JFE TECHNICAL REPORT
No. 20 (Jan. 2015)

Multiple-Electrode Submerged Arc Welding Process with Low Heat Input†

KOZUKI Shohei*1 HAYAKAWA Naoya*2 OI Kenji*3

Abstract:

In recent years, mechanical properties of weld joint for natural gas transportation U-ing O-ing expansion (UOE) pipes have been more stringent. JFE Steel developed a new submerged arc welding (SAW) process for high-strength and heavy wall thickness UOE pipes. A new SAW process which can reduce heat input of 25% due to its high deposition rate and deep penetration is performed with multiple electrode SAW using small diameter welding wire on lead electrode. Improvement of heat affected zone (HAZ) toughness in seam welding on API X65 (API: American Petroleum Institute) heavy wall linepipe and refinement of prior austenite grain size in HAZ was achieved in order to reduce its heat input.

1. Introduction

Demand for natural gas has increased greatly in response to growing demand for energy and heightened concern about global environmental problems. In Russia and Northern Europe, which are leading natural gas producing regions, a number of long-distance pipelines as long as several thousand kilometers have already been laid, joining gas fields and consuming regions. However, in anticipation of further increases in demand, a series of large-scale pipeline projects have been planned under national leadership, beginning with the South Stream Project and Nord Stream Project, which will join Russia and Europe, and those concerned are actively promoting infrastructure improvement in order to ensure safe, efficient transportation of natural gas. Against this background, increasingly strict performance requirements are being applied to the steel pipes (linepipe) which are used in pipelines. High strength, high toughness, and heavy wall thickness are now required in steel plates used in linepipe, particularly from the viewpoints of high operating pressures accompanying the increased demand of recent years[1,2)], fracture resistance to longitudinal crack[3)], and crush resistance against water pressure when pipelines are laid in deep waters[4)]. On the other hand, the performance requirements for girth welds when laying linepipe and the seam welds in the pipe manufacturing process are not exceptions to this trend. In particular, in seam welds, high toughness has been realized in the weld metal by application of high basicity flux for submerged arc welding (SAW), and improved toughness of the heat affected zone (HAZ) has been achieved by optimization of the steel microstructure[5,6)].

In U-ing O-ing expansion (UOE) pipes, which are widely used in linepipe applications, a seam weld exists at the plate butting position as a distinctive feature of the manufacturing process, in which a flat plate is press-formed into a round pipe shape and the plate edges are then welded together. From the viewpoint of securing productivity, seam welds are welded by double submerged arc welding (DSAW) by using multiple electrodes in one pass on the inside and outside of the pipe. Because the heat input to seam welds has tended to increase accompanying the construction of heavy wall thickness pipelines in recent years (**Fig. 1**), obtaining high HAZ toughness in the as-welded condition is an issue.

Although techniques for improving HAZ toughness differ somewhat depending on whether the main component of the matrix structure is ferrite or bainite, in gen-

† Originally published in *JFE GIHO* No. 34 (Aug. 2014), p. 34–38


*1 Joining & Strength Res. Dept.,
Steel Res. Lab.,
JFE Steel


*2 Senior Researcher Manager,
Joining & Strength Res. Dept.,
Steel Res. Lab.,
JFE Steel


*3 Dr. Eng.,
General Manager, Joining & Strength Res. Dept.,
Steel Res. Lab.,
JFE Steel

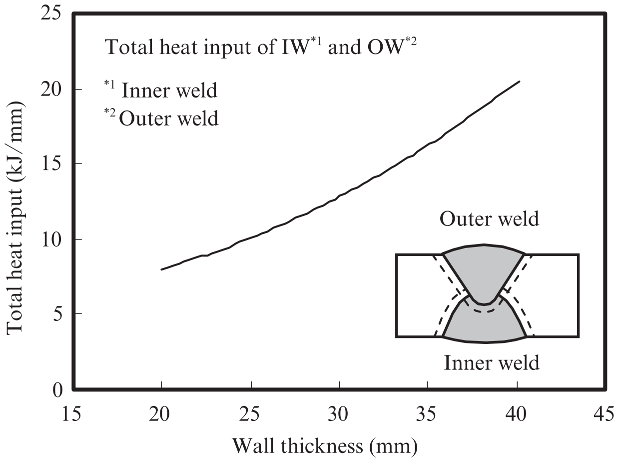


Fig. 1 Relationship between wall thickness and heat input on seam welded joint on UOE linepipe

eral, the following are effective[7]:

(1) Refinement of the fracture facet size by refinement of the austenite grain size
(2) Reduction of the volume fraction of martensite-austenite constituent: island-shaped martensite (M-A), which is a hard phase
(3) Higher purity of the base metal (reduction of N and P)

From the viewpoint of the welding process, reduction of the weld heat input is one of effective techniques for improving HAZ toughness by the above-mentioned (1).

