Development of Vertical Submerged Arc Welding Method for Aboveground LNG Storage Tank Construction

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Manual metal-arc welding has mainly been applied to vertical joints in LNG storage tanks made of 9%Ni steel abroad. To shorten the construction period and improve welding efficiency, a new welding method using simple equipment and without using shielding gas has been required. IHI has developed a new vertical submerged arc welding method with small diameter wire and weave technique. Stable welding and quality have been obtained by developing welding equipment and new welding consumables. Deposition rate of the method is in the 50 g/min to 80 g/min range. This shows possibility of welding efficiency improvement using vertical submerged arc welding method.

1. Introduction

IHI constructed Japan's first aboveground 9%Ni steel LNG storage tank in the Negishi LNG Terminal of Tokyo Gas Co., Ltd. in 1969. Since then, the company has enjoyed the top domestic share in the LNG receiving terminal and LNG storage tank construction market. In addition, making full use of domestically developed technology, it has been actively expanding overseas. At the head of the overseas construction list is India's first LNG receiving terminal, which started commercial operation in 2004. The company has also constructed LNG receiving terminals and LNG storage tanks in Mexico, Taiwan, the US, Qatar, Spain and other countries. In recent years, PCLNG tanks using prestressed concrete (PC) for the outer shell and 9%Ni steel for the inner shell have become the main type of aboveground LNG storage tank both in Japan and overseas. **Figure 1** shows the structure of one of the PCLNG storage tanks now commonly constructed overseas.

For the welds of the 9%Ni steel inner shell, manual metal arc welding (hereinafter called MMA) was initially used and, since the 1970s, horizontal submerged arc welding has come to be used for circumferential joints. For vertical joints, use of automatic tungsten inert gas welding (hereinafter called automatic TIG welding) became increasingly widespread within Japan and since the 1980s the magnetic controlled TIG (MC-TIG) welding method, which is a hot wire method with improved deposition rate, has been used not only for vertical but also major joints. With the aim of further improving the efficiency of automatic TIG welding, IHI has developed remote controlled automatic TIG welding equipment[1] and a high-efficiency automatic TIG welding method (SEDAR-TIG), [2] and put them to practical use.

However, for the welding in overseas construction work, the welding method is chosen according to the required specifications, local environment, and equipments available to the subcontractors who are directly in charge of the work, and for the welding of vertical joints, MMA is mainly used. With MMA, however, craters must be treated using a grinder after welding stops. As a result, there are limitations on improvement of welding efficiency and therefore the development of a simple, efficient welding method was desired.

With submerged arc welding, the deposition rate is high, no shielding gas is required, and the process can be carried out in a stable manner. In order to apply this welding method to vertical joints, IHI developed vertical submerged arc welding (hereinafter called vertical SAW : Submerged Arc Welding).[3] Because submerged arc welding uses powders known as flux, it has so far been limited to flat and horizontal positions. However, it was confirmed that even with vertical up welding of 9%Ni steel, stable work and quality could be obtained through the development of suitable welding equipment and consumables.

2. Outline of vertical SAW

With submerged arc welding, a welding wire is automatically fed into the scattered granular flux and an arc is struck under the flux. In the general method, a thick wire

