Development of Automatic Welding System for 9% Ni Steel LNG Tanks

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Abstract

The demand for liquefied natural gas (LNG) is expected to rise, and 9% Ni steel is the material of choice for the tanks (both for above-ground and marine applications) used to store and transport it. However, welding of 9% Ni steel requires high skill levels and is prone to defects like lack of fusion. To address this issue, this paper introduces a portable, specialized robot system designed for the highly efficient and deskilled welding of 9% Ni steel. The system utilizes a cartesian coordinate robot with mounting jigs, sensing methods, welding power supply, and optimal welding conditions tailored to the manufacturing of 9% Ni steel LNG tanks. This robot system allows welders to produce sound-quality welded joints during vertical welding of 9% Ni steel, with reduced defects. Furthermore, by using two robots simultaneously with one operator, significant improvements in efficiency can be expected.

Introduction

In line with the global trend towards decarbonization for carbon neutrality, there has been a sharp increase in demand for natural gas, which is a crucial transition energy with lower CO_2 emissions than oil and coal[1]. When storing and transporting gas by vessels, it is common for it to be liquefied at -162℃ and sealed in dedicated tanks. Therefore, many tanks for LNG are manufactured using 9% Ni steel, which excels in strength and low-temperature toughness.

This paper relates to the welding of 9% Ni steel LNG tanks, whose demand is expected to increase, and introduces the development of an automatic welding system using a compact portable robot (product name, "KI-700"), which enables deskilling and high efficiency by combining Kobe Steel's nickel-based alloy flux-cored wire (hereafter referred to as Ni-based FCW) for 9% Ni steel LNG tanks.

1. Development background

Nickel-based alloys exhibit high viscosity when melted, leading to poor fluidity. Additionally, their melting point is lower than that of the 9% Ni steel base metal, making lack of fusion defects more likely to occur during welding. Consequently, establishing an appropriate groove shape and employing special electrode manipulation are necessary to sufficiently melt the groove during welding. Blow holes are also prone to occur due to the infiltration of oxygen and moisture from the atmosphere and other factors, necessitating proper shielding and control of arc length. Thus, the use of nickel-based alloy welding consumables demands a high level of skill, with variations in quality likely due to the welder's expertise. On the other hand, the shortage of highly skilled welders has become a serious issue, further exacerbated by the retirement of experienced welders. The environment for welding 9% Ni steel structures has become more tough[2].

Against this background, Kobe Steel has commercialized an automatic welding system using a compact portable robot, named "KI-700", that can be applied to the welding of LNG tanks, which are experiencing a rapid increase in demand. This system is expected to compensate for the shortage of welders and decline in skill, thereby contributing to the high efficiency and high-quality construction of storage facilities, which are indispensable for CO_2 reduction.

2. Development of process for Nickel-based-alloy flux-cored arc welding (Ni-based FCAW)

The process introduced in this paper involves a specialized welding robot optimized for Kobe Steel's HASTELLOY® [Note 1)] type Ni-based FCW, recognized for its outstanding resistance to hot cracking. The configuration also incorporates a digital welding power supply and dedicated rails. This section provides detailed information about the robot, power supply, and rails. In the development of this process, one factor causing the decrease in working efficiency of semi-automatic welding in a vertical position is considered to be the need for repair work associated with the occurrence of short-length bead connection. Therefore, the focus has been placed on achieving long-seam welding. The goal is to complete the welding without stopping midway in the vertical welding of 4 meters, the maximum width of 9% Ni steel plates, ensuring the production of sound weld metal.

Note 1) HASTELLOY is a registered trademark of HAYNES International Inc.

2.1 Development of compact portable robot

The KI-700 is a portable Cartesian coordinate robot system developed on the basis of a conventional model, which has a track record in the short-length welding of the medium-to-thick plate made of general carbon steel used in industries such as structural steel, bridges, and shipbuilding. The name "KI-700" covers a manipulator, controller, and teaching box. The appearance of the KI-700 is shown in **Fig. 1**.

