Progress in Productivity and Weld Quality in UOE Pipes
by Four-wire Submerged Arc Welding*

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Synopsis

Spurred by the growing demand for heavy wall UOE pipes with excellent
toughness, recent progress by the 4-wire submerged arc welding (SAW)
method is reported from the aspects of productivity and weld quality. The
4-wire SAW method is found to bring about 10~30 % improvement in
productivity and to result in a remarkable suppression of slag inclusion
under optimized welding conditions, for example, in current phase and cur-
rent ratio. It is also confirmed that the speedup by the 4-wire SAW
method does not deteriorate weld quality.

Special attentions are paid on the weld quality of heavy wall pipes to
meet the recent market situation. This was because there are two prob-
lems, i.e., the formation of coarse microstructures of low toughness owing to
slow cooling rate and the deterioration of external bead appearance. To
cope with them, firstly, the control of nitrogen, oxygen and boron contents
in weld metal must be conducted. The optimum ratio between nitrogen
and boron contents for excellent toughness is found to be B=0.7·[N]±15
(ppm) for [N]≤80 ppm. Secondly, a fused type flux is developed, which
has excellent performances in both lowering oxygen content in weld metal
to 250~300 ppm and suppressing the deterioration of bead appearance.
Charpy V-notch Energy more than 100 J at -60 °C has, then been
achieved based on above studies.

I. Introduction

Recently, demand for UOE steel pipes for the pipe-
lines and the off-shore structures in the Arctic are
growing. Therefore heavier wall pipes with excellent
toughness are in great demand.

In view of this, the improvement of welding tech-
nology can be the key point to tide over these sit-
uations and the development of the 4-wire SAW
method5,6) is one of latest advances in UOE pipe
manufacturing process. In this paper, fundamental
studies on 4-wire SAW method and its practical appli-
cation are reported.

II. Progresses in Productivity by the 4-wire SAW
Method

In general, the SAW process is apt to become a
bottleneck of UOE pipe mill capacity so that high
speed SAW is necessary. However, although the
speedup of SAW increases the overall productivity, it
often induces many weld defects. The 4-wire SAW
method is expected to be usefull in overcoming the
problems of productivity as well as in improving weld
quality.

1. Method for Speedup of Welding

With regard to speedup of SAW, increasing the
electrode number seems to be the most effective. The
speedup, however, cannot be achieved without opti-

mization of welding conditions preventing undercut
because the occurrence of undercut decides the upper
limit of welding speed.

The authors presumed, based on the studies on the
3-wire SAW1-4) that the strong stream of molten metal
which caused undercut could be suppressed when the
4th electrode's arc was appropriately deflected against
that stream direction and the deflection of 4th arc
could be controlled by the transformer connection
even in all A.C. SAW.

Figure 1 shows the relationship between the under-
cut occurrence, UC, defined as the percentage of sum
total length of undercut to welded length and the
electromagnetic force acting on the 4th arc Fx4
calculated by Eq. (1).

Fx4 = (mu0I4 / 2piR) { sum Ij cot (phi4j - phi4j) / 2 * sin phi4j * sin phi44
* cos phi4j - sum Ij (1 + cos phi4j) * cos theta4j }
(N/m)

- where, j: Electrode number
I: Effective current (A)
theta4j: Phase difference between 4th electrode
current and j electrode current
phi: Electrode inclination
R: Distance between base metal surface and
wire melting tip (m)

Fig. 1. Effect of electromagnetic force acting on the 4th
arc (Fx4) on undercut occurrence.

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μ_0 : Permeability in the space ($4\pi\times10^{-7}$ N/A²).

Here, F_{x4} was selected as a parameter corresponding to the arc deflection and varied by changing only the transformer connection under the same welding condition as shown in Table 1. UC was remarkably suppressed in a limited range of F_{x4} and this optimum range did not change even when currents were varied.