2. Outline of SAW Welding Technology with Low Heat Input

The HAZ toughness of UOE pipe seam welds improves as the welding heat input decreases[4]. **Figure 2** shows the relationship between the grain size of prior austenite near the fusion line and the welding heat input. The austenite grain size is one of the factors that govern HAZ toughness. As the welding heat input decreases, the austenite grain size decreases and HAZ toughness improves. One effective technique for reducing welding heat input is application of low heat input SAW technology, in which a small diameter welding wire is applied as the leading electrode in multiple-electrode SAW[4,8]. This technology improves HAZ toughness while reducing the welding heat input by utilizing three effects obtained by applying a small diameter welding wire as the leading electrode: namely, (1) increased amount of deposited weld metal, (2) increased penetration depth, and (3) sharpening of the weld metal tip shape.

2.1 Increased Deposition Rate by Application of Small Diameter Welding Wire

Figure 3 shows the effect of the welding wire diameter on the amount of deposited weld metal per unit of time (deposition rate) in single wire SAW. With both the 2.4 mm wire and 4.0 mm wire, the deposition rate increases exponentially as the welding current increases. The deposition rate generally follows the relationship shown in Eq. (1), which was proposed by Hirata et al. [9].

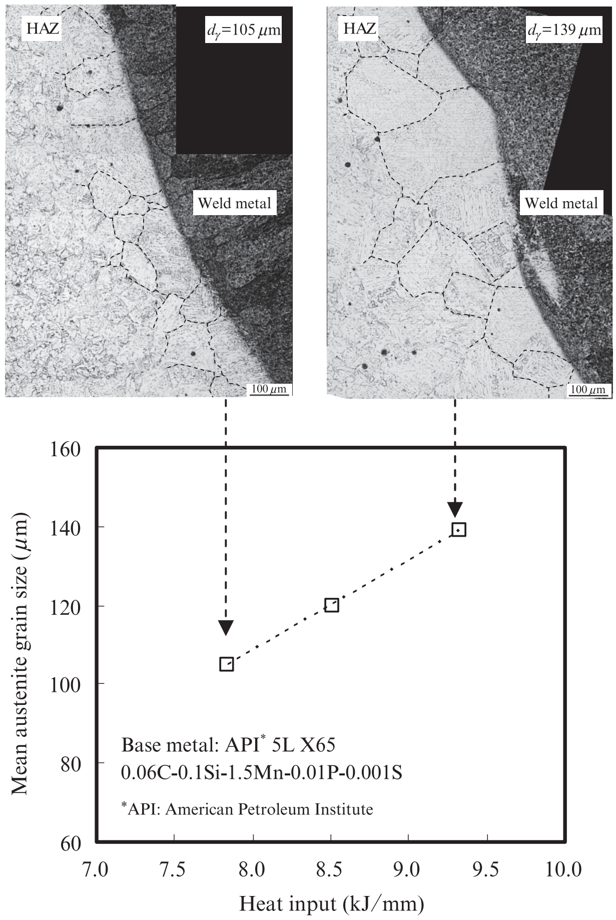


Fig. 2 Effect of heat input of double submerged arc welding (DSAW) on austenite grain size

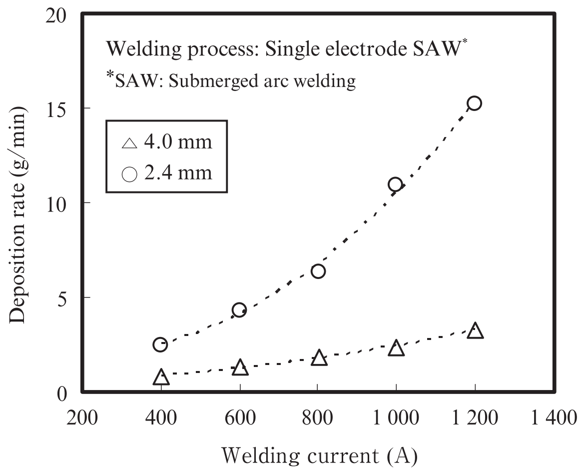


Fig. 3 Effect of welding wire diameter on deposition rate

$$V_{\mathrm{m}} = \frac{1}{\rho H_0}\left(\varphi J + R_0 \mathrm{Ex} J^2\right) \quad (1)$$