The KI-700 features a manipulator weight of approximately 6 kg, making it both compact and lightweight. Another notable attribute is its capacity for remote operations using the teaching box. Additionally, its software functionality enables the automatic generation of a suitable build-up sequence and welding conditions tailored to Ni-based FCW, utilizing groove shape data automatically detected through touch sensing. Consequently, it can effectively address variations in machining and assembly precision, ensuring stable welding quality with straightforward operations, even without the need for highly skilled operators.

Fig. 1 Appearance of KI-700 compact portable welding robot for Ni steel

Improvements to the groove sensing method are depicted in **Fig. 2**. In the conventional welding of medium-to-thick plates, commonly involving robotic applications, a root gap of approximately 4 to 10 mm is utilized. However, in the application of welding marine tanks, where the KI-700 is expected to be utilized, the anticipation is for thin plates with an envisioned zero-millimeter root gap. Therefore, precise shape detection is essential due to the relative narrowing compared to the grooves traditionally considered in sensing methods. The KI-700 addresses this need by adopting a teaching-dedicated metal tip that excels in machining precision and rigidity, departing from the conventional practice of combining sensing with slightly bent welding wire. During sensing, the contact tip is replaced with this dedicated tip. Furthermore, the newly developed touch sensing, in contrast to conventional methods limited to obtaining location information from the welding groove surface, now captures location information from both the welding groove surface and the adjacent base metal surfaces.

2.2 Optimization of function for automatically generating welding conditions/build-up sequence

As indicated in Section 2.1, the KI-700 automatically generates suitable welding conditions and a build-up sequence tailored to Ni-based FCW on the basis of groove shape data. The unique aspects of this capability will be further detailed below.

As mentioned at the outset of Section 1, in vertical LNG tank welding, critical considerations encompass: inadequate fluidity leading to lack of fusion; joint strength reduction attributed to the disparity in melting points between the base metal and the weld metal; and the decrease in alloy components in the weld metal due to base

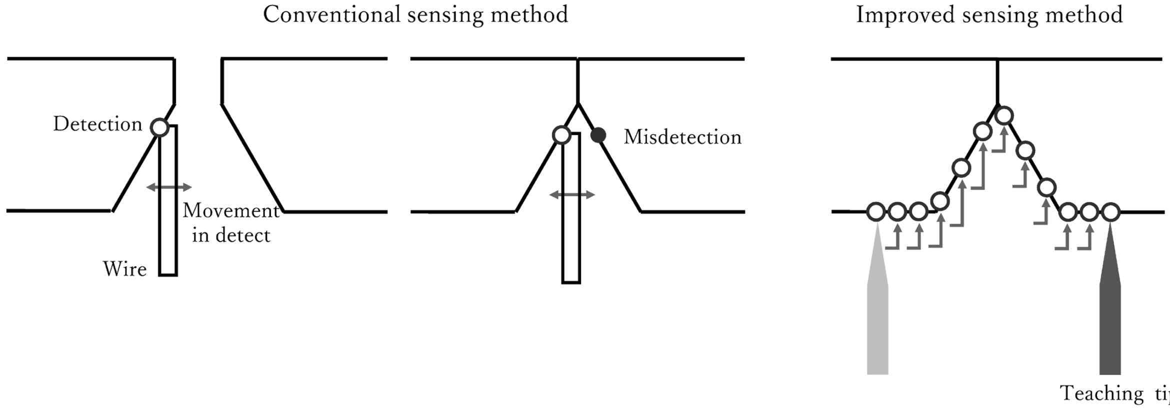


Fig. 2 Schematic diagram of improved sensing method

metal dilution. The decline in joint strength poses a particular challenge, especially with thin plates. This arises from the base metal temperature easily rising during welding, coupled with a substantial proportion of the root section where base metal dilution is more pronounced. Taking these factors into consideration, optimizations have been implemented.

