Development and Practical Applications of Welding Core Technologies

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Abstract

In the process of manufacturing steel structures, there are numerous challenges related to welding. Customers expect to obtain welded joints with excellent quality in a reliable and highly efficient manner. Even if the welding processes, robots, and consumables individually excel, they often do not fully address the challenges faced by customers. Kobe Steel's Welding Business possesses all the essential technologies related to arc welding, including processes, robots, and consumables, providing welding solutions to customers. This article introduces, as examples, the core technologies in each of these areas that constitute welding solutions. It also presents the practical applications of welding solutions as an essential aspect of the materiality of the Welding Business.

Introduction

Kobe Steel's Welding Business goes beyond providing welding consumables (rods, wire, flux, backing bar) and welding robot systems. This division supplies a comprehensive range of technologies related to arc welding, including articulated robots, small and portable robots, custom equipment, power sources, processes, and consumables. Our welding solutions solve our customers' challenges related to carbon-neutral, safe and secure manufacturing. Our core welding technologies that set the foundation for welding solutions supporting the betterment of society can be classified into three categories:
(1) Process control technology for high-speed control of the high currents of welding power sources. (2) Tip position control technology for welding robots to ensure accurate positioning of heat from the arc relative to the workpiece. (3) Welding consumables optimization technology, which coordinates material characteristics with the process controls of the welding machine and the movement of the heat source by the welding robot.

This paper describes MAG (metal active gas) welding, a type of arc welding, to cover an overview of the three core technology categories alongside examples of their implementation in society as well as future trajectories including new developments.

1. MAG welding and CO_2 shielding gas

MAG welding is the most common arc welding method. It is suitable for automated welding and is widely used in Europe, the United States, China, Korea, and Japan.[1)] **Fig. 1** shows the general setup of MAG welding.[2)] This type of welding falls under the umbrella of GMAW (gas metal arc welding). In contrast to MIG (metal inert gas) welding, which uses an inert gas such as argon (Ar) for shielding gas, MAG welding uses an active gas such as 100% CO_2 or an 80/20 blend of Ar with CO_2. The continuously fed wire (positive terminal) (1) receives electricity from the electrode connected to the power supply and undergoes Joule heating, (2) melts following arc discharge, (3) falls as a droplet, (4) forms a molten pool and the weld metal, and (5) forms a firm weldment with the base metal (negative terminal), or in other words, the workpiece. The use of fine wire with a diameter of about 1.2 mm increases melting efficiency. At this diameter, Joule heating alone preheats the wire to a temperature close to the melting point of iron before arc discharge.

The 1990s saw widespread use of inverter-based welding power sources, enabling welding current control on the order of milliseconds.[3)] Pulsed MAG welding transfers one droplet from solid wire per pulse of welding current. This method has been implemented in automatic robot welding applications.[4)] Gas blends such as an 80/20 blend of Ar with CO_2, or Ar with a low concentration of O_2, are still widely used in applications where