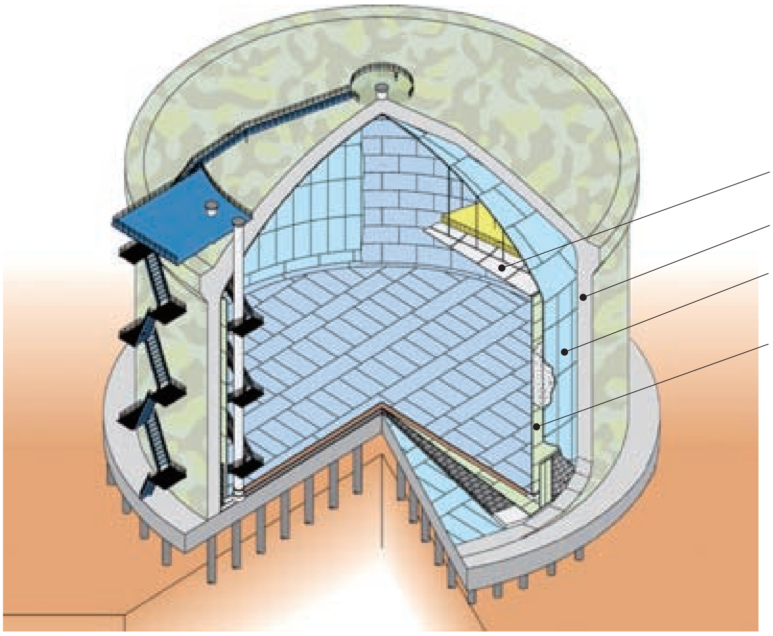


Fig. 1 Structures of PCLNG storage tank (overseas specification)

4.8 mm in diameter is used and a large current of several hundred amperes is passed during welding, so that welding efficiency is high. In contrast, the vertical SAW developed by IHI uses a thin wire, 1.2 mm in diameter, and moves it in the manner of a weaving motion during welding. A low current range is used, so that a feature of this method is its ability to hold down the welding heat input and control bead shape.

Figure 2 shows the principle of vertical SAW. Because upward welding takes place in a vertical position, a flux basket is used to hold the flux, preventing it from falling. Both the flux basket, positioned to cover the joint to be welded, and a semi-automatic torch with its nozzle removed are mounted on a traveling welding cart. A DC power supply with general constant voltage characteristics is used as the welding power source. Submerged arc welding is made possible through using weaving, which swings the torch from side to side, and an upward welding technique simultaneously. For SAW of 9%Ni steel, welding wire of the same composition as the 70%Ni alloy-based material used for the downward or horizontal position was employed.

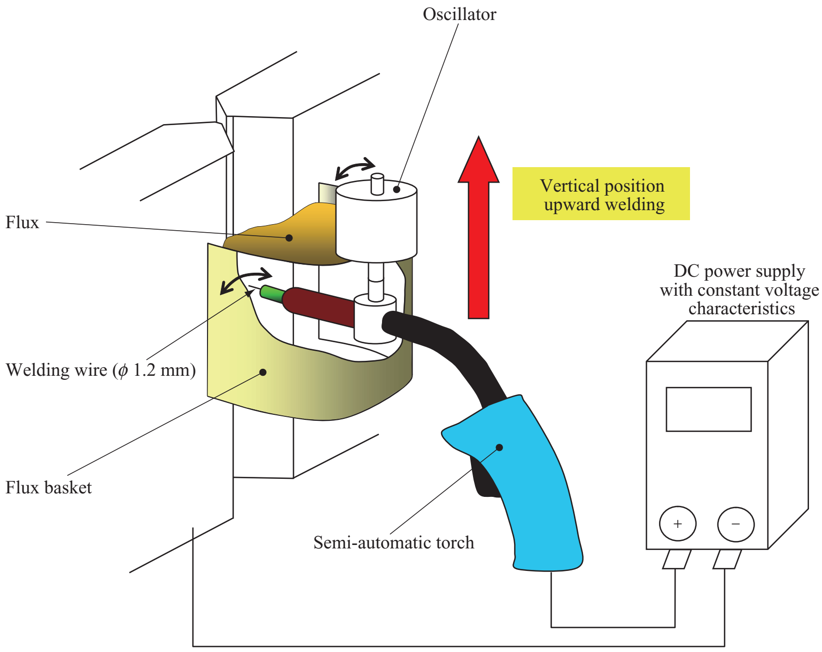


Fig. 2 Schematic illustration of vertical SAW

3. Development of 9%Ni steel vertical SAW welding consumables

3.1 Comparison of welding usability using commercial fluxes

Prior to the development of dedicated welding consumables, the welding usability of vertical SAW was evaluated using commercial fluxes. For this comparison, not only fluxes for 9%Ni steel but also those for other uses were included. The types of evaluation included bead shape smoothness, slag (nonmetallic substances generated on the surface of the weld) detachability, and quality determined by radiographic testing (hereinafter called RT). In the test, the carbon steel plate used was of thickness 19 mm with a U-slot 20 mm wide and 10 mm deep, and a 70%Ni alloy-based material 1.2 mm in diameter was used for the welding wire.