Specifically, attention has been paid to wire aiming positions to prevent lack of fusion, adjusting welding heat input and weaving width for each path to prevent dilution, ensuring proper conditioning of the molten pool for arc stability in root welding, and considering the build-up sequence and weaving conditions that promote the attainment of a flat bead shape. Consequently, the capability to successfully perform vertical welding has been realized, as demonstrated by positive test results presented in Section 3 and subsequent sections.

2.3 Welding power source

The welding of 9% Ni steel using Ni-based FCW is carried out within a relatively low current range to mitigate the risk of hot cracking. In conventional power sources with thyristors, the low control frequency contributes to insufficient arc stability in the low current range, prompting a preference for inverter-controlled power sources. The robot-specific digital control inverter welding power source, SENSARC™ AB500, introduced by Kobe Steel in 2010, is equipped with advanced current and voltage control capabilities. Leveraging these features, it offers high-quality and versatile welding modes, rendering it optimal for medium-to-thick plate welding[3]. Furthermore, to enable the use of Ni-based FCW in the vertical welding position and improve arc stability in the low current range of 200 A and below, the KI-700 has been enhanced with a dedicated mode for the Ni-based FCAW process.

Assuming a welding length of 4 meters in an LNG tank, the external appearance of the shield nozzle after 40 minutes of continuous welding is displayed in **Fig. 3**. This outcome affirms that spatter adhesion to the shield nozzle, which can disrupt the shielding gas, is minimized. This is credited to the inherent low spatter design of Kobe Steel's Ni-based FCW and the additional reduction achieved through the digital control of the power source. Even during 40 minutes of continuous welding, the spatter adhesion to the shield nozzle remains minimal. Moreover, considering the heat resistance required for prolonged welding, a welding torch with a higher rated duty cycle than conventional robots has been chosen.

2.4 KI-700 dedicated rail

The length of the vertical welding joint in a 9% Ni steel LNG tank depends on the width of the steel plate, with a maximum length of approximately 4 meters. Furthermore, 9% Ni steel is susceptible to magnetization, leading to welding defects caused by magnetic arc blow during welding. As a result, the use of magnets, commonly employed to prevent the manipulator from falling and for securely fixing metal rails with a rack as the running axis to the base metal, is not feasible. Hence, owing to the lightweight effect of the KI-700 manipulator, it has been determined that secure fixation is achievable with easily attachable and detachable vacuum clamps. Consequently, the system has adopted vacuum clamps.

The overview of the dedicated rail developed for the KI-700 is illustrated in **Fig. 4**. To ensure rigidity, considering the lifting process, a reinforcement frame has been attached to the main rail. The suction power of the vacuum clamp is designed to withstand the weight of the manipulator and cables. To prevent unintended falls, a fall prevention fixture has also been added to ensure safety.

3. Vertical welding test using KI-700

This section presents the details of the vertical welding tests specifically designed for actual LNG tank welding using the KI-700.

The 9% Ni steel LNG tank is broadly classified into "above-ground storage tanks" and "marine tanks" employed for transportation on ships or as fuel tanks. To meet the distinct mechanical performance requirements of the welding sections, two types of Ni-based FCWs have been lined up, namely, PREMIARC™ DW-N709SP (above-ground storage) and PREMIARC™ DW-N609SV (marine).

Fig. 3 Nozzle appearance after 40 minutes continuous of welding

Both products share the common advantage of excellent workability during vertical welding. As outlined in Section 2.1 and Section 2.2, the KI-700 automatically computes the optimal welding conditions (current-voltage-speed-weaving condition) and build-up sequence for each Ni-based FCW on the basis of the sensed groove shape. The results of welding tests conducted under these specified welding conditions and build-up sequence demonstrated exceptional welding quality, as shown in Section 3.1 and Section 3.2. Further details are shown below.

