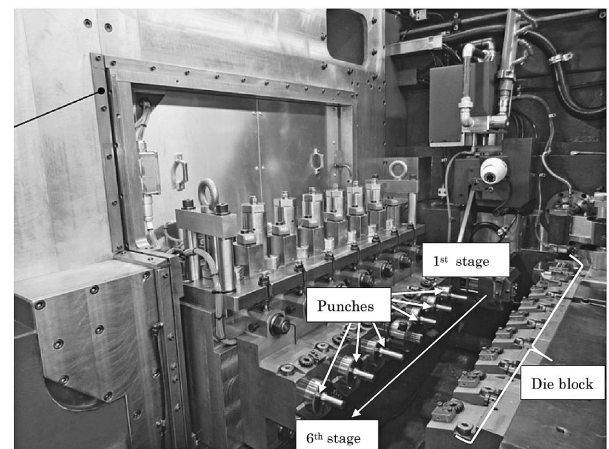
We then coated the samples using the SFC2 and Kobe Steel μ -ARC evaporation sources. The metal particles (droplets) adhering to the surface of the coating were removed by blasting to prepare the punches for testing. Table 2 shows the cold forging test conditions. Figs. 4(a) and (b), respectively, show a schematic and an image of the 6-stage cold forging former used for the test.

1.7 Reciprocating sliding friction tests

We performed reciprocating sliding friction tests using a reciprocating tribometer (RTF-070, TPR Trading Co., Ltd.) under the conditions in Table 3 and Fig. 5. According to forging simulations, the highest surface pressure load on the cemented carbide punch, which is at the tip radius, is 1,380 MPa. Therefore, the pin shape was designed such that the load on the tip of the pin during the sliding friction test corresponded to this value. The pins used for the sliding friction test were made from the same material as the cemented carbide punches used in the forging test. The pins for the sliding friction test were coated with AlCrN using a target with 70 at% Al via SFC2 and μ -ARC. The pins were blasted before testing to remove metal particles adhering to the coating surface. These test pins were then subjected to sliding friction testing.



(a) Schematic diagram of cold forging former



(b) Cold forging six stage former (BPF-680SSL)

Fig. 4 Cold forging former

Table 3 Reciprocating sliding test conditions

Load (N)	1,000 (Pmax 1,380 MPa)
Sliding speed (m/second)	0.5
Sliding length (mm/sliding)	50
Lubricant	Oil
Reciprocating sliding number	50,000
Replacement frequency of counter material	2,000 reciprocating
Pin material	Solid carbide
Counter material	SUJ2

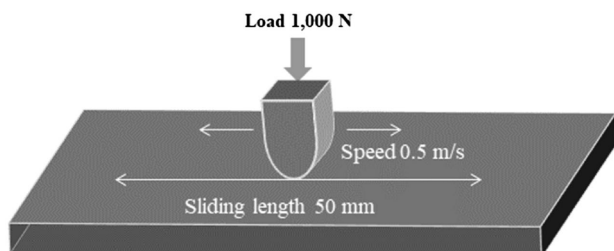


Fig. 5 Schematic diagram of reciprocating sliding test

2. Results and discussion

2.1 Coating composition and surface roughness

Fig. 6 shows the results of the SEM/EDS (scanning electron microscopy/energy dispersive spectroscopy) analysis to determine coating composition. In all samples, the Al composition in the coating was 2 to 3 at% below the Al composition in the target. Furthermore, comparing samples coated using targets of the same composition shows that samples coated at higher bias voltages have a lower Al content. As explained above, AIP is characterized by a high ionization rate of the deposited atoms. This is presumed to be due to the acceleration of ions by the negative bias applied to the substrate, causing partial sputtering of the coating. It is further hypothesized that the Al atoms, which are lighter than Cr atoms, are preferentially sputtered from the coating, reducing the Al composition of the coating.

Fig. 7 shows the results of the surface roughness measurements. There are no significant differences among the samples coated via μ -ARC. Al has a melting point of 660°C, which is relatively low among the metals. Therefore, some of the metal is readily released as molten droplets during arc discharge. These droplets adhere to the substrate, which tends to increase surface roughness. However, as described above, the physical structure of the μ -ARC system and its characteristic magnetic field enable this technology to form coatings with minimal droplets.⁸⁾ As such, our research demonstrates that μ -ARC can maintain low surface

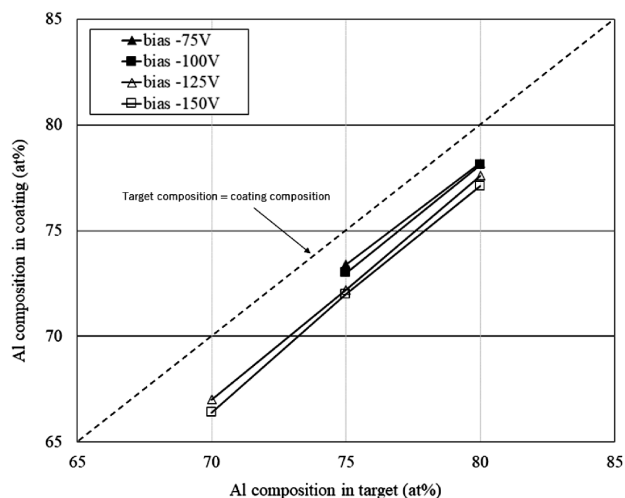


Fig. 6 Relationship between Al composition in target and Al composition in coating

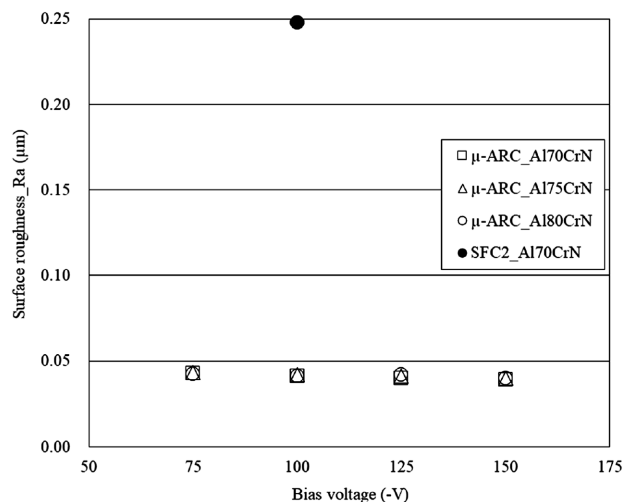
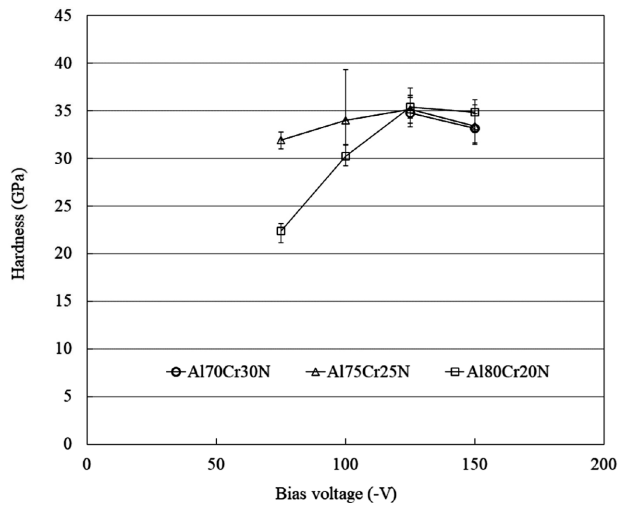


Fig. 7 Relationship between bias voltage and surface roughness

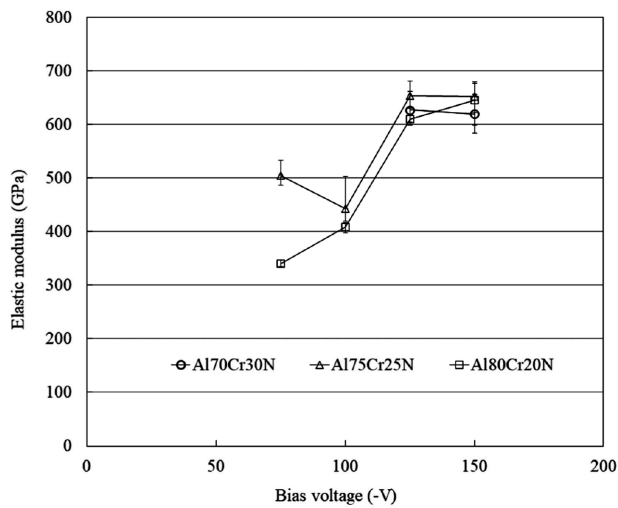
roughness even when using a target with a high Al content, which otherwise tends to result in high surface roughness, such as with the Al70CrN coating applied via SFC2.

2.2 Mechanical properties and crystalline structure of the coating

Fig. 8 shows the coating hardness and Young's modulus as measured by nanoindentation testing. Samples with higher bias voltages tended to exhibit higher values for both hardness and Young's modulus. However, there were no significant differences in these properties for bias voltages of 125 V and 150 V. Samples produced from a target with an Al content of 80 at% exhibited a lower hardness and Young's modulus at the lower bias voltages of 75 V and 100 V. This suggests that due to insufficient ion irradiation energy during coating,



(a) Relationship between bias voltage and film hardness

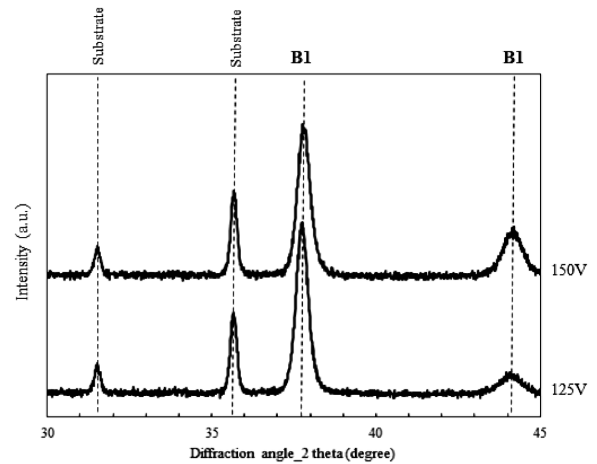


(b) Relationship between bias voltage and elastic modulus

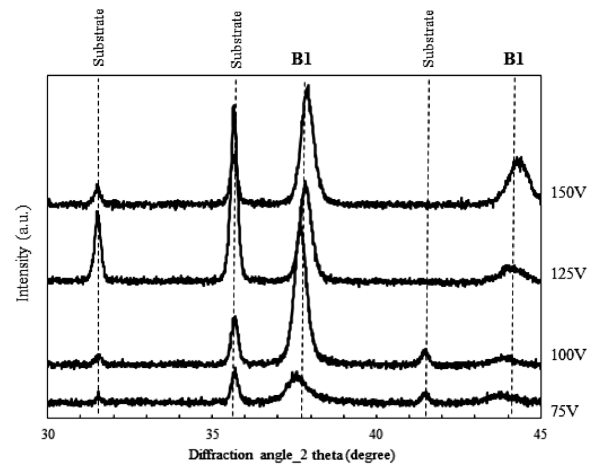
Fig. 8 Relationship between bias voltage and mechanical properties for each AlCrN coating

AlN with a metastable cubic structure (B1) did not form a solid solution within the crystalline CrN, and instead, soft AlN with a stable hexagonal structure (B4) precipitated.

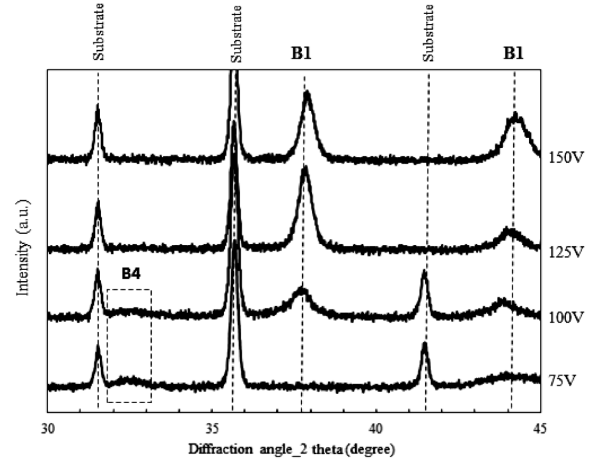
Fig. 9 shows the results of the crystalline structure analysis via XRD. Among the samples produced using a target with an Al content of 80 at% at bias voltages of 75 V and 100 V, there were peaks originating from the cubic structure (B1) of CrN around 38° and 44° and from the hexagonal structure (B4) around 33°. This indicates that hexagonal AlN precipitated in the cubic CrN in these samples, supporting the aforementioned theory regarding a reduction in coating hardness. All other samples were single-phase cubic crystals. These results show that by using μ -ARC and applying a bias voltage above a certain value, it is possible to form a solid solution of cubic AlN in AlCrN up to the theoretical upper limit of 77 at%.



(a) Al composition in target : 70at%



(b) Al composition in target : 75at%



(c) Al composition in target : 80at%

Fig. 9 Relationship between bias voltage and AlCrN crystal structure

2.3 Cold forging tests of AlCrN-coated cemented carbide punches

Previous testing confirms that when applying AlCrN using μ -ARC, a bias voltage of at least 125 V enables the formation of cubic AlCrN if the Al content of the target is 70 at% to 80 at%. Conversely,

when using SFC2, coating hardness decreases due to the precipitation of hexagonal AlN when the Al content exceeds 70 at%.⁹⁾ Therefore, for this test, we used an AlCr target with 70at% Al, which can form cubic AlCrN with both μ -ARC and SFC2. The bias voltage and coating duration were adjusted to yield AlCrN-coated samples with a hardness of approximately 35 GPa and a coating thickness of 5 μ m for each evaporation source. The coated cemented carbide punches were blasted before testing by means of up to 7,000 cold forging shots. Imaging of the edge of the punch tip after testing was performed at angles of 0°, 90°, 180°, and 270°, as shown in **Fig.10**. **Fig.11** shows the width of exposed substrate and imaging of the punch after the 7,000-shot forging test. As shown in Fig.11(a), the coating on the punch coated with SFC2 was gone after 7,000 shots, exposing the substrate. By contrast, the surface of the coating on the punch coated with μ -ARC (Fig.11(b)) was only slightly scratched, with no substrate exposure. These results indicate that using μ -ARC to apply an AlCrN coating to cemented carbide punches for cold forging extends punch life.

Next, we conducted reciprocating sliding friction tests simulating the test environment to analyze

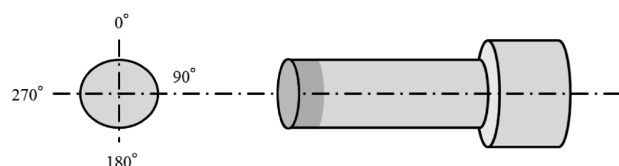


Fig.10 Observation angle of punch after forging test

the results of the cold forging tests. **Fig.12** shows SEM images of the pin surfaces after coating, after blasting, and after the sliding friction test. As shown in Fig.12(a), the coating applied via SFC2 has a rough surface with numerous adhered metal particles, whereas the coating applied via μ -ARC has a smooth surface and fewer adhered metal particles. Fig.12(b) compares the samples after blasting to remove metal particles from the surface. Although the metal particles were removed from the surface of both samples, the sample coated via SFC2 exhibits the formation of numerous small dimples where the metal particles were removed. Fig.12(c) compares the surfaces of the samples after the sliding friction test. The coating applied using μ -ARC shows absolutely no change in surface characteristics. Conversely, the coating applied using SFC2 has filler material in the dimples from before the test. **Fig.13** shows the results of SEM/EDS analysis of this area, which shows that the filler material contains oxygen, chromium, and iron, corresponding to the worn and oxidized counter material. This indicates that the worn counter material was rubbed into and filled the dimples during sliding. Based on the results of this sliding friction test, we surmise that the process of the wear mechanism of the coating on the cold forging die is as shown in **Fig.14**. Step 1 represents the state immediately after coating via SFC2. There are many metal particles on and in the surface of the coating. Since the surface roughness of a die has an effect on its performance, coated dies are polished before use to remove these particles, causing the formation of numerous dimples in the surface of the

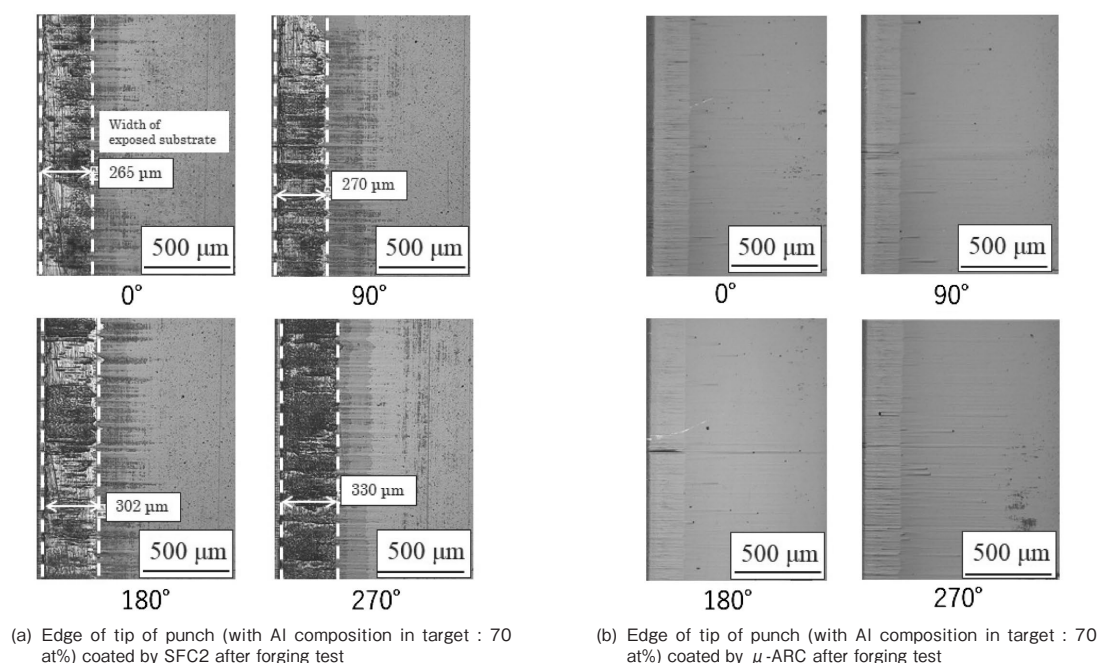


Fig.11 Images of edge of tip of punch with Al70Cr30 coated by μ -ARC and SFC2 after forging test

coating (Step 2). When this die is used, oxidized iron from the workpiece fills the dimples (Step 3). The workpiece comes into contact with the workpiece material embedded in the coating surface, and

adhesion occurs due to the high load of processing (Step 4). As the workpiece slides horizontally across the surface of the coating, it pulls the mating surface layer of the coating in the same direction.

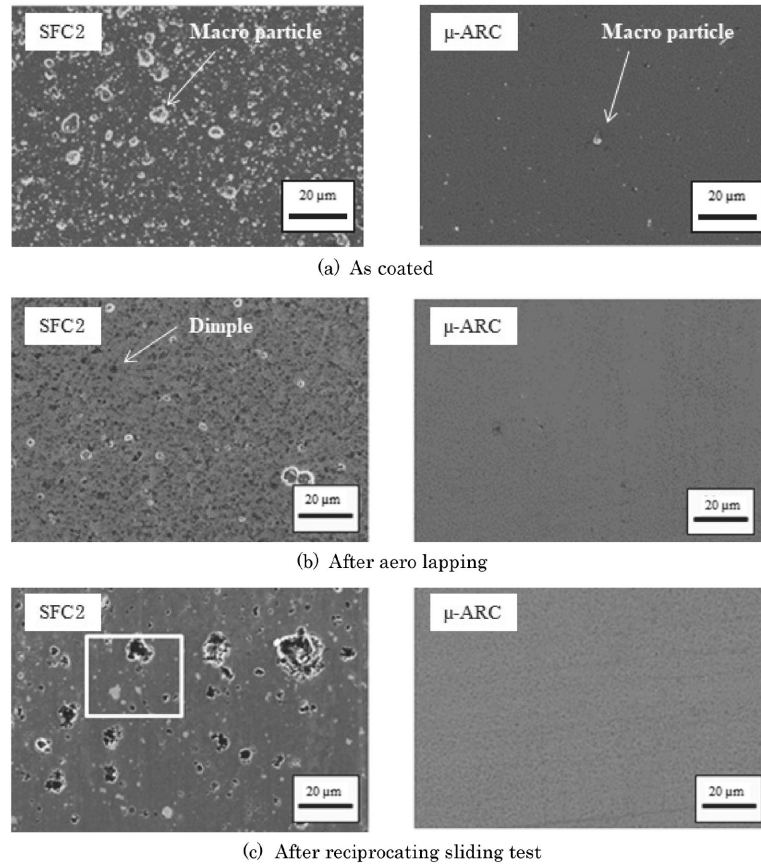


Fig.12 Surface properties for before/after polishing and after sliding test

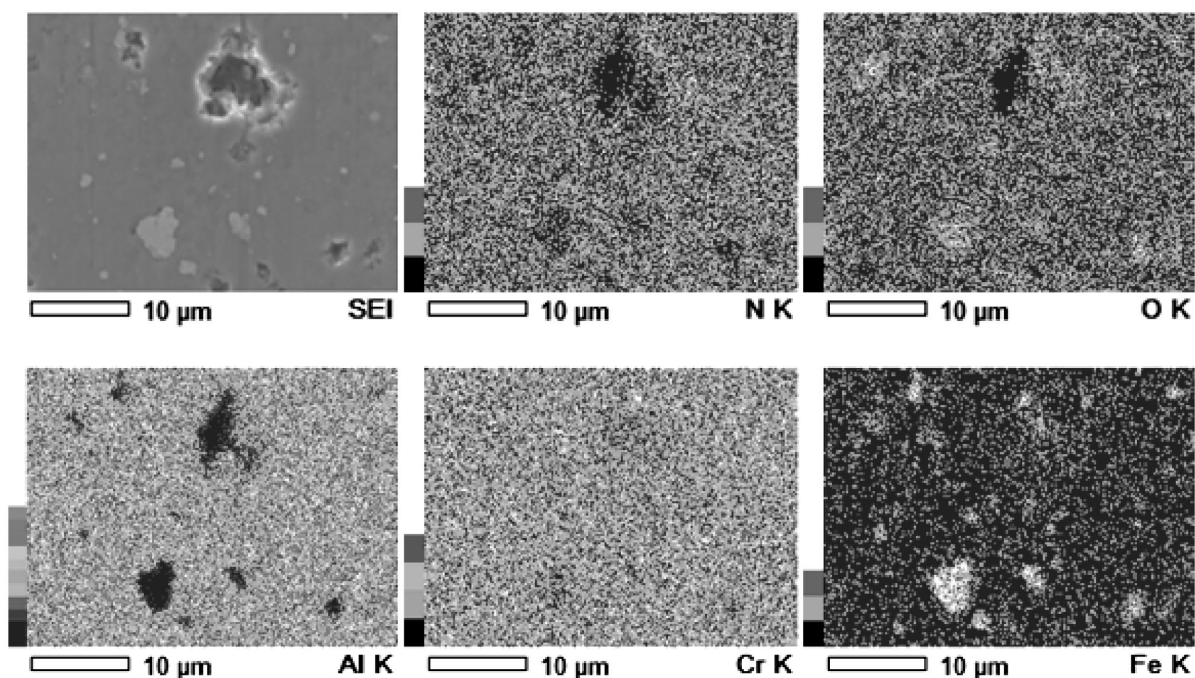


Fig.13 Elemental mapping of SFC2 coating after sliding test using SEM-EDS

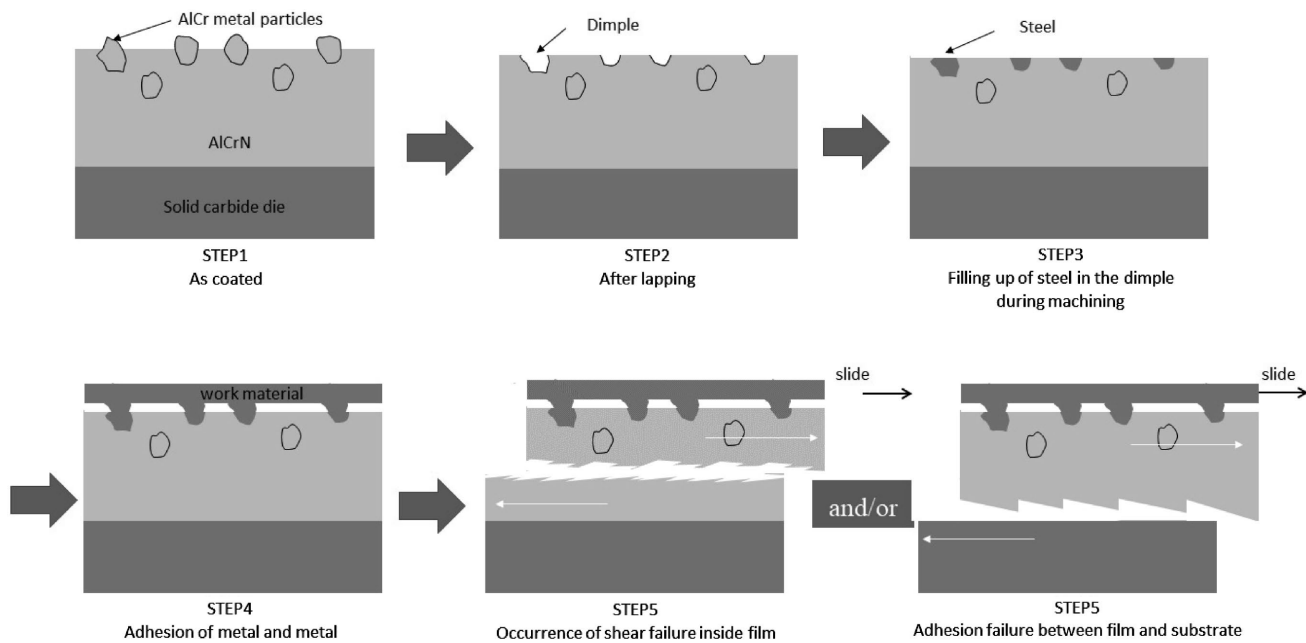


Fig.14 Coating wear mechanism for cold forging process

This creates a shear force within the coating in the opposite direction, resulting in fracture either within the coating or at the interface, wherever mechanical strength is lower (Step 5).

Based on the results of the sliding friction tests, we surmise that the forging test caused shear fracture within the coating, originating from the droplets in the coating as described previously, and delamination at the substrate/coating interface. Therefore, since the AlCrN has fewer droplets when formed by μ -ARC as opposed to SFC2, this technology is hypothesized to extend the service life of dies.

Conclusions

We used Kobe Steel's new AIP evaporation source, μ -ARC, to produce AlCrN coatings with varying concentrations of Al. Our findings from investigating the effects of target composition and bias voltage on coating properties and crystalline structure are as follows:

The Al content in the target has no effect on the surface roughness of the AlCrN coating. We hypothesize that this is because the structure characteristic to the μ -ARC evaporation source eliminates droplets.

Applying a bias voltage of at least 125 V during coating enables the solid solution of cubic AlN in AlCrN up to the theoretical upper limit of 77 at%.

Furthermore, we used SFC2 and μ -ARC to coat cold forging dies with a target containing 70 at% Al and then compared die performance. Our findings from the reciprocating sliding friction tests simulating die testing conditions are as follows:

Using μ -ARC technology, cold forging dies coated with AlCrN using a target with an Al content of 70 at% could be used for continuous processing without exposing the substrate, yielding a longer lifespan compared with coatings applied by SFC2.

AlCrN coatings applied by μ -ARC are characterized by fewer droplets on the surface and within the coating, which is believed to have a positive effect on the service life of the die.

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KOBELCO's Materials and Solutions for Architecture and Civil Engineering

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Abstract

The architecture and civil engineering sectors face a range of pressing social challenges, including the need to respond to increasingly frequent natural disasters, a shrinking workforce caused by a declining birthrate and aging population, and the urgent task of reducing greenhouse gas emissions. To address these challenges, the KOBELCO Group has identified five materialities (key issues) and is actively pursuing initiatives to resolve them. The Kobe Steel Group operates a diverse range of businesses, and in addition to leveraging the technologies cultivated in each field, KOBELCO Group contributes to society by integrating expertise across its business areas to generate powerful synergies. This article introduces the materials and solutions that the KOBELCO Group provides for the architecture and civil engineering sectors, organized according to these key materialities.