Figure 3 shows examples of the appearance of the beads when various fluxes were used. The best results in terms of bead shape and slag detachability were obtained with Flux No. 3 (**Fig. 3-(c)**). With Flux No. 2 (**Fig. 3-(b)**), the slag detachability was relatively good, but the bead shape was convex. With Fluxes No. 1 (**Fig. 3-(a)**), No. 4 (**-(d)**), and No. 5 (**-(e)**), the bead shape was convex and the slag was deeply bit. Flux No. 3 was a bond type flux and included a large amount of TiO_2 and Al_2O_3.

Figure 4 shows the range of appropriate welding conditions when Flux No. 3 is used. The arc voltage and weaving speed were appropriately adjusted in accordance with the welding current and speed. It was confirmed from the above that stable work was possible in a wide range of welding current, from 160 to 200 A, and welding speeds from 10 to 16 cm/min. However, the results of RT showed large numbers of blowholes (globular or nearly globular cavities caused in the weld metal), indicating the necessity for improvements in welding consumables with respect to blowhole suppression.

3.2 Development of welding consumables for 9%Ni steel vertical SAW

In the light of the results described in **Section 3.1**, for implementation of vertical SAW we addressed ourselves to developing welding consumables that would produce a combination of smooth bead shape and slag detachability, both relating to the workability of multi-pass welding, and that would achieve blowhole suppression, a property relating to weld quality.

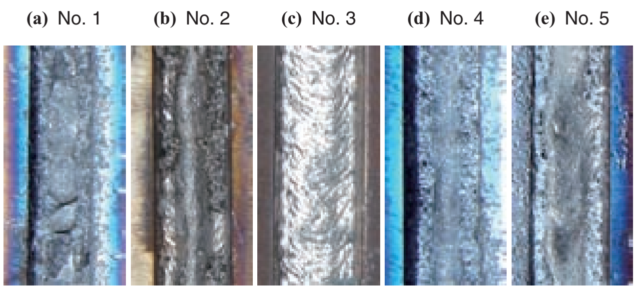
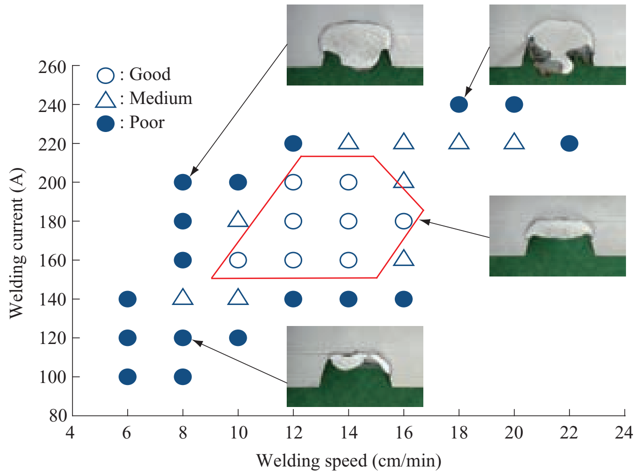


Fig. 3 Examples of bead appearances by vertical SAW using commercial fluxes



(Notes) Welding method : Vertical SAW (with weaving)
Wire : 70%Ni alloy, ϕ 1.2 mm
Arc voltage : 25 to 30 V

Fig. 4 Appropriate welding condition range of vertical SAW (Flux No. 3)

In vertical SAW, the welding wire and flux are fused by the heat of the welding arc to form a molten pool, which becomes slag and weld metal when it solidifies on cooling. The slag solidifies more quickly than the weld metal and retards the flowing-down of the weld metal, so that flat beads are obtained. For this reason, the rate of solidification of the slag is important and we evaluate it as the softening temperature of the flux. Because arc stability also affects bead shape smoothness, we examined the influence of flux particle size.