Where, ρ: Density of welding wire (kg/m^3)
H_0: Quantity of heat of droplet (J/kg)
φ: Equivalent voltage of electrode heating (V)
$\varphi = V_A + V_{WA} + V_r$
V_A: Anode drop voltage (V)
V_{WA}: Work function of anode material (V)
V_r: Equivalent voltage of enthalpy of electron in arc plasma
J: Current density at wire stickout part (A/m^2)
$J = I/(\pi d^2/4)$
I: Current of wire stickout part (A)
d: Diameter of welding wire (m)
R_0: Resistivity (Ω • m)
Ex: Wire stickout length (m)

In other words, because the deposition rate increases in proportion to the second power of the current and in inverse proportion to the square of the diameter of the welding wire, if the cross-sectional area of the welding wire can be decreased by using a smaller diameter wire, deposition can be increased dramatically, even at the same welding current.

2.2 Increase of Penetration Depth by Application of Smaller Diameter Welding Wire

Figure 4 shows the effect of the welding wire diameter on the penetration depth. The welding method is single wire SAW. The penetration depth increases remarkably as the wire diameter decreases. This is because the current density increases as the wire diameter decreases, thereby increasing the density of the arc energy, and the arc is also focused more narrowly due to the increased electromagnetic pinch force, and as a result, the penetration depth increases. As conditions for reducing welding heat input, welding is performed while securing the minimum penetration depth and amount of deposited weld metal necessary in the joint without causing welding defects such as lack of fusion, incomplete penetration, undercut, etc. Therefore, by using a small diameter wire, it is possible to decrease the welding heat input by increasing the welding speed by an amount corresponding to the increased weld metal deposition and penetration depth which are possible with the smaller diameter wire.

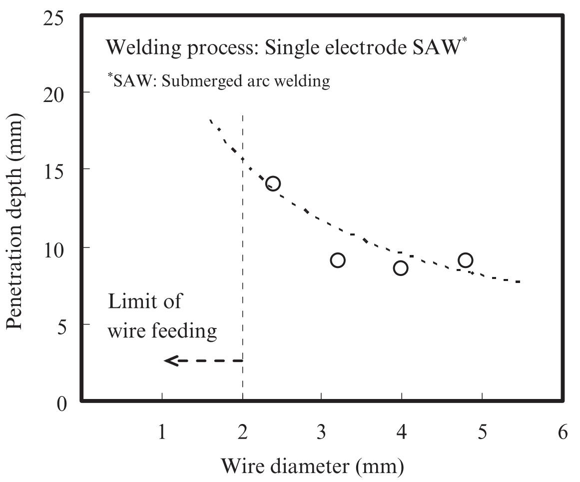


Fig. 4 Effect of wire diameter on penetration depth

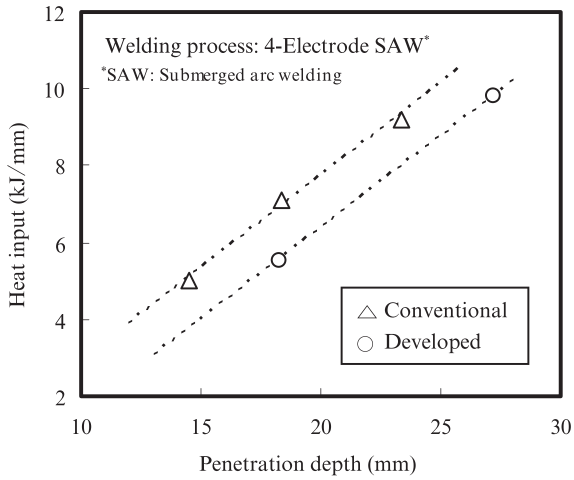


Fig. 5 Heat input reduction effect on 4-electrode SAW

Figure 5 shows the heat input reduction effect in case a small diameter wire (diameter: 2.4 mm) is applied as the leading wire in four-electrode submerged arc welding. In comparison with the conventional method, it is possible to reduce the welding heat input by a maximum of approximately 25%.