Introduction

Thirty years have passed since the Kobe Earthquake of 1995 struck the southern part of Hyogo Prefecture on January 17, 1995. The KOBELCO Group suffered immense damage from this disaster and experienced firsthand the threat such catastrophes bring and the challenges of recovery. Just the earthquakes of a maximum seismic intensity of 7 alone since the Kobe Earthquake of 1995 include the 2004 Niigata-Chuetsu Earthquake, the 2011 Tohoku Earthquake and Tsunami (Great East Japan Earthquake), the 2016 Kumamoto Earthquakes, and the 2024 Noto Peninsula Earthquake.¹⁾ The challenge of ensuring safety and security against increasingly severe natural disasters has become a top priority for Japan. Further pressing challenges standing before the country include reducing greenhouse gas emissions to achieve carbon neutrality by 2050 and overcoming labor shortages due to the rapid trend of an aging population alongside a declining birthrate.

The KOBELCO Group's corporate philosophy served as a springboard in 2021 for identifying the company's five materialities (key issues). We must address these to become an indispensable part of society by ensuring the continuous growth of the KOBELCO Group, which will stem from resolving societal challenges and creating value over the medium to long term.

This paper centers around the KOBELCO Group's materialities most relevant to the societal challenges detailed above and broadly introduces KOBELCO's materials and solutions that support the architecture and civil engineering needs associated with these materialities.

1. Societal challenges in architecture and civil engineering

1.1 Increasingly severe natural disasters

Japan is an earthquake-prone country. Listed above are the earthquakes with a maximum seismic intensity of 7; however, since 1995, there have been 10 earthquakes with a maximum seismic intensity of 6-, including the 2018 earthquake with an epicenter of the northern part of Osaka Prefecture, and six earthquakes with a maximum seismic intensity of 6+, including the 2007 Niigata Chuetsu-oki Earthquake.¹⁾ Furthermore, the Nankai Trough megaquake, predicted to have a 30-year probability of 70% to 80%, is expected to reach a maximum seismic intensity of 7 and generate tsunami waves over 10 meters high.²⁾ This event is anticipated to affect an extensive area in the form of substantial casualties and damage to buildings, essential utilities, and infrastructure.

Beyond earthquakes, natural disasters caused by torrential rains and typhoons believed to be influenced by climate change are increasing in frequency. The extensive and prolonged heavy rainfall of the July 2020 Kumamoto heavy rains caused flooding, landslides, and the washing away of 10 bridges, significantly damaging the roadway network.³⁾

The increasing severity of natural disasters points to the dire need for a safe and secure society through national resilience. In turn, the pertinent needs are to extend the lifespan of societal infrastructure through inspection and repair, ensure structures are outfitted with safety measures, and update aging infrastructure.

1.2 Labor shortages due to a declining birthrate and aging population

Japan's population has been declining since its peak of 127.84 million in December 2004. It is

Table 1 KOBELCO's Materiality

Materiality	Indicators
Contributing to a green society	Response to climate change / Response to resource recycling
Ensuring safety and security in community development and manufacturing	Supplying energy focused on S+3E Providing materials and machinery that meet needs
Providing solutions for the future connecting people and technology	Reforms in manufacturing and operations through digital transformation (DX) Integration and innovation of diverse intellectual assets
Promoting active participation of diverse human resources	Diversity and Inclusion (D&I) / Work style reform Human resources development
Pursuing governance that supports sustainable growth	Compliance and risk management / Human rights Safety and health / Quality assurance / Corporate governance

projected to reach 115.22 million (90.1% of the peak) by 2030. Furthermore, it is projected to fall below 100 million around 2048 and drop to 95.15 million (74.4% of the peak) by 2050. Meanwhile, the aging rate – the proportion of the population aged 65 and over – was 19.6% in 2004 but is projected to reach 31.8% in 2030 and 39.6% in 2050.⁴⁾ This rapid shift of a declining birthrate alongside an aging population poses a serious challenge, as it will lead to shortfalls in the workforce and successors needed to support society and industry.

The Ministry of Land, Infrastructure, Transport and Tourism is promoting i-Construction as a countermeasure.⁵⁾ Introducing ICT at construction sites and similar operations as well as achieving remote operation and automation of construction machinery will significantly improve productivity. Accordingly, further developments are anticipated in BIM/CIM, which are technologies that enable centralized digital control of processes from design to execution and maintenance management.

1.3 Reducing greenhouse gases

One outcome of the October 2020 extraordinary Diet session was the declaration of the goal of “achieving a carbon neutral, decarbonized society by 2050.” Japan’s CO₂ emissions in fiscal year 2023 totaled approximately 988.71 million tons. The industrial sector accounted for the largest share, at 34.3%. Within the industrial sector, the steel industry accounts for 38.7%.⁶⁾ As such, developing technologies to reduce CO₂ emissions in the ironmaking process is critical for achieving carbon neutrality. The construction industry has already taken various strides toward this objective. Examples include decarbonizing buildings and construction materials, reducing CO₂ emissions at construction sites, and using digital technologies to improve construction efficiency.

2. The KOBELCO Group's materialities

Table 1 shows the five materialities of the KOBELCO Group.⁷⁾ We used a three-step process to identify these materialities. Step 1: Make a comprehensive list of significant societal challenges. Step 2: Map the importance of societal challenges and select relevant issues for the Group. Step 3: Consolidate similar issues and narrow them down to key issues.

This paper focuses on three materialities that are particularly relevant to the societal challenges detailed in Section 1: ensuring safety and security in community development and manufacturing, providing solutions for the future connecting people and technology, and contributing to a green society.

3. KOBELCO's materials and solutions supporting architecture and civil engineering

The KOBELCO Group solves the challenges faced by customers and society through its three core business areas: the materials business area, which includes steel, aluminum, advanced materials, and welding; the machinery business area, which includes machinery, engineering, and construction machinery; and the electric power business area, which leverages the technologies and expertise cultivated over many years of operating in-house power generation systems in our ironmaking plants. **Table 2** shows the products in each business area that center around the fields of architecture and civil engineering.

The technologies honed in each business area have led to unique solutions in which value and approach are prioritized over scale, in turn yielding many technologies, products, and services that have captured top market shares all over the world. Furthermore, integrating expertise across these business areas creates synergies that serve as seeds for innovation. We continuously create

new value in myriad ways, such as in the form of technological developments that combine steel and welding technologies, and in the form of low-carbon ironmaking technologies that combine steel and engineering technologies.

Table 3 shows KOBELCO's materials that support architecture and civil engineering. In addition to various steel materials and welding consumables, we produce iron powder, slag products, bolts, and aluminum products. We have also recently begun using crafting technology for construction and industrial machinery to produce custom furniture.

Table 4 shows KOBELCO's solutions (including

machines and systems) that support architecture and civil engineering. In the area of steel product application technologies, we have developed a design method for column-to-beam connections and a lateral buckling restraint method for steel beams, fostering safety and optimization in steel structures. Furthermore, many of our customers are already using our various welding robots to optimize steel frame fabrication and on-site welding work. We are also engaged in the engineering of projects such as direct reduced iron plant operations and analysis and testing of construction machinery and materials.

The following sections introduce the latest technologies of the materials business and

Table 2 KOBELCO's Businesses for architecture and civil engineering

Businesses		Products
Materials businesses	Steel & Aluminum	Wire rods and bars, steel sheets (hot-rolled, cold-rolled, surface treated), steel plates, slag products
	Advanced materials	Steel castings and forgings, steel powder
	Welding	Welding materials (covered welding electrodes, wires for automatic and semi-automatic welding, fluxes), welding robots, welding power supplies, robotic welding systems, welding-related testing, analysis, and consulting
Machinery businesses	Machinery	Various plants (steel rolling, nonferrous metals, etc.), analysis and evaluation of various materials
	Engineering	Various plants (direct reduction ironmaking, waste treatment, etc.), civil engineering, urban transit systems
	Construction machinery	Hydraulic excavators, mini excavators, environmental recycling machinery, crawler cranes, wheel cranes, DX Solution
Electric Power Business		Electric power supply, heat supply

Table 3 Materials by KOBELCO supporting architecture and civil Engineering

Items	Materials
Steel plates for buildings ²²⁾	TMCP Steel plate for building structures / 780 N/mm ² -class steel plate for building structures
Circular steel tube ²²⁾	Circular steel tube for building structures
Rectangular steel tube ²²⁾	Rectangular steel tube for building structures 590 N/mm ² -class rectangular steel tube for building structures
Steel plates for bridges ²³⁾	Corrosion resisting steel Eco-view Plus TM , a repaint term extension under high humid environment Crack initiation resistant steel "EX-Facter TM "
Welding materials ²⁴⁾	Gas shielded arc welding materials / Submerged arc welding materials Electroslag welding materials
Anchor bolts sets	TS700 anchor bolts
High-strength reinforcing bars	High-strength shear reinforcing bars ²⁵⁾
High-strength bolts	Shinko high-strength bolts
Wire rods and bars	PC steel products / Steel wires Earthquake-resistant cable braces [®] / Stealth brace for traditional wooden buildings RE-SET cables / Cable inspection and repair
Steel sheets	Highly corrosion-resistant hot-dip coated steel sheet KOBEMAG [®]
Steel slag	Ground granulated blast-furnace slag Steel slag as a ground improvement material / Steel slag as marine environment restoration
Steel powder	Steel powder for purifying soil and groundwater ECOMEL ^{TM21)}
Aluminum	Aluminum honeycomb panels ²⁶⁾
Wooden furniture(Fig.14)	Custom-made wooden furniture ²⁷⁾

Table 4 Solutions by KOBELCO supporting architecture and civil engineering

Items	Solutions
Design and construction method	Design technology for column to beam connection of circular hollow section steel columns Design technology for column to beam connection of square hollow section CFT steel columns Lateral buckling restraint method for steel beams using the stiffening effect of the slab Structural performance of exposed column bases using TS700 anchor bolts
Direct reduced iron field process	MIDREX® Process
Welding system ²⁴⁾	Structural steel welding robot system ARCMAN™ Compact portable welding robot ARCMAN™ PORTABLE
Construction machinery	Hydraulic excavators / Crawler cranes Telework system for construction sites K·DIVE® Revit® Add-in software for crane construction planning K·D2PLANNER Drone-based inspection solution K·AIR REAL
Structural evaluation	Structural evaluation, evaluation of structural components, various structural analyses ^{28) 29)}

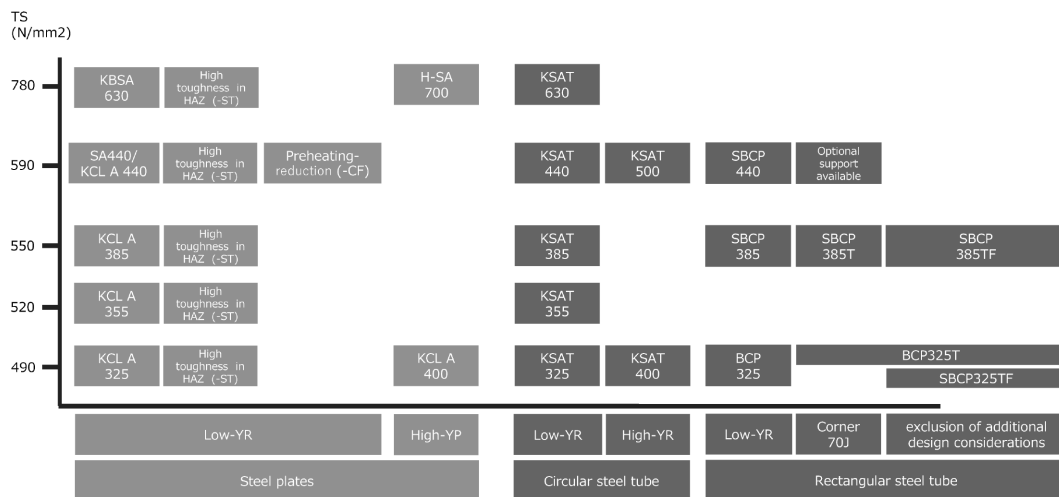


Fig. 1 Steel plates, circular steel tubes, rectangular steel tubes for buildings

machinery business that serve the architecture and civil engineering fields. Each section covers a different materiality.

4. Ensuring safety and security in community development and manufacturing

This section introduces materials that contribute to a safe and secure society and strengthen resilience against the societal challenges described in Section 1.1.

4.1 Steel plates, rectangular steel tubes, and circular steel tubes for building

Steel plates used in large structures such as high-rise buildings are available in a wide range of tensile strength classes, from 490 N/mm² to 780 N/mm² (Fig. 1). Particularly in recent years, as structures have grown larger, steel plates used in high-rise buildings and skyscrapers have become thicker and stronger. Kobe Steel's steel plate and welding divisions collaborate to develop technologies that

yield higher-quality weld joints. One result of these efforts is that we can ensure the high HAZ toughness and weld metal strength required of electrosag welds in welded box columns.

Additionally, we are collaborating with Sasaki Pipe & Tube Co., Ltd., which has a 15,000-ton press (one of the largest in Japan), to commercialize rectangular and circular steel tubes. Our extensive range of tubing includes rectangular steel tubes in tensile strength classes from 490 N/mm² to 590 N/mm², and circular steel tubes in tensile strength classes from 490 N/mm² to 780 N/mm² (Fig. 1). We are also developing application technologies for rectangular and circular steel tubes, which will be described later.

4.2 Steel plates for bridges

Beyond general-purpose steel materials, Kobe Steel develops and markets steel plates that reduce the life cycle cost of bridges and extend the service life of steel bridges.

In developing and commercializing Eco-

View Plus™, we became the first in the industry to release corrosion-resistant steel plate that is suitable for high-humidity environments and works synergistically with coatings. This product was registered in the Ministry of Land, Infrastructure, Transport and Tourism's New Technology Information System (NETIS) on February 20, 2024. For more information, see p.71 of this issue, "Corrosion Resisting Steel Eco-view Plus™, a Repaint Term Extension under High Humid Environment."

In October 2023, we released the fatigue crack-resistant steel EX-Facter™, a steel plate with added elements for fatigue crack initiation resistance to extend fatigue life. We anticipate that this product will be used where fatigue cracks are difficult to detect, such as in the case of steel deck inspections, and we will promote its widespread adoption.

4.3 Welding materials

Kobe Steel's lineup of welding materials is tailored to the strength classes of steel used in the gas-shielded arc welding, submerged arc welding, and electroslag welding of structural steel column fabrication. Some of our forthcoming developments will satisfy needs for further improvements in productivity and welding quality. For instance, we are developing a robot system and specialized welding wire for structural steel columns, as well as welding materials compatible with steel materials of various strength classes, including steel with a tensile strength class of 780 N/mm². For more information, see p.86 of this issue, "Latest Trends and Lineup of Welding Consumables for Structural Steel."

4.4 PC (prestressed concrete) strand/wire

Kobelco Wire Company, Ltd. offers a wide range of PC strands for use in bridges and buildings to enhance strength and compensate for weaknesses in concrete. We have been involved researching PC construction methods since PC was first introduced in Japan, and have since focused on improving the quality of PC steel strand, fostering mass production, and developing new products.

Tourism to cultural heritage buildings has been increasing; since these buildings are accessed by the general public, structural soundness is critical. The $\phi 7$ mm Stealth Brace^{Note)} for traditional wooden architecture has high-strength galvanized

Note) " $\phi 7$ Stealth Brace" is a trademark of Kobelco Wire Company, Ltd.



Fig. 2 Earthquake-resistant cable brace

steel wire to improve seismic resistance while preserving the cultural elements of structures. For more information, see p.95 of this issue, "Stealth Brace for Traditional Wooden Architecture."

Our earthquake-resistant cable braces, which use high-strength PC steel strands⁸⁾, are lighter and more flexible than conventional braces (Fig. 2). They substantially reduce temporary scaffolding needs and construction periods. Since its launch in 2013, this technology has been adopted in over 200 projects.

This product is key for the bridge sector, as the number of bridges requiring reinforcement is increasing due to deterioration and increased design loads.

4.5 Hot-dip zinc-aluminium-magnesium alloy-coated steel sheet

Kobe Steel began manufacturing and marketing KOBEMAG® hot-dip zinc-aluminium-magnesium alloy-coated steel sheet in 2017. Its applications are expanding and now include residential construction, secondary framing, shutter slats, and perforated steel sheets. Currently, Kobe Steel handles the manufacturing process up to the hot rolling of thin steel sheets and outsources the pickling and plating processes to Nippon Steel Corporation and Nittetsu Steel Sheet Co., Ltd. However, we announced the allocation of capital expenditure in November 2024 to achieve in-house integrated production of KOBEMAG® by fiscal year 2029. Our core task in doing so is to modify the existing hot-dip zinc-aluminium-magnesium alloy-coated steel sheet equipment at Kakogawa Works.

5. Providing solutions for the future connecting people and technology

This section introduces innovations designed to address the societal challenges outlined in Section 1.2. It covers technologies for optimizing construction, application technologies for steel

product design methods, and technological solutions related to infrastructure maintenance.

5.1 Design and construction methods for steel products

As one of our application technologies for steel plates, we developed a lateral buckling restraint method for steel beams that exploits the upper flange restraint effect of floor slabs. This method was certified by the General Building Research Corporation of Japan (GBRC).

For another one of our developments, which will expand the scope of application of 780 N/mm²-class steel plates, we are studying the joint strength of undermatch-welded splices in the 780 N/mm²-class steel plate of welded box columns.

Additionally, we have commercialized multiple application technologies for steel tubes that have already amassed a proven track record. One example is our design technology for the column-to-beam connection of circular hollow section steel columns (Fig. 3), which eliminates the need for diaphragms. Another is our design technology for the column-to-beam connection of square hollow section CFT (concrete-filled tube) steel columns (Fig. 4), which significantly reduces the projection dimension of conventional exterior ring diaphragms.⁹⁾

Kobe Steel was the first in the industry to obtain certification from the Minister of Land, Infrastructure, Transport and Tourism for TS700 anchor bolts, which have a standard strength of 490 N/mm². To verify the strength and rigidity of these

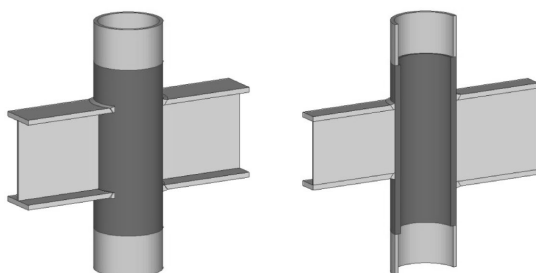


Fig. 3 Design technology for column to beam connection of circular hollow section steel columns

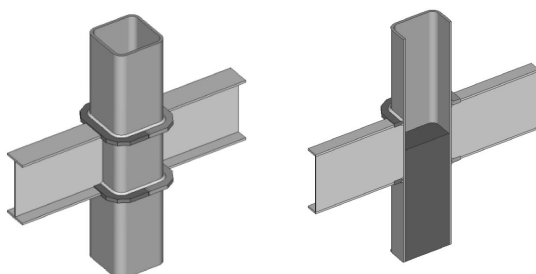


Fig. 4 Design technology for column to beam connection of square hollow section CFT columns

bolts, we are researching the structural performance of exposed column bases that use these anchor bolts. We hope this contributes to the design of exposed column bases using high-strength anchor bolts.

5.2 Welding systems

In recent years, the societal challenge of labor shortages has intensified the need for automation through robotics. This has expanded the use of large arc welding robot systems in steel frame fabrication plants and spurred a marked trend toward the use of portable arc welding robots on site. The KOBELCO Group offers a large portfolio of applicable systems, including the ARCMAN™ steel frame welding robot system. We are leading the industry by producing superior welding systems and by optimizing welding processes through perfectly coordinated welding consumables.

The ISHIMATSU™ compact portable welding robot series (Fig. 5) can handle a broad spectrum of welding demands, including long and multi-layer welds, not only in steel frame fabrication plants but also on construction sites. Weighing only about 6 kg, it is one of the lightest in the industry. Its fully automated welding functionality enables one operator to manage multiple units, and it is already active on numerous construction sites.¹⁰⁾

A further technological development underway for this compact portable robot lies in machine vision. We will outfit the robot with an image sensor to enable recognition of key features in the image of the molten pool for coordinated responses in control. For more information, see p.107 of this issue, “Compact Portable Welding Robot System with Vision Sensor,” and p.102 of this issue, “Introducing New Automation System and CAD-Linked Software for Architectural Steel Frame Beam Welding.”

5.3 DX (digital transformation) in construction machinery

Kobelco Construction Machinery Co., Ltd. offers a wide range of construction machinery, including



Fig. 5 Compact portable welding robot ISHIMATSU™



Fig. 6 K-DIVE®



Fig. 8 K-AIR REAL



Fig. 7 K-D2 PLANNER®

hydraulic excavators and crawler cranes. Some of our developments in this area center around overcoming today's societal challenges such as labor shortages and changes in the landscape of work arrangements. In this way, our various DX technologies make a strong contribution to society.

For example, K-DIVE® (Fig. 6)¹¹⁾, a remote operation system for heavy machinery, promotes DX at the worksite by maintaining a constant connection between people, heavy machinery, and the site. Specifically, it enables the remote operation of heavy machinery from a cockpit in a location remote from the construction site. An operator in a single cockpit can switch between multiple machines, eliminating standby and travel time and thereby increasing efficiency in personnel allocation and process management.

We have also released the crane construction planning software K-D2 PLANNER® (Fig. 7)¹²⁾ as an add-in for the BIM software Revit (a registered trademark of Autodesk, Inc.). Placing cranes in the BIM model during construction planning makes it possible to run simulations and to streamline construction planning through functions such as selecting the optimal crane for a given task.

As a final example, K-AIR REAL (Fig. 8)¹³⁾ is a solution for using the autonomous flight capabilities of drones to photograph and support inspections of mobile cranes. It handles complex shapes, such as crane operating and idle postures, with great flexibility. With this solution, it is possible to quickly

take high-quality images and confirm conditions even in confined sites where lowering the boom is difficult. We anticipate that the scope of application of this solution will extend beyond mobile cranes by supporting the inspection of other types of equipment.

6. Contributing to a green society

This section introduces materials and solutions that reduce CO₂ emissions, such as by decarbonizing buildings and construction materials, developed in response to the societal challenges described in Section 1.3.

6.1 Low-CO₂ Blast Furnace Steel, Kobenable® Steel¹⁴⁾

In releasing Kobenable® Steel, which significantly reduces CO₂ emissions in the blast furnace process, Kobe Steel became the first in Japan to commercialize a low-CO₂ blast furnace steel. Our engineering business uses the MIDREX® Process to produce HBI (hot briquetted iron, Fig. 9). Through high-volume charging of HBI into the blast furnace at the Kakogawa Works, we are able to substantially reduce blast furnace CO₂ emissions. Applicable steel products are classified based on the degree of reduction using the mass balance method, with blast furnace steel products with a 100% reduction in CO₂ emissions being classified as "premium," and those with a 50% reduction being classified as "half." This development has already been widely adopted in the architecture and civil engineering fields. We are currently pursuing similar initiatives for aluminum products.¹⁵⁾

6.2 The MIDREX® Process¹⁶⁾

Direct reduced iron (DRI) is an ironmaking process that is an alternative to operating a blast furnace. It uses hydrogen-rich reducing gas produced by reforming natural gas, or hydrogen

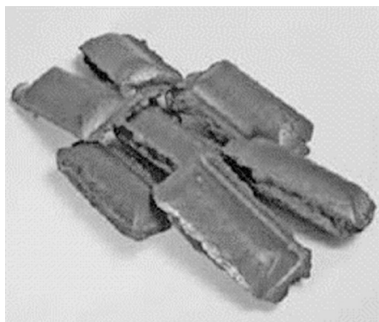


Fig. 9 HBI (Hot Briquetted Iron)



Fig.11 Carbonated granulated product



Fig.10 MIDREX® PLANT

itself as the reducing gas, to directly reduce iron ore. Since direct reduction ironmaking does not require coke or large-scale facilities as do blast furnaces, DRI plants have typically been established in natural gas-producing countries. In recent years, there has been a rise in demand for DRI as a clean iron source to replace scrap and as an ironmaking process with low CO₂ emissions. Kobe Steel owns the license for the MIDREX® Process, which has approximately 80% of the global market share in gas-based direct reduction ironmaking. We are expanding our business globally in collaboration with Midrex Technologies (Kobe Steel's wholly owned subsidiary). **Fig.10** shows a MIDREX® plant. We offer solutions for various phases of the energy transition to hydrogen, beyond the conventional MIDREX NG™ process that uses natural gas. These include MIDREX Flex™, which allows for the flexible replacement of the reducing agent of natural gas with 100% hydrogen, and MIDREX H2™, which uses 100% hydrogen as the reducing gas.

6.3 CO₂ fixation and mineralization via Carbonel® rapid carbonation technology¹⁷⁾

Kobelco Eco-Solutions Co., Ltd. has been developing the rapid carbonation technology Carbonel®. This technology makes use of industrial byproducts that contain elements such as calcium (Ca), potassium (K), and magnesium (Mg) as raw materials. Examples of such byproducts include coal ash, fly ash, and slag. Reacting these substances with

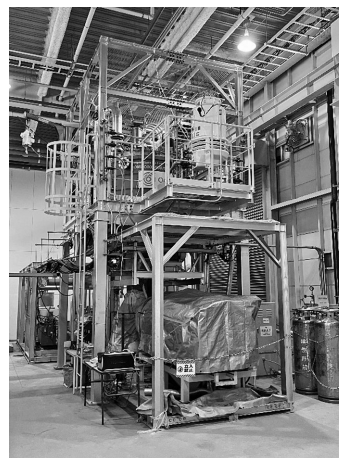


Fig.12 Demonstration Plant for Carbonation and Mineralization

CO₂ in the presence of a small amount of water fixes CO₂ as carbonates (e.g., calcium carbonate, CaCO₃). As an extension of this technology, we are working on carbonation applications for wood biomass ash and other materials. Carbonated granulated product (**Fig.11**) holds promise for use as a concrete material, and sales of the standard Carbonel® unit (**Fig.12**) have already commenced. Furthermore, concrete materials created using this technology served as the raw material for the HPC® panels of the exterior cladding of the signature pavilion “Adventure of Life” (Kawamori Pavilion) at Expo 2025 Osaka, Kansai, Japan.¹⁸⁾ We anticipate that the application of this material will expand greatly.

6.4 Hydrogen fuel cell excavator

In support of carbon neutrality, Kobe Steel and Kobelco Construction Machinery Co., Ltd. are engaged in the research and development of hydrogen-related technologies and the commercialization of products that use hydrogen. As part of these efforts, Kobelco Construction Machinery Co., Ltd. has been working toward the practical application of a fuel cell excavator powered by hydrogen since 2021. Initial testing of the prototype that was completed in March 2023

is in progress.¹⁹⁾ Kobe Steel's Takasago Works has already installed high-pressure hydrogen filling equipment for the hydrogen fuel cell excavator (Fig.13). This development is scheduled for domestic demonstration testing in fiscal year 2026. To prepare for the field introduction of the hydrogen fuel cell excavator, the Takasago Works began practical operational evaluation including continuous excavation in March 2025.²⁰⁾

6.5 Steel slag

Steel slag products hold high value as materials that reduce environmental impact from the perspectives of CO₂ reduction and of resource and energy conservation. Examples of steel slag products with an active presence on the market and in goods include ground granulated blast furnace slag, roadbed materials, civil engineering materials, and fertilizers. Recent years have seen the practical application of steel slag as a soil stabilizer.

6.6 ECOMEL® iron powder for purifying soil and groundwater²¹⁾

ECOMEL® is an iron powder that purifies soil and groundwater through chemical reactions on the surface of the iron powder that adsorb heavy metals and decompose volatile organic compounds (VOCs). Its primary applications span a wide range of civil engineering fields and include purifying soil during urban renewal, processing contaminated soil during



Fig.13 Fuel Cell Excavator



Fig.14 Wooden furniture

tunnel excavation, and controlling groundwater pollution.

Conclusions

This paper addresses solutions pertinent to the societal challenges of intensifying natural disasters, labor shortages due to the declining birthrate and an aging population, and greenhouse gas emissions. Covered next are KOBELCO's materials and solutions supporting architecture and civil engineering as they relate to the KOBELCO Group's materialities.

The societal challenges outlined here are expected to increase in intensity and complexity. One of the KOBELCO Group's strengths is that the company's expertise spans a broad range of business areas. We are committed to leveraging this strength to tackle the challenges afflicting society. In doing so, we will achieve extensive value creation and foster a sustainable society.

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Development of 780 N/mm²-Class Structural Steel for Building Structures Suitable for High Heat Input Welding

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Abstract

As steel building structures become taller, there are high hopes for the use of 780 N/mm²-class steel for welded box columns. However, it has been difficult to ensure the strength and toughness of welded joints when using high-heat input welding. To counter this, Kobe Steel has developed a steel plate that improves the toughness of the heat-affected zone in high-heat input welding by suppressing the formation of the M-A constituent (island martensite), a brittle hard phase, through increased Cr and Mo and reduced C, Si, and Mn. Evaluation of the mechanical properties of the base material, electroslog, and submerged arc welded joints confirmed favorable results in terms of strength, toughness, and weldability, making this plate suitable for high-efficiency construction.