3.2.1 Adjustment of flux composition based on evaluation of softening temperature

Raising the slag solidification temperature, i.e., raising the flux softening temperature, is effective for smoothing bead shape. Therefore, an evaluation was performed in which the main flux components were changed and the Al content adjusted. The flux was compacted into a cylindrical mass and its shape changes were observed as the temperature was raised. Here, the flux softening temperature is defined as the temperature at which the projected area of the flux mass falls by 50% with respect to the projected area at room temperature. The evaluation test results are shown in **Fig. 5**. A good bead shape was obtained with Fluxes A and B, whose softening temperatures are higher than the melting temperature of the weld metal. Also, good results were obtained in terms of blowhole suppression by adding Al to fluxes and wires. This may be because the Al content promoted deoxidation and denitrification, suppressing blowhole formation.(4)

3.2.2 Determination of flux particle size by evaluation of arc stability

It may be effective for bead shape smoothing to keep the arc in a stable condition. The following findings have been obtained for the effect of flux particle size on arc stability. **Figure 6**(5) shows the measurement results of the weld

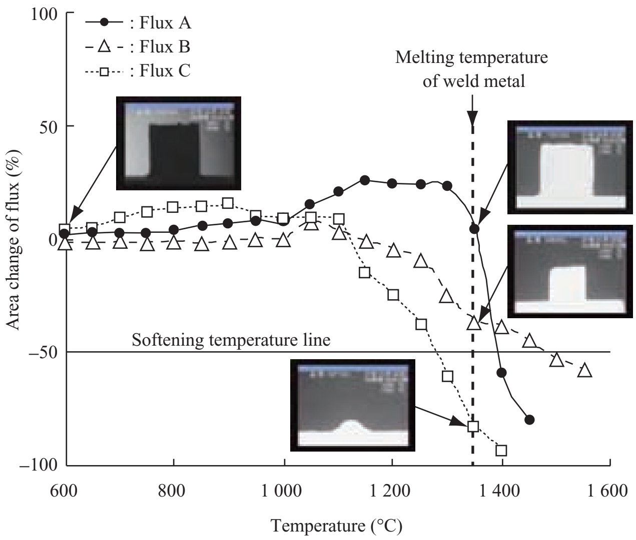


Fig. 5 Results of flux softening temperature evaluation test[4]

current and arc voltage waveforms with respect to flux particle size. The arc voltage fluctuations were smaller, the welding current was more stable, and a smoother bead shape was obtained when the flux had a higher fine particle content. This may be because a flux of finer particle size results in a more homogeneous melt.[5]

3.2.3 Developed welding consumables

Based on the results stated above, two pairs of welding consumables were developed: X (wire X and flux X) and Y (wire Y and flux Y), which combine bead shape smoothness and slag detachability with blowhole suppression properties. Their chemical compositions are shown in **Tables 1 and 2**.[4], [5]

4. Development of vertical SAW process

Keeping in mind that the process would be carried out as on-site construction work, we developed automatic welding equipment for performing vertical SAW and evaluated the deposition rate using the developed welding consumables.

4.1 Development of vertical SAW equipment

Figure 7 shows the developed vertical SAW equipment. The overall structure is based on a traveling rail and a traveling cart equipped with horizontal and vertical sliders and an oscillator. Giving consideration to on-site workability, we aimed at structural simplicity by employing a unit system, which allows easy assembly. For the welding torch, a general semi-automatic torch with the nozzle removed is used, and the torch tip is inserted into the flux basket. The basket is supplied with flux from the hopper mounted on the cart. To allow work to be carried out in an intuitive manner, welding conditions are indicated using an analog display.