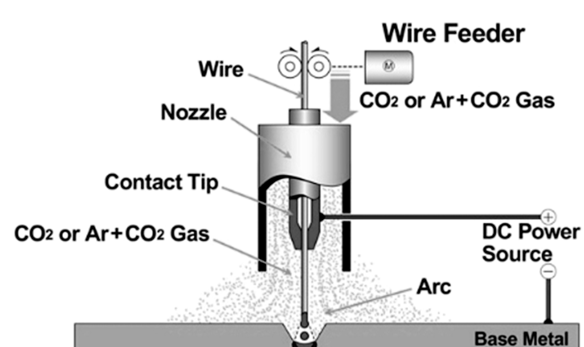


Fig. 1 Configuration of MAG welding

spatter must be limited, such as automotive suspension parts and construction machinery.[5] Argon recovery from atmospheric air via cryogenic air separation[6] is costly. In addition, the greatest disadvantage of MAG welding using an argon-rich gas mixture is the narrow penetration width even at high currents, resulting in a high likelihood of welding defects in multi-pass welding (**Fig. 2**(a)). By contrast, recovering and purifying CO_2 from plant exhaust gas released into the atmosphere[7] is inexpensive. The LCA (life cycle assessment) index of CO_2 shielding gas is higher than that of argon shielding gas if the CO_2 in exhaust gas becomes part of CCUS (carbon capture, utilization, and storage). However, this is not an issue because some of the CO_2 that would otherwise be released into the atmosphere is diverted and reused as shielding gas in the welding process. MAG welding with 100% CO_2 for shielding gas is widely practiced in applications demanding high penetration, such as architectural steel frame.[8] 100% CO_2 shielding gas concentrates the arc discharge at the tip of the droplet (positive terminal), causing the droplet to grow larger. When large, hot droplets fall into the molten pool (negative terminal), they agitate the molten pool and widen penetration, as shown in Fig. 2(b). This deep and wide penetration is the most effective way to prevent welding defects in multi-pass welding. However, droplets that grow and agitate excessively cause spatter that adheres to the area around the molten pool.[9] This detracts from the aesthetics, coating capability, and mechanical joining and sliding properties. There is constant demand for a process that can control spatter, fumes, heat input, penetration depth, and wire melting rate to support efficiency, high-quality heating from the arc, and effective droplet transfer. This can be achieved via MAG welding with fine wire that uses Joule heating effectively, stabilizes droplet transfer, and enables agitation and deep penetration of the molten pool by large droplets through the use of 100% CO_2 shielding gas.[10]

2. Control technology for effective droplet formation and transfer

We will cover process control technology as the first welding solution core technology. This category of technologies controls droplet formation and transfer in MAG welding using 100% CO_2 gas. Controlling the formation and transfer of droplets improves the welding environment by minimizing spatter and fumes. Weld pool agitation can also reduce welding defects. Introduced next are some of our efforts in developing control technology for droplet formation and transfer.

2.1 Control technology for operation with two pulses per droplet

Rapid advancements in digital measurement technology in the 2000s made it possible to synchronize welding current waveforms with droplet transfer video recordings for measurement and analysis. At that time, no digital welding power supply offered discretionary setting of waveforms. We used a transistor-type DC welding power source (DAIHEN TR-800[3]) to separately control droplet formation and transfer with two different pulses, thereby achieving both deep penetration and a significant reduction in spatter.[11] **Fig. 3** shows a control waveform[12] that correlates a current waveform with droplet formation and transfer. The large droplets formed stabilize transfer, reduce spatter, and yield uniform and deep penetration.[11] This welding method has been implemented by combining the SENSARC™ AB500 digital welding power source with a welding robot, forming the REGARC™ process. With these innovations, we have won a very large market share of welding equipment. Our equipment is held in particularly high regard in the architectural steel frame market.

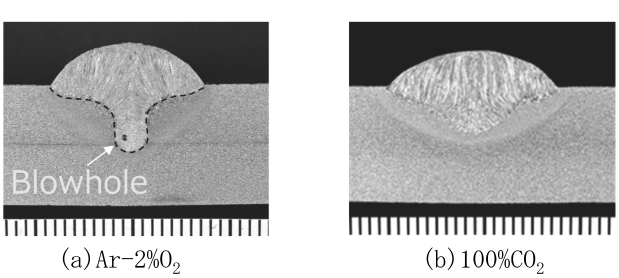


Fig. 2 Difference in penetration shape due to shielding gas (300 A)