Introduction

Recent years have seen a trend toward larger and taller steel building structures. As such, we anticipate the expanded application of 780 N/mm²-class steel to welded box columns. For the sake of efficiency, the convention in box column fabrication is to use electroslog welding (ESW) for inner diaphragms and submerged arc welding (SAW) for the corners. These are high-efficiency, high-heat input welding processes performed in a single pass, traditionally applied to box columns using 590 N/mm²-class steel or lower. Employing high-heat input welding with conventional 780 N/mm²-class steel makes it difficult to ensure the necessary strength and toughness of the welding joint. As such, low-heat input multi-pass welding is generally used, which is relatively inefficient. The high number of labor hours required for steel frame fabrication involving 780 N/mm²-class steel means that this class of steel is rarely used for said application.

This drove Kobe Steel to develop steel plate capable of maintaining strength and toughness during high-heat input welding to improve the efficiency of welding 780 N/mm²-class steel for box column fabrication.

This paper describes technology for ensuring high toughness of the heat-affected zone (HAZ) in the high-heat input welding of 780 N/mm²-class steel. It also introduces the properties of the

base material of the developed steel plate and the properties of ESW joints intended for inner diaphragms and SAW joints at corners.

1. Development objectives

Tables 1 and 2 show the chemical composition and base material properties of Kobe Steel's 780 N/mm²-class steel that is designed for high-heat input welding in building construction applications (KBSA630C; see Note). The mechanical properties of the developed steel are designed to improve the toughness of high-heat input welds, including the HAZ of the inner diaphragm and corners, while meeting the specifications of Kobe Steel's high-performance 780 N/mm²-class steel for building construction.

There is concern regarding brittle fracture originating from the area where toughness is reduced in the HAZ of the inner diaphragm. Past research into preventing brittle fracture in 490 N/mm²-class steel reports that the weld should have a Charpy impact test result of at least 47 J to meet the standard strength specification (325 N/mm²) for 490 N/mm²-class steel used for the inner diaphragm.¹⁾ Studies^{1), 2)} to confirm the necessary performance characteristics of ESW areas when using steels above a strength class of 490 N/mm² provide notable results: Assuming 780 N/mm²-class steel for the columns and 590 N/mm²-class high-performance steel for building structures for the beams (SA440), even columns made from 780 N/mm²-class steel

Table 1 Specification for chemical composition of KBSA630C

Steel	Chemical compositions (%)					P _{CM} (%)
	C	Si	Mn	P	S	
KBSA630C	≤ 0.13	≤ 0.55	≤ 2.50	≤ 0.015	≤ 0.008	≤ 0.30

P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Table 2 Mechanical properties of KBSA630C

Steel	Tensile properties				Impact properties
	YP or 0.2%YS (N/mm ²)	TS (N/mm ²)	El. (%)	YR (%)	J _{E₀} (J)
KBSA630C	630-750	780-930	17 ≤	≤ 85	47 ≤

Tensile test specimen: JIS Z2241 No.4-1/4t-Transverse

Charpy impact test specimen: JIS Z2242 Full size-1/4t-Longitudinal

Note) KBSA is a trademark of Kobe Steel, Ltd. (4936432).

Table 3 Base chemical composition of conventional steel

(%)						
C	Si	Mn	P	S	Others	P _{CM}
0.05	0.27	2.00	0.008	0.002	Cr, Mo, etc.	0.28

yield similar trends as for columns made of 490 N/mm²-class steel or SA440. Therefore, to ensure the standard strength of the inner diaphragm in the ESW areas of columns made of 780 N/mm²-class steel, we set a target of 47 J or greater for the Charpy impact test result of the welds of the developed steel.

2. Technology for high HAZ toughness in the high-heat input welding of 780 N/mm²-class steel

The HAZ becomes a single-phase austenite (γ) structure near the boundary of the weld metal when exposed to high temperatures. Higher welding heat input results in a longer duration of exposure to a high temperature and a decrease in the cooling rate. Consequently, the final microstructure in the HAZ of high-heat input welds tends to be coarser due to the transformation from the coarsened γ phase. Furthermore, during cooling, the concentration of C stabilizes untransformed γ due to a slow cooling rate, promoting the formation of island martensite (MA), a brittle hard phase, and thereby reducing the toughness of the HAZ.

However, it has been reported that dispersing oxides finely within the steel suppresses γ coarsening in the HAZ due to pinning by the oxides.³⁾ It has also been reported that reducing the Si content can suppress MA formation⁴⁾, which is being applied to steels suitable for high-heat input welding in strength classes of 590 N/mm² and under.

Furthermore, for 590 – 780 N/mm²-class steels in which the microstructure of the HAZ is bainite, a fine low-carbon bainite technique (low-carbon multi-orientation bainite) has been reported.⁵⁾ This technique suppresses the formation of MA by using weak carbide-forming elements to cause multi-orientation of the bainite structure in the HAZ, thereby refining the microstructure and reducing the amount of C added.

The welding heat input of electrosag-welded box columns is as high as 1,000 kJ/cm, so the HAZ cools more slowly than with the heat input conventionally applied to 780 N/mm²-class steel. Furthermore, compared with steel plates of strength classes 590 N/mm² or lower, where ESW has traditionally been applied, a higher alloy content is required with 780 N/mm²-class steel to ensure the required strength of the base material. Consequently, the γ phase in the HAZ stabilizes more readily. This effect combined

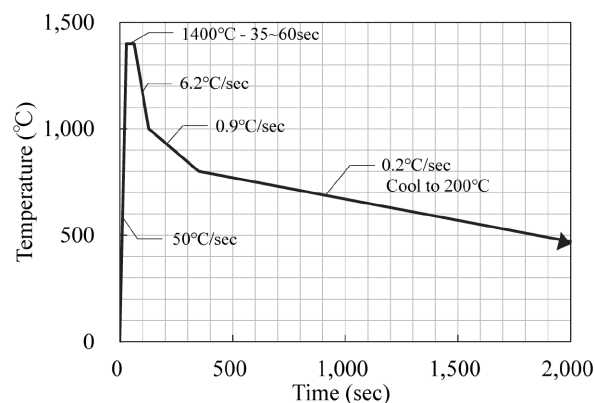


Fig. 1 Thermal history assumed for ESW

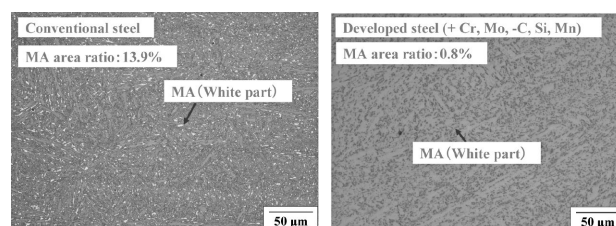


Fig. 2 Effect of increased Cr and Mo and reduced C, Si, and Mn on MA suppression

with the slower cooling rate of high-heat input welding further promotes the formation of MA.

Therefore, in this development, we investigated the chemical composition of a steel sheet that would further suppress MA formation in the ESW of 780 N/mm²-class steel. Using the base chemical composition of conventional steel (**Table 3**), square test specimens measuring 12.5 mm × 33 mm × 55 mm were taken from steel samples with varying amounts of Cr, Mo, C, Si, and Mn. To uniformly reproduce the microstructure of the HAZ during high-heat input welding, we used a thermal cycling device to apply a single cycle (**Fig. 1**) simulating the thermal history of an ESW bond area. We observed the microstructure after thermal cycling to determine how the amount of each element added affects the formation of MA. The results confirm that MA formation is suppressed in compositions in which Cr and Mo are increased and C, Si, and Mn are reduced (**Fig. 2**). As mentioned at the beginning of Section 2, MA is said to form when γ stabilizes due to the concentration of C in untransformed γ during the transformation from γ . It is hypothesized that increasing Cr and Mo inhibits the formation of MA by forming a low-temperature transformation

structure without thermally stabilizing γ . It is further hypothesized that reducing C, Si, and Mn not only reduces the amount of C that concentrates in the untransformed γ , but also promotes the formation of iron carbides, thereby inhibiting the formation of MA from the untransformed γ .

3. Properties of the developed steel

3.1 Composition and base material properties

Table 4 shows the chemical composition of the developed steel. Based on the results detailed in Section 2, we increased the Cr and Mo and decreased the C, Si, and Mn from their amounts in the test steel to yield the developed steel.

We used TMCP (thermomechanical control processing) technology to produce this steel. **Table 5** shows the results of tensile and Charpy impact

testing of the developed steel, which meet the target standards of 780 N/mm²-class steel (KBSA630).

3.2 Weldability

We performed Y-groove weld cracking tests on the developed steel. **Tables 6** and **7**, respectively, show the welding conditions and test results. The evaluation using welding consumables of both the 780 N/mm² and 590 N/mm² classes revealed that both exhibit good weldability.

3.3 Welding joint properties

3.3.1 ESW joint properties

We evaluated the properties of a high-efficiency, high-heat input, single-pass ESW joint intended for an inner diaphragm. **Table 8** shows the welding

Table 4 Representative chemical composition of the developed steel

Steel	C	Si	Mn	P	S	Others	P_{CM}
Developed steel	0.04	0.03	1.42	0.004	0.002	Cr, Mo, etc.	0.28

Table 5 Mechanical properties of the developed steel

Thickness (mm)	YS (N/mm ²)	TS (N/mm ²)	EL (%)	YR (%)	vE ₀ (J)
25	712	886	23	80	238
50	708	889	22	80	219
85	690	869	21	79	254
KBSA630C	630-750	780-930	17 ≤	≤ 85	47 ≤

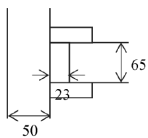
Table 6 Welding conditions for Y-groove weld cracking test

Thickness (mm)	85
Welding consumables	JIS Z3312 G59JA1UC3M1T MG-60(1.2φ) JIS Z3312 G78A2UCN4M4T MG-80(1.2φ) JIS Z3312 G78A2UCN4M4T MG-82(1.2φ)
Heat input (kJ/cm)	17.0
Preheating temperature (°C)	5
Testing atmosphere	5°C, humidity-60%

Table 7 Results of Y-groove cracking test

Welding consumables	Cracking ratio (%)	
MG-60(1.2 φ)	Surface	0
	Section	0
	Root	0
MG-80(1.2 φ)	Surface	0
	Section	0
	Root	0
MG-82(1.2 φ)	Surface	0
	Section	0
	Root	0

Table 8 Condition of ESW

Thickness (mm)	Groove shape	Welding consumables	Welding conditions
Skin plate: 50 mm (developed steel) Diaphragm: 65 mm (590 N/mm ² steel)		Wire: JIS Z3353 YES602-M Flux: JIS Z3353 FES-CS	380 A-52 V Welding speed: 1.02 cm/min Heat input: 1,146 kJ/cm

conditions. The inner diaphragm was made of 590 N/mm²-class steel.

After construction, we collected tensile test specimens from the weld joints per JIS Z 3111 A1 of the Manual for Standard Mechanical Tests of Weld Zone in Steel Building Structures.⁶⁾ Charpy impact test specimens, prepared as JIS Z 2242 V-notch specimens, were taken from the weld metal (bond -1 mm), bond, and HAZ (bond +1 mm). **Fig. 3** shows the specimen collection locations.

Fig. 4 shows the macrostructure of the joint, which confirms sufficient penetration. As **Table 9** shows, the weld metal of the ESW meets the minimum standard for a base material of 590 N/mm²-class steel for the inner diaphragm (0.2% offset yield strength ≥ 440 N/mm², tensile strength ≥ 590 N/mm²). The Charpy impact test results ranged

from 84 to 193 J. This is an improvement over the conventional steel welded via the same method (**Table 3**) and confirms that the development target of ≥ 47 J at 0°C is satisfied.

3.3.2 SAW joint properties

We evaluated the properties of a high-efficiency, high-heat input single-pass SAW joint intended as a corner joint. **Table 10** shows the welding consumable specifications and welding conditions. The welding consumable is the developed SAW material.⁷⁾

Fig. 5 shows the macrostructure of the cross-section, which confirms good penetration. **Fig. 6** depicts the specimen sampling locations. In accordance with the Manual for Standard

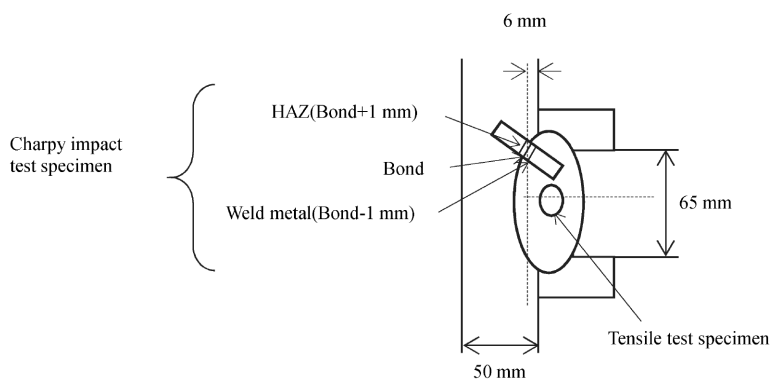


Fig. 3 Test specimen sampling position (ESW)

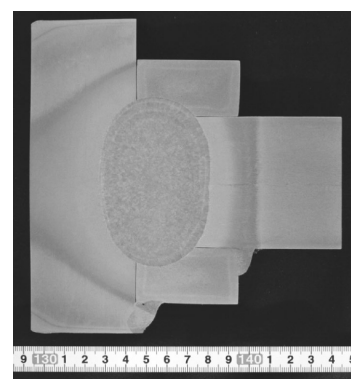
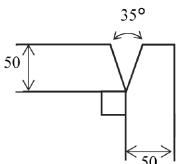


Fig. 4 Cross-sectional macrostructure (ESW)

Table 9 Mechanical properties of ESW joint

Steel	Tensile test of weld metal		Charpy impact test, vE ₀		
	YS (N/mm ²)	TS (N/mm ²)	Weld metal (Bond-1 mm) (J)	Bond (J)	HAZ (Bond+1 mm) (J)
Developed steel	497	698	84	86	193
Conventional steel	-	-	-	15	-
590 N/mm ² steel	440 $\leq$	590 $\leq$	47 $\leq$	47 $\leq$	47 $\leq$

Table 10 Condition of SAW

Thickness (mm)	Groove shape (mm)	Welding consumables	Welding conditions
Skin plate: 50 mm (developed steel)		Wire: JIS Z3351 YS-NM6 6.4 mm Φ Flux: JIS Z3352 SACG-I1	L: 2050A-40V T: 1500A-48V Welding speed: 20 cm/min Heat input: 462 kJ/cm

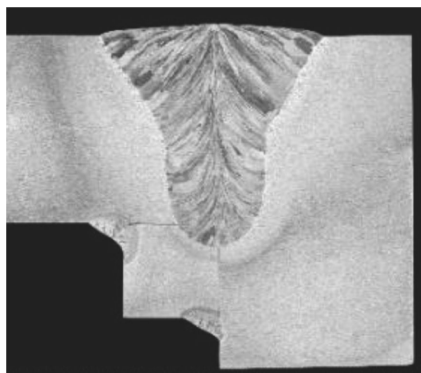


Fig. 5 Cross-sectional macrostructure (SAW)

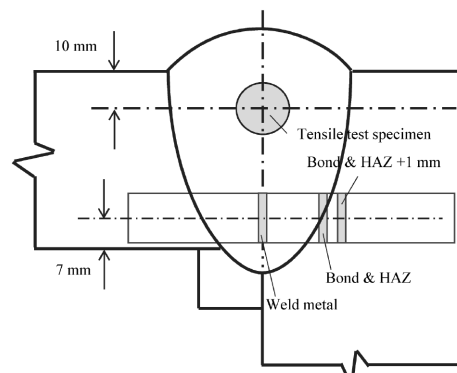


Fig. 6 Test specimen sampling position (SAW)

Table 11 Mechanical properties of SAW joint

Steel	Tensile test of weld metal		Charpy impact test, vE_0		
	YS (N/mm ²)	TS (N/mm ²)	Weld metal (J)	Bond&HAZ (J)	Bond&HAZ+1 mm (J)
Developed steel	652	829	46	55	51
Conventional steel	-	-	-	20	-

Mechanical Tests of Weld Zone in Steel Building Structures⁶⁾, we prepared tensile test specimens collected from the center of the deposited material, 10 mm from the surface of the base metal, per JIS Z 3111 A1. Charpy impact test specimens were prepared as JIS Z 2242 V-notch specimens. The designations and sample locations are “Weld metal,” which is 7 mm from the rear face of the base metal; “Bond&HAZ” on the flange side; and “Bond&HAZ+1 mm,” which is 1 mm into the HAZ as measured from “Bond&HAZ.”

Table 11 shows the mechanical properties of the SAW joint. The tensile properties of the weld metal meet the lower limits for a base material of 780 N/mm²-class steel (0.2% offset yield strength $\geq$ 630 N/mm², tensile strength $\geq$ 780 N/mm²). The Charpy impact test results ranged from 46 to 55 J, confirming an improvement over conventional steel fabricated using the same welding method (Table 3).

Conclusions

We validated that our developed steel has excellent base material properties and welding joint properties. In this way, we solved the challenge of uniting construction efficiency with performance characteristics in a way that even applies to the high-heat input, single-pass welding of 780 N/mm²-class steel. Our next steps are to validate our developed steel in actual structures and to promote its use as a material that enhances performance and efficiency in steel building structures.

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Corrosion Resisting Steel Eco-view Plus™, a Repaint Term Extension under High Humid Environment

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Abstract

In transportation infrastructure such as bridges, there is demand for reduction of life-cycle costs from construction through to rebuilding. For steel bridges, a key challenge is addressing corrosion under paint coatings, particularly in areas exposed to harsh environments, such as girder ends and edges. “Eco-view Plus” is a corrosion-resisting steel that contains Ta, Mg, and rare earth metals (REM) which inhibit the underfilm corrosion of steel by enhancing the corrosion resistance of inclusions, and promoting the formation of zinc rust by zinc-rich paint which shields steel surface and the coating-steel interface from corrosive environments. Eco-view Plus can extend the time for the growth of coating blisters to approximately twice than that of conventional steel materials. Its application to girder ends and edges is therefore expected to significantly reduce the life-cycle cost of steel bridges.

Introduction

In the transition toward a sustainable society, it is highly important to account for the life-cycle cost (LCC) of roadway infrastructure such as bridges. The LCC factors in the labor needs and financial aspects of construction, maintenance, repair, and replacement. A primary cause of damage in steel bridges is the corrosion of the steel itself. Therefore, to reduce the LCC of these structures, the steel must have better corrosion resistance, and the coating must inhibit corrosion.^{1), 2)} Stormwater and sediment from the surface of the road infiltrate bridges at the girder ends in particular, as shown in Fig. 1. Corrosion promoting agents such as moisture and salt stagnate in these poorly ventilated, enclosed areas for extended periods, creating an adverse corrosion environment. This makes the interface between the steel plate and the coating prone to underfilm corrosion.³⁾ The corrosion protection afforded by the coating then degrades, and periodic recoating is necessary. The associated maintenance costs have prompted ample research into various countermeasures.^{4), 5), 6)} Using steel with superior resistance to underfilm corrosion (i.e., underfilm

corrosion-resistant steel) in areas exposed to such adverse corrosion environments could extend the period before repainting is necessary and thus reduce the LCC.⁷⁾

Kobe Steel has been a trailblazer in developing underfilm corrosion-resistant steel designed to extend the period until repainting is necessary. We helped reduce the LCC of bridges in commercializing Eco-View, a steel with underfilm corrosion suppression functionality.^{8), 9)} We also developed Eco-View Plus^{Note)} to further improve corrosion resistance particularly at the plate edges of bridges, where the paint tends to become thinner, and at their girder ends, where the corrosion environment is particularly adverse. This underfilm corrosion-resistant steel combines the enhanced corrosion resistance of the steel itself with the corrosion prevention functionality of the paint. This product significantly extends the period until a bridge must be repainted to ensure functionality. Eco-View Plus is expected to reduce the LCC of bridges, particularly in regions with adverse corrosion environments, such as coastal areas with high airborne salinity as well as regions that see high usage of deicing agents due to heavy snowfall.¹⁰⁾ This steel exhibits good weldability and impact resistance, and yields welding joints with good tensile properties. It also meets the base material

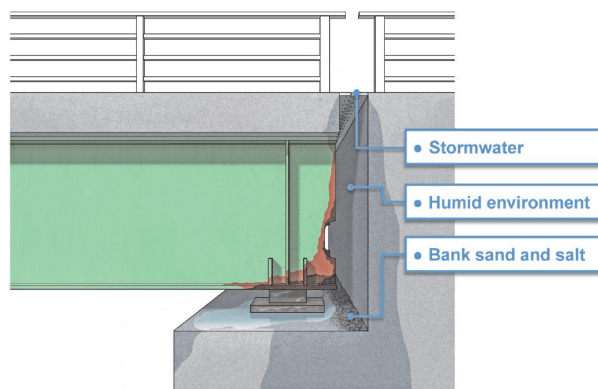


Fig. 1 Image of corrosion environment at girder ends of bridges

Note) Registered trademark of Kobe Steel, Ltd. (6769816)

standards of JIS SM and SBHS for rolled steel for welded bridge structures, so it can be handled in the same way as conventional steel.¹¹⁾ This paper introduces the mechanism behind the characteristic underfilm corrosion resistance function of Eco-View Plus and its effect on extending the period until repainting is necessary.

1. Characteristics of Eco-View Plus

Eco-View Plus shares Eco-View's base composition of Cu-Ni-Ti. However, it exhibits improved corrosion resistance by including certain amounts of Ta, Mg, and REMs (rare earth metals; Ce, La) to protect the surface of the steel against corrosion environments. **Fig. 2** shows the mechanism of underfilm corrosion in typical steels and the mechanism of underfilm corrosion suppression in Eco-View Plus. The coating system is assumed to be a heavy-duty anti-corrosion coating, which has become standard in recent years.¹²⁾ Unevenness and flaws in coatings often occur at the corners and edges of coated steel structures, creating initiation points for corrosion promoting agents such as moisture to penetrate the surface of the steel and cause corrosion. When conventional steel corrodes, the coating blisters and cracks as rust primarily composed of Fe forms and grows under the coating. Conversely, Eco-View Plus contains additives that suppress Fe rust and enhance the capacity of the Zn-rich paint to promote white rust, in turn preserving the surface of the steel. In this way, Eco-View Plus boosts the corrosion prevention functionality of the paint and suppresses underfilm corrosion.

This section covers the mechanism behind improving the underfilm corrosion resistance of steel by adding Ta and Mg and details the validation via testing.

1.1 Enhancing the corrosion resistance of steel by neutralizing the corrosion initiation points

Steel typically contains inclusions made up of trace elements present in the base metal. If these inclusions are more soluble than the steel, they can serve as corrosion initiation points.¹³⁾ Some studies have reported that adding elements to the steel can modify the inclusions by electrochemically stabilizing them, thereby preventing them from becoming corrosion initiation points.¹⁴⁾⁻¹⁶⁾ Therefore, using JIS G3106 rolled steel for welded structures as the reference steel (abbreviated "SM" in this paper), we conducted research to identify elements that can render insoluble the inclusions that serve as corrosion initiation points.

As **Table 1** shows, we observed inclusions made up of elements such as S, C, and Mn on the surface of the SM steel. By contrast, in the Ti-SM steel (Ti added to SM), compounds primarily composed of Ti precipitated on the surface of the inclusions. Similarly, we confirmed that in the Ti-Ta-SM steel (Ti and Ta added to SM), compounds primarily

Table 1 SEM image and elemental composition of inclusions on(a) SM, (b) Ti-SM, (c) Ti-Ta-SM

SEM image

(a) SM

1 μm

(b) Ti-SM

1 μm

(c) Ti-Ta-SM

1 μm

Point	Elemental composition (at%)									
	C	N	Al	S	Ca	Ti	Mn	Fe	Ta	
a	30	-	-	21	2	-	21	25	-	
b	18	20	2	1	1	50	-	8	-	
c	35	6	-	-	-	20	-	24	15	

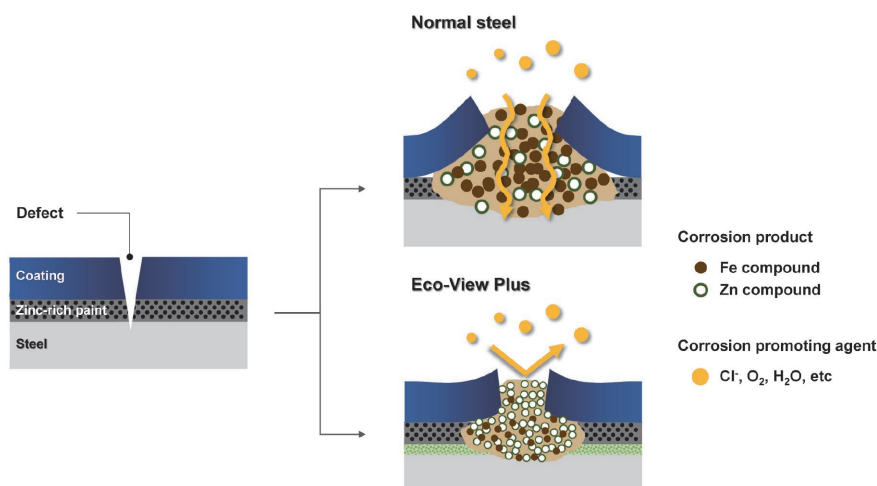


Fig. 2 Inhibition mechanism of under-film corrosion of Eco-View Plus

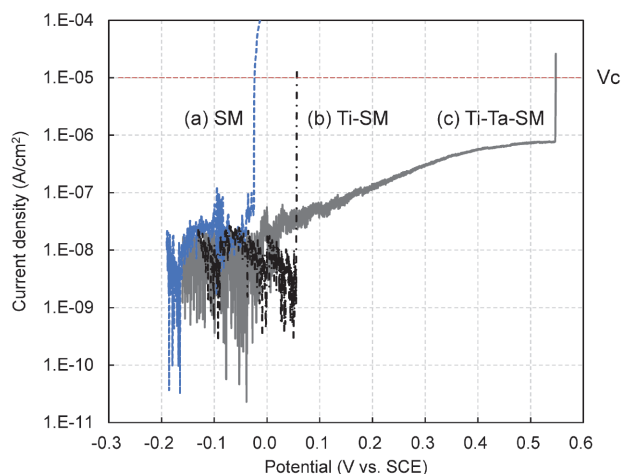


Fig. 3 Anodic polarization curves of (a) SM, (b) Ti-SM, (c) Ti-Ta-SM

comprising Ti and Ta precipitated on the surface of the inclusions. These results suggest that added Ti and Ta coat inclusions effectively.

Next, we conducted polarization tests to measure the corrosion initiation potential of each steel, which confirms the degree to which the added Ti or Ta improves the corrosion resistance of inclusions. The test was conducted in an aqueous solution of 0.15M H_3BO_3 -0.0375M $Na_2B_4O_7$ -0.010M NaCl at 25°C per JIS G0577, "Methods of pitting potential measurement for stainless steels." The potential at which the current density during anodic polarization exceeded 10^{-5} A/cm² was taken to be the corrosion initiation potential (V_c) of the steel. As Fig. 3 shows, while the V_c of the SM steel was -0.024 V, that of the Ti-SM steel was 0.056 V, indicating an increase in the corrosion initiation potential. Furthermore, the V_c of the Ti-Ta-SM steel was 0.55 V, suggesting a significant improvement in the steel's corrosion resistance. These results indicate that adding Ti or Ta provides electrochemical stabilization by coating the surface of inclusions, and that the combined addition of both elements yields a particularly large effect.