4.2 Deposition rate evaluation test results

The deposition rate was measured using the developed welding consumables, and the results are shown in **Fig. 8**.[4] For vertical SAW, we succeeded in confirming that stable welding can be performed in the deposition rate range from 50 to 80 g/min. In the figure, the deposition rate of MMA in a vertical position is also shown for comparison. With vertical SAW, continuous automatic welding is possible,

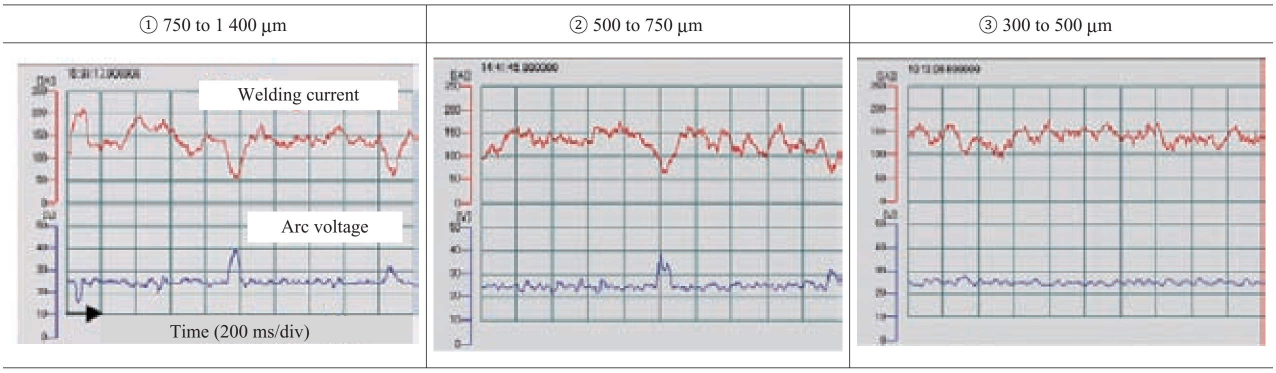


Fig. 6 Influence of particle size distribution on welding current and arc voltage[5]

Table 1 Chemical compositions of welding wires[4], [5]

Welding wire	Wire diameter (mm)	Chemical composition (wt%)							
		C	Si	Mn	Ni	Cr	Mo	W	Al
Wire X	1.2	0.02	0.05	0.01	76.4	—	20.1	3.0	0.01 - 0.43
Wire Y	1.2	0.02	0.05	< 0.1	70.2	2.0	19.0	3.0	—

Table 2 Chemical compositions of fluxes[4], [5]

Flux	Main components	Particle size
Flux X	TiO_2-MgO-CaF_2	12 × 100 mesh
Flux Y	MgO-ZrO_2-CaO-Al_2O_3-SiO_2	12 × 65 mesh

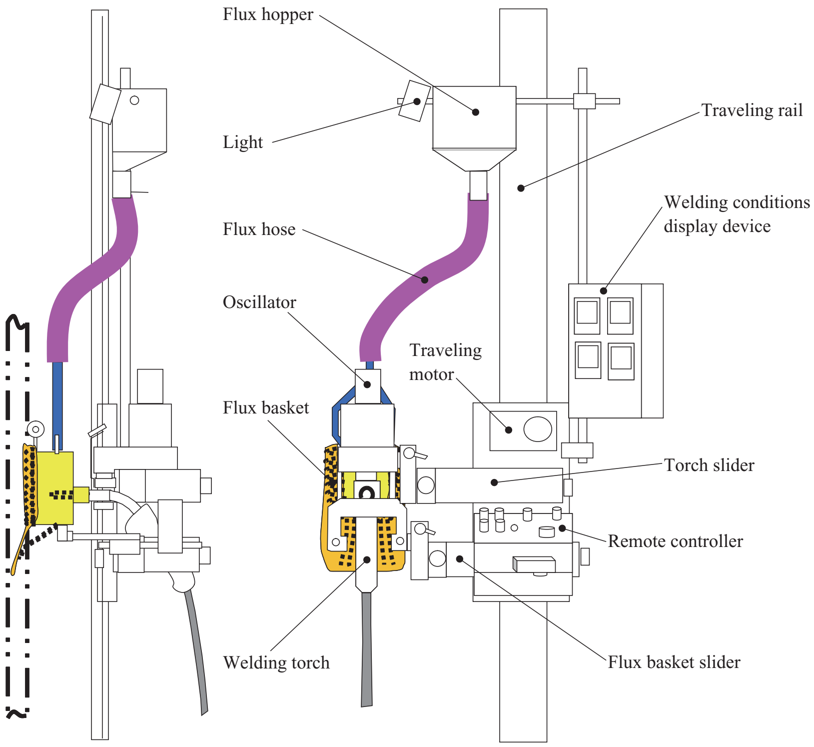
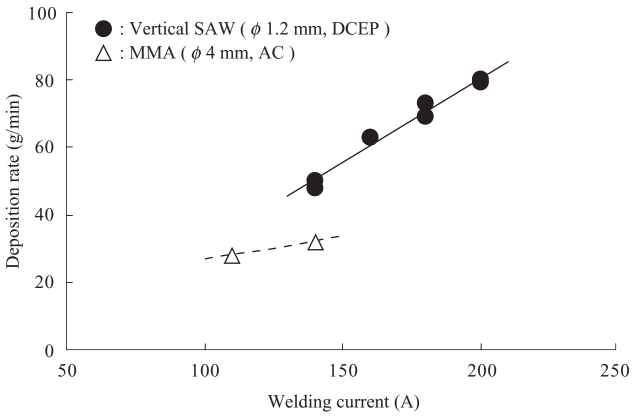