Assumptions used in the above equation are:

- (1) The arc current flows along an extension of the electrode axis.
- (2) The distance R between the base metal surface and the wire melting tip is constant (10^{-2} m).
- (3) The ground current flows backwards (x direction) along the welding line.

Based on these studies, the optimum current phase discovered is shown schematically in Fig. 2. It was also confirmed that terrible undercut occurred even by this optimum current phase in the case when the ground point was set at the finishing end of the work.

2. Method for Preventing Internal Weld Defect

Slag inclusions are the first internal defect to be depressed for speedup. They are the slag particles remained in weld metal, not floating out of molten metal. It is expected that evolution of this defect would be prevented by proper stirring of molten pool or its remelting. For this purpose, the function of each electrode arc in forming bead shape was studied.

Figure 3 shows the contribution of each electrode arc on bead dimensions of depth and width at several

welding speeds. Contributions (defined as the ratio to the final dimensions) were obtained by sequential ignition of arc from the 1st to the 4th in one run welding. Photograph 1 shows an example of the changes of cross-sectional bead appearances corresponding to the line at 220 cm/min in Fig. 3.

The welding condition used here was nearly the same as in Table 1 and Fig. 2. Although there was a little difference in contribution of each arc with welding speed, the function of each arc is summarized as follows;

Both of the 1st and the 2nd arc had a great contribution of 85~100 % to the final depth from Fig. 3. This means that they have a strong gouging function so that slag inclusions would be induced by them as observed in Photo. 1. On the other hand, the 4th arc only rectified the width and had almost no contribution (≤ 5 % from Fig. 3) to depth so that the significant affection on preventing slag inclusion could be hardly expected.

The 3rd arc had an intermediate contribution to both depth (0~15 %) and width (≈ 30 %). This means that it has the ability to stir the molten pool effectively or melting the slag particles trapped. It is expected that it can be available for preventing slag inclusions by proper choice of its current ratio to the 1st arc. It has been revealed that the slag inclusion occurrence greatly depends on the current ratio of the 3rd arc and its optimum ratio is about 0.7 as shown in Table 2.

Fig. 2. The best combination of current phases.

Fig. 3. Contribution of each electrode arc to the final bead shape.

Photo. 1. Change in cross-sectional bead appearance by sequential ignition of each electrode arc (corresponding to the line at 220 cm/min in Fig. 3).

Table 1. Welding condition and wire arrangement used.

Electrode	I (A)	E (V)	e (mm)	ϕ (deg.)	l (mm)
1st	1 150	38	25	0	13
2nd	1 050	42	25	15	13
3rd	900	42	30	30	13
4th	800	42	35	45	13

3. Improvement of Productivity

Figure 4 compares the 4-wire SAW method with the 3-wire SAW method in welding speeds and shows the improvement in the productivity by use of the 4-wire SAW method. By this speedup, the bottleneck of the welding process was eliminated and 10~30 % improvement of productivity was achieved. The improvement of welding speed is greater for the thicker wall pipes and this tendency is more advantageous for the production of the heavy wall pipes.

Table 2 demonstrates the success in prevention of slag inclusions by the optimized 4-wire SAW method. The occurrence of the slag inclusion was remarkably suppressed to a level (0.5 %) lower than that (1.2 %) of the 3-wire SAW method. This result suggests that the 4-wire SAW method is certainly effective in preventing slag inclusions. This is because the function of each electrode arc is more distinct and the 3rd arc function could be used more appropriately and effectively in the 4-wire SAW method.

Fig. 4. Improvement of productivity by the 4-wire SAW method.

Table 2. Effect of current ratio of 4-wire SAW on slag inclusion occurrence and comparison between 4-wire SAW and 3-wire SAW in resistance to slag inclusion under optimized condition.