Fig. 4 shows the average V_c from five measurements as a function of the amount of Ta added to the steel. The Ti-Ta-SM steel with an added Ta content of 0.03% had a higher V_c compared with the SM and Ti-SM steels, indicating improved corrosion resistance. However, no further improvement in corrosion resistance was observed with higher levels of added Ta. Fig. 5 shows images of the inclusions in Ti-Ta-SM steels with different Ta contents. These images show that more Ta compound precipitates with a higher Ta content. These results indicate that there is an upper limit to the effect of coating inclusions by adding Ta. Excessive addition causes the precipitation of Ta

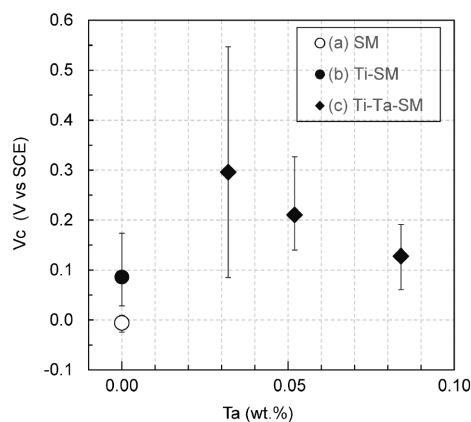


Fig. 4 Relationship between V_c and Ta content of steels (a) SM, (b) Ti-SM, (c) Ti-Ta-SM

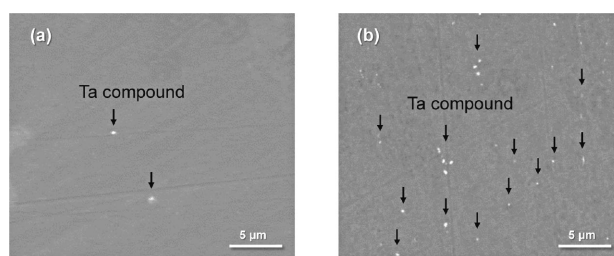


Fig. 5 SEM image of inclusions in Ti-Ta-SM with different Ta content (a) Ta 0.03wt%, (b) Ta 0.08wt%

compounds that do not coat inclusions, in which case the effect on corrosion resistance has reached saturation.¹⁴⁾

The results of this study indicate that appropriate amounts of added Ti and Ta can coat inclusions that serve as corrosion initiation sites, thereby improving the corrosion resistance of the steel.

1.2 Providing a barrier against corrosion environments by coordinating with coating composition

Zinc-rich paint, which has recently become standard as a base coating for bridges, has metallic zinc particles that impart steel with sacrificial protection against corrosion. Dissolved zinc forms corrosion products (white rust) that cover the surface of the steel, creating a barrier against the corrosion environment. It has been reported in particular that basic zinc compounds (white rust) formed in the presence of basic compounds containing Mg provides excellent protection because it is chemically stable and has a dense crystalline structure.¹⁷⁾ Therefore, we added Mg to steel sheet and studied how this affected the environmental barrier effect of white rust formed under Zn-rich paint.¹⁸⁾

The SM and Mg-SM steels were primed with zinc-rich paint (thickness 35 µm) and top-coated

with a polyurethane coating (thickness 25 μm). We used a utility knife to make cross-cuts in the dried coating to simulate damage and thin areas that occur during application. We subjected the specimens to a 1.5-year outdoor exposure test at the Japan Weathering Test Center in Miyakojima City, Okinawa Prefecture. The topcoat was clear so it would be possible to visually observe the formation of underfilm corrosion.

Fig. 6 shows the change in the appearance of the SM and Mg-SM steels during exposure testing. The SM steel exhibited reddish-brown Fe rust around the cross-cuts after three months of exposure. The Mg-SM steel exhibited less Fe rust than the SM steel. After nine months, Fe rust had formed in the cross-cut and the intact painted surface of the SM steel. By contrast, the cross-cut of the Mg-SM steel exhibited white rust. After 15 months, Fe rust had spread over almost the entire surface of the SM steel, and there was significant blistering and peeling of the paint. Although the Mg-SM steel also developed rust in the intact painted area, it was primarily basic Zn compounds, meaning that the corrosion products are substantially different.

Fig. 7 shows images of the cross-sections of the specimens' damaged areas after the exposure test alongside the results of the chemical analysis. In the SM steel, thick Fe rust formed between the white rust and the base metal, confirming that Cl penetrated into the Fe rust. By contrast, basic Zn compounds grew to cover the surface of the Mg-SM steel, inhibiting the formation of iron rust. Furthermore, most Cl had concentrated on the surface of the basic Zn compounds rather than penetrating into it.

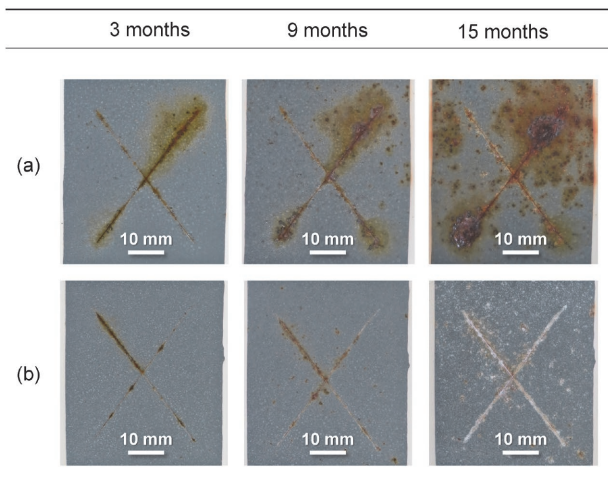


Fig. 6 Appearance of painted steels of (a) SM and (b) Mg-SM during exposure test at Miyakojima

Table 2 shows the crystallite phases and diameters of the corrosion products formed on the surfaces of the specimens as determined by X-ray diffraction. Unlike the SM steel, the Mg-SM steel did not have FeOOH-based compounds, the main component of Fe rust. Instead, it showed a high proportion of basic zinc compounds such as simonkolleite and gordaite. Additionally, the crystallite diameter of the gordaite was smaller in the Mg-SM steel than in the SM steel. These results indicate that adding Mg to steel promotes the formation of basic zinc compounds in corrosion environments, thereby affording high corrosion resistance.

1.3 Protection at the coating/steel interface

REMs react with water to form a dense precipitate of hydroxides, which improves corrosion resistance by serving as a protective coating on the surface of the steel.¹⁹⁾ As such, when moisture penetrates the coating/steel interface of steel with REM additives, it reacts with the REMs in the steel to form a dense coating on the surface of the steel. This coating should afford protection at the steel/coating interface. The increased corrosion potential of steel has been confirmed based on polarization tests in aqueous solutions with REMs. We will detail the effects of REMs on another occasion.

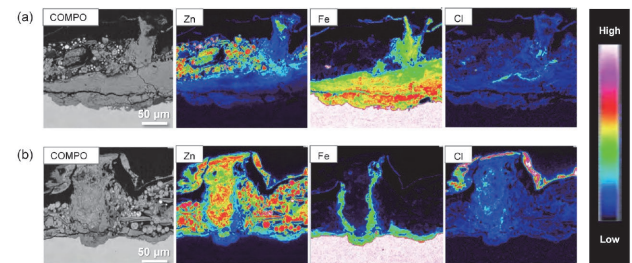


Fig. 7 Cross-sectional images of corrosion product of (a) SM and (b) Mg-SM after exposure test

Table 2 Composition and crystallite size of corrosion products of steels after exposure test

	Corrosion products	SM		Mg-SM	
		Fraction (%)	Crystallite diameter (nm)	Fraction (%)	Crystallite diameter (nm)
Fe based compound	α -FeOOH (Goethite)	31.6	20.7	-	-
	β -FeOOH (Akaganeite)	19.3	27.6	-	-
Zn based compound	$\text{Zn}_5(\text{OH})_6\text{Cl}_2\cdot\text{H}_2\text{O}$ (Simonkolleite)	-	-	20.6	66.6
	$\text{NaZn}_4(\text{SO}_4)\text{Cl}(\text{OH})_5(\text{H}_2\text{O})_6$ (Gordaite)	8.9	95.4	26.1	57.1
	ZnO (Zincite)	35	36.7	45.2	35.8
	Metal Zn	5.2	-	8.0	-

2. Developing Eco-View Plus

As explained in Section 1, Ta and Mg improve the corrosion resistance of steel and provide a barrier against corrosion environments through different mechanisms. By incorporating these elements and REMs into Eco-View, Kobe Steel's underfilm corrosion-resistant steel should yield excellent durability in adverse corrosion environments such as the girder ends of bridges. This concept served as a springboard in developing Eco-View Plus, a steel that provides underfilm corrosion resistance in high-humidity environments. This section introduces the results of evaluating Eco-View Plus in terms of underfilm corrosion resistance as well as the expected extension of the period before repainting is necessary.

2.1 Evaluating underfilm corrosion resistance via cyclic corrosion testing (CCT)

We used CCT to evaluate the underfilm corrosion resistance of the SM steel and Eco-View Plus with the compositions shown in **Table 3**. Our coating for the test was based on the C5 corrosion protection rating, which is currently standard for bridges. The three-layer structure of the coating comprised a zinc-rich paint as the anti-corrosion base coat, an epoxy-based intermediate coat, and a fluoropolymer topcoat. To shorten the test period, we applied a thinner coating than usual.²⁰⁾ Steel specimens were iteratively exposed to cycles of salt spray, humidity, and air drying. We measured the coating blister

length and area around the cross-cuts every two weeks. To simulate the environment at the girder ends of bridges, we based the conditions of CCT on JIS K 5600-7-9 Cycle D, making adjustments according to the results of environmental monitoring at the girder ends of bridges as shown in **Table 4**.²¹⁾

Fig. 8 shows the cross-cuts after 16 weeks of CCT. Reddish-brown Fe rust developed near the cross-cut of the SM steel. Additionally, swelling of rust due to underfilm corrosion caused the coating to blister. Conversely, the Eco-View Plus was white near the cross-cut. This result is similar to the exposure test described in Section 1.2 and confirms that white rust formed and iron rust was suppressed. Furthermore, the blister length and area were smaller than those of the SM steel.

2.2 Effect on extending the period until repainting is necessary

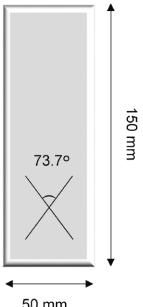
Fig. 9 shows the change over time in the blister length and blister area at the cross-cut of each steel. Eco-View Plus tends to suppress increases in blister length and area compared with the SM steel. For example, the time required to reach a blister length of 5.0 mm was about 1.5 times longer for Eco-View Plus (10.3 weeks for SM steel, 15.5 weeks for Eco-View Plus) (**Fig. 9(a)**).

In determining the service life of coatings on steel sheets, various approaches have involved predicting the time required to reach a certain deterioration area by using a coating deterioration curve to regress the change in coating blister area over time.²²⁾

Table 3 Chemical compositions of SM and Eco-View Plus

Steel	Elemental composition (wt%)									
	C	Si	Mn	P	S	Cu	Cr	Ni	Ti	Others
SM (JIS G3106)	0.17	0.36	1.38	0.015	0.003	0.01	0.04	0.01	0.001	-
Eco-View plus	0.05	0.30	1.24	0.010	0.001	0.70	<0.01	0.48	0.05	Ta, REM, Mg

Table 4 Cyclic corrosion test (CCT) conditions

Sample image	Surface preparation	CCT process	Environment	Time
	Sand blast • ISO Sa2 1/2 Coating • Inorganic zinc 35 μm • Epoxide (Clear) 20 μm • Fluoride (Clear) 20 μm	Salt spray	30°C ± 2°C 5% NaCl	0.5 h
		Condensation humidity	30°C ± 2°C 95 ± 3%RH	2.5 h
		Air drying 1	50°C ± 2°C 20 ± 3%RH	1.5 h
		Air drying 2	30°C ± 2°C 20 ± 3%RH	1.5 h

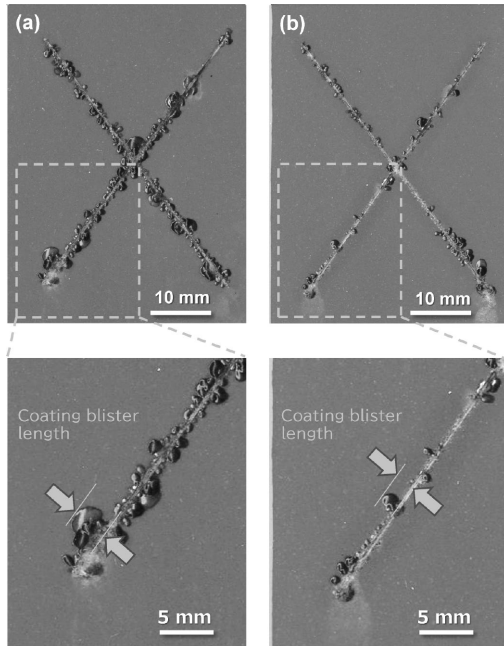


Fig. 8 Appearance of painted steels of (a) SM and (b) Eco-View Plus after 16 weeks of CCT

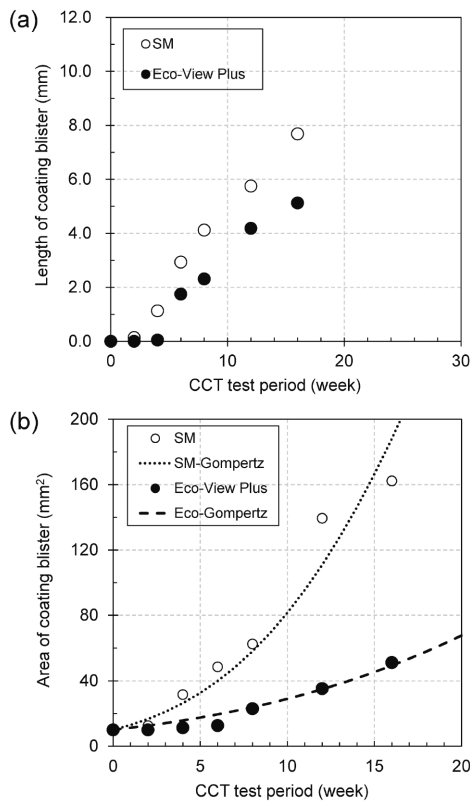


Fig. 9 Changes in (a) maximum length and (b) total area of coating blister on steels during CCT

A Gompertz curve²³⁾ can be used to estimate long-term deterioration behavior based on early-stage coating deterioration results such as those obtained in this study. Therefore, we estimated the period until repainting is necessary using the Gompertz curve resulting from Equation (1).

Table 5 Prediction results of repainting cycles on steels with Gompertz curve

Steel	K (mm ²)	a	b	Correlation coefficient	$t_{6.6}$ (week)
SM	2,000	0.005	0.9982	0.94	14
Eco-View Plus	2,000	0.005	0.9992	0.89	29

$$y(t) = K \cdot a^{b^t} \quad \dots \dots \dots (1)$$

Here, $y(t)$ = blistered area of the coating (mm²)

K = evaluation area (mm²)

t = test duration (weeks)

a, b = constants ($0 < a, b < 1$)

Note that $y(t)$ represents the deterioration area of the steel and is defined as the area with Fe rust. K is 2,000 mm² (50 mm long × 40 mm wide) to encompass the entire cross-cut area as shown in Table 4. The early-stage deterioration area ratio (a at $t = 0$) was defined as 0.5%. Fig. 9(b) and Table 5 show the results of regression analysis using a Gompertz curve for the time-dependent change in blister area. The standard period until repainting is necessary is regarded as the period until the blister area reaches 6.6 - 36.8% of the total painted surface.²³⁾ Calculating the time required for each steel to reach the minimum threshold of 6.6% ($t_{6.6}$), that is, $y = 132$ mm², yields 14 weeks for the SM steel and 29 weeks for Eco-View Plus. This indicates that Eco-View Plus extends the period until repainting is necessary to approximately twice that of the SM steel in an environment simulating the girder end of a bridge.

Conclusions

We developed Eco-View Plus, an underfilm corrosion-resistant steel suitable for high-humidity environments. This steel exhibits high corrosion resistance even in the adverse corrosion environment at the girder ends of bridges. Eco-View Plus incorporates Ta, Mg, and REMs to (1) enhance the corrosion resistance of the steel via Ta, (2) provide a barrier against the corrosion environment via functional matching between Mg and the coating composition, and (3) protect the coating/steel interface via REMs. These benefits suppress underfilm corrosion on steel plates in high-humidity and high-salinity environments. Using this product in areas such as the girder ends of bridges, where coating life is short, extends the period until repainting is necessary. This reduces the management and maintenance costs necessary for maintaining bridge functionality, in turn reducing life cycle costs (LCC).

Acknowledgments

The staff of the Miyagi Prefecture Ogawara Civil Engineering Office and the Yamagata Prefecture Road Maintenance Division provided invaluable support in this research and the product development process. For this, we express our sincere gratitude.

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Kobelco Group's Welding Technologies for Architectural Steel Frames

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Abstract

Joining is the most important production technology in the manufacturing and assembly of architectural steel frames. The Kobelco Group has long contributed to advancement of the construction industry through its high-tension bolts and arc welding technologies. Recent labor shortages have increased the need for automation by robotization. This has led to a notable trend toward the expansion of large-scale arc welding robot systems in steel frame manufacturing factories, as well as the adoption of portable arc welding robots on-site. In addition, efforts are being made to lower the barriers to training for welders, who are becoming increasingly rare, by combining practical and virtual training methods.

Introduction

As an earthquake-prone country, Japan's history includes numerous major earthquakes that have caused significant casualties and damage. As such, the country has put great effort into the technological development of materials, structures, and joining methods to improve the seismic resistance of all of types of structures, from tall historical wooden buildings such as five-story pagodas to modern steel-framed skyscrapers.

The KOBELCO Group has contributed to these efforts by developing numerous technologies for constructing resilient building structures to strengthen Japan's infrastructure. One area in which we possess exceptional strength is that of technologies and products related to the arc welding of steel, which has steadily gained importance in recent years.

This paper broadly introduces the KOBELCO Group's standout solutions for quality improvement, optimization, and automation, focusing on the various types of steel structures and the associated joining methods.

1. Materials used in building construction¹⁾

The main materials used for the structural elements of buildings are wood, concrete, and steel. Common construction methods using these materials include (1) reinforced concrete (RC) construction, (2) steel-reinforced concrete (SRC) construction, and (3) steel frame (S) construction.

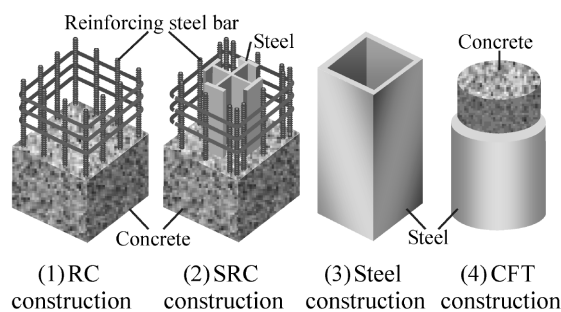


Fig. 1 Column styles in large buildings

There are many other structures, including hybrid structures combining wood and steel, as well as (4) concrete-filled steel tube (CFT) construction, in which steel columns are filled with concrete (Fig. 1).

Selection of the optimal construction depends on a building's intended use and is influenced by the recent trend of structures becoming increasingly larger and taller. Multistory apartments and condominiums often use RC construction because livability is prioritized. Conversely, high-rise offices, hotels, and production facilities often use S or CFT construction. Particularly with these two construction types, the steel must have high strength and toughness to ensure maximum seismic performance of the building, and the joints must likewise exhibit high stress transmission capabilities.

2. Column and beam connection types in S construction

S constructions often employ rigid-frame structures, in which columns and beams are rigidly connected (Fig. 2). Such structures are generally one of two main configurations: (a) continuous beam, where column segments are attached to the beam, or (b) continuous column, where beam segments are attached to the column (Fig. 3).

Configuration (a) is also known as the "continuous diaphragm" type and has seen expanding use particularly in Japan. While relatively uncommon from a global perspective, its widespread adoption is owed to high compatibility with arc welding robots and significant advantages in terms of safeguarding quality and reducing labor needs. Configuration (b) uses inner diaphragms and is commonly used in Japan for welded box columns in skyscrapers.

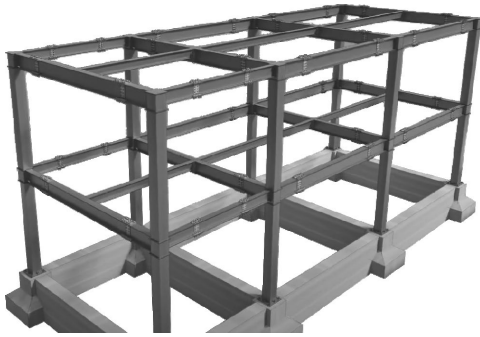


Fig. 2 Image of steel rigid-frame structure

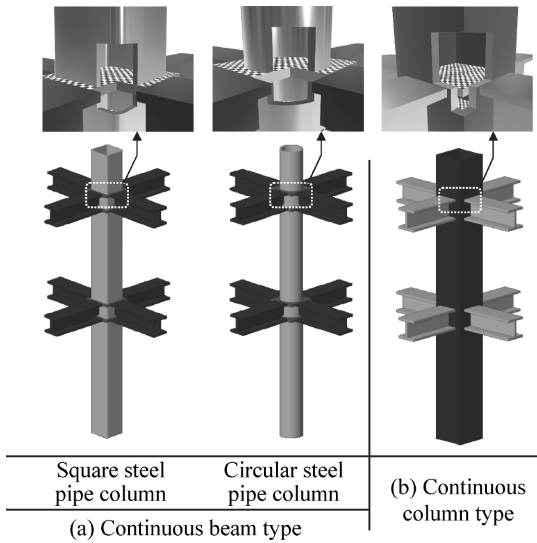


Fig. 3 Types of column and beam connections

3. Main types of joining methods and Kobe Steel's approach

Metal joining methods can be broken down into the categories of (1) mechanical joining, (2) metallurgical joining, and (3) chemical joining. (1) includes nut/bolt fastenings, rivets, nails, etc.; (2) includes arc welding, resistance welding, laser welding, pressure welding, gas welding, etc.; (3) primarily consists of adhesives. The most common methods used in the construction of architectural steel frames are nut/bolt fastenings and arc welding (examples of (1) and (2)). These methods have the advantages of high joint strength, long-term reliability, fire resistance, efficiency, and versatility (Fig. 4).

Further benefits of nut/bolt fastenings include the following: (a) high tolerance for gaps (joint can be tightened to close gaps), (b) process does not degrade the material, (c) low skill requirement, (d) low defect rate, (e) ease of defect detection, and (f) safe execution. Disadvantages of nut/bolt fastenings include the following: (a) can loosen over time, (b)

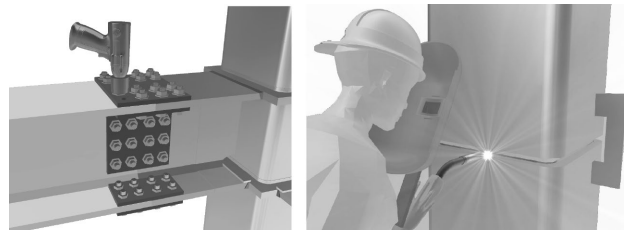


Fig. 4 Images of joining via nut/bolt and arc welding

limitations in scope of use based on joint geometry and plate thickness, (c) unsuitable for automation, (d) cross-sectional decreasing in steel plates, and (e) being a partial joint.

The advantages of arc welding include the following: (a) ability to join any geometry, (b) high reliability owing to high strength and toughness, (c) ease of automation, (d) high efficiency, and (e) low cost. Disadvantages of arc welding include the following: (a) process can degrade the material, including the surrounding base metal, (b) high skill requirement, (c) susceptible to internal defects, which are difficult to detect, and (d) health and safety concerns such as sparks and spatter, light, smoke, and intense heat.

Joining methods are selected based on their characteristics because each comes with its own advantages and disadvantages. Within the KOBELCO Group, Kobelco Bolt, Ltd. provides nut and bolt products, and a wide range of arc welding solutions are provided by companies including our Welding Business, KOBELCO WELDING TechnoSolutions Co., Ltd., and Kobelco ROBOTiX Co., Ltd. Additionally, Kobe Steel's Steel & Aluminum Business provides high-performance wire rod for nuts and bolts, as well as thick steel plate with excellent weldability.

4. Arc welding

Arc welding is used in a broad spectrum of applications, ranging from the in-plant assembly of steel pipes and structural steel members into architectural steel frames, to field welding when erecting frames at construction sites. The types of arc welding, in chronological order of technological maturity, are (1) shielded metal arc welding (SMAW), (2) submerged arc welding (SAW), (3) electroslag welding (ESW) (not arc welding per se, but included here as a related process), (4) self-shielded tubular cored arc welding, (5) gas metal arc welding (GMAW), and (6) electrogas arc welding (EGW). Kobe Steel's Welding Business provides all the welding consumables needed for these processes and has been advancing the field of building infrastructure since its founding in 1940.

Furthermore, to promote the widespread adoption of arc welding, which requires great technical proficiency, we established a training center in the early 1960s and launched a welding training program. As a result of this initiative, we have helped cultivate outstanding welders who accomplish high-quality welding throughout Japan.

Our efforts in the welding equipment business have ensured a high degree of automation as well as high efficiency and quality in welding. The welding robot system we developed in the mid-1980s for steel frame construction is still widely used in steel frame fabrication plants and on construction sites today.

4.1 Welding technology for RC and SRC constructions

The joining of reinforcing bar is an integral part of the RC and SRC construction methods. This need drove Kobe Steel to develop and promote the KEN (Kobe Steel's Enclose Narrow-gap) process in the 1960s.²⁾ This method involved placing a copper backing plate over the joint and filling the joint with weld metal. The welding consumable used was a covered arc welding electrode. Then, in 1989, we developed an advanced version that uses CO₂ shielded arc welding: the KEN-SH (Kobe Steel's Enclose Narrow-gap Welding-Semiautomatic High-Performance) Process (Fig. 5).³⁾

These methods were originally implemented by Shinko Welding Service Co., Ltd., the predecessor of KOBELCO WELDING TechnoSolutions Co., Ltd. However, in 2010, the business was transferred to the Japan Reinforcing Bar Joints Institute, and the method was renamed the "JCe method." It is currently implemented in the reinforcing bar industry as an association-certified method.⁴⁾

4.2 Welding technology for continuous-column S construction

The members used for the columns in continuous-column construction include H-beams, H-beams combined to form cruciform columns, and welded box columns. As the main member used, we will focus on the welded box column, also known as a "built-up box column."

This fully welded structure consists of four steel plates, called "skin plates," and numerous inner diaphragms for reinforcement. Excluding position changes, the process mainly involves two steps, each of which requires a different welding method (Fig. 6).

Where the plates meet along the longitudinal axis of the column are called the "corner joints." These

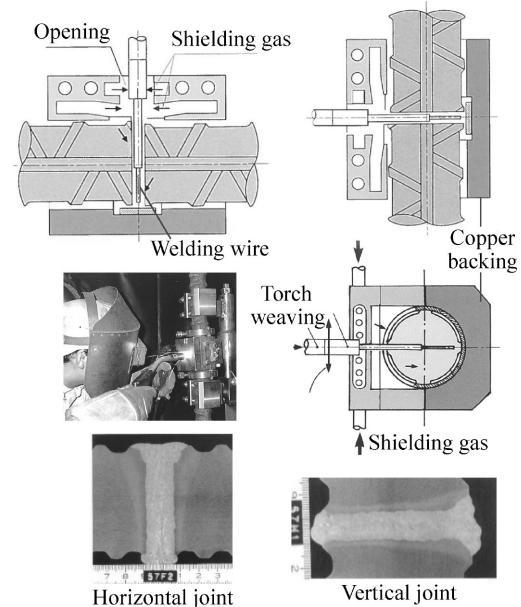


Fig. 5 Reinforcing steel bar welding process "KEN-SH"

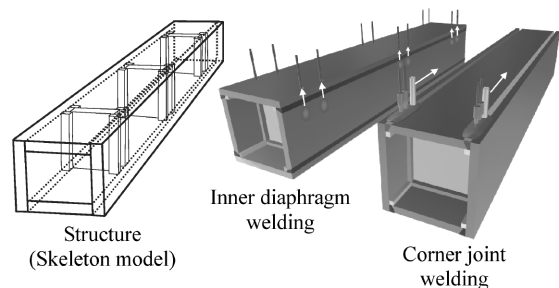


Fig. 6 Structure and assembly welding methods of built-up box section column

are usually welded by high-current SAW in a single pass (Fig. 7) using a tandem configuration with two electrodes arranged in series. Single-pass welding is challenging with a plate thickness greater than about 60 mm. In such cases, the common method applied is to use CO₂ shielded arc welding to build up the weld metal and then perform SAW, requiring at least two passes in total (Fig. 8). We are now starting to see steel plate thicknesses of up to 100 mm in today's skyscrapers. Since building up weld metal is a low-efficiency process, research is being pursued intensively to increase the maximum single-pass thickness for SAW and to develop multi-pass SAW techniques.

Kobe Steel has a long history in the development and marketing of multi-electrode SAW systems for high-efficiency welding of the corner joints of welded box columns.^{5), 6)} Fig. 9 shows a recent iteration of one of these welding systems.