Fig. 7 Equipment for vertical SAW



(Notes) Welding consumable : 70%Ni alloy
DCEP : Electrode positive

Fig. 8 Comparison of deposition rate between vertical SAW and MMA

so an improvement in work efficiency can be expected in comparison with MMA, which requires welding rod replacement.

5. Joint performance test

5.1 Basic joint performance

Using the developed welding equipment and consumables, we evaluated the basic performance of weld joints. For the base metal, a 25 mm thick 9%Ni steel plate (ASTM A553M-95 TYPE1) was used. **Table 3** shows the chemical composition and mechanical properties of the base metal. **Figure 9** shows the groove shape and **Table 4** shows the welding conditions. The following types of evaluation were performed : ① Macroscopic cross-sectional observation, ② Microscopic cross-sectional observation, ③ Hardness test, ④ RT, ⑤ Weld metal tensile test, ⑥ Joint tensile test, ⑦ Bending test, and ⑧ Charpy impact test. **Figure 10** shows the macroscopic cross-sectional view. In the macroscopic and microscopic cross-sectional observations, no hazardous defects or structures were observed. The Vickers hardness gave a maximum hardness of HV348 in

Table 3 Properties of 9% Ni steel plates used

Thickness (mm)	Chemical composition (wt%)									Mechanical properties			
	C	Si	Mn	P	S	Cu	Ni	Cr	Al	0.2% Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Absorbed energy (–196°C) (J)
25	0.06	0.24	0.6	0.004	0.001	0.01	9.16	0.02	0.037	680	730	28.2	240
28	0.06	0.26	0.61	0.005	0.001	0.01	9.13	0.02	0.041	665	715	28.6	212

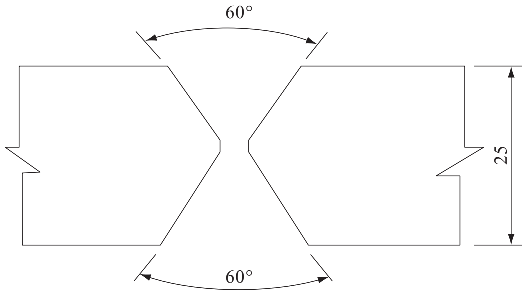
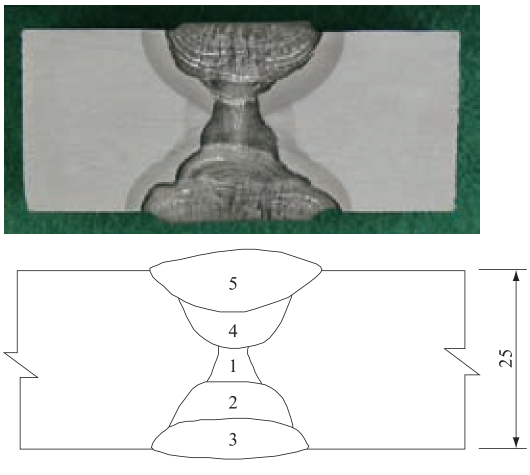


Fig. 9 Shape of X-groove (unit : mm)

Table 4 Welding conditions of test plate

Parameter	Unit	Range
Heat input	kJ/cm	18.5 - 21.6
Oscillation pitch	mm	2 - 2.8
Number of oscillation	N/min	25 - 35



(Note) 1 - 5 : Pass sequence

Fig. 10 Macro section and pass sequence (unit : mm)

the heat affected zone. The joint performance test results are shown in **Table 5**. Favorable results were obtained for all the evaluation types.