3. Effectiveness of Small Diameter Wire Seam SAW Technology

3.1 Experimental Method

Small diameter wire seam SAW technology was applied to seam welding of UOE pipes, and the mechanical properties of the seam welds was evaluated. The material used in this experiment was a X65 (yield strength: 65 kpsi) class high strength steel plate, which is a linepipe material provided in the American Petroleum Institute (API) standards. The chemical composition of this tested material is shown in **Table 1**. The DSAW was performed under the same welding conditions as the manufacturing conditions for UOE pipe using plates with a thickness of 29 mm. The main welding conditions are shown in **Table 2**. Welding was performed using a butt welded joint with an X groove, in which continuous tack welding was performed by gas

Table 1 Chemical composition of base metal (mass%)

C	Si	Mn	P	S	Others
0.05	0.15	1.6	0.005	0.001	Ni, Cr, Mo, Nb, Ti

Table 2 Welding condition of 4-electrode submerged arc welding (SAW)

Process	Electrodes	Electrode diameter (mm)	Heat input (kJ/mm)	Travel speed (m/min)
Conventional	1st	4	7.2	1.3
	2nd	4		
	3rd	4		
	4th	4		
Developed	1st	2.4	5.5	1.6
	2nd	4		
	3rd	4		
	4th	4		

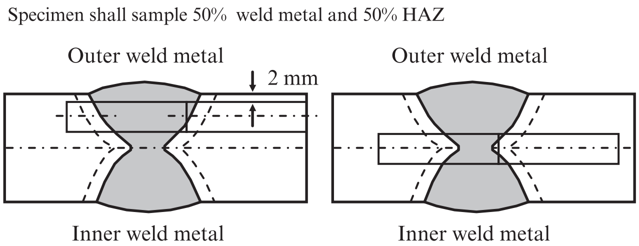
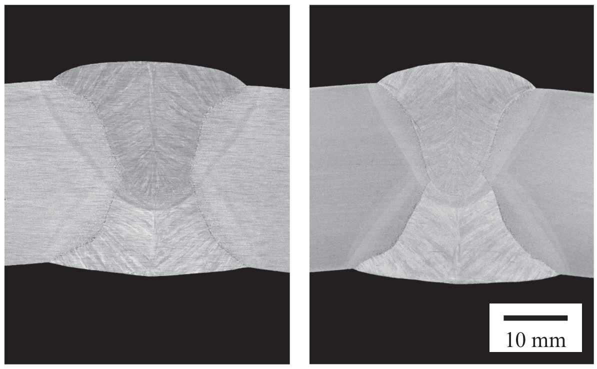


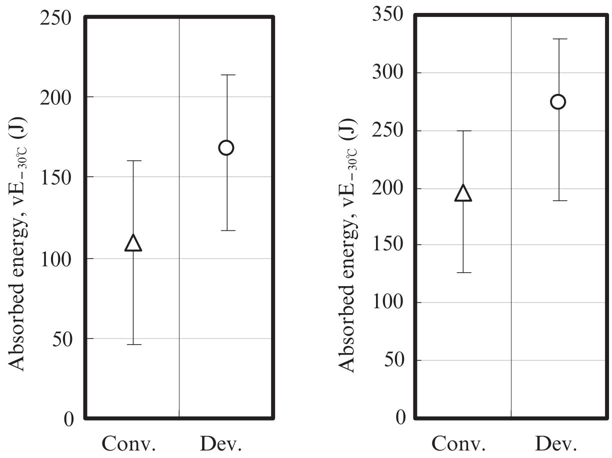
Fig. 6 Charpy V-notch impact test specimen positions



(a) Conventional SAW* (b) Developed SAW

*SAW: Submerged arc welding

Photo 1 Macrostructure of conventional SAW and developed SAW



(a) Outer weld metal HAZ* (b) Root HAZ

*HAZ: Heat affected zone

Fig. 7 Charpy impact test results of HAZ

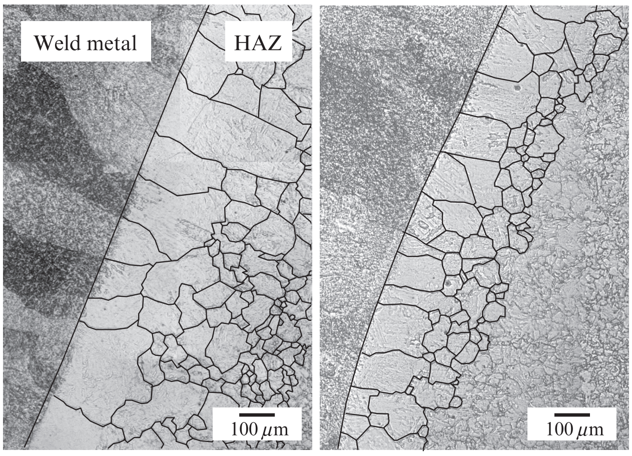
shielded welding at the bottom of the outside groove, and final welding was then performed in the order of internal welding followed by external welding. For observation of the base metal HAZ structure around the fusion line, after welding, the bead cross section was polished with emery paper and alumina powder, after which the austenite grain boundary was exposed by etching with picric acid. The specimens were observed with an optical microscope. In addition, for evaluation of HAZ toughness, V-notch Charpy impact test specimens (JIS Z 2242, JIS: Japanese Industrial Standards) were taken from the position shown in **Fig. 6**. Charpy impact tests were performed with the respective specimens at the test temperature of −30°C, and the absorbed energy $vE_{-30°C}$ was evaluated.