Inner diaphragms, however, are welded via ESW. The structure, as shown in Fig. 10, is a closed space formed by a side skin plate, the diaphragm,

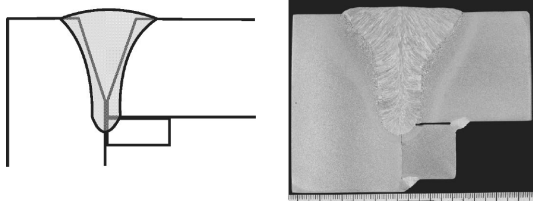


Fig. 7 Example of cross section of single pass corner welding joint by double electrode submerged arc welding method (Steel thickness: 50 mm)

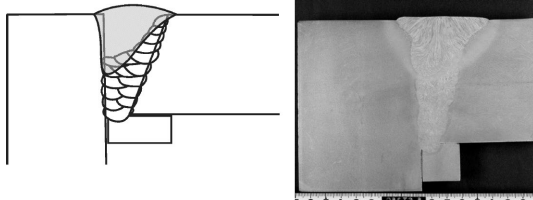


Fig. 8 Example of cross section of multi-pass corner welding joint by CO₂ arc welding and double electrode submerged arc welding mixed method (Steel thickness: 80 mm)



Fig. 9 Example of Kobe Steel's multi-electrode submerged arc welding system for corner joints of built-up box section column (Customer: OATEC corporation)

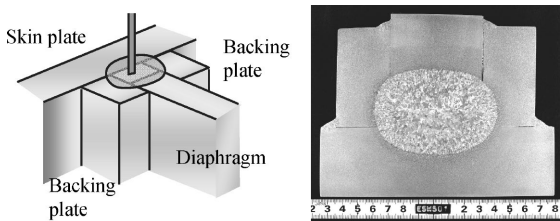


Fig.10 Example of cross-section and structure of electroslog-welded joint of diaphragm and skin plate

and two backing plates. A nozzle for introducing the welding wire is inserted into a hole in the top skin plate, and welding is performed while the nozzle is drawn upward. This process, which is more like casting than welding, is highly efficient. However, its heat input is extremely high, and the limited pathway for heat dissipation during welding slows the rate of cooling of the weld zone, potentially

causing material degradation around the weld. As such, we are focusing on developing not only ESW consumables that achieve high strength and toughness, but also steel plates that are suitable for this method by having the capacity to withstand high heat input. Also called “high-HAZ toughness steel,” such materials address the growing demand for large-section columns, which increase usable floor space by reducing the number of columns per floor. In response, Kobe Steel has developed high-strength steel plate capable of withstanding high-heat input welding. For more information, see p.66 of this issue, “Development of 780 N/mm²-Class Structural Steel for Building Structures Suitable for High Heat Input Welding”.

4.3 Welding technology for continuous-beam S construction

The joint construction that has seen the most significant development and become the mainstream approach in recent years is the continuous-beam type. This construction uses steel tube columns fabricated by cold-pressing thick plates into square or circular cross-sections and creating one or two welds along the length of the column. The welding method primarily used for steel tube fabrication is SAW, occasionally combined with CO₂ shielded arc welding. A specialized SAW fixture called a “boom welder” is used for welding the inside of these narrow spaces (Fig.11).⁷⁾

Improvements in steel pipe manufacturers' forming technologies and general capabilities have made it possible to produce high-strength steel pipe with greater wall thicknesses for continuous-beam constructions. Another reason this type of construction is gaining prevalence is because its manufacturing process is simpler than that of welded box columns, yielding greater economic efficiency.

Fig.12 shows how steel frame fabricators execute continuous-beam constructions. First, core parts (sometimes called “dice”) are fabricated for the joints between the steel columns and the beams. Specifically, diaphragms are circumferentially welded to a short steel pipe.

Short steel H-shaped sections (sometimes called “brackets”) for nut/bolt fastenings during on-site construction are then welded to the diaphragms of the core parts. Multiple such sections are then welded to long steel pipes to form the final structure as it will depart from the factory. A potential exception is that if the beams will be joined on site via welding rather than nut/bolt fastening, the H-shaped brackets are omitted. The advantage

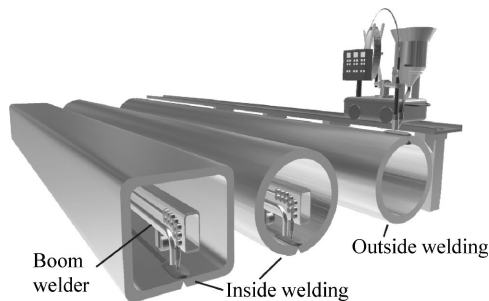


Fig.11 Seam welding of press-formed pipes

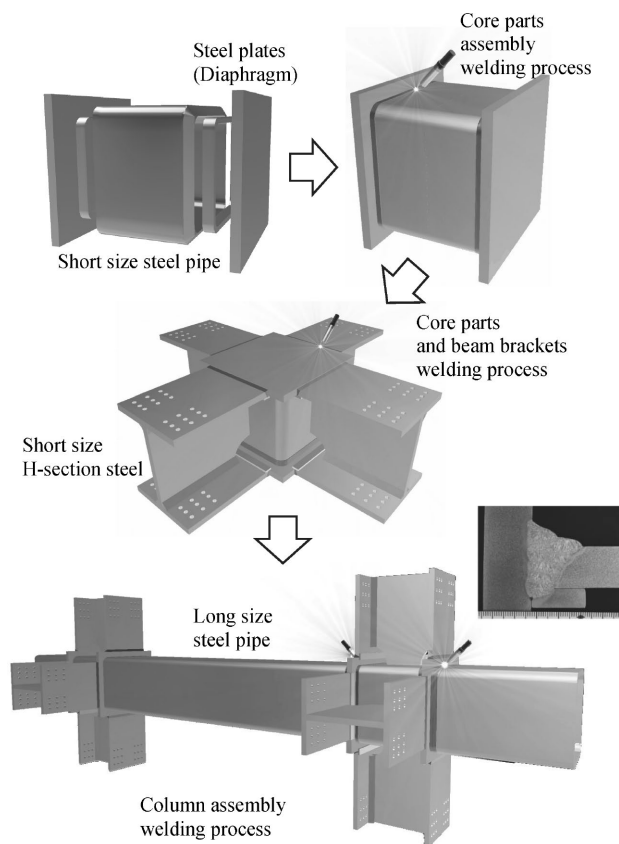


Fig.12 Typical welding assembly process of continuous-beam type column and an example cross-section of a weld joint

of the non-bracket method is that nothing is protruding from the beams, enabling more units to be loaded per truck for transport from the factory to the site, which in turn increases efficiency and reduces costs. However, unlike in the factory, on-site welding during erection of the structure is subject to constraints in terms of available welding positions. This leads to design changes to the details of the welding joints, which can reduce seismic performance. Research and practical testing are underway to resolve these challenges that are unique to on-site welding. Kobe Steel is developing on-site construction methods using arc welding that mitigate stress concentration and achieve excellent

seismic performance in welding joints, although the details are beyond the scope of this paper.^{8), 9), 10)}

The CO₂ shielded arc welding process shown in Fig.12 was traditionally a manual operation. However, it is now performed by welding robot systems comprising articulated robots, linear rails and guides for robot translation, workpiece positioners, and similar components. Such systems enable continuous, long-term operation around the clock, completely transforming the landscape of steel frame fabrication plants. The main elements of such systems are, as shown in Fig.13: (1) a space-saving, multi-purpose welding system for assembling steel frame core parts and brackets (primarily for welding the core part); (2) a steel frame core part welding system for continuously welding multiple core parts; (3) a steel frame bracket welding system for continuous welding of brackets; and (4) a large-column assembly welding system that accommodates long columns.

One technology that has improved weld quality is the REGARC™ process. It drastically reduces spatter – conventionally a drawback of CO₂ shielded arc welding – by using the welding power source to control current and voltage waveforms accordingly.^{11), 12), 13), 14)} This unique technology, feasible only with Kobe Steel's SENSARC™ series arc welding power sources (Fig.14), yields significant cost savings. Specifically, reducing spatter adhesion on the workpiece significantly reduces the labor and time necessary for spatter removal before subsequent ultrasonic testing (Fig.15).

After releasing REGARC™ to market in 2008, we released an upgraded version, New REGARC™, in 2021 to achieve even lower spatter levels.

4.4 Welding technology for beam members

The base raw material for a beam member is a steel H-beam. There are two types of steel H-beams: rolled H-beams are formed by rolling, while welded H-beams are constructed by welding. Large beams and non-standard shapes are typically welded H-beams. For welded H-beams, the mating faces of the web plate and flange plates are fillet welded, usually by SAW (Fig.16).

Processes within beam member fabrication include drilling holes, welding on reinforcing elements called “stiffeners,” and welding on reinforcing elements around the holes. Following their application to column fabrication, welding robot systems have recently entered the stage of full-scale welding of beam members (Fig.17).



Fig.13 Steel frame welding systems using "ARCMAN™" robots for column assembly

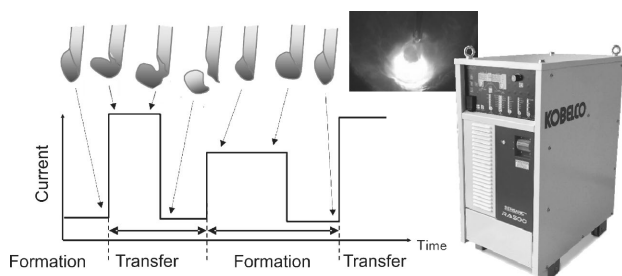


Fig.14 Basic current waveform of low-spatter CO₂ arc welding process REGARC™, and the latest model of SENSARC™ series that generates this function, RA500

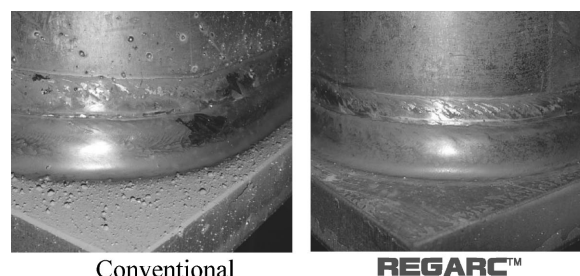


Fig.15 Comparison of spatter adhesion states with conventional CO₂ arc welding and REGARC™ process

4.5 Welding technology for on-site construction

Buildings are assembled floor by floor at the construction site. As cranes lift structural components such as prefabricated columns and beams into place, workers execute high-strength nut/bolt joints and perform arc welding. However, in recent years, the construction industry and related sectors have been facing the challenge of a growing shortage of skilled welders available for on-site

erection work. Kobe Steel's ISHIMATSU™ compact portable welding robot is helping to overcome this issue. One key feature of the ISHIMATSU™ is its ultra-lightweight body, weighing around 6 kg. It requires no safety fencing and travels on a guide rail, which may be linear or contoured to fit a steel pipe. Fig.18 shows this robot and its setup. The ISHIMATSU™ can operate in any position (flat, horizontal, overhead). Fig.19 shows how this automatic welding robot operates in the challenging position of overhead welding, and a cross-section

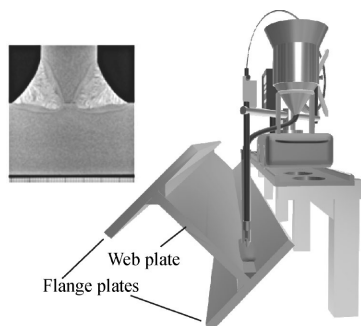


Fig.16 Fillet welding of welded H-beam assembly (submerged arc welding in a flat position) and an example cross-section of a weld joint



Fig.17 Welding of beam parts and “ARCMAN™” steel frame welding robot system for H-beam assembly

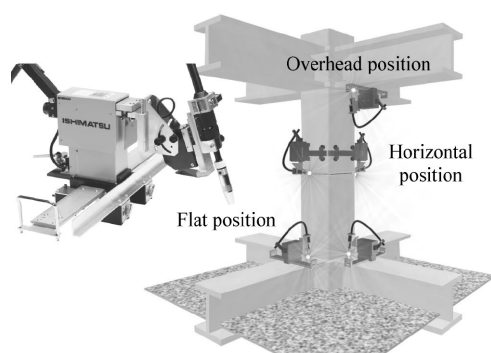


Fig.18 Portable welding robot “ISHIMATSU™” and image of on-site application

of the weld joint. This technology leverages not only robotic technology, but also the unique characteristics of Kobe Steel’s specially designed flux-cored welding wire, Familiarc DW-1ST and -55ST.¹⁵⁾ While overhead welding is extremely labor intensive for human welders, who must also take

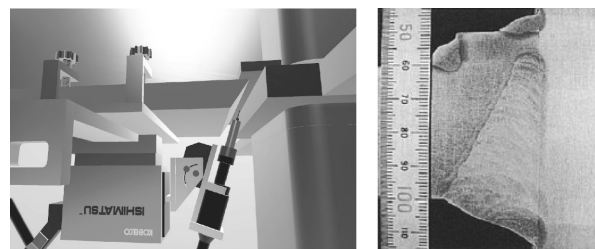


Fig.19 On-site welding of 40 mm-thick- beam-column joint using ISHIMATSU™ robot in overhead position¹⁷⁾

breaks, it presents no particular challenge to robots. The most frequently executed process in building construction is horizontal welding of the joints between columns. We are developing innovative control techniques to enhance the quality of such welds.¹⁶⁾

There are only a few robots in the world like the ISHIMATSU™, and their high versatility has garnered favorable reviews from steel frame fabrication companies the world over. Outside of Japan, this robot is marketed under the name ARCMAN™ PORTABLE.

4.6 Further information

The Kobe Earthquake of 1995 spurred a wave of discussions, led primarily by the Architectural Institute of Japan, regarding the need to enhance seismic resistance, such as through high-performance welding consumables. For details on technologies related to welding consumables, see “Latest Trends and Lineup of Welding Consumables for Structural Steel” on p.86 of this issue. As a leading manufacturer of welding consumables, Kobe Steel spearheaded efforts within The Japan Welding Engineering Society to create JIS standards for high-strength, high-toughness welding consumables and thermal management indices.^{17), 18)}

To support the widespread use of welding robots, we worked with The Japan Welding Engineering Society and the Japan Robot Association to establish certification systems for robot models and for structural steel welding robot operators. These initiatives have since taken root as integral parts of the industry.

While automation represents the greatest need and prevailing trend in the welding of architectural steel frames today, fully robotizing the entire process is not realistic. Because manual welding will always be necessary, it remains important to continuously improve the competence of human welders. This is why, as stated in the introduction to Section 4, Kobe Steel also focuses on enhancing the skills of its welders (Fig.20).¹⁹⁾

As part of our venture in practical welding skills training, we have recently commercialized a virtual welding training system, “NAP Welding Training,”^{20), 21)} designed for those with little to no welding experience (Fig.21).

Our Welding Training Center at Kobe Steel Fujisawa Industrial Operations in Kanagawa Prefecture has provided hands-on training for over 60 years. We rebuilt the facility, opening the New Welding Training Center on October 7, 2025 (Fig.22). We will continue advancing the industry, including by fostering the development of welders and welding robot operators.



Fig.20 Skills training at the Welding Training Center in Fujisawa industrial operations



Fig.21 Virtual welding training system “NAP welding training”



Fig.22 New Welding Training Center in Fujisawa industrial operations

Conclusions

When buildings undergo significant deformation, the joints become the most likely failure points. With Japan being an earthquake-prone country, this means the welds and joints in steel structures must be of very high quality to protect the buildings themselves and human lives. The shortage of skilled personnel in the construction industry adds to the urgency of this issue. The practical application of the KOBELCO Group’s various technological developments, particularly in welding, will help overcome both challenges.

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Latest Trends and Lineup of Welding Consumables for Structural Steel

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Abstract

This paper presents the latest trends in consumables for gas shielded arc welding, submerged arc welding, and electroslag welding, which are commonly used in the construction of structural steel. Also introduced is the lineup of welding consumables, which is tailored to the strength class of the steel.

Introduction

Construction demand grew in the Tokyo metropolitan area in particular in 2025. Activity in this region is being driven by projects such as the Mori JP Tower in Azabudai Hills – now Japan's tallest skyscraper, at 325 meters – and the TOKYO TORCH, a 385-meter skyscraper scheduled for completion in 2028. The trend in high-rise and commercial buildings in recent years has been to shift toward larger columns and wider spans between columns to maximize space and improve economic efficiency. This entails increased thicknesses and cross-sectional areas of steel frames, and the associated increased weight of these steel frames poses the challenge of higher costs for processing and freight. One way to overcome this challenge is to develop higher-strength steel. High-strength steels, such as those in tensile strength grades of 550 MPa and 590 MPa, have recently started seeing increased use. Steels with tensile strengths as high as 780 MPa are now starting to be used in skyscrapers.¹⁾

These trends are increasing the demand for improved productivity and quality in welding, but there is a shortage of skilled welders for structural steel column fabrication. Automated welding using vertical articulated robots to weld cold-formed square steel pipe has gained widespread use in structural steel column fabrication. For welded box columns, however, high-heat input methods such as multi-electrode submerged arc welding (SAW) and electroslag welding (ESW) are commonly used.

Some of Kobe Steel's forthcoming developments will satisfy needs for further improvements in productivity and welding quality. For instance, we are developing a robot system and specialized

welding wire for structural steel columns, as well as welding consumables compatible with steel materials of various strength classes, including steel with a tensile strength grade of 780 MPa. In this paper, we introduce our lineup of consumables for the gas-shielded arc welding, SAW, and ESW of structural steel columns. The steel strength class and latest trends applicable to each type of consumable are described.

1. Solid wires for CO₂ shielded arc welding

1.1 Lineup of welding consumables by steel strength class

Table 1 shows the lineup of solid wires for building structures broken down by steel strength class.

A common material used for structural steel columns is square steel pipe for building structures (hereafter, “columns”), which is made by cold-forming steel plates. The resulting columns are stronger than the steel plates they are made up of due to the work hardening that occurs as part of cold forming. As such, the welding consumables chosen must account for the effects of work hardening.²⁾ For example, columns with a tensile strength of 590 MPa require TRUSTARC™ MG-70 and TRUSTARC™ MG-70R(N)^{Note 1)}, which are solid wires for the CO₂ shielded arc welding of 690 MPa-grade steel.

Welding robot systems with vertical articulated robots are widely used for column welding in steel column fabrication plants. Kobe Steel's welding robot systems for structural steel columns use the REGARC™ process^{Note 2)}, which achieves high efficiency and low spatter. The (N) series and (A) series are welding wires specially designed for this process, with the (N) series specifically being coordinated to the REGARC™ process, and the (A) series to the NEW REGARC™ process.

Note 1) TRUSTARC is a trademark of Kobe Steel, Ltd.

Note 2) REGARC is a trademark of Kobe Steel, Ltd.

Table 1 List of CO₂ solid wires for building structures

Grade of steel plate		TS ^{※1} 400 MPa / YP ^{※2} 235 MPa	TS 490 MPa / YP 325 MPa	TS 520 MPa / YP 355 MPa	TS 550 MPa / YP 385 MPa	TS 590 MPa / YP 440 MPa	TS 780 MPa / YP 630 MPa
Welding joint	Column type						
Column-Column (for robot welding)	Square pipe column	FAMILIARC™ MG-50R			TRUSTARC™ MG-60R	TRUSTARC™ MG-70	
		FAMILIARC™ MG-50R(N)			TRUSTARC™ MG-60R(N)	TRUSTARC™ MG-70R(N)	
		FAMILIARC™ MG-50R(A)			TRUSTARC™ MG-60R(A)		
		FAMILIARC™ MG-56R					
		FAMILIARC™ MG-56R(N)					
		FAMILIARC™ MG-56R(A)					
	Circular pipe column	FAMILIARC™ MG-50R		TRUSTARC™ MG-60R			TRUSTARC™ MG-80
		FAMILIARC™ MG-50R(N)		TRUSTARC™ MG-60R(N)			TRUSTARC™ MG-82
		FAMILIARC™ MG-50R(A)		TRUSTARC™ MG-60R(A)			
			FAMILIARC™ MG-56R				
			FAMILIARC™ MG-56R(N)				
			FAMILIARC™ MG-56R(A)				
Column-Beam, Beam-Beam, Column-Column (for semi-auto welding)		FAMILIARC™ MG-50					TRUSTARC™ MG-80
			FAMILIARC™ MG-56				TRUSTARC™ MG-82
				TRUSTARC™ MG-60			

※1 TS : Tensile Strength
※2 YP : Yield Point

1.2 NEW REGARC™ solid wire for welding FAMILIARC™ MG-56R(A) ^{Note 3)}

Improvements of the NEW REGARC™ process over the original REGARC™ process include optimized waveform control, enhanced stability of droplet transfer in the globular mode, reduced spatter, an increase in the maximum wire feed speed from 16.4 m/min to 18.0 m/min, and an increase in the maximum welding current from 320 A to 340 A. However, with a higher wire feed speed, the inside of the feeding path exerts a higher reaction force on the wire. This makes the copper plating on the wire more likely to peel. The peeled plating accumulates in the feeding path on the inner tube, conduit liner, and tip, causing unstable wire feeding.³⁾ This phenomenon drove us to develop a special type of welding wire for this process: the (A) series, which features a special surface treatment to ensure stable wire feeding and reduce clogging.

We compared the amount of contamination on the inner tube, conduit liner, and tip using the NEW REGARC™ process and two different solid wires – specifically, FAMILIARC™ MG-56R(N) as a benchmark and FAMILIARC™ MG-56R(A) of the improved (A) series. Welding was performed at a welding current of 350 A for 5 hours. **Fig. 1** shows an example of the amount of contamination clogging the feeding path per 10 kg of wire, and **Fig. 2** shows photos of the base of the contact tip. It can be surmised that the copper plating of FAMILIARC™ MG-56R(A) was less prone to peeling in the feeding

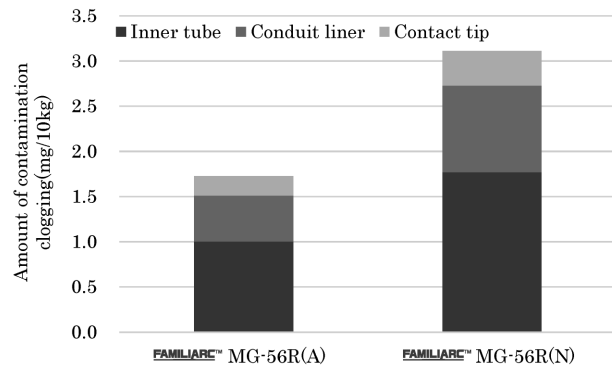


Fig. 1 Example about amount of contamination clogging wire feeding path parts

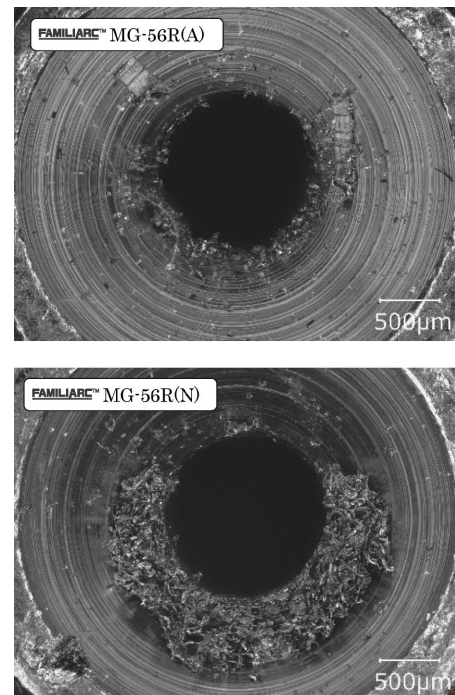


Fig. 2 Contamination clogging at base of the contact tip

Note 3) FAMILIARC is a trademark of Kobe Steel, Ltd.

path due to reduced sliding friction between the surface of the wire and the inner tube or conduit liner.

We evaluated the performance of the welding joints of a column (490 MPa grade, plate thickness 32 mm) and a through-diaphragm (JIS G 3136 SN490B, plate thickness 36 mm). We fabricated two joints with root gaps of 4 mm and 10 mm at a maximum heat input of 35 kJ/cm and a maximum interpass temperature of 250°C. **Fig. 3** shows the macroscopic cross-sections of the straight and corner sections as well as a depiction of the welding layers. **Table 2** shows the mechanical properties of the weld metal for the joint with a root gap of 10 mm. We collected Charpy impact specimens 7 mm from the top surface of the column, in the direction of the plate thickness. The macroscopic cross-section shows good penetration and good geometry of the surface of the bead. Furthermore, the strength of the weld metal and the absorbed energy upon Charpy impact testing meet the standards for structural steel.

1.3 TRUSTARC™ MG-82 solid wire for 780 MPa-grade steel

Both in-plant and on-site semi-automatic welding processes for structural steel columns must be

highly efficient. Welding consumables must not only result in favorable mechanical properties of the weld metal, but also ensure weldability to streamline upstream and downstream processes. In particular, there is a demand for improvements in spatter control and wire feedability. Kobe Steel is developing technologies to address these needs, for instance through our surface treatment technology to improve wire feedability. We have pursued this avenue in developing solid wires for high-tensile strength steel, such as in our TRUSTARC™ MG-82 solid wire for 780 MPa-grade steel.

This line is an improved version over earlier TRUSTARC™ products in that it receives a surface treatment during production to achieve superior wire feedability and arc stability. We conducted testing to evaluate the feedability of the wire under adverse conditions. As shown in the conceptual diagram in **Fig. 4**, we used a 6-meter torch cable with a coil diameter of 300 mm in the feeding path and evaluated the welding current, arc voltage, and feed resistance during welding. **Fig. 5** shows the results of welding with a wire diameter of 1.2 mm at 300 A, 36 V, and 30 cm/min. Compared with the conventional product, the improved product exhibits less fluctuation in wire feed resistance and thus more consistent results. Fluctuations in wire feed

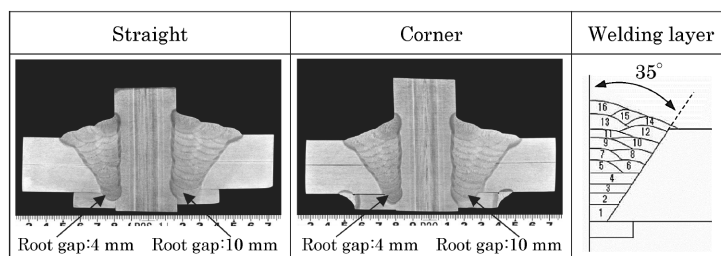


Fig. 3 Cross-sectional macro comparison [F] MG-56R(A) welded joint and welding layer

Table 2 Mechanical properties of weld metal by [F] MG-56R(A)

		YP(MPa)	TS(MPa)	vE _{0°C} (J)
FAMILIAR™ MG-56R(A)	Straight	567	645	Avg. 108
	Corner	-	-	Avg. 124
Spec.(490 MPa Grade)		≥ 325	≥ 490	≥ 27

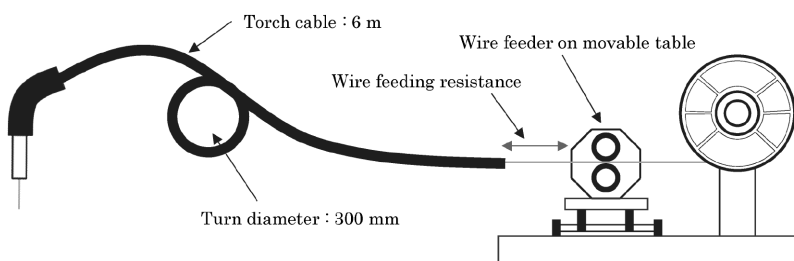


Fig. 4 Schematic illustration of wire feeding path

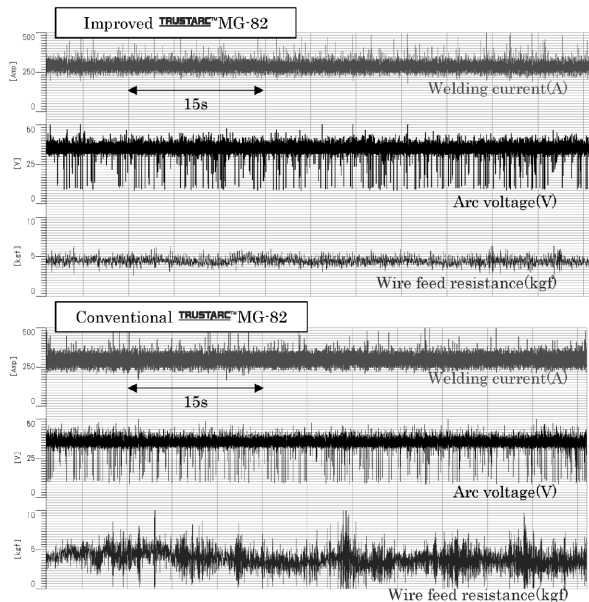


Fig. 5 Fluctuation of welding current, arc voltage and wire feed resistance of improved and conventional [T] MG-82

resistance affect arc stability and spatter generation. In semi-automatic welding, fluctuations also increase torch vibration. As such, the improved product is expected to not only ensure consistent welding performance, but also reduce operator fatigue.