5.2 Brittle fracture characteristics

The 9%Ni steel and corresponding welds used in aboveground LNG storage tanks are required to have sufficiently good properties with respect to prevention of brittle fracture initiation to ensure that they do not give rise to brittle fracture, and to possess properties that will arrest crack propagation before it eventually results in large-scale breakage if brittle cracking should actually occur. We therefore evaluated the fracture toughness required to prevent brittle fracture initiation and the fracture toughness required to arrest brittle crack propagation for the welds.

The fracture toughness required to prevent brittle fracture initiation was evaluated by crack tip opening displacement (CTOD) tests conducted at −165°C. The test results are shown in **Fig. 11**. The obtained CTOD values were large, more than 0.4 mm, at all positions for the weld metal, weld interface (the position at which the ratio of weld metal to base metal is 1 to 1) and the heat affected zone (HAZ) (at distances of 1, 3, and 5 mm from the weld interface). The results suggest that the joints have a low risk of brittle fractures occurring. However, these values are too large to be treated as CTOD values which can be used to evaluate brittle fracture initiation. Further testing concepts will need to be developed in order to consider the fracture mechanical behavior.

The fracture toughness required to arrest brittle crack propagation was evaluated by duplex ESSO tests conducted at −165°C. The shape of the test specimen is shown in **Fig. 12**. The test plate used was made of a weld specimen 500 mm wide, 350 mm long and 28 mm thick, to which a 9%Ni steel plate subjected to embrittling heat treatment was welded using a 3.5%Ni-based welding consumable. With a tensile stress of 392 MPa imposed, a wedge was dropped on the notch section to make a brittle crack enter the heat affected zone of the specimen's weld joint from

Table 5 Results of weld joint performance tests

Standard	JIS Z 3106	ASME SECTION Ⅸ							API620 APPENDIX Q			
Test contents	RT	Tensile test					Longitudinal bead bend test		Charpy impact test (−196°C)			
		Weld metal (ϕ12.7)				Weld joint						
		0.2% Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)	Tensile strength (MPa)	Face bend test	Root bend test			Absorbed energy (Notch position : weld metal) (J)	Ave. (J)
Requirement	Type 1 Class 1 or 2	≧ 390	≧ 690	—	—	≧ 690	< 3 mm	< 3 mm			≧ 37	≧ 50
Result	Type 1, Class 1	435 440	698 710	35 36	33 30	719 737	Defect-free	Defect-free	Sampling position	t /2	110	108
											110	
											104	
										t /4	102	107
											109	
											112	