3.2 Test Results and Discussion

Photo 1 shows photographs of the cross-sectional macrostructures of the weld metal. These results confirmed that it is possible to manufacture welded joints which are free of incomplete penetration and inadequate weld metal deposition with a welding heat input of 75% of that in conventional welding, while also securing the same penetration depth as with the conventional method, by applying a small diameter welding wire in external welding. It may be noted that no welding defects such as incomplete penetration, slag inclusion, etc. were found over the full length of the weld line, and formation of sound welded joints was confirmed in ultrasonic testing and radiographic testing, which were performed after welding.

Figure 7 shows the results of the Charpy impact test of the HAZ of the outer weld metal. The plotted values are the mean values of absorbed energy at −30°C, $vE_{-30°C}$. The results confirmed that the HAZ toughness of the outer weld metal and the HAZ toughness of the root HAZ (inner-outer weld metal interface) are improved by applying the small diameter wire seam SAW technology.

Photo 2 shows the results of observation of the microstructure of the HAZ of the outer weld metal. The observation position corresponds to the position of the notch bottom in the Charpy test specimen. When the



(a) Conventional SAW* (b) Developed SAW

*SAW: Submerged arc welding

Photo 2 Heat affected zone (HAZ) micrograph of conventional SAW and developed SAW

mean austenitic grain size of the austenite etched with picric acid was measured by linear analysis, refinement from approximately 140 μm to approximately 80 μm was achieved by application of the small diameter wire seam welding technology. This decrease in the austenite grain size reduces the fracture facet size in the Charpy impact test and is considered to be the main factor in the improved HAZ toughness of the external weld. Similarly, it is thought that the HAZ toughness of the root HAZ also improved because coarsening of austenite grains at the root was suppressed by the decrease in external welding heat input.

On the other hand, in the multiple-heat cycle region, where the heat effect of external welding is added to parts that receive the heat effect of internal welding, a local brittle zone (LBZ), which is called the intercritically coarse grain heat affected zone (ICCGHAZ) exists, and formation of martensite-austenite constituent (M-A) is a concern, as M-A generally reduces toughness. It is estimated that the decreased LBZ due to the lower heat input also contributes to improved root HAZ toughness.

The mechanical properties of the weld metal and joint properties were also evaluated in a separate study, and performance on the same level as with the conventional method was confirmed.

4. Summary

A newly-developed small diameter wire seam submerged arc welding (SAW) technology, in which a small diameter welding wire is used in the leading electrode in four-electrode SAW, was applied in order to improve the HAZ toughness of seam welds of high strength and heavy wall thickness UOE pipes of API X 65 class. The following knowledge was obtained.

(1) By applying a small diameter welding wire (diameter: 2.4 mm) as the leading electrode in four-electrode submerged arc welding, the welding heat input was reduced by approximately 25% while securing the same penetration depth as with the conventional method.

(2) Due to the decrease in the welding heat input, the austenite grain size around the fusion line of the external weld metal was refined by approximately 40% and HAZ toughness improved.

5. Concluding Remarks

In response to heightened concern about global environmental problems, demand for natural gas is increasing year by year[10]. The CO_2 emission per unit of heating value, expressed as the ratio of coal: crude oil: natural gas, is generally said to be 100: 80: 50[11]. According to a trial calculation[12], global demand for natural gas in 2035 is expected to reach as much as 1.6 times the level in 2009. Based on this, continuing increases in the requirements for high strength and heavy wall thickness linepipe for natural gas are expected.

Moreover, the trend toward higher strength is not limited to the energy transportation field; remarkable increases in the strength of steel materials have also been seen in construction, shipbuilding, offshore structures, and other fields. In responding to the even higher strength levels expected in the future, the low heat input welding method described in this paper will of course be utilized, and use of new welding technologies such as high energy density beam welding by fiber laser welding systems, etc., and friction stir welding is also expected. The authors will work to ensure that it is possible to meet customer needs by utilizing more advanced technologies.

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