2. Welding consumables for SAW

2.1 Lineup of welding consumables for corner joints of box columns

Fig. 6 shows a schematic diagram of a box column. Single-pass high-heat input SAW is commonly used for corner joints. Table 3 shows the lineup of SAW consumables for the corner joints of box columns broken down by steel grade.

Recent developments include our welding consumables for 780-MPa grade steel and for two-layer, two-pass welding, which is necessary for high-strength, ultra-thick plates that cannot accommodate single-layer, single-pass welding. The subsections that follow introduce the performance characteristics of these consumables.

2.2 Welding consumables for two-pass welding of corner joints made of ultra-thick 550- and 590-MPa grade steels

Buildings today are taller and larger, meaning skin plates are becoming thicker. This has created a strong need for high-efficiency fabrication methods. Our SAW consumables for welding the corner joints of box columns are designed to

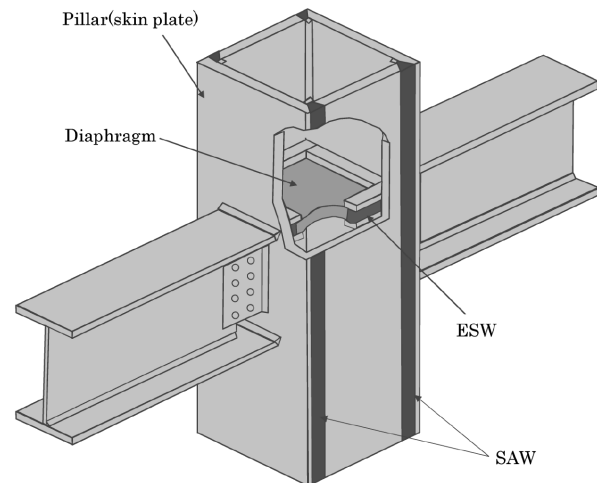


Fig. 6 Weld joints in box columns

ensure consistent weld quality even when used in high-heat input, single-layer, single-pass welding processes involving plate thicknesses of up to 60 mm. For plate thicknesses exceeding 60 mm, however, meeting the demand for high-efficiency construction of ultra-thick steel plate is challenging because it is difficult to ensure consistent bead shape and penetration. To address this challenge, research is underway to devise 3-layer, 4-pass and 2-layer, 3-pass welding methods employing relatively high heat input. However, experience has shown that weld metal subjected to two heat cycles is prone to microcracking. We surmised that a 2-layer, 2-pass process could provide both high efficiency and consistent weld quality since it involves just one heat cycle. This led us to develop a new flux, TRUSTARC™ PF-I60K, to be used specifically in combination with the conventional wire TRUSTARC™ US-49. The performance characteristics of TRUSTARC™ PF-I60K and TRUSTARC™ US-49 are described next.

For the skin plates, L-shaped test specimens simulating the corners of a box column were fabricated using KCL A385C (75 mm) and SA440C-ST (80 mm) steels. Table 4 shows the welding conditions, Table 5 shows the mechanical properties of the weld metal, and Fig. 7 depicts the sampling locations.⁴⁾ The results satisfy the standards of the respective steels in terms of the tensile properties of the weld metal and in terms of the individual values and averages for the absorbed energy upon Charpy impact testing (≥ 27 J).

Performing multi-layer welding on ultra-thick steel plate introduces concerns regarding low-temperature cracking resistance. As such, we validated the preheating and interpass temperature conditions using a window-type restraint weld cracking test. Fig. 8 depicts the specimen for said

Table 3 List of recommended SAW consumables for box columns

Grade of steel plate	TS 400 MPa / YP 235 MPa	TS 490 MPa / YP 325 MPa	TS 520 MPa / YP 355 MPa	TS 550 MPa / YP 385 MPa	TS 590 MPa / YP 440 MPa	TS 780 MPa / YP 630 MPa
1layer: 1pass	FAMILIARC® PF-I53ES / FAMILIARC® US-36L					TRUSTARC® PF-180ES ^{※1} / TRUSTARC® US-80SP
			FAMILIARC® PF-I53ES / TRUSTARC® US-49			
		FAMILIARC® PF-I55ES / FAMILIARC® US-36L				
				FAMILIARC® PF-I55ES / TRUSTARC® US-49		
2layers: 2 passes				TRUSTARC® PF-I60K ^{※1} / TRUSTARC® US-49		

※1 : New lineup

Table 4 Welding conditions

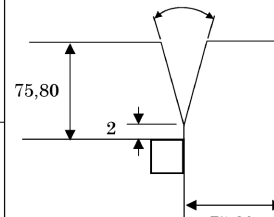
Pass	Electrode (6.4φ)	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)	Preheating · inter pass temperature (°C)	Groove shape
1	L	2250	38	16	618	RT.	
	T	1650	48				
2	L	2000	42	24	396	≦ 250	
	T	1550	48				

Table 5 Mechanical properties of weld metal

Specification (thickness)	Specimen location	Tensile test ^{※1}			Charpy impact test ^{※2}
		YP (MPa)	TS (MPa)	El. (%)	vE _{0°C} (J)
KCLA385 (75 mm)	Face	459	626	26	106 111 100 Avg.106
	Back	533	654	26	97 121 142 Avg.120
Spec.		≥ 385	≥ 550		≥ 27
SA440C-ST (80 mm)	Face	471	641	24	120 97 123 Avg.113
	Back	506	648	25	143 121 144 Avg.136
Spec.		≥ 440	≥ 590		≥ 27

※1 Size of tensile specimen; Dia. = 12.5 mm, G.L. =50.0 mm

※2 10×10 mm, 2 mm V notch

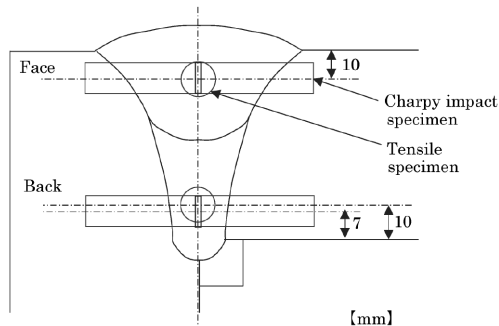


Fig. 7 Specimen location

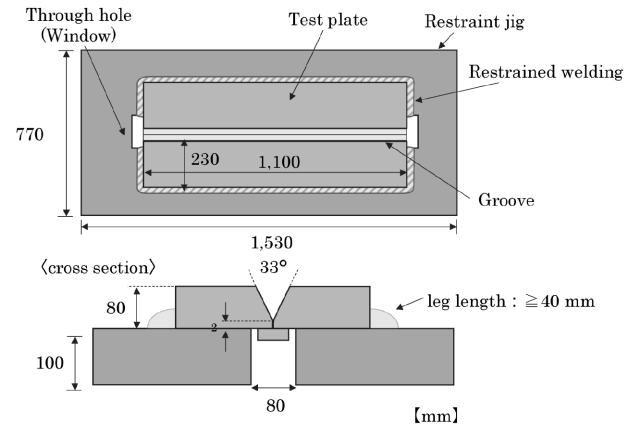


Fig. 8 Schematic illustration of layout of both restraint and test plate

test. We used JIS G 3106 SM490A for the test plate, as it has a relatively high Pcm, indicating a higher susceptibility to weld cracking. The welding conditions were as shown in Table 4, with no preheating for the first pass (approximately 15°C) and an interpass temperature of 150°C for the second pass. After welding, the test plate was left at room temperature for 48 hours. We then removed it from the restraint jig to perform ultrasonic testing (UT) at reference sensitivity +10 dB with the transducer over the ground weld bead. Testing revealed no echoes above the detection threshold, confirming that there are no issues regarding low-temperature cracking resistance under the practical conditions of no preheating and an interpass temperature of 150°C (specification ≤ 250°C).

Welding consumables used for building structures must correspond to the classifications for deposited metal in JIS Z 3183. Tensile testing, impact tests, and diffusible hydrogen content tests were conducted on the deposited metal created using the combination of TRUSTARC™ PF-I60K and TRUSTARC™ US-49. **Table 6** shows the results. The quality classification of the deposited metal is JIS Z 3183 S621-H4, confirming that it can be used for 590 MPa-grade high-tensile strength steel.

2.3 Welding consumables for single-pass welding of corner joints of box columns made of 780 MPa-grade steel

Recent years have seen a trend toward reducing skin plate thickness through the use of stronger

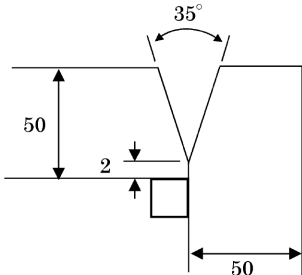
steel, driving the increased use of 780 MPa-grade steel. The most common process used for the corner joints of box columns in steel grades up to 590 MPa is single-pass SAW. For 780 MPa-grade steel, however, the low-efficiency process of multi-pass welding with low heat input is mainstream. Preheating and interpass temperatures must be strictly controlled with this grade because its weld metal is highly susceptible to low-temperature cracking. Furthermore, low-heat input, multi-pass welding involves long arc-on times, which is operator-intensive. This section introduces the properties of SAW consumables that enable single-pass welding of the corner joints of box columns made of 780 MPa-grade steel: flux TRUSTARC™ PF-I80ES and wire TRUSTARC™ US-80SP.

The standards for these welding consumables are JIS Z 3351 YS-NM6 for the wire and JIS Z 3352 SACG-I1 for the flux. The quality classification of the weld metal per JIS Z 3183 is JIS Z 3183 S804-H4. We evaluated the performance of the welding joint using a skin plate made of 780 MPa-grade steel (thickness 50 mm) using a high-heat input process under the welding conditions in **Table 7**. **Fig. 9** shows the weld bead, and **Fig.10** shows the macroscopic cross-section. Weldability is comparable to that of welding consumables used with steel plate of 590 MPa grade or lower, and the penetration geometry is good. **Table 8** shows the mechanical properties of the weld metal. Tensile test specimens were taken from the center of the weld metal, 10 mm from the surface of the base metal. Charpy impact test specimens were taken 7 mm from the rear surface of the base metal.

Table 6 Mechanical properties of [T] PF-I60K / [T] US-49 deposit metal

Wire /Flux	Tensile test			Charpy impact test	Diffusible hydrogen content(ml/100g)
	YP (MPa)	TS (MPa)	El. (%)	vE _{-5°C} (J)	
TRUSTARC™ PF-I60K / TRUSTARC™ US-49	606	686	26	120, 105, 132 Avg.119	Avg. 4.4
JIS Z3183 S621-H4	≥ 500	≥ 610	≥ 17	≥ 27	≤ 8.5

Table 7 Welding conditions

Flux / Wire	Electrode (6.4φ)	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)	Groove shape
TRUSTARC™ PF-I80ES / TRUSTARC™ US-80SP	L	2050	40	20	462	
	T	1500	48			

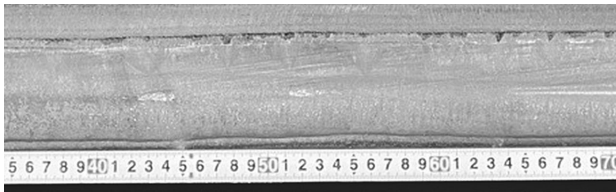


Fig. 9 Bead appearance of [T] PF-I80ES / [T] US-80SP welded joint

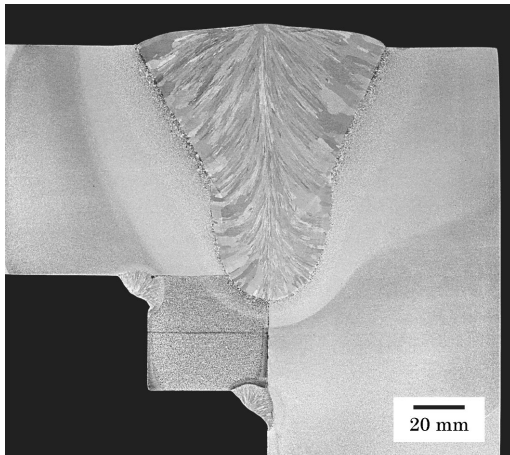


Fig.10 Cross-sectional macro comparison of [T] PF-I80ES / [T] US-80SP welded joint

Table 8 Mechanical properties of welded metals

Flux / Wire	Tensile test			Charpy impact test
	YP (MPa)	TS (MPa)	El. (%)	vE _{0C} (J)
TRUSTARC™ PF-I80ES / TRUSTARC™ US-80SP	644	822	19	Avg. 79
Spec.(780MPa Grade)	≥ 630	≥ 780	-	≥ 27

The results confirm that the tensile properties of the weld metal satisfy the specifications for the base metal of the skin plate, and that the absorbed energy upon Charpy impact testing meets the standard of an average of ≥ 27 J.

3. Welding consumables for ESW

3.1 Lineup of welding consumables by steel strength class

ESW is a high-efficiency welding process primarily used for the vertical welding of thick plates. In this welding method, a wire is continuously fed into a pool of molten slag formed in a weld groove. Current flowing through the wire generates heat due to resistance, heating the molten slag and melting the wire and base metal.⁵⁾ In the architectural steel frame sector, ESW is widely used to join the skin plates and inner diaphragms of box columns, as shown in Fig. 6. Table 9 shows the product lineup broken down by steel strength

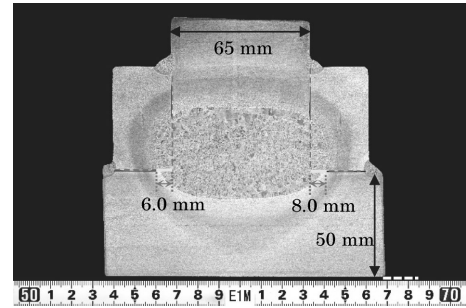


Fig.11 Example of ESW cross-section macro

class. Fig.11 shows the macroscopic cross-section of a typical welding joint as well as the penetration depth, which confirms sufficient penetration.

ESW enables single-pass welding across a wide range of plate thicknesses, with minimal spatter generation and a welding efficiency near 100%. However, because it is a high-heat input process, guaranteeing welding joint performance is a major challenge. Kobe Steel is developing ESW wire for structural steel to overcome this challenge.

3.2 Flux-cored wires for 550-MPa- and 590-MPa-grade steels

The recent trend toward high-strength, thick-walled materials means that to ensure the performance of welding joints, the alloy content introduced via the welding wire must be increased to compensate for the higher heat input. However, solid wires may harden excessively, potentially introducing manufacturing challenges and adversely affecting wire feedability. This challenge served as our impetus for developing FAMILIARC™ EM-56ST and TRUSTARC™ EM-60ST for use with 550-MPa- and 590-MPa-grade steels. The design of these products is based on flux-cored wires to facilitate alloy composition design. FAMILIARC™ EM-56ST is classified as JIS Z 3353 YES560-M, and TRUSTARC™ EM-60ST is classified as JIS Z 3353 YES600-M.

Table 10 shows a sample of the results of testing the mechanical properties of the weld metal per JIS Z 3353. Both wires had a diameter of 1.6 mm and were used in combination with FAMILIARC™ EF-38 flux.

We used diaphragms and skin plates with dimensions of 60 mm × 40 mm and 65 mm × 45 mm to evaluate weld joint performance in the plate thicknesses and high heat inputs frequently encountered in actual structures. Simple T-joints were constructed to simulate the conditions of a diaphragm in a box column. Table 11 shows the combinations of steel materials and consumables, and Table 12 shows the welding conditions and the groove shape.

Table 9 List of Electroslag Welding Materials for building structures

Grade of steel plate	TS 400 MPa / YP 235 MPa	TS 490 MPa / YP 325 MPa	TS 520 MPa / YP 355 MPa	TS 550 MPa / YP 385 MPa	TS 590 MPa / YP 440 MPa
Solid wire (Flux / Wire)	FAMILIARC™ EF-38 / FAMILIARC™ ES-55			FAMILIARC™ EF-38 / TRUSTARC™ ES-60ST	
		FAMILIARC™ EF-38 / FAMILIARC™ ES-55ST			
			FAMILIARC™ EF-38 / FAMILIARC™ ES-56ST		
Flux cored wire (Flux / Wire)		FAMILIARC™ EF-38 / FAMILIARC™ EM-56ST ※1			FAMILIARC™ EF-38 / TRUSTARC™ EM-60ST ※1

※1 : New lineup

Table10 Mechanical properties of the weld metal in compliance with JIS Z 3353

Grade of steel (thickness)	Flux	Wire	Tensile test (center)			Charpy impact test (center)	
			YP(MPa)	TS(MPa)	El.(%)	vE _{5°C} (J)	vE _{0°C} (J)
550 MPa (25 mm)	FAMILIAR TM EF-38	FAMILIAR TM EM-56ST	483	657	26	—	51, 73, 57 Avg.60
JIS Z 3353 YES560-M			≥ 400	≥ 550	≥ 20	—	—
590 MPa (25 mm)	FAMILIAR TM EF-38	TRUSTAR TM EM-60ST	556	737	23	126, 111, 115 Avg.117	—
JIS Z 3353 YES600-M			≥ 450	≥ 590	≥ 20	—	—

※SESNET[®] Note 4), GAP:23 mm, DCEP, 1 layer-1 pass, 380 A-48 V

Table11 Welding consumables and steel plate

No.	Flux	Wire	Skin plate	Diaphragm	Backing bar
1	FAMILIAR TM EF-38	FAMILIAR TM EM-56ST	KCL A385C-ST (t: 40 mm)	KCL A385C (t: 60 mm)	JIS G 3136 SN490B
2		TRUSTAR TM EM-60ST	KCL A440C-ST (t: 45 mm)	KCL A440B (t: 65 mm)	

Table12 Welding conditions and groove shape

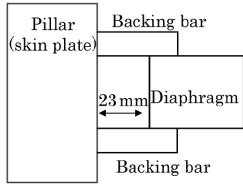
No.	Welding conditions		Groove shape
1	380A-50V Wire feed speed:9 m/min	H.I. : 861 kJ/cm	
2		H.I. : 964 kJ/cm	

Table13 Mechanical properties of the weld metal

No.	Tensile test (center)				Charpy impact test vE _{0°C} (J)		
	YP (MPa)	TS (MPa)	El. (%)	RA (%)	Weld metal (Bond+1 mm)	Skin plate side	
						Bond	HAZ (Bond+1 mm)
1	460	659	26	70	119, 84, 128 Avg.110	141, 122, 83 Avg.115	117, 120, 127 Avg.121
Spec.	≥ 385	≥ 550	—	—	≥ 27J		
2	481	700	25	70	167, 114, 166 Avg. 149	115, 68, 109 Avg.97	124, 111, 108 Avg.114
Spec.	≥ 440	≥ 590	—	—	≥ 27J		

Note 4) SESNET is a trademark of Nippon Steel Welding & Engineering Co., Ltd.

Table 13 shows the mechanical properties of the welding joints, which confirm that the tensile properties and Charpy impact properties of all welding joints satisfy the requirements of the applicable specifications. The Charpy impact properties fully meet specifications not only in the weld metal, but also in the base metal as required in the weld zone of the ESW – specifically, the bond and the HAZ (heat-affected zone, bond + 1 mm).

Conclusions

The construction industry today has a clear need for thicker and higher-strength plates for structural steel columns as well as increased efficiency in the construction of such columns. As such, we are actively pursuing technological developments in welding consumables and welding processes to meet these requirements. We will continue these development efforts to solve our customers'

challenges and ultimately contribute to safe and secure community development and manufacturing.

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Stealth Brace for Traditional Wooden Architecture

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Abstract

In recent years, there has been an increasing incidence of traditional wooden architecture collapsing or suffering damage as a result of earthquakes. These buildings often have open structures with few walls, making their seismic reinforcement challenging. This paper proposes a seismic reinforcement method utilizing high-strength, galvanized steel wire, which possesses sufficient yield strength, toughness, and rigidity to meet the required earthquake resistance performance. Both ends of each steel wire are processed with so-called button heads, allowing the steel wire to bear the stress through the button heads when a tensile load is applied. When a compressive load is applied, the steel wire-end escapes to avoid bearing stress. Therefore, it is expected that the stress generated in the metal-fitting body or column/beam members will be reduced. A horizontal load test has confirmed that the proposed reinforcement method yields sufficient strength and toughness. Going forward, the arrangement angle and fixing anchoring fittings will be employed as parameters to expand the scope of application.

Introduction

Japan is a highly earthquake-prone country. Since the introduction of new earthquake resistance design standards in 1981, there has been a growing demand to improve the seismic performance of buildings. However, important cultural property buildings made of wood before these standards were introduced lack sufficient seismic performance and are at high risk of collapse upon a major earthquake. There are many reports of such traditional wooden buildings suffering damage from earthquakes and losing historical value.

There are currently around 5,500 Important Cultural Properties and 14,000 Registered Tangible Cultural Properties in Japan, and it has become a major challenge to ensure they are properly preserved and to fortify them against seismic activity. Though challenging, it is critical to safety to ensure structural soundness because tourism to cultural heritage buildings has been increasing. As such, the demand for seismic retrofitting of cultural property buildings is expected to further increase.

However, there are numerous challenges associated with this task. First, obtaining permits for retrofitting plans and their execution takes a long time, making it difficult to act quickly. There have

been instances in which structures have collapsed in an earthquake despite plans for seismic retrofitting being complete, highlighting the need for swift action. One such example is the Former Yubikan¹⁾, an educational institution from the Edo period (1603-1867). Furthermore, in buildings from the late Edo period that feature openings with few walls, it is difficult to perform seismic retrofitting without compromising the landscape or architectural design. Current retrofitting methods include sacrificing the openness of a space by installing load-bearing walls, or using lattice walls and steel columns. Such alterations may be discordant with the landscape and design and thus be in opposition to the cultural elements of the structure. Thus, balancing seismic performance with the preservation of cultural assets has become a major challenge. However, new seismic retrofitting technologies have been developed in recent years to overcome this challenge. As one example, we introduce the $\phi 7$ Stealth Brace^{Note)}, a seismic retrofitting method that uses high-strength galvanized steel wire. This solution's small-diameter steel wire makes installation possible even in narrow spaces in a way that minimizes damage to existing members, such as from drilling holes. Furthermore, this product leverages the characteristics of steel wire through the use of components that bear stress during tensile loading and prevent damage to members due to buckling under compressive load.

This paper reports on the results of horizontal load testing of full-scale models, which we conducted to understand the basic mechanical properties of the proposed reinforcement method. This technology will serve as a new option for enhancing seismic performance while preserving the open layouts of historical architecture, thereby improving the safety of cultural property buildings and safeguarding their cultural value.

1. Proposed reinforcement method

The system consists of steel wires and connecting hardware (terminal fittings and anchoring fittings). **Fig. 1** shows an overview of the reinforcement method. The anchoring fittings and the timber of the foundation are secured using coach screws or bolts.

Note) " $\phi 7$ Stealth Brace" is a trademark of Kobelco Wire Company, Ltd.

Fig. 2 shows the behavior of the terminal fittings. Under compressive load, the ends of the steel wires slide outward and do not bear the compressive load. This action maintains the straightness of the steel wires to prevent bowing. This structure counteracts the tensile forces that occur during events such as earthquakes and should prevent damage to shoji (traditional Japanese sliding paper doors) and structural framework. Since the terminal fittings may protrude as the steel wire extends during high-angle compression, they are tapered to ensure a smooth return to their original position.

This paper proposes three structures of reinforcement methods. The structures of the different anchoring fittings are shown in Figs. 3²⁾, 4²⁾, and 5.²⁾

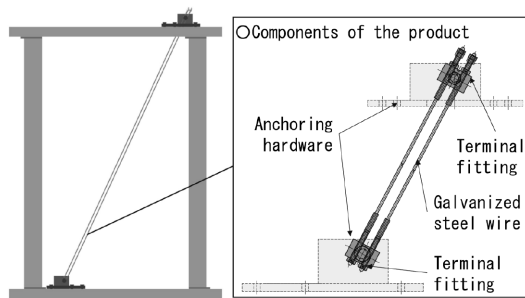


Fig. 1 Overview of reinforcement method

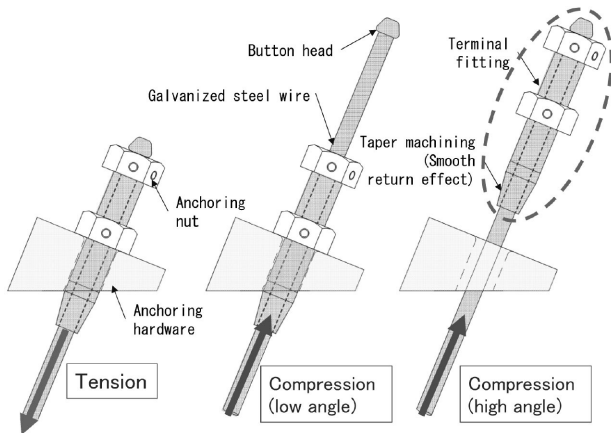


Fig. 2 Behavior of terminal fittings under tensile and compressive conditions

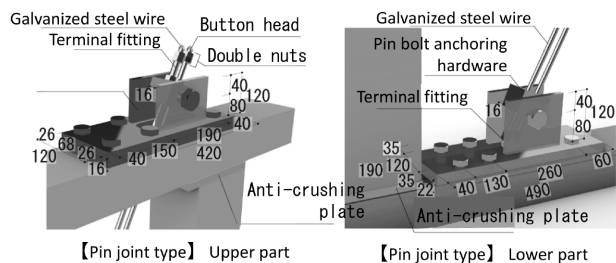


Fig. 3 Structures of Anchoring Fittings [pin joint type]

1.1 Characteristics of galvanized steel wire

Galvanized steel wire is a tried-and-true material typically used in bundles in applications such as cable-stayed bridges. Such cables possess excellent mechanical properties, which we exploited in developing a construction method that uses individual strands. Fig. 6 and Table 1, respectively, show the stress-strain curve and

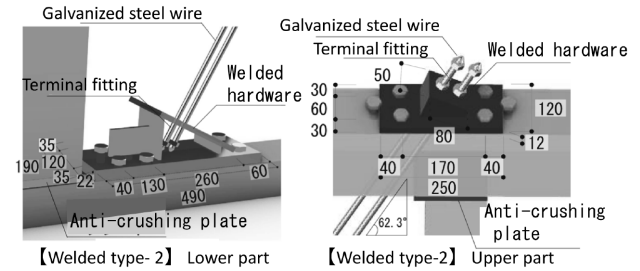


Fig. 4 Structures of anchoring fittings [welded type - 2 wires]

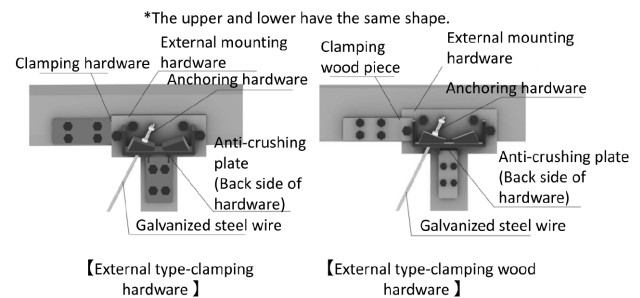


Fig. 5 Structures of anchoring fittings [External type - clamping hardware], [External type - clamping wood hardware]

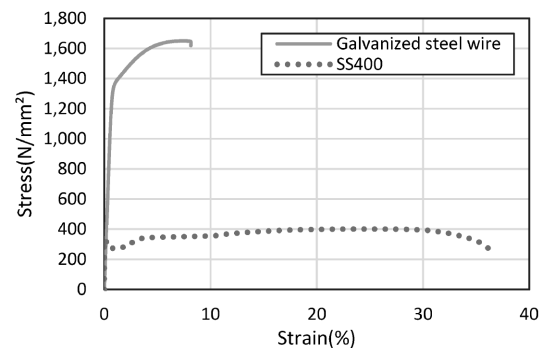


Fig. 6 Stress - strain curve

Table 1 Mechanical properties of galvanized steel wire

Property	Value
Nominal cross-sectional area (mm ²)	38.48
Unit mass (kg/km)	301
Tensile strength	Tensile load (kN) (60.3)
	Tensile stress (N/mm ²) 1,570
Yield strength	Yield load (kN) (44.5)
	Yield stress (N/mm ²) 1,160
Elongation at break	Elongation (%) 4.0
	Gauge length (mm) 250
Elastic modulus (N/mm ²)	(196,000)

mechanical properties of galvanized steel wire. Its yield strength is approximately five times that of SS400, and its tensile strength is approximately four times that of SS400. Further, its elongation at break of approximately 4% means it can track the deformation of wood.

As a further design feature, the button head end (Fig. 7) anchors the ends of the steel wires. Specifically, this cold-formed protrusion provides bearing pressure for anchoring. This method eliminates the need for crimping to the terminal fitting, creating a purpose-built anchoring structure that is active only under tensile load.