(Notes) t : Plate thickness
Ave. : Average

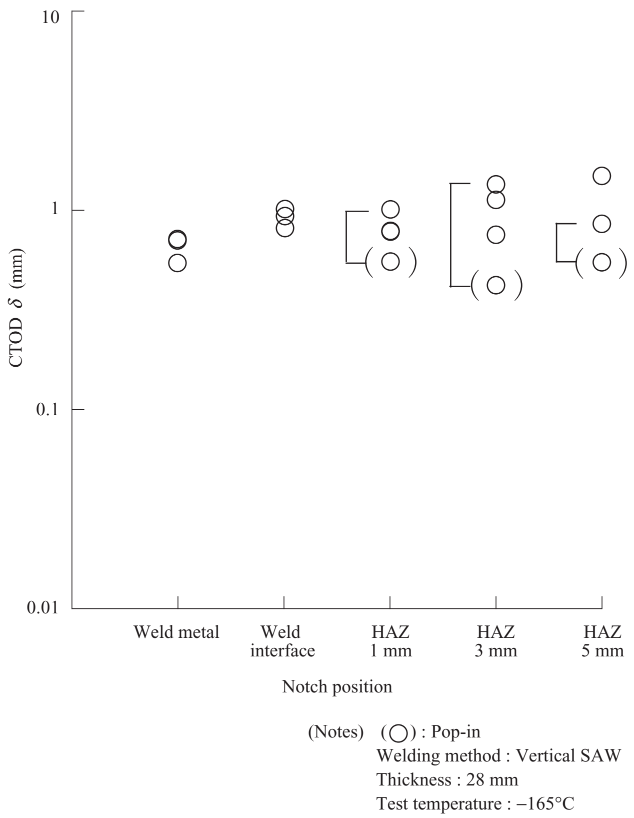


Fig. 11 CTOD values of welding joint by vertical SAW

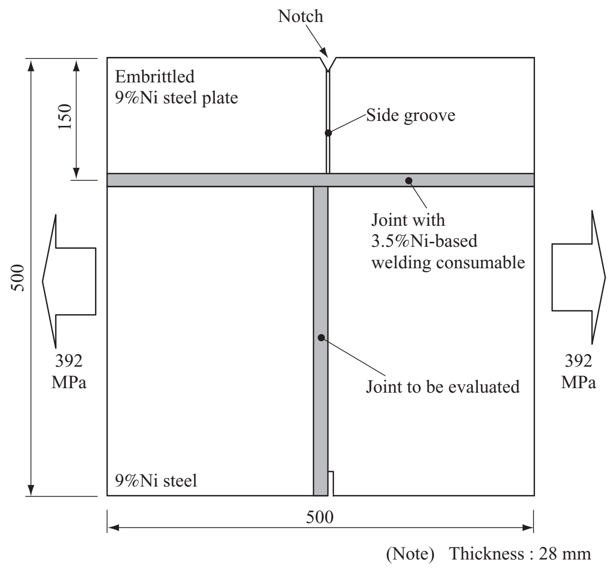


Fig. 12 Duplex ESSO test specimen (unit : mm)

the embrittled plate and the length to the crack tip was evaluated. Our test results show the arresting of crack propagation in the target area to be an experimental fact.

6. Large welding test

In order to simulate actual construction work, mock-up tests involving a weld length of 4 meters were conducted so that welding stability and other properties could be evaluated. **Figure 13** shows a view of the welding setup.

Fig. 13 Appearance of welding mock up tests with using large-size test plate (Plate thickness : 28 mm)

These tests were conducted using an actually used movable stage to reproduce the conditions on a construction site. It was confirmed that continuous welding along a length of 4 meters could be performed in stable manner, and in order to simulate accidental interruption to the welding, repair welding by MMA and resumption of automatic welding were also carried out. In the inspection performed after welding, no hazardous defects were identified, and a good quality was obtained.

7. Conclusions

We developed a vertical submerged arc welding method for use in the vertical joints of the 9%Ni steel side plates present in aboveground LNG storage tank inner shells. The developmental results for this welding method are shown below.

(1) The developed vertical SAW method uses a thin wire of diameter 1.2 mm, and utilizes an original process employing oscillation that is performed while welding is in progress.

(2) Dedicated welding consumables for vertical SAW were developed. They combine blowhole prevention properties with bead shape smoothness and slag detachability, these being related to the workability of multi-pass welding.

(3) It was confirmed that, with vertical SAW, stable welding can be performed at a deposition rate of from 50 to 80 g/min.

(4) The use of the developed welding equipment and consumables resulted in the joints achieving the required quality in the joint performance tests. Furthermore, the joints showed a low risk of developing brittle fractures in the brittle fracture tests.

(5) Using the developed vertical SAW equipment and simulating on-site construction work, mock-up tests involving welding along a length of 4 meters

were conducted. It was confirmed that continuous welding could be performed in a stable manner and, on simulating an interruption to welding, it was also confirmed that a good quality was obtainable at the position of the repair weld.

Making full use of the advantages of this new welding method, we aim to put it to practical use as an efficient welding method capable of replacing MMA for the vertical joints of the 9%Ni steel inner shell present in aboveground LNG storage tanks.

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