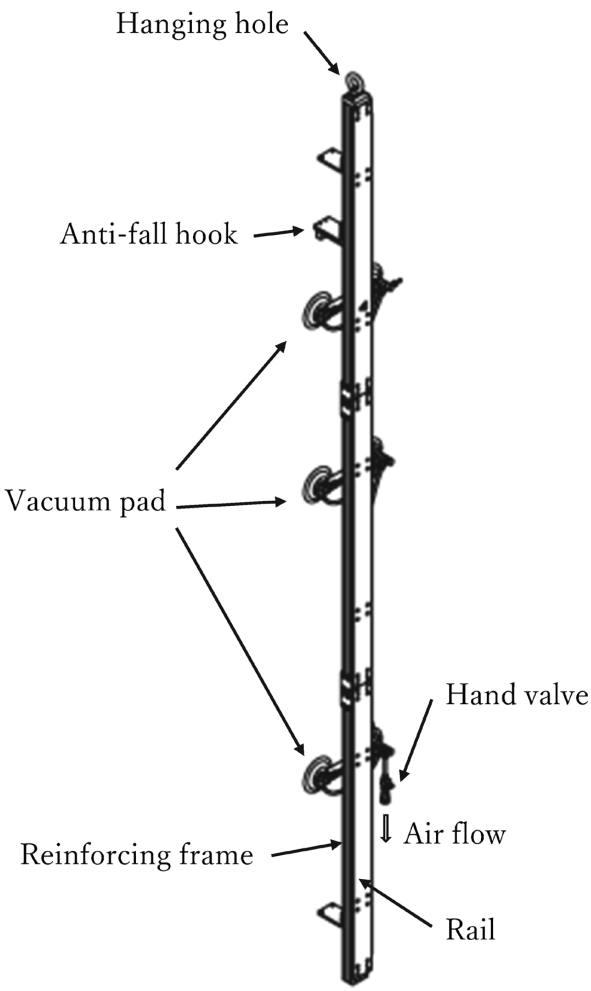


Fig. 4 KI-700 dedicated 4 m long welding rail

3.1 Conditions assumed for above-ground LNG tanks

Table 1 presents the scope of application for the KI-700, considering welding for an above-ground LNG tank. Additionally, **Table 2** displays the output results of the recommended welding conditions automatically generated for joint welding with a plate thickness of 12 mm, considering the combination with the PREMIARC™ DW-N709SP welding wire for the above-ground LNG tank. On the basis of these results, a groove was actually formed. The process involved a combination of gas cutting and grinding on the 1st side, and on the 2nd side, mechanical processing such as milling was performed after welding on the 1st side. **Table 3** shows the bead appearance, cross-sectional macro photographs, and mechanical performance obtained when automatic welding has been conducted under the conditions specified in Table 2. Under both conditions with a root gap of 3 mm and

Table 1 KI-700 applicable groove dimension for aboveground LNG storage tank

Welding position	Thickness	Groove angle	Root gap
Vertical upward	12-35 mm	55-65°	3-7 mm

Table 2 Welding conditions for PREMIARC™ DW-N709SP generated by KI-700

Root gap 3 mm				
	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Welding heat input (kJ/mm)
1st	150	26	156	1.5
	160	26	219	1.1
2nd	160	26	132	1.9
	160	26	114	2.2

Root gap 7 mm				
	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Welding heat input (kJ/mm)
1st	150	26	96	2.4
	160	26	162	1.5
2nd	160	26	132	1.9
	160	26	114	2.2

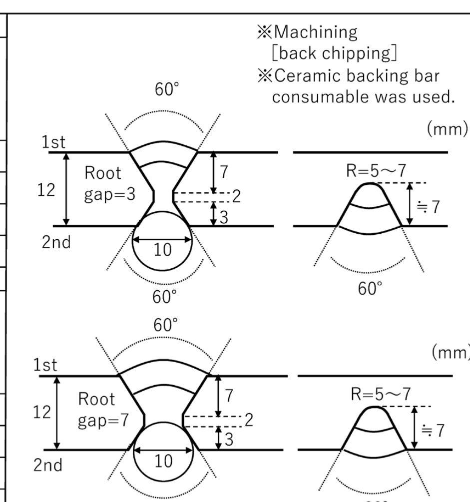
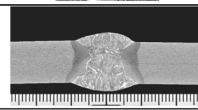
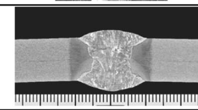