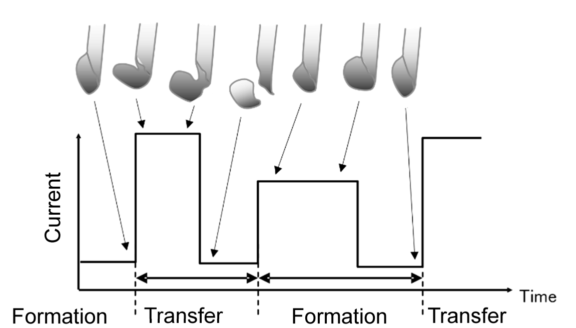


Fig. 3 100% CO_2 shielding gas, 2 pulses per transfer of 1 droplet

2.2 Control technology for operation with one pulse per droplet

In 2005, Fronius of Austria released the CMT (cold metal transfer) process,[13] which combines pulsed welding current control with wire feed control for steady droplet transfer through the creation of a short circuit. Droplets do not fall freely, but rather are transferred to the molten pool by surface present in conjunction with the formation of a short circuit. Characteristics of this welding process include low current, low heat input, and low thermal strain. CMT is popular around the world because these characteristics are desirable in the welding of thin steel and aluminum plate; in overlay welding, which is sensitive to dilution; and in additive manufacturing, which is sensitive to thermal strain.

Kobe Steel developed a welding power source platform with the capability of on-demand digital adjustment of the current waveform. Digital control makes it easy to synchronize external equipment such as servo motors. We used this welding power source platform to feed and retract the wire in a sinusoidal pattern, as shown in **Fig. 4**. This synchronized the pulse current waveform with the phase of the wire feed waveform. As shown in Fig. 4a) - b), moving the wire forward during droplet formation at the wire tip causes the droplet to accelerate toward the molten pool. Even after the wire feed direction is reversed (Fig. 4c)) the droplet at the wire tip tends to move toward the molten pool because of inertia. A neck forms at the top of the droplet (Fig. 4d)). Droplet separation occurs without a short circuit (Fig. 4e)), achieving the periodic free fall of one droplet per pulse. The large molten droplets formed when 100% CO_2 shielding gas is used are allowed to free fall into the molten pool by inertia, thereby minimizing spatter and fumes while agitating the molten pool efficiently. From single-pass welding of thin plate to multi-pass welding of thick plate, molten pool agitation stabilizes penetration, mitigates welding defects, and fosters a uniform weld bead shape. We patented this process and registered it under the trademark AXELARC™ ahead of the applicable press release.[14), 15)] The release of this technology in the SENSARC™ RA500 digital welding power source is forthcoming. This technology will overhaul the way society thinks about MAG welding.

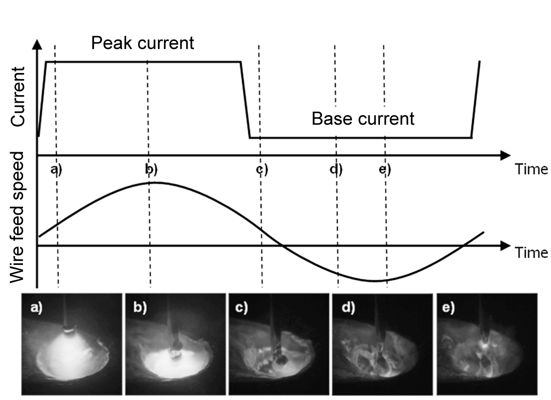


Fig. 4 100% CO_2 shielding gas, 1 pulse per transfer of 1 droplet

3. Welding robot control technology

A further core technology in welding solutions is tip position control technology, which enables the welding robot to detect the shape and weld line of the workpiece alongside unrestricted, accurate tip position control.

This section introduces the following core technologies supporting tip position control in welding robots: 1) high-precision weaving control technology, 2) automatic programming technology, 3) system monitoring technology, and 4) control technology for automated welding with backing bar.

3.1 High-precision weaving control technology

Welding robots used for thin plate such as automotive sheet metal panels trace a defined three-dimensional path from the start point to the end point in a single stroke. Conversely, welding robots used for medium-to-thick plate use a method known as weaving, in which the robot tip oscillates on its way to the next teaching point. This method ensures weld quality by depositing molten metal over a wide area to compensate for gaps and misalignments.