Condition		Current ratio ($I_1:I_2:I_3:I_4$)	Piece percentage of pipe with slag inclusion (%)
4-wire*	I_3 (small)	1:0.86:0.60:0.55	18.2
	Optimum	1:0.86:0.70:0.55	0.5
	I_3 (large)	1:0.86:0.84:0.55	3.1
3-wire**	Optimized	1:0.70:0.60	1.2

* $I_1=1\ 150\ \text{A}$, $v=2.1\ \text{m/min}$

** $I_1=1\ 120\ \text{A}$, $v=1.6\ \text{m/min}$

III. Progresses in Weld Quality

1. Effect of the 4-wire SAW Method on Oxygen Content in Weld Metal

It is of particular interest to see how much the speedup by the 4-wire SAW method influences the weld metal toughness. Therefore the influence of welding method, such as 2-, 3- and 4-wire, on the oxygen content in weld metal has been investigated knowing that it is one of the dominant factors in controlling the weld metal toughness.

1. Experimental Procedure

Experimental welding was conducted by the 2-, 3-, and 4-wire method on coupons which were extracted from a 25 mm thick steel plate and machined into V-shape grooves. Tack welding was not deposited to delete the effect of oxygen content in the tack weld metal and special attention was paid to ensure that the flux height did not vary with the methods. Welding consumables were a low basic fused type flux of $\text{SiO}_2\text{-CaO-CaF}_2$ system, whose basicity was about 0.8 by B_L index, defined in Fig. 11 and welding wire of Si-Mn system.

2. Results and Discussion

Experimental results are summarized in Table 3. It is well known in SAW that the oxygen content in weld metal is governed by the slag-metal reaction.

Supposing that the reaction speed would not depend on the welding method, the oxygen content in weld metal should be governed only by the reaction time.

But it is so difficult to obtain the reaction time exactly that the average staying time of a point within the molten pool, τ which can be calculated through dividing the crater length by the welding speed, was considered as a parameter corresponding to the reaction time.

Based on the thermal conduction theory of the moving point heat source on the semi-finite plate, τ is also expressed by Eq. (2).

$$\tau = Lc \cdot \frac{1}{v} = \frac{2a}{75.4} \cdot \eta_0 \cdot q \cdot \frac{1}{v} \text{ (sec)} \dots\dots\dots(2)$$

Table 3. The summary of test results.

Welding methods	Heat input (kJ/cm)	Welding speed (m/min)	Crater length L_c (mm)	τ (sec)	Oxygen* content (ppm)
2 wire	18.2	1.40	105	4.5	334
	31.2	1.15	130	6.8	317
	59.6	0.80	145	10.9	301
3 wire	20.9	2.00	185	5.6	376
	31.4	1.60	182	6.8	336
	61.6	0.85	160	11.3	305
	106.7	0.55	212	23.1	279
4 wire	25.9	2.40	250	6.3	368
	31.0	2.10	213	6.1	347
	58.5	1.20	210	10.5	295
	112.1	0.75	310	24.8	286

* average value of two

where, L_c : Length of the molten pool (cm)
 v : Welding speed (cm/sec)
 a : Thermal diffusivity (cm²/sec)
 q : Heat input per unit time (cal/sec)
 η_0 : Thermal efficiency.

This equation suggests that τ is proportional to the welding heat input per unit length (q/v). τ had a good correspondence with the theoretical values supposing that the thermal efficiency, η_0 , would be about 70 %, as shown in Fig. 5.

The relationship between τ and the oxygen content in weld metal, [O], is shown in Fig. 6. Equation (3) is the approximate expression based on a model established by Tsunetomi *et al.*⁷⁾

$$[O] = \frac{79.5}{\tau - 5.0} + 280 \text{ (ppm)} \dots\dots\dots(3)$$

Fig. 5. Relation between welding heat input and staying time, τ , in molten pool.

Fig. 6. Relation between staying time, τ , in molten pool and oxygen content in weld metal.

This relation suggests that the oxygen content in weld metal is governed almost entirely by the time, τ , and is not affected by the electrode number as much as stated by Nakanishi *et al.*⁸⁾ and the 4-wire SAW method would rather have the possibility of using higher basic fluxes than ever.

2. Improvement of Weld Quality in Large