Table 3 Bead appearance, cross-sectional shape of weld metal, mechanical test results of weld metal by PREMIARC™ DW-N709SP

	Root gap 3 mm	Root gap 7 mm
Bead appearance		
Macro-structure		
Tensile strength (MPa) (Test temperature : 20℃) [Target value ≧ 690 MPa]	754 (Fractured position : weld metal)	725 (Fractured position : weld metal)
Absorbed energy (J) (Test temperature : -196℃) V notch [Target value ≧ 55 J]	91,78,92 Avg. 87	86,95,78 Avg. 86

7 mm, satisfactory appearances and mechanical properties have been achieved. In the joint tensile test, the weld metal has fractured, but it satisfies the strength standards for the base metal and meets the requirements of the pressure vessel standard JIS B 8265. In semi-automatic welding performed by a welder, it is estimated that the maximum continuous welding length in a vertical position is generally around 700 mm. With the KI-700, there is no such limitation, enabling stable continuous welding even for long-length welds exceeding 1 meter. To evaluate the stability in long-length welding, a 1-meter-long vertical welding joint was created, and radiographic testing was conducted. The welding conditions and results are presented in **Table 4**. For a welding length of 900 mm, no lack of fusion has occurred, and there are a total of 7 blowholes. This level of performance is well within the passing criteria of JIS B 8265 (either Class 1 or Class 2 according to JIS Z 3106). It confirms the high-quality stability of long continuous welding achieved through the combination of PREMIARC™ DW-N709SP and KI-700.

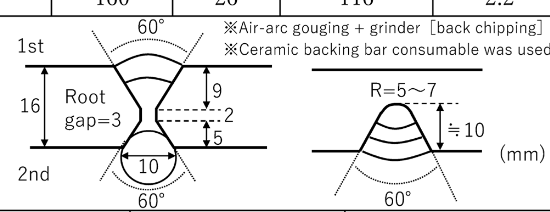
3.2 Conditions assumed for marine LNG tanks

Table 5 outlines the KI-700's application scope, considering welding for a marine LNG tank. Given its role as a fuel tank, strict capacity assurance is required. To prevent deviation towards lower capacity due to welding-induced deformation, the allowable root gap range is narrower, specifically ranging from 0 to 3 mm, in comparison with above-ground LNG tanks. As demonstrated in Section 2.1, the conventional sensing method shows a reduction in touch sensing points at a 0 mm gap, with increased likelihood of detection errors in the groove width direction sensing. Consequently, a newly developed sensing method has been adopted for marine LNG tank conditions.

Table 6 shows the output results of the recommended welding conditions using the marine LNG tank welding wire PREMIARC™DW-N609SV,

Table 4 Welding conditions for PREMIARC™ DW-N709SP generated by KI-700 and radiography results

	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Welding heat input (kJ/mm)
1st	150	26	126	1.9
	160	26	149	1.7
2nd	160	26	136	1.8
	170	27	143	1.9
	160	26	116	2.2



Linear defect	Spherical defect	JIS B 8265
N.D.	Blow hole 7pieces (dia. 0.6~0.9 mm)	Satisfied.