Welding robots have a function called arc sensing that tracks the weld line during the welding process; tip position accuracy during weaving is critical in arc sensing. **Fig. 5** depicts the operating principle behind arc sensing. The welding power source has constant voltage characteristics, so changes in the distance between the tip position and the workpiece are measured as changes in current. In (a), the weaving path center and the groove center are coincident. In (b), the weaving path center is to the right of the groove center. It is thus possible to detect and track the groove center by tracking welding current changes. However, arc sensing performance declines if the tip shifts up and down because of interference, as depicted in (c). Therefore, arc welding robots used for groove welding of medium-to-thick plate must have high tip position accuracy.[16)] Various control theories, such as state observers, have been implemented into robot controllers to meet this need.

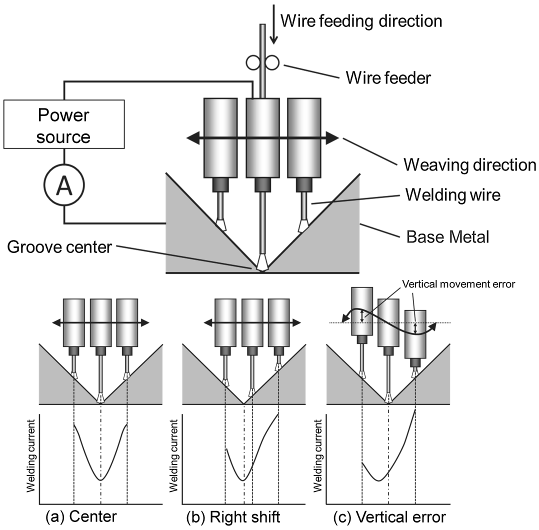


Fig. 5 Arc sensor configuration and operating principle

3.2 Welding workpiece detection and automatic programming technology

Companies are introducing welding robots at an accelerating pace, partly because there are fewer skilled welders and because it is challenging to recruit new welders. Welding robot systems are not generally ready for operation immediately following installation. Rather, they require a teaching process, in which the robot operator teaches the robot the necessary movements. However, customers desire an immediate return on their investment, so they want to start using the automated welding system on installation day. Teach-less operation, in which welding programs are automatically generated without a person teaching the weld points,[17] is a core technology of robotic welding. However, the nuances of teach-less technology differ by industry.

Workpieces in architectural steel frame, for example, are similar in shape. As such, teach-less operation occurs via the entry of geometries and plate thicknesses into a software interface. What makes this method successful is our robotic welding technology cultivated through years of experience as a manufacturer of robots for welding medium-to-thick plate and data generation algorithms based on workpieces. A different method is seen in the bridge construction and shipbuilding sectors, which use 3D CAD modeling to achieve teach-less operation. Weld locations and parameters are derived from 3D design data, eliminating the need for specialized knowledge of robot operations or welding. Weld location data is transferred to the welding robot system, the appropriate weld line is determined for the steel part automatically, and welding begins.

The remaining methods of teach-less medium-to-thick plate welding are used with machinery for construction and other industries (railroad cars, agricultural machinery, etc.). Although systems can detect workpiece shape and weld lines based on 3D CAD data, this information is insufficient for the automatic generation of a welding program for a large and complex workpiece. Potential programs must first be generated based on the position and pose of the welding robot and the angle of the positioner, and then the most suitable program for the weld must be selected. In addition, the cable carrier supplying the welding wire and power can interfere with large, complex workpieces. Depending on the pose of the welding robot, cables might also interfere with the robot tip and inhibit the welding process. Teach-less operation of construction equipment and general machinery necessitates instantaneous simulation and verification of cable status. To meet this need, we devised a teach-less system for construction equipment and general machinery that can handle challenging welding operations such as welding with a positioner and circumferential welding. Our system, depicted in **Fig. 6**, uses an algorithm based on the fabrication methods of senior welders and generates optimized welding programs based on our proprietary metrics.