1.2 Reinforcement method using pin bolt joints

This method consists of two steel wires and anchoring fittings. At the upper part of the structure, the two steel wires pass through a horizontal member and connect to anchoring fittings that have pin mechanisms. With this design, only axial forces are carried, even during deformation. This reinforcement method is called the [pin joint type].

1.3 Reinforcement method using welded fittings

The anchoring fitting of this method has a fitting welded at the same angle as the initial angle of the steel wire (62.3° in the study for this paper). The connection to the horizontal member is the same as for the [pin joint type]. The size and weight of the fittings are about 60% of those of the [pin joint type].

The steel wire penetrates the horizontal member at the top part and is secured to the fitting. This reinforcement method is called the [welded type].

1.4 Reinforcement method using external fittings

To minimize alteration of existing members and achieve simple construction, this method is designed such that the steel wire is attached to the external surface of the structure without penetrating horizontal members. It consists of one single steel wire and an external anchoring fitting, with the fitting attached to the side of the horizontal member

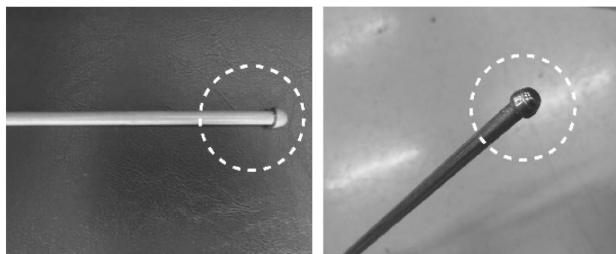


Fig. 7 Button head

and the foundation. Since the steel wire does not penetrate the horizontal member, this method minimizes alteration to existing members. This method also incorporates hardware or a wooden block to resist shear forces by supporting the anchoring fitting. These reinforcement methods are referred to as the [external type – clamping hardware] and the [external type – clamping wood hardware], respectively.

2. Horizontal load testing

2.1 Test method

In the research for this paper, horizontal load testing was conducted on a timber frame to verify the structural characteristics of the proposed reinforcement method. Fig. 8²⁾ shows a schematic diagram of the reinforcement method used for testing, Table 2²⁾ shows the dimensions of the test specimens, Table 3²⁾ shows the dimensions of the main elements of the test structure. The number of steel wires for each reinforcement type was based on considerations of structural stability and stress distribution. Further, we used different numbers of steel wires to elucidate how structural behavior varies depending on the number of wires used. The [pin joint type] has a two-wire configuration to ensure stability. For the [welded type], we conducted tests with one wire and with two wires to determine how the number of steel wires affects the results. For the [external type – clamping hardware] and [external type – clamping wood hardware], we only tested a single-wire configuration in the interest

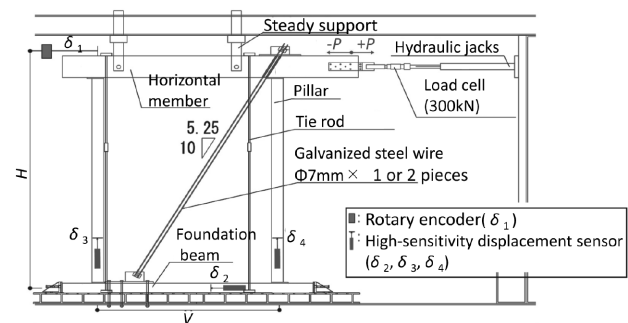


Fig. 8 Overview of reinforcement method

Table 2 Dimensions of test specimens

	H (mm)	V (mm)
【Pin joint type】	2,760	1,820
【Welded type—1】	2,730	1,820
【Welded type—2】	2,760	1,820
【External type— clamping hardware, clamping wood hardware】	2,730	1,177

of structural preservation.

We assembled three test specimens for the pin-joint type and one each for the other types. Testing was conducted in accordance with Allowable Stress Design for Wood-Frame Residential Structures (2017 Edition), with the “tie-rod method” used to apply load.

Load was applied from a deformation angle γ of 1/450 to 1/15 in eight stages. The direction in which tensile force was generated in the steel wires was defined as the positive direction. Cyclic loading – alternating between the positive and negative directions – was performed three times per stage.

Monotonic loading was then performed in the positive direction until a deformation angle of 1/10 rad was reached.

For test specimens with two steel wires, the beam height was increased from 210 mm to 270 mm to prevent the horizontal members from splitting.

2.2 Test results and discussion

Fig. 9²⁾ shows the hysteresis curves for the [pin joint type]. The envelope curves for the [pin joint type], [welded type], and [external type] are shown in Figs. 10²⁾, 11²⁾, and 12²⁾, respectively.

Table 3 Material dimensions

	【Pin joint type】	【Welded type—1】 / 【Welded type—2】	【External type— clamping hardware, clamping wood hardware】
Foundation beam (Douglas fir/E110)	120×120×2,180		120×120×1,897
Horizontal member (Douglas fir/E110)	210×270×3,000	210×210×3,000 210×270×3,000	210×210×2,357
Right pillar (Cedar wood/E70)	120×120×2,561		120×120×2,685
Left pillar (Cedar wood/E70)	120×120×2,541		
Galvanized steel wire	φ 7-3,280×2	φ 7-3,126×1 φ 7-3,207×2	φ 7-2,926×1

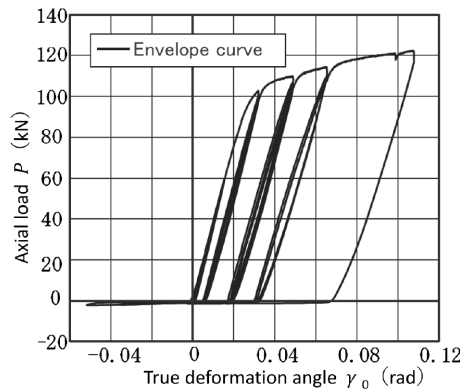


Fig. 9 Pin joint type hysteresis characteristics

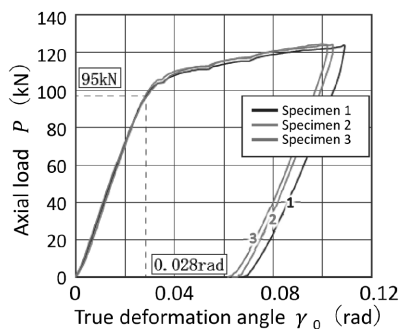


Fig.10 Pin joint type envelope curve

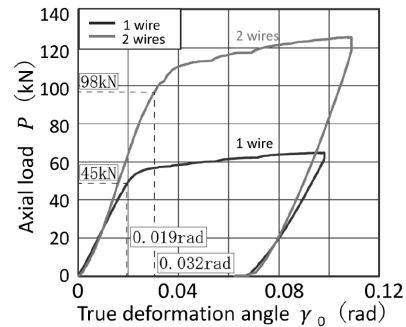


Fig.11 Welded type (1, 2 Wires) envelope curve

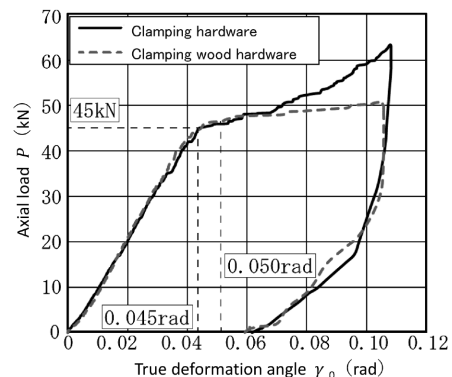


Fig.12 External type (clamping hardware, clamping wood hardware) envelope curve

A comparison and analysis of the test results for each reinforcement method revealed the common behaviors and characteristics described next.

All reinforcement methods exhibited a linear relationship between load and deformation during the initial loading phase and clearly exhibited stiffness until the yield load of the steel wire was reached. Specifically, the respective approximate values are 95 kN for the [pin joint type] (2 wires), 45 kN for the 1-wire [welded type], and 98 kN for the 2-wire [welded type]. For the [external type], yielding was confirmed at approximately 45 kN (1 wire), and it was clear that the load increased essentially linearly up to the yield load.

After the steel wires yielded, all test specimens exhibited a decrease in stiffness, indicating a transition to plastic behavior. However, none of these cases exhibited a sudden decrease in load-bearing capacity or a significant loss of structural performance due to localized failure. This demonstrates that each reinforcement method retains the capacity to bear a certain load even beyond the yield point, ensuring ductile toughness (deformation performance).

Furthermore, in the course of reaching the maximum load, even when the steel wire came near its standard breaking load, no significant damage or failure was observed in the terminal fittings, anchoring fittings, or timber members (pillars and beams). This indicates that sufficient structural safety was maintained. Regarding behavior during compressive loading, all reinforcement methods exhibited a tendency for the steel wires and bolts to extend from the joints at the anchoring points. This definitively indicates that the steel wires were no longer bearing load, thereby confirming the working mechanism of the reinforcing components.

In summary, the results above indicate that for all three reinforcement methods, there is obvious stiffness during the initial loading phase, clear yielding behavior of the steel wires, and high ductility after yielding.

3. Calculation and evaluation of characteristic values for each reinforcement method

3.1 Calculation methods and overview of characteristic values

Fig.13²⁾ shows the bilinear models³⁾ and substitution results of horizontal load testing. **Table 4** shows the calculation results for the short-term standard shear strength and characteristic values.

3.2 Discussion of characteristic values

Fig. 13 confirms similar behavior among the [pin joint type], [welded type], and [external type] structures, as explained below.

The ultimate displacement for all structures falls between 1/20 and 1/10 rad, indicating that they satisfy the safety limits (interstory drift of 1/30 to 1/20 rad) applicable to “extremely rare earthquakes (major earthquakes).” This means it is possible to reuse these structures following repair, permitting a certain degree of damage.

In particular, the [external type] exhibited lower initial stiffness and short-term standard shear strength than other types. Possible causes include localized crushing from the initial deformation angle near the attachment points of the fittings and clamping wood hardware, and torsion and eccentricity in the top part of the horizontal member (upper beam). Nevertheless, even at a deformation of 1/10 rad, there was no significant decrease in load-bearing capacity. The structure has a high capacity to track deformation and exhibits structural properties characterized by high toughness (deformation capacity). Therefore, the method is effective for reinforcing existing timber structures in a way that limits localized damage.

4. Case study (Kobuntei)

Kobuntei⁴⁾, an ancient villa in Mito Kairakuen (one of Japan’s Three Great Gardens), is a historic building designed by Tokugawa Nariaki in the late Edo period. **Fig. 14** shows the exterior of this building. Situated near Lake Senba and Mount Tsukuba, it offers picturesque views from the third floor and is known for the open structure and delicate features of its design. This building has numerous open spaces and a correspondingly low number of walls, putting it at risk of collapse during a major earthquake and therefore prompting seismic retrofitting using $\phi 7$ Stealth Braces. **Fig. 15** shows a conceptual image of seismic retrofitting with lattice windows beside images of the installed $\phi 7$ Stealth Braces. $\phi 7$ Stealth Braces have accomplished seismic retrofitting while preserving the building’s original appearance. With seismic retrofitting completed in 2021 and visitor safety ensured, tea service can now be offered year-round. Similar design elements have been incorporated into two other properties, indicating that this system is gaining traction as a solution for cultural heritage buildings.

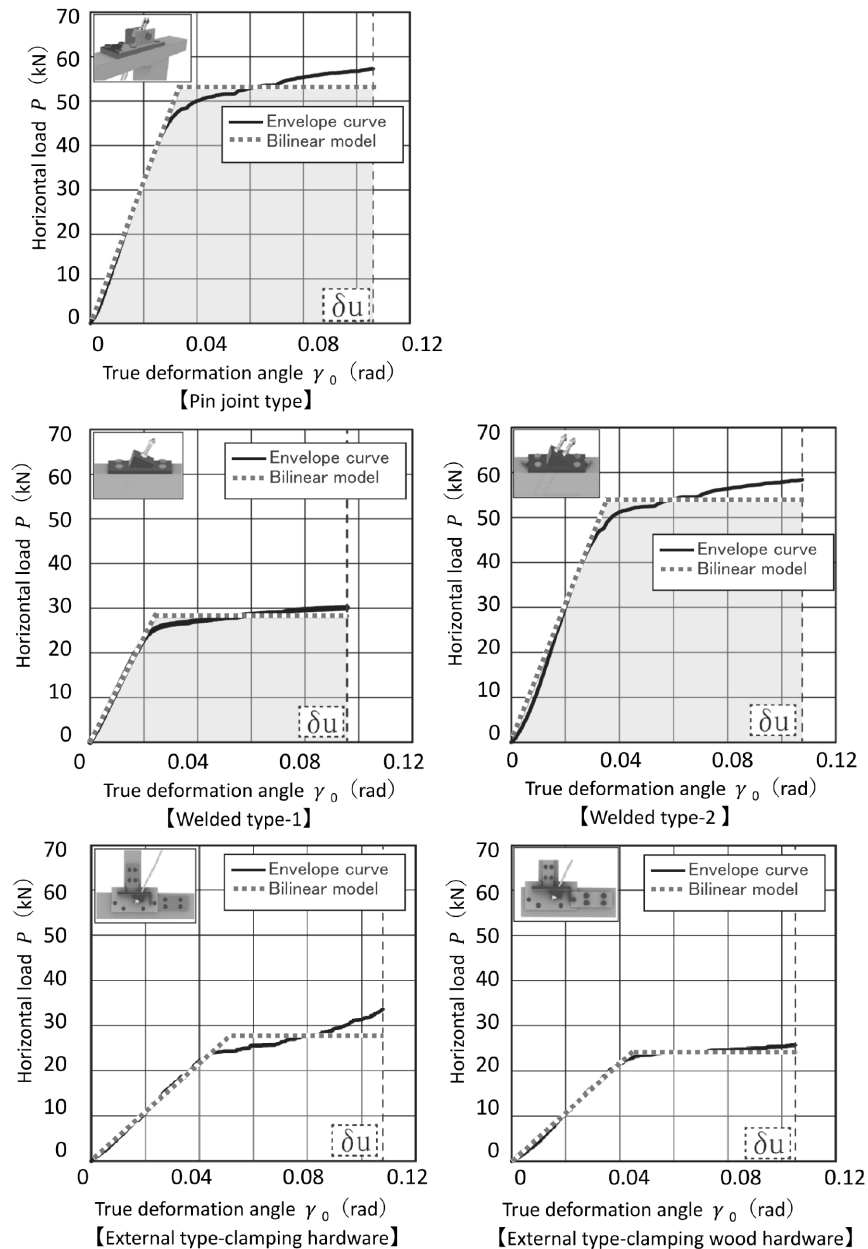


Fig.13 Bilinear model and substitution results

Table 4 Calculation of characteristic values

	【Pin joint type】			【Welded type】		【External type】	
	First unit	Second unit	Third unit	1 wire	2 wires	Clamping hardware	Clamping wood hardware
Initial stiffness K (kN/mm)	0.547	0.549	0.539	0.415	0.529	0.190	0.190
Yield strength P_y (kN)	42.15	39.68	40.60	22.81	39.43	23.08	19.17
Yield displacement δ_y (rad)	0.027	0.025	0.026	0.020	0.026	0.043	0.036
Ultimate strength P_u (kN)	53.20	53.58	53.54	28.23	53.97	27.73	24.19
Ultimate displacement δ_u (rad)	0.106	0.098	0.104	0.096	0.108	0.108	0.105
Plasticity ratio μ	3.163	2.914	3.040	3.924	3.050	2.099	2.340
Structural characteristic coefficient D_s	0.433	0.455	0.444	0.382	0.443	0.559	0.521
Short-term standard shear strength P_d (kN)	8.613			7.699	6.697	3.138	2.723

* The gray shading indicates the test of a single steel wire.



Fig.14 Exterior of Kobuntei

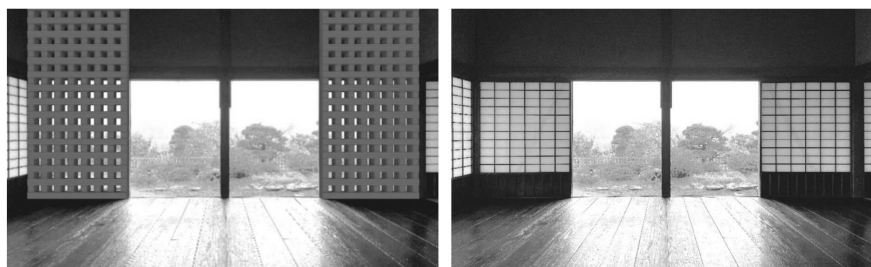


Fig.15 Potential and actual reinforcement methods at Kobuntei
left: Lattice window (conceptual image) right: $\phi 7$ stealth brace (installation photo)

5. Summary of findings

In the research for this paper, we performed horizontal load testing on three types of reinforcement methods. The results confirm that all methods exhibit excellent structural characteristics in terms of initial stiffness, yield behavior, and ductility, indicating that these methods constitute effective new options for the seismic retrofitting of historic buildings.

Common seismic retrofitting methods include sacrificing the openness of a space by installing load-bearing walls, or using lattice walls or steel columns to provide reinforcement in a way that maintains natural light and airflow. These methods nearly always compromise the architectural design. Our development exploits the characteristics of shoji, which maintain full-width openings and have two panels that overlap when slid aside for opening. Specifically, by installing reinforcement members in the gap between the two panels, our technique improves seismic performance without compromising traditional aesthetic. Seismic retrofitting using $\phi 7$ Stealth Braces made it possible to preserve the original appearance of Kobuntei.

Conclusions

The positive results detailed in this paper have driven us to pursue several related initiatives. First, to expand the product's scope of application, we will conduct further validation tests regarding differing angles resulting from changes in beam span. In conjunction, we will establish standards based on our results and create a brochure that clearly summarizes the product's characteristics. Finally, we will educate architectural firms and cultural heritage preservation organizations to raise awareness of the $\phi 7$ Stealth Brace and promote its use.

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Introducing New Automation System and CAD-Linked Software for Architectural Steel Frame Beam Welding

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Abstract

Steel frame fabricators are facing challenges such as shortages of skilled workers and the need to improve productivity, driving demand for automation solutions. Kobe Steel has developed beam welding software that integrates with steel frame design CAD data and has also created a system that automates the assembly process, which is the process before beam welding. The developed software automatically generates operating programs for the system directly from the CAD data of the frame design. The automated assembly system supports a wide variety of beam and column shapes, enabling automated assembly and welding. This facilitates deskilling and improved assembly precision, while also achieving high-quality welding, which helps resolve the challenges faced by steel frame fabricators.

Introduction

Based on the statistics on building starts published by the Ministry of Land, Infrastructure, Transport and Tourism, the demand for steel frames in fiscal year 2024 was about 3.65 million tons. This marks the second consecutive year that demand was below 4 million tons.¹⁾ Although there are large-scale projects such as redevelopment in the Tokyo metropolitan area, the demand for steel frames remains low, owing to factors including sharp increases in material costs and construction plan pivots made necessary by labor shortages.²⁾

Amidst this environment, steel frame fabricators are feeling the pressure to automate every stage of their operations – not just welding – both to improve productivity and quality and to counteract the labor shortages that have intensified over the last few years. Structural steel beams have lagged behind structural steel columns in terms of automated fabrication, revealing the former as the next challenge to tackle.

This paper introduces our SMART TEACHING™ software (Note 1), which automatically generates welding information based on CAD data. It also introduces our structural steel beam automatic assembly and welding system, which automates the assembly process that precedes main welding.

Note 1) SMART TEACHING is a trademark of Kobe Steel, Ltd.

1. Background of development

Efforts toward automating the fabrication of architectural steel frames have traditionally centered around box columns, and more specifically on structural steel columns. The pertinent processes are characterized by long welding times and high arc generation frequencies. These factors are particularly concerning because the average age of the workforce is increasing and because the steel fabrication sector is susceptible to the impacts of labor shortages. Furthermore, Japan's work hour limits mandated in 2024 have made it increasingly difficult to maintain throughput.³⁾

Against this backdrop, steel frame fabricators are likely to automate processes that have traditionally relied on manual labor. Welding robots can handle an ever-growing range of workpieces, making consistent, high-quality welding possible and simultaneously helping to alleviate labor shortages impacting welding operations. The welding process for structural steel beams has a shorter welding time than that of structural steel columns. However, there has been relatively little progress toward automating the former. This is due in part to the wide variety of workpiece dimensions, which does not lend itself well to automation. Consequently, increasing attention has centered around automated welding systems for structural steel beams.

Furthermore, the construction industry is promoting digital transformation (DX) and BIM (building information modeling), which uses 3D models of buildings to improve productivity. Integrating CAD data for steel frame design using the concept of BIM enables continuous data management from design to construction, which will reduce errors in every process and improve efficiency.

Labor shortages are afflicting societies all over the world. In North America in particular, the severe shortage of welders and increasing labor costs are driving momentum in the automation of assembly and welding. A related issue is that because Japan experiences frequent earthquakes, building columns are usually box columns and circular steel tube columns, or SRC (steel-reinforced concrete) structures. Many regions outside Japan, including North America, have relatively low seismic activity.

As such, the columns in high-rise buildings in these areas usually use H-beams (similar to building beams). These markets can make use of automated systems designed for H-beams.

This situation led us to develop SMART TEACHING™, which links to CAD data for steel frame design, as well as our structural steel beam automatic assembly and welding system. These developments will improve construction efficiency and quality, thus enhancing productivity and competitiveness for steel frame fabricators that adopt these innovations.

2. Challenges in assembly process and overview of the system and software developed

In steel frame structures, various parts are attached to the main members, such as H-beams and box columns. These parts are positioned so as to reinforce the main members and connect them to each other or to structural elements such as floors. **Fig. 1** shows an outline of the conventional assembly process. In the part assembly process, technicians first read drawings to determine the attachment positions of each part. They then align parts in the specified positions and finally perform tack welding. There are multiple issues associated with this process. First, reading drawing dimensions properly and aligning parts in the specified positions takes great skill – it is challenging to secure competent personnel. Next, even a skilled technician takes quite some time to execute this process, leaving room for optimization. Additionally, weld quality and thus product quality may vary because the process is dependent upon the technician's skill level. Furthermore, errors in reading drawing dimensions or low accuracy during alignment could lead to rework during main welding or during assembly at the construction site.

We developed our automatic assembly and welding system for structural steel beams precisely to address these issues. **Fig. 2** shows a 3D representation of the system. It comprises a parts identification device, a handling robot with slide, a turn-over positioner, and a welding robot with slide. It also has a PC with our SMART TEACHING™ software, which links to CAD data for steel frame design.

The purpose of each device and how it fits into the system are described next. First, the operator uses SMART TEACHING™ to generate the information needed for assembly and welding processes from CAD data and load it to each element. The operator then loads the beam onto the turn-over positioner, loads parts onto the parts

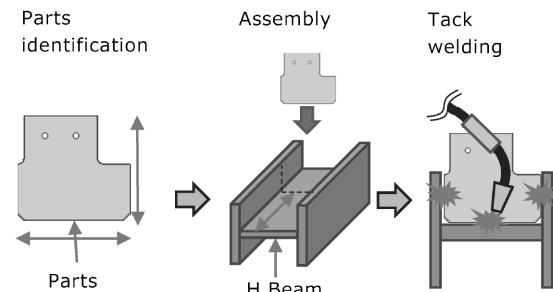


Fig. 1 Assembly process

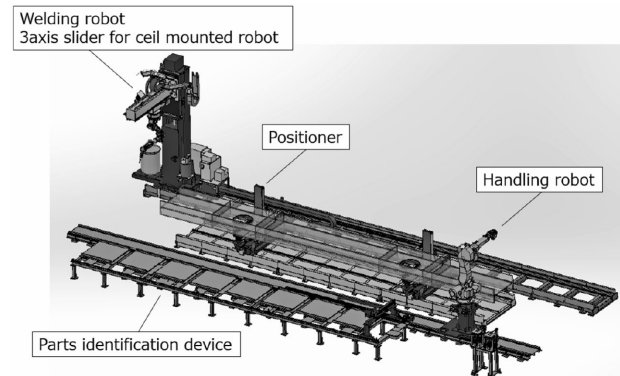


Fig. 2 Structural steel beam auto assembly welding system

identification device, and starts automatic operation. During automatic operation, the parts identification device determines the geometry of the parts, assesses whether the parts can be assembled, and locates the parts. A handling robot with a gripper retrieves a part from the parts identification device, moves to the attachment position for the part, and positions the part on the beam, which is on the turn-over positioner. The handling robot has a tool changer so it can handle parts with various geometries. After the handling robot positions the parts, an welding robot performs tack welding. Part assembly occurs through iterations of these steps of part identification, part positioning, and tack welding. When a part must be attached to a different face of the main member, such as the rear, the turn-over positioner changes the orientation of the beam. After part assembly is complete, the welding robot and turn-over positioner perform main welding.

This system automatically generates welding information and operating programs for assembly and main welding based on CAD data for steel frame design, yielding the core feature of automating both assembly and main welding in steel beam fabrication. The following sections describe SMART TEACHING™ and its components.

3. Features and operation of the CAD-linked software SMART TEACHING™

In conventional welding systems for steel frames, operators consult drawings for workpiece dimensions and welding variables, measure workpiece dimensions, and manually enter data into a program. By contrast, SMART TEACHING™ is linked to the CAD data for steel frame design so it can automatically extract the information necessary for assembly and welding from the CAD data. This eliminates input errors and time wasted on manual input. SMART TEACHING™ is operated from both the office and the shop floor.

Fig. 3 illustrates operation from the office, where the scope of automation is initially determined based on factors such as the parts to be attached and equipment operating time. If the system determines that assembly and welding will be performed, it processes an IFC file with CAD data on an entire building. SMART TEACHING™ then automatically generates an ST file for each main member to be welded. Kobe Steel's proprietary ST file format is an XML-based file with dimensional data on an individual main member and the parts to be welded to it. If an ST file cannot be prepared, the design data on an individual main member can be exported from the BIM software as an IFC file. The ST or IFC file generated is then transferred to the shop floor PC via USB or LAN, completing the preparatory work in the office.

Fig. 4 illustrates the subsequent process at the

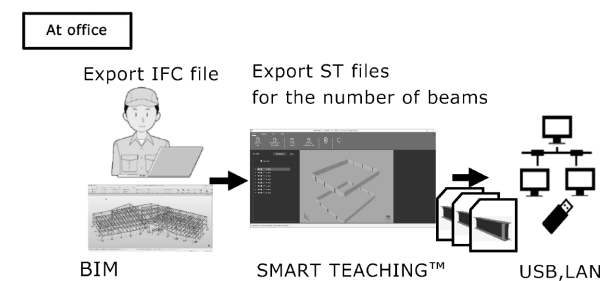


Fig. 3 Operation of SMART TEACHING™ software in the office

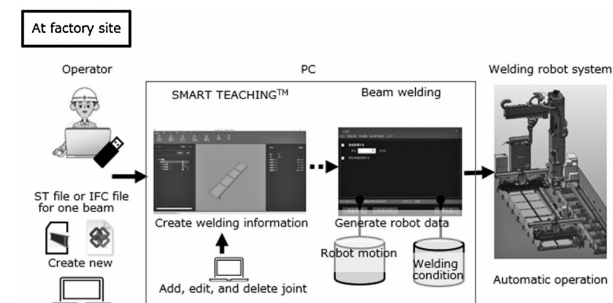


Fig. 4 Operation of SMART TEACHING™ software at factory site

shop floor PC. Once the ST or IFC file for a main member has been loaded from the office and sent to SMART TEACHING™ on the shop floor PC, the main member viewer on the shop floor PC can be used to compare key specifications in the program with the actual main member and parts. These specifications include dimensions, geometry, the serial number of the main member, and welding information such as leg length and the length of parts that cannot be welded by the welding robot. Parts can be added, deleted, or edited as needed. Verifying the physical object against the data in the system on the shop floor prevents damage to equipment caused by errors and welding mistakes. After the operator confirms that all specifications are correct, the motion program is generated and sent to the welding robot, and automatic welding begins.

4. Features of each component of the structural steel beam automatic assembly and welding system

Described next are products and technologies we developed to automate assembly and welding.

First, we have developed various handling tools for handling robots to accommodate parts with different geometries and attachment processes in the automated assembly of parts. One of these tools is a magnetic end effector for gripping stiffeners and gusset plates. Another tool uses linear motion devices, proximity sensors, and similar components to grip ring-shaped reinforcement members of various sizes for through-holes.

The parts identification device (**Fig. 5**) consists of a pallet section for arranging parts and a device that measures part geometries. The measuring device has a profile sensor that reads the three-dimensional measurements of a target object to a resolution of 0.1 mm. This sensor is on a carriage mounted on a gantry-type frame. As the sensor travels over the pallet in a precise manner, it reads the part geometries, including thickness. The system uses the precise measurements to determine whether a part can be assembled to the main member. It also calculates the positioning coordinates for the handling robot to grasp the parts, achieving positioning accuracy with a total error of ± 1.0 mm.

We also developed the welding robot's slide and the workpiece positioner for this system. The slide is designed for an overhead-mounted robot and is capable of 3-axis motion. By routing the torch cable through the robot's rotating parts, we reduced interference with equipment and workpieces, making this system usable in a wider spectrum of cases. Additionally, because the weaving accuracy

of a welding robot is critical to welding quality, we ensured that the robot can operate with a very high level of accuracy.

The positioner we developed is a turn-over positioner (**Fig. 6**) capable of handling H-beam workpieces weighing up to 8 tons. This positioner has two pairs of hydraulic arms that operate in unison to turn the beam over. It accommodates beams with a depth of up to 1,200 mm. Thus, it has an expanded maximum dimensional capacity compared with our conventional rotary positioners, which have a workpiece width limit of 1,000 mm. The key feature of the turn-over positioner, however, is the scope of capabilities it makes possible. Conventional rotary positioners, which are primarily designed for box columns and circular steel tube columns, grip the workpiece using a ring-like chuck. The chuck can interfere with the welding robot at the gripping point, creating an area of up to 4,400 mm on the beam that is inaccessible for assembly or welding. The main member must be shifted and repositioned for the robot to access these remaining sections. By contrast, since the turn-over positioner supports the main member from below, no areas are made inaccessible due to interface points between a gripping mechanism and the beam. A further benefit of supporting the main member from below is that the labor to chuck the beam is eliminated, improving production efficiency and yielding savings in labor costs. However, it does take longer to turn the main member over compared with rotating on a conventional rotary positioner. Since the two pairs of hydraulic arms must operate in sync to turn the



Fig. 5 Parts identification device



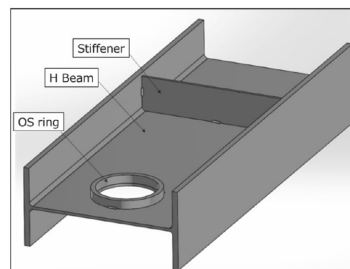
Fig. 6 Positioner

workpiece over while supporting its weight, the speed of this operation had to be limited to prevent the workpiece from falling. To address this issue, we developed a control method that increases the speed of the arms while supporting the full weight of the workpiece. Kobe Steel's turn-over positioner now incorporates load monitoring via oil pressure sensors and oil flow control to reduce turn-over time by about 20%.

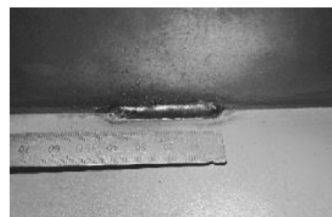
5. Expansion of scope through tack welding

Kobe Steel has extensive experience developing tack welding techniques that improve the efficiency and quality of main welding. In developing the system covered in this paper, we also developed techniques to support robotic tack welding, which involves different techniques from main welding.

Many different types of parts get welded to beams, and they come in a variety of shapes and sizes. We have established various tack welding techniques to address this diversity of scenarios. We have achieved tack welding that meets the leg length and bead length specified by Japanese Architectural Standard Specification (JASS6) in not just the horizontal position, but also the vertical position (**Figs. 7(a), 7(b)**). Furthermore, by combining a turn-



(a)



(b)



(c)

Fig. 7 Appearance of welded assembly (a) Sample 3D model, (b) Web and stiffener tack welding, (c) OS ring and web tack welding

over positioner with an overhead-mounted slide, this system can weld ring-shaped parts such as OS Rings ^(Note 2), which could not be handled by Kobe Steel's conventional products (Figs. 7(a), 7(c)).

6. Benefits of the system

This system achieves automation in a way that includes the structural steel beam assembly process, which has not yet been widely automated in Japan. As such, the system should solve multiple challenges faced by steel frame fabricators.

First, it addresses labor shortages and improves productivity. Automation using robots reduces the labor required for the assembly process, thereby counteracting labor shortages. Furthermore, because automation reduces the skill level required for assembly and welding, it counteracts shortages in skilled labor specifically. Additionally, since an automated system can operate 24 hours a day, it significantly improves productivity.

Automation also improves product quality. Robotization enables the production of high-quality products even without skilled workers who have advanced technical expertise in assembly or welding. Furthermore, linking to CAD data reduces manufacturing defects caused by operator input error and should increase yields.

FAMILIARC™ MX-Z200MP ^(Note 3), the recommended consumable for this system, yields favorable slag adhesion characteristics and a lustrous bead appearance. In this way, it is possible to achieve high-quality fillet weld joints (a common joint type in structural steel welding). In addition, the reduced spatter positively affects downstream processes. The associated time savings in cleaning and finishing processes is expected to reduce costs.

Finally, our system improves workplace safety. Specifically, craning is not required, even to attach parts to large components, ensuring a safe work

environment by reducing the risk of accidents. Advancing automation through robots is helping to relieve physical strain on operators.

This system solves two key challenges faced by steel frame fabricators: labor shortages and the demand for increased productivity. Reduced labor and personnel costs, improved safety, shorter production lead times, lower technical skill requirements, and continuity through CAD integration together yield efficient, high-quality production. In this way, our system enhances competitiveness and enables sustained growth.

Conclusions

This paper introduces the technologies and key features of SMART TEACHING™ and our structural steel beam assembly and welding system. We are expanding the scope of parts to which these technologies can be applied and are fostering automation in the material handling of main members and parts. Our end goals in doing so are to increase the proportion of cases in which these technologies can be used and to automate the processes upstream of welding.

Moving forward, we will improve welding technology and develop automation technologies for the processes upstream and downstream of welding. In this way, we will continue developing products that meet users' automation needs.

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Note 2) OS Ring is a trademark of OKABE Co., Ltd.

Note 3) FAMILIARC is a trademark of Kobe Steel, Ltd.

Compact Portable Welding Robot System with Vision Sensor

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Abstract

The use of welding robots in the welding field is on the rise, driven by a shortage of skilled welders and the growing demand for higher productivity. Concurrently, research involving vision sensors is being explored to address complex welding tasks that are difficult to handle with traditional robotic systems. This paper presents our work on automating horizontal first-layer penetration welding using a compact, portable robotic welding system equipped with a vision sensor. The system achieves welding automation by integrating a vision sensor with a portable robot. During first-layer welding, the system automatically tracks variations in the root gap and follows the welding path by identifying key features of the molten pool, adjusting the weaving motion as needed. From the second layer onward, the system updates the build-up parameters based on groove information acquired during the first layer, enabling fully automated welding through to the final layer.

Introduction

Welding is an indispensable technology in manufacturing, and one that requires craftsmanship. However, Japan's declining birthrate and aging population alongside a decrease in the hiring rate of young workers has created a major societal challenge in the form of a shortage of welders. Full-penetration welding in particular demands a high level of technical skill and does not lend itself well to automation.

This requirement led Kobe Steel to develop technology that uses a vision sensor (i.e., a camera) and deep learning (hereafter, AI) to recognize key features in molten pool images and control the welding process accordingly. This technology enables optimal full-penetration welding in a way that tracks changes in the root gap (RG) and incorporates anomaly detection as a countermeasure against disturbances during welding.^{1)–7)}

In this paper, we introduce a system comprising a compact portable robot with this technology and a vision sensor system. The overall system (hereafter, “this system”) is made up of the ARCMAN™ PORTABLE^(Note 2) and AIWelder™^(Note 1). We also report on our research into automating horizontal

first-layer full-penetration welding with a ceramic backing bar assuming a horizontal joint, which takes great skill to weld.

1. Overview of this system

Fig. 1 shows the configuration of the hardware of this system. There is a vision sensor on the torch of a compact portable welding robot. A computer (hereafter, PC) collects molten pool image data captured by the camera for inferential control. Feature points are extracted in real time for the calculation of control correction values, which are transmitted to the robot controller. The system executes welding by referencing correction instruction values against a torch motion control database constructed beforehand to control robot motion.

1.1 AIWelder™

In this system, a camera captures molten pool images so a PC can perform AI-based image recognition for robot control. In tandem, the images and welding information are displayed on an Android smartphone^(Note 3). This configuration of the camera, PC, and smartphone makes up AIWelder™, shown in Fig. 2.

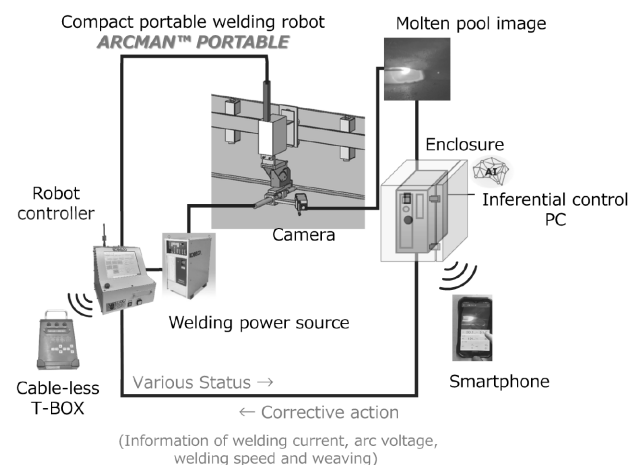


Fig. 1 System hardware configuration

Note 1, 2) AIWelder and ARCMAN are trademarks of Kobe Steel, Ltd.

Note 3) Android is a trademark of Google LLC.

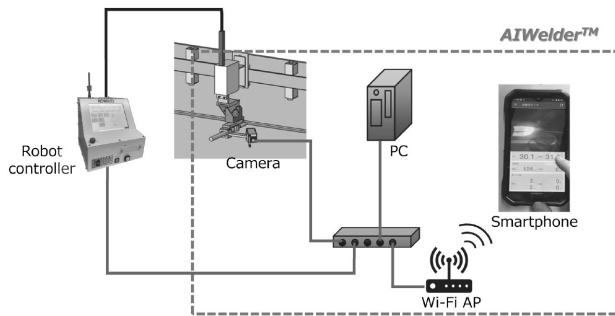


Fig. 2 AIWelder™ overview

A critical factor in high-quality welding is adjusting the motion of the torch based on the shape of the molten pool. The elements of AIWelder™ work together to enable welding comparable to that of a skilled welder. The camera serves as the eyes monitoring the molten pool, the AI serves as the brain interpreting its shape, and the PC controls the motion of the torch based on the characteristics of the molten pool.

The first part of the system to explain is the camera, or the “eyes” of the system. A standard color camera cannot effectively capture the molten pool because either the intensity of the light from the arc overexposes the image, or the light intensity must be so low that the shape of the molten pool is indistinguishable. Therefore, the system’s camera uses HDR (high dynamic range) technology, which combines multiple frames at different exposures to capture clear molten pool images.

Next is the “brain” of the system, the AI, which is detailed in Section 4.1. We trained the AI on numerous molten pool images so it can not only estimate the root gap from molten pool images, but also adjust welding speed and the target position of the wire.

Last is the PC, which acquires molten pool images, performs calculations using the AI image recognition model, calculates the correction values necessary for robot control, and sends the correction values to the controller. At the same time, it collects various status parameters (e.g., welding current, arc voltage, and welding speed) from the controller to create an execution record. For each pass, a report is compiled with the status parameters as well as an assessment regarding the presence of welding anomalies based on AI image recognition. Additionally, the molten pool images are saved as videos. Upon completion of the final pass, the system compiles a final execution report with a summary of the execution records for all passes. This report makes it easy to manage the execution records.

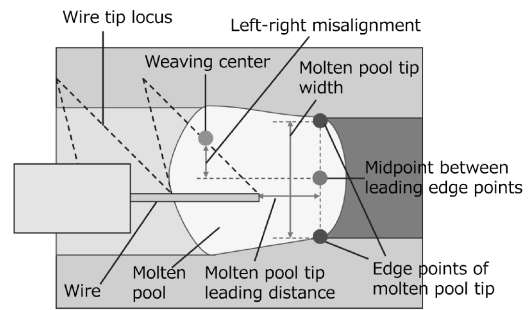


Fig. 3 Measurement of molten pool

1.2 Basics of the control method

One method for controlling torch position in robotic welding is arc sensing. This method involves detecting the relative positions of the groove and the center of the joint based on welding current and using this result to make the wire tip track the groove.^{8), 9)}

The torch position control method in this system controls the wire tip position by using the feature point coordinates from the molten pool images received from the PC to directly calculate the relative positions of the groove and wire tip. The system measures three core distances (Fig. 3): molten pool tip width (i.e., root gap), based on the edge points of the molten pool tip; left-right misalignment (i.e., relative positions of the wire tip and the edge points of the molten pool tip); and molten pool tip leading distance (i.e., the distance from the wire tip to the molten pool tip). After these parameters are measured, welding conditions such as weaving width, standard welding speed, welding current, arc voltage, and weaving angle are constantly adjusted based on molten pool tip width. Using these values, welding is performed under the conditions that are optimal for the root gap. Additionally, the system performs fine adjustments to the welding speed based on the molten pool tip leading distance, and fine adjustments to the torch position based on the left-right misalignment (see Section 4.2).

2. Market needs and target joints

We collected data on the market needs for this system through a great deal of interviews with customers and surveys conducted at international welding exhibitions. Results show that many companies consider the shortage of skilled welders to be a major challenge looming in the near future, and that there is a high demand for this system to be applied in flat and horizontal welding positions. In particular, we found that horizontal first-layer penetration welding using a ceramic backing bar

often entails longitudinal variation in the root gap. We also found that this welding process was still considered too challenging to automate. Our data also revealed the applications with the highest potential for making use of this system. These included applications in the bridge and shipbuilding sectors, specifically for the horizontal joints in the main towers of steel bridges and for the horizontal joints in the side plates of ships.

3. Welding method concept

Fig. 4 shows the three main elements behind this system's welding method concept.

The first element is that sensing before welding occurs at only a single point, which is near the starting point. Conventional compact portable welding robots are guided primarily using multi-point sensing, requiring sensing at dozens of points for weld lines several meters long. By contrast, this system has a camera to capture key information during welding. Specifically, it captures the root gap and weld line specifications as measured by the sensing process described above. This is how the system achieves control by sensing just a single point near the starting point, significantly reducing sensing time.

The second element is that during first-layer welding, the robot tracks the root gap and weld line based on information obtained from the camera using an AI image recognition model. In conventional welding executed based on multi-point sensing, groove data between sensing points cannot be acquired. As such, welding is performed based on information calculated through methods such as linear interpolation between two given points. By using a camera, root gap and weld line information can be acquired in real time along the entire weld line of the first layer, enabling appropriate control of the torch. Better weld quality ensues because this welding method closely resembles that of the carefully executed semi-automatic welding of a skilled technician.

The third element is that to weld the second layer

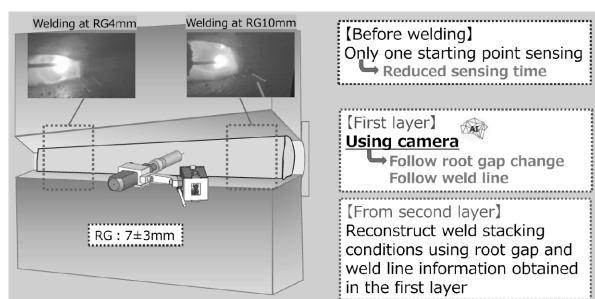


Fig. 4 Welding method concepts

onward, the build-up parameters are updated to reflect the root gap information obtained in the first layer. This function, detailed further in Section 4.3, enables automatic welding from the first layer to the final layer.

4. Key underlying technologies

This section introduces the five underlying technologies required for this system: AI image recognition, torch motion control architecture, build-up parameter updating, anomaly detection, and dedicated welding consumables.

Next is an explanation of how these technologies relate to the three elements described in Section 3. Single-point sensing is made possible simultaneously through root gap and weld line tracking during first-layer welding. This root gap and weld line tracking during first-layer welding is made possible through the combination of AI image recognition, torch motion control architecture, anomaly detection, and dedicated welding consumables. Meanwhile, build-up parameter updating for the second layer onward is made possible through the build-up parameter update function.

4.1 AI image recognition

To control the robot based on the weld line and changes in the root gap, this system uses AI image recognition to identify feature points in molten pool images. The three feature points recognized and used for control are the wire tip, the top of the molten pool tip leading edge, and the bottom of the molten pool tip leading edge (Fig. 5).

The system uses these feature points to calculate the molten pool tip width (i.e., root gap); the midpoint between leading edge points (i.e., weld line); and the molten pool tip leading distance, which is used to determine the appropriate welding speed. Regression models that can output numerical values are the typical method used to predict numerical values from input data. One approach to molten pool recognition is to create a model that predicts the coordinate values of individual feature points in the form of image data. This system, however, uses an AI model that outputs a probability map indicating the probability of the existence of a feature point. The probability map makes it possible to consider the reliability of the prediction results. This in turn enables high control stability through the use of only highly reliable predictions.

We trained the model described above using

approximately 23,000 images under various conditions to achieve highly accurate and consistent feature point recognition.

However, even a highly accurate recognition rate does not preclude recognition errors when large spatter particles or scale in the groove partly obscure the molten pool, as shown in Fig. 6. Erroneous feature point positions could lead to erroneous values being used for robot control (e.g., molten pool tip width), potentially reducing the robot's tracking performance. Therefore, the system continuously monitors values such as molten pool tip width and filters them using an anomaly detection filter that operates based on the Hampel test. Fig. 7 compares the proposed method with a moving average filter – a type of conventional low-pass filter – based on time series data of the calculated molten pool tip width. The proposed method clearly removes (ignores) sharp deviations caused by recognition

errors. When an anomaly occurs, the system holds the value from immediately before the anomaly and resumes normal control once the system recovers from the anomalous condition. This makes the system robust against disturbances that could cause recognition errors.

4.2 Torch motion control

This section introduces three control guidelines for torch motion control during first-layer welding. These guidelines are driven by the feature points recognized by the AI image recognition model described in Section 4.1.

The first guideline is that of diagonal weaving and edge stop conditions. This part of torch motion control supports diagonal weaving that improves bridging during first-layer welding. Based on the molten pool tip width calculated from the molten pool image, the system uses a torch motion control database to control the angle, width, and top and bottom edge stop conditions (time, welding current, and arc voltage offset) during diagonal weaving. This control guideline achieves the optimal torch path based on the root gap.

The second guideline is welding speed. The system controls this parameter based on molten pool tip width by referencing the torch motion control database. The system simultaneously calculates the molten pool tip leading distance. If this deviates from the reference value, the system increases or decreases welding speed accordingly. This control guideline maintains a constant distance between the molten pool tip and the wire tip, ensuring a consistent back bead shape and preventing burn-through.

The third guideline is weld line tracking. The system monitors the wire tip to align the center of the weaving path with the center of the molten pool tip width. This control guideline makes tracking possible even when the weld line is not parallel with the robot's travel axis or is not straight.

4.3 Build-up parameter update function

First-layer welding is controlled based on measurements from an AI image recognition model, as described in Section 4.1, enabling welding that adapts to changes in the groove shape.

For the second layer onward, however, measurements using feature points from the AI image recognition model are not performed. Automatic welding of these layers is accomplished by controlling torch position and welding speed based on measurements from the first layer.

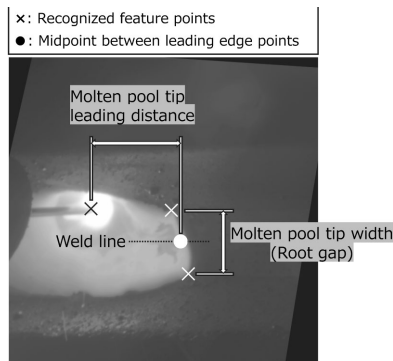


Fig. 5 Feature points recognized by AI

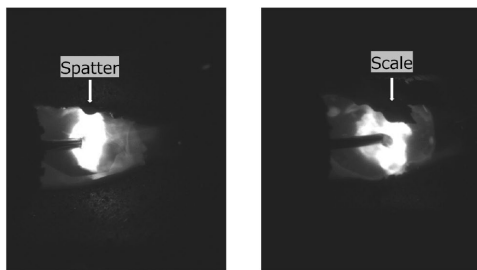


Fig. 6 Example of spatter and scale in groove

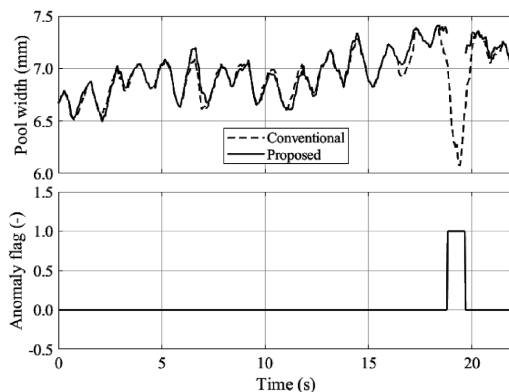


Fig. 7 Filtering results by anomaly detection filter

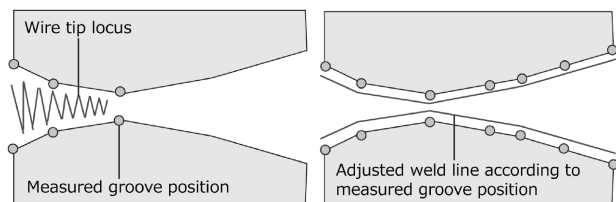


Fig. 8 Process of first layer

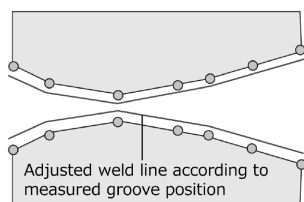


Fig. 9 Process of second layer and following

Reference build-up parameters are established upon the start of first-layer welding. These reference build-up parameters are automatically generated based on preset parameters and on groove geometry detected by sensing. Once reference build-up parameters are established, first-layer welding occurs via the control method described in Section 4.2. During first-layer welding, the edge points of the groove are recorded every time a specified interval of weld length is welded, or whenever the root gap or the center position of the groove changes by a threshold value (Fig. 8). For the second layer onward, the target position and welding speed are adjusted based on the reference build-up parameters to align with the edge points of the groove recorded during first-layer welding, ensuring a uniform bead height along the entire groove (Fig. 9). This control function makes it possible to automate multi-layer welding for grooves with varying geometries.

4.4 Anomaly detection function

To this point, we have described our technologies for automating the first layer of one-sided full-penetration welding and for incorporating first-layer groove parameters into subsequent layers for build-up parameter updating. However, during actual application, welding problems can arise from disturbances or from groove geometries or conditions outside the control range. This system has a camera to monitor molten pool conditions. It also has a function to stop welding or send a warning to a terminal (smartphone) when it detects an anomaly, such as when the molten pool tip width is outside the root gap control range.

4.5 Dedicated welding consumables

This system requires uniformity of the back bead with a root gap of 4 to 10 mm during horizontal first-layer welding, which is a highly challenging process. As such, the key challenge is to ensure effective bridging, particularly for the wider end of the root gap range. We also tackled the challenge of preventing a lack of fusion and improving cracking resistance by developing dedicated wire to suppress

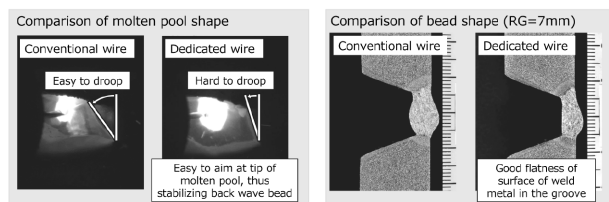


Fig.10 Comparison of conventional and dedicated FCW

welding defects.

We used the composition of conventional mild steel flux-cored wire (hereafter, FCW) as a baseline for developing the optimal weld metal and slag component compositions. To do so, we ran simulations using thermodynamic equilibrium prediction software and conducted testing to evaluate slag fluidity. The result is a wire composition that exhibits satisfactory bridging performance with root gaps of 4 – 10 mm and yields favorable back bead geometry. Additionally, our composition helps ensure a flat front bead to which slag does not readily adhere. This is important for suppressing lack of fusion in the second weld layer, which can occur if residual slag cannot be completely removed. Furthermore, this composition prevents sagging of the molten pool tip leading edge. This makes it possible to ensure a consistent molten pool tip leading distance, in turn stabilizing torch motion control driven by AI image recognition. Fig.10 compares the results of conventional mild steel FCW and the dedicated FCW. Furthermore, we considered how each individual element of the composition affects hot and cold cracking susceptibility. Based on this information, we optimized the composition by reducing the ratio of elements that negatively affect cracking resistance. These various studies culminated in our completion of the dedicated wire.

5. Joint testing

This section describes the results of welding performed using this system. Table 1 and Fig.11 show the welding conditions. The base metal was SM490A (JIS G3106). The root gap tapered from 4 mm to 10 mm, and the terminal end of the weld line was offset laterally by 5 mm relative to the robot rail (travel axis) (i.e., slope of 1.0%).

Fig.12 shows the beads and cross-sectional macrostructures after welding. The welding speed and bead width varied in conjunction with the root gap, confirming proper weld line tracking. The front and back beads have good visual characteristics, and the cross-sectional macrostructure for each root gap exhibits good penetration geometry. Ultrasonic

Table 1 List of welding conditions for joint

Base metal groove shape	Single bevel groove 35°
Welding position	Horizontal
Root gap (mm)	4⇒10 Taper shape
Welding line	5 mm upward displacement from rail parallel height
Shielding gas	100%CO ₂
Wire extension (mm)	21
Backing material	Ceramic

Using wire	Layer-Path	Welding current (A)	Arc voltage (V)
Dedicated wire φ1.2 mm	1-1	170-180	22.5-23.5
	2-2,2-3	280	31
	3-4~	260	29
	(Final layer)	240	27
	(Final path)	220	26

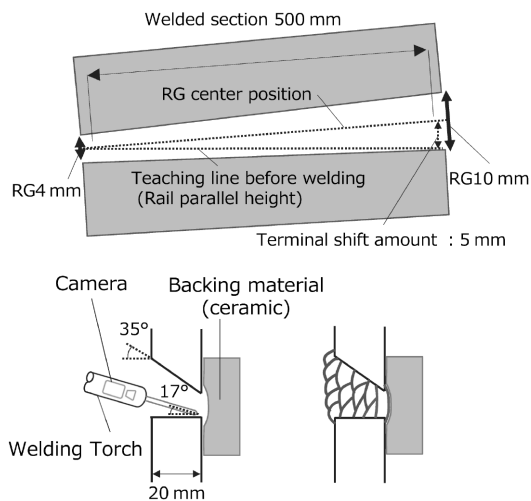


Fig.11 Test plate shape and layer pass conditions

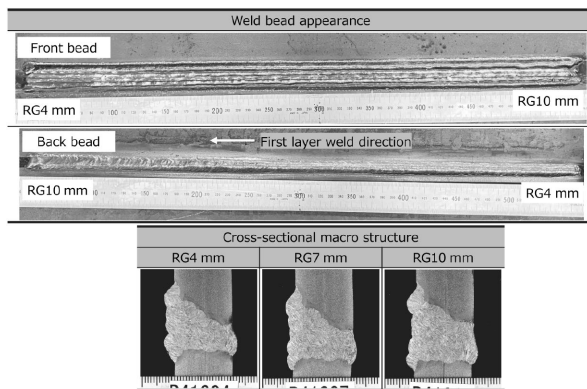


Fig.12 Bead appearance and cross-sectional macro structure in welded joint

testing, which was conducted in accordance with JIS Z 3060 (2015), revealed defect-free welds. The sensitivity was set for echo from the RB-41B reference hole at the H-line, and the detection level was set to the L-line. We fabricated an additional specimen with identical geometry to conduct mechanical performance tests on the weld joint. **Table 2** shows the results of the mechanical property

Table 2 Mechanical properties of welded joint

Tensile properties*1			Notch toughness*1
0.2%PS (MPa)	TS (MPa)	El. (%)	Absorbed energy (J) @0°C
615	667	24	49, 63, 65 Avg.59

*1 Tensile test specimen: round tensile specimen, Dia.=10.0 mm, G.L.=50 mm
Impact test specimen: 10 x 10 mm square shape, 2 mm V notch based on AWS B4.0

tests, which are satisfactory. These results confirm that this system enables effective automatic welding from the first layer to the final pass.

Conclusions

We have been working to automate one-sided full-penetration welding, which requires great technical skill, in response to the societal challenge of a shortage of welders. This paper introduces welding technology that forms a suitable back bead in full-penetration horizontal welding. This technology works by using a camera and an AI image recognition model to appropriately control the motion of the torch in a way that tracks changes in the root gap and weld line. This paper also introduces technology to detect anomalies caused by disturbances during welding.

Kobe Steel is committed to strengthening sustainability management through transformation and is promoting seven “X initiatives” (KOBELCO-X) from AX to GX to ensure the company remains an appealing enterprise. The technologies introduced in this paper are the result of multiplying these “X’s,” and they constitute welding solutions capable of resolving our customers’ challenges. We will promote the practical application of these technological developments to help solve the societal challenge of the shortage of welders.

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