※Evaluation length in radiography : 900 mm

Table 5 KI-700 applicable groove dimension for marine LNG storage tank

Welding position	Thickness	Groove angle	Root gap
Vertical upward	12-35 mm	55-65°	0-3 mm

Table 6 Welding conditions for PREMIARC™ DW-N609SV generated by KI-700

	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Welding heat input (kJ/mm)
1st	160	27	181	1.4
	170	27	151	1.8
2nd	160	25	237	1.0
	170	27	191	1.4

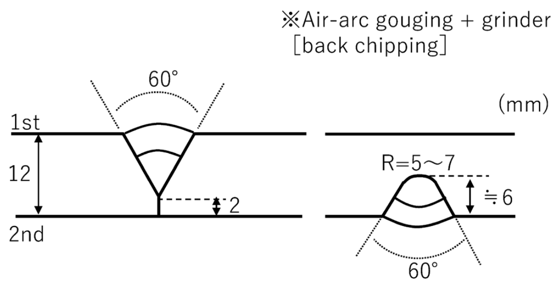
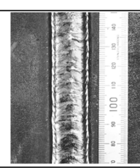
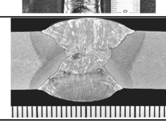


Table 7 Bead appearance, cross-sectional shape of weld metal, mechanical test results of weld metal by PREMIARC™ DW-N609SV

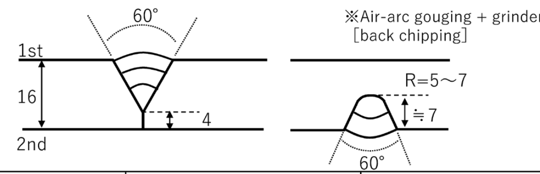
	Root gap 0 mm
Bead appearance	
Macro-structure	
Tensile strength (MPa) (Test temperature : 20℃) ［Target value ≧ 690 MPa］	722 (Fractured position：weld metal)
Absorbed energy (J) (Test temperature : -196℃) V notch ［Target value ≧ 34 J］	84, 80, 80 Avg. 81

with input conditions specified for joint welding with a plate thickness of 12 mm. On the basis of these results, an actual groove was formed. The process involved a combination of gas cutting and grinding on the 1st side, and on the 2nd side, a combination of air arc gouging and grinding was performed after welding on the 1st side. **Table 7** shows the bead appearance, cross-sectional macrographs, and mechanical properties obtained by automatic welding under the conditions outlined in Table 6. It is evident that excellent appearance and mechanical properties have been achieved.

Similarly to the case of above-ground LNG tanks, a vertical welding joint with a welding length of 2 meters was created to evaluate the stability of

Table 8 Welding conditions for PREMIARC™ DW-N609SV generated by KI-700 and radiography results

	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Welding heat input (kJ/mm)
1st	160	27	207	1.3
	170	27	194	1.4
	170	27	167	1.7
2nd	160	25	199	1.2
	170	27	153	1.8



Linear defect	Spherical defect	JIS B 8265
N.D.	Blow hole 5pieces (dia. 0.6~0.9 mm × 4, dia. 1.0 mm × 1)	Satisfied.

※ Evaluation length in radiography :1800 mm

long-length welding in the groove of the marine tank, and radiographic testing was conducted. **Table 8** presents the welding conditions and results. For 1,800 mm of welding length, there are 5 blowholes, and no lack of fusion has occurred. This performance level, akin to the previously mentioned PREMIARC™ DW-N709SP, aligns well with the passing criteria of JIS B 8265, confirming the high-quality stability in long continuous welding achieved through the combination of PREMIARC™ DW-N609SV and KI-700.

4. Enhancement effect on work execution efficiency achieved by using KI-700.

In Ni-based alloys, cracks almost invariably occur at the bead's terminal crater. Therefore, it is necessary to completely remove the crater with a grinder for bead connection. As discussed in Section 3, the use of KI-700 in LNG tank vertical upward welding enables stable long-length welding with consistent quality. This reduces the need for grinding work during bead connection approximately every 700 mm, as required in semi-automatic welding. Furthermore, there is no longer a need for the welder to move scaffolding to align with the welding position of the vertical joint. Moreover, the KI-700 can continuously weld without constant monitoring, except for the task of removing slag. This allows a single operator to simultaneously execute work on two joints.