3.3 Recording and monitoring technology for welding robot system operation

Kobe Steel's welding robot system automatically records the system's operating status and welding data via our operation monitoring software, ARCMAN™ PRODUCTION SUPPORT. In 2022, we also launched the ARCMAN™ View[18] remote monitoring system, which correlates operational data to footage from network camera recordings (**Fig. 7**).

ARCMAN™ View uses a network camera to record real-time welding robot system operations and provide video playback correlated to operating data upon a sudden stoppage or welding defect. Welding conditions at the time of an issue can be checked via the recording provided by the software, making it possible to perform in-depth root cause analysis of sudden stoppages and welding defects. ARCMAN™ View also enables real-time remote operation of the robot in conjunction with a live video feed. If the robot stops during production and the workpiece is in a high position, an operator can view the weld tip on the robot via the camera and restore the system. This function enables the robot to be operated from outside the safety fence, minimizing operations in dangerous places such as at height.

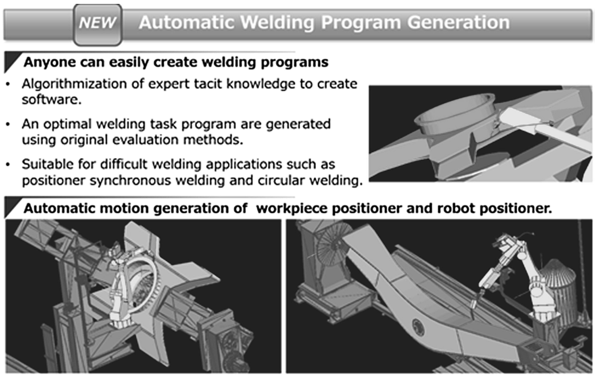


Fig. 6 Automatic generation of welding programs for large and complex workpiece shapes

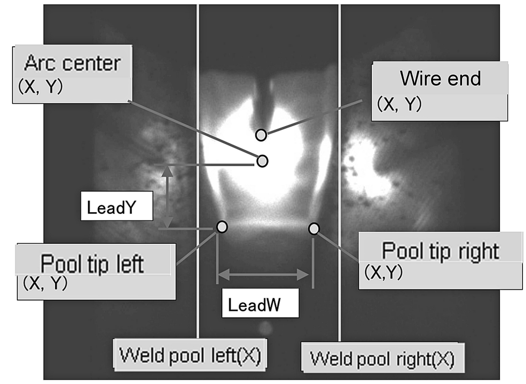


Fig. 8 Feature value extraction of molten pool and surroundings

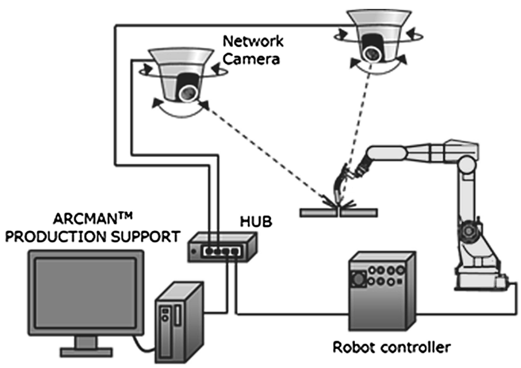


Fig. 7 System configuration of ARCMAN™ View

3.4 Automated penetration welding with backing bar

Medium-to-thick plate usually entails greater variation in the machining and assembly of welding workpieces compared with thin plate. The larger and more complex the workpiece, the more difficult it is to maintain precise alignment of the groove and root gap. This challenge is more prominent when welding components for construction machinery than when welding automotive undercarriage components, and it is even more prominent when welding shipbuilding blocks. In contrast to lasers, arc welding arcs are a heat source with a relatively low energy density. Arcs can accommodate gap variations by weaving, making penetration welding with backing bar a valid technique, albeit one known to require great skill. The skilled welder makes weaving motions while evaluating the groove shape and root gap along with the molten pool, adjusting welding current and voltage if necessary. Welding robot performance at least on par with a skilled welder requires molten pool status detection and real-time robot tip position control. Methods proposed to this point have involved imaging the molten pool with a camera and then binarizing, edge filtering, and labeling the image to extract the features required for control.[19] However, there is too much interference in data processing for this method to be practical. This drove Kobe Steel to focus on deep learning and AI image recognition technologies. We achieved stable penetration welding with backing bar by extracting features related to the molten pool and its surroundings (wire tip, arc center, molten pool width, and molten pool tip width - see **Fig. 8**) and by tracking and compensating for root gap changes.[20] A multi-pass weld from one side is effective for welding the shell plating of a shipbuilding block if a backing material is used. However, the weld length exceeds 10 m, the gap width varies, and variations in the plate thickness direction can be as large as 3 mm. Additionally, there are dirt and adhesions to contend with when the groove is cut. We used state-of-the-art deep learning technology to more accurately and effectively detect abnormalities such as gap variation, misalignments, and adhesions. We will outfit a welding robot with this technology in the coming years to automate the welding of shipbuilding blocks with backing bar at a quality rivalling that of experienced welders.

4. Welding consumables control technology

Seven years after ESAB of Sweden invented the coated welding electrode in 1907, Japan began researching the use of shielded metal arc welding (SMAW) for efficient steel ship construction in the Nagasaki shipyards. Kobe Steel began producing SMAW electrodes in 1930 to support domestic production of welding consumables. Welding consumables development begins with research into fluxes and their chemical compositions. The advent of MAG welding in the United States in 1953 also spurred research into steel compositions for solid wire. The chemical compositions and structures of welding consumables, fluxes, and weld metals have been optimized across more than 100 years.[21]

Control technology related to the composition and microstructure of mild steel, high-strength steel, heat-resistant steel, and high-alloy steel has also matured in the meantime.

Expertise in tuning the chemical composition of welding consumables and weld metals continues to support core technologies in welding today. Alongside macroscopic adjustments to chemical composition, new optimization technologies for welding consumables include surface control of welding wire, the use of materials informatics (MI), and microstructure control. Examples of each are presented next.

4.1 Surface control of welding wire

The conventional focus of tuning chemical composition to satisfy the requisite mechanical properties of the weld metal (strength, toughness, etc.), shape, appearance, and slag removal is no longer regarded as sufficient. Rather, there is increased attention on wire surface control technology that responds predictably to the control system of the welder and the movement of the heat source by the welding robot to enable intermittent and long-term continuous welding.

In MAG welding, current flows from the contact tip to the welding wire through a sliding point of contact. If the sliding contact is a circle with a diameter of 100 μm and the contact tip delivers a DC current of 300 A, the current density at the point of contact is 4×10^4 A/mm^2. When pulse control is used, the welding current fluctuates, and when feed control is used, the sliding speed also changes, setting up adverse conditions at this contact point. Variability at the point of contact causes imbalances at the wire tip, inhibiting effective droplet transfer even upon changes in the welding current and feed rate. Controlling the geometry and chemistry of the wire surface makes it possible to achieve excellent current-carrying properties, tip fusion resistance, and wire feeding properties suitable for pulse waveform control. This technology in tandem with our special REGARC™ wire (**Fig. 9**) fosters steady intermittent and long-term continuous welding.

4.2 Designing the composition of welding consumables using MI

Technological breakthroughs such as increased computer processing power, the expansion of big data, and deep learning have rapidly increased the ways in which AI can be used in industrial applications. AI uses models based on training data to reproduce human thought. MI involves the use of AI technology in materials development. Three particular challenges in welding consumables development are (1) maturity of metal material composition, (2) commoditization of welding consumables, and (3) shortage of materials development engineers, including insecurities in passing on technology. To overcome these challenges, we are focusing on MI technology as a means of increasing development efficiency and strengthening design capabilities. Such developments set the foundation for maximizing the use of experimental data and historical welding expertise.

There are two main categories of techniques in the field of welding consumables development. Prediction techniques calculate the problem in the forward direction (→), working from the design of the material to the mechanical properties of the weld metal. Optimization techniques solve the problem in the reverse direction (←), working from the mechanical properties of the weld metal to the design of the material. Welding consumables development must account for relationships between (1) raw material composition, (2) chemical composition of welding consumables with multiple raw materials (weld material composition), (3) chemical composition of the weld metal after welding (weld metal composition), and (4) mechanical properties of the weld metal (weld metal properties). We developed an MI-based technique that accounts for the characteristics of welding consumables in the form of a prediction (→) and optimization (←) technique (**Fig.10**) that connects all the relationships between (1) and (4).[22)] Our prediction technique uses linear relationships to determine weld material composition from raw materials (→). Conversely, our optimization technique determines raw materials from weld material composition (←) based on convex optimization.

Defining clear mathematical relationships to predict (→) weld metal composition from weld material composition, and weld metal properties from weld metal composition, is a challenging

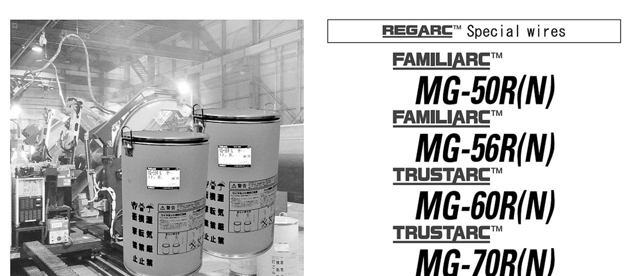


Fig. 9 Special wires of REGARC™

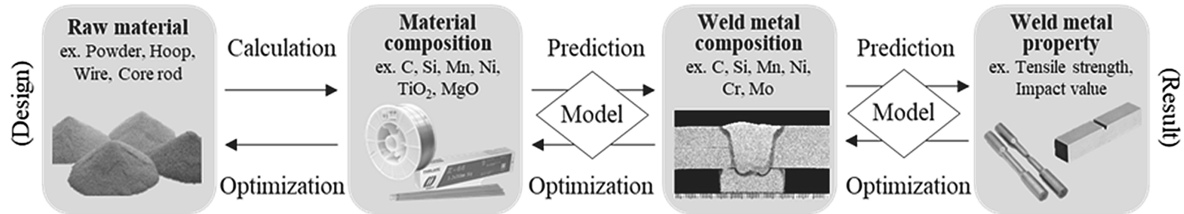


Fig.10 Welding consumables composition design using MI

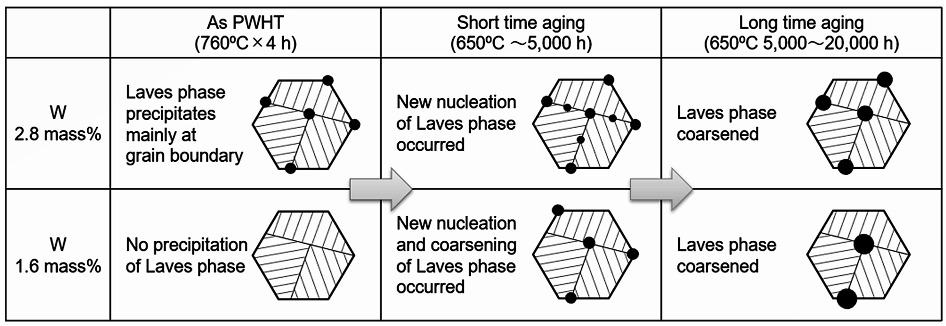


Fig.11 Microstructure control of heat-resistant steel weld metal

process involving complex welding phenomena and material microstructure morphology based on theoretical physics. Therefore, we used machine learning to construct a prediction model (→) based on an expansive repository of experimental data. In addition, we used a machine learning model to optimize (←) weld metal composition based on weld metal properties and to optimize weld material composition based on weld metal composition.

4.3 Microstructure control

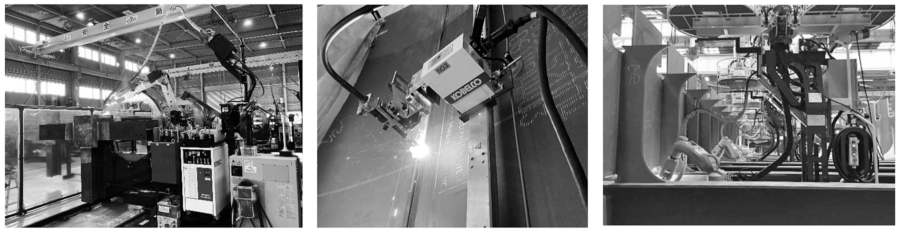
Japan's Strategic Energy Plan[23)] includes the goals of reducing coal-fired power generation and of using thermal power generation to compensate for the unstable supply of energy from renewable energy sources. Thermal fatigue of boilers becomes a problem when thermal power plants are frequently started up and shut down.

Countermeasures to mitigate thermal fatigue include increasing the strength of the steel, or in other words improving creep properties, and using thinner-walled piping. ASME Grade 93 steel (9Cr-3W-3Co-Nd-B) has improved creep strength and creep rupture ductility compared with conventional 9% Cr heat-resistant steel.[24)] Tungsten (W) is added for solid-solution strengthening and precipitation strengthening, but the morphology of tungsten precipitation in the weld metal depends on its fraction. We scrutinized the microstructure of steel after post-weld heat treatment (PWHT), a creep test simulating short-term operation, and a creep test simulating long-term operation. **Fig.11** shows the location, density, growth, and disappearance of Laves phase precipitation (Fe_2W) in terms of tungsten concentration. By managing tungsten content appropriately, we uncovered metallurgical evidence that the weld metal exhibits good creep properties even at the ultra-supercritical temperature of 650℃.

5. Examples of practical application within the materiality of welding (Fig.12)

(a) shows our new steel frame welding robot system (NEW REGARC™) that combines the ARCMAN™ A60 six-axis arc welding robot, SENSARC™ RA500 digital welding power source, FAMILIARC™ MG-56R(A) carbon steel solid wire, and REGARC™ MAG welding process with CO_2 shielding gas. This system has been well received by fabricators for on-site welding of columns and beams for high-rise buildings, large warehouses, factories, and other urban structures. Kobe Steel has been promoting automation in the architectural steel frame industry for about 30 years. By continuously providing high-efficiency, high-quality steel frame robot systems, the company has taken on a share of about 90% of the Japanese market.

(b) shows a vertical welding system for LNG tanks that combines a KI-700 small and portable arc welding robot, SENSARC™ AB500 digital welding power source, and PREMIARC™ DW-N609SV Ni-based composite wire. Among fossil fuels, LNG is expected to see increased demand because of its ability to reduce carbon emissions. We provide automation technology for high-efficiency welding of LNG tanks on land and on ships.



(a) Steel construction welding robot system (b) LNG tank vertical up welding robot system (c) Shipbuilding assembly welding robot system

Fig.12 Welding materiality, examples of practical application

(c) shows a large shipbuilding assembly welding robot system that combines an ARCMAN™ A30 compact 6-axis arc welding robot, SENSARC™ AB500 digital welding power source, and FAMILIARC™ DW-100R composite wire. We have developed and released a variety of robot systems that meet the need for automation in shipyards, where labor shortages are becoming apparent.

Conclusions

Arc welding is economical and highly efficient, and it is highly conducive to welding all steel materials from thin sheet to thick plate. Arc welding is and will continue to be indispensable for making structures out of the nearly 1.9 billion tons of steel produced worldwide. The need for automation in welding, and specifically for robotic welding that surpasses the quality humans can achieve, will become ever greater to compensate for a shortage of welders. As the only company in the world possessing all technologies related to arc welding, we will continue refining welding process control technology, robotics control technology, and materials optimization methodologies to release effective welding solutions to society and help our customers overcome their challenges.

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