The estimated results for the total working hours when a welder individually executes 36 locations of vertical welding joints with a plate thickness

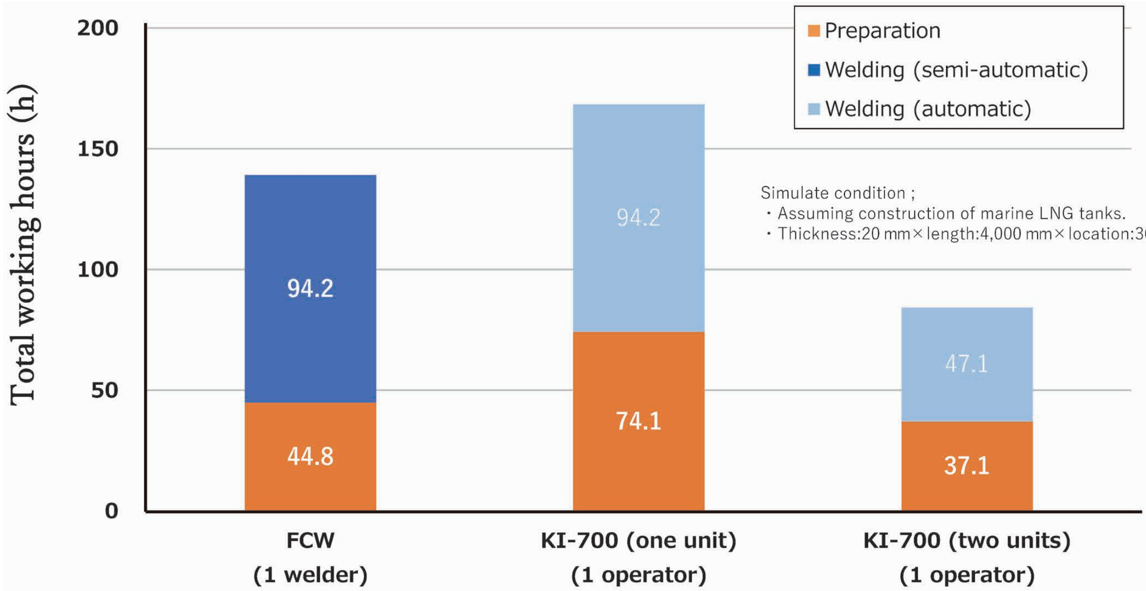


Fig. 5 Comparison of total working hours for various welding procedures

of 20 mm and a welding length of 4 meters are presented in **Fig. 5**. The breakdown of welding preparation includes slag removal, grinding of craters (bead connection), back chipping, and contact tip replacement. When applying the KI-700, the preparation time increases due to rail installation work and the time required for groove sensing with the KI-700. However, the welding process is automated, resulting in an approximately 50% working hour reduction for workers. While welding hours remain unchanged from those of semi-automatic welding, the productivity per day increases, as the operation continues even when welders are taking breaks. Furthermore, by having one worker handle two KI-700 units, alternately performing the preparation and welding, the total working hours, including welding, are reduced by approximately 40% compared with semi-automatic welding, contributing to a shorter project duration.

Conclusions

This paper has outlined Kobe Steel's initiatives in achieving de-skilling, high efficiency, and stable quality in LNG tank vertical welding. Kobe Steel aspires to become the "most trusted welding solution company in the world." The automatic welding system utilizing KI-700 in conjunction with Ni-based FCW represents a welding solution product that capitalizes on Kobe Steel's expertise in robotics, welding consumables, welding power sources, and welding execution methods. In recent years, there has been a noticeable surge in the demand for constructing energy infrastructure, encompassing not only LNG tanks but also hydrogen/ammonia tanks, and liquefied CO_2 tanks, aligning with the pursuit of carbon-neutral goals. The Kobe Steel welding solutions presented in this paper are put forth to make meaningful contributions to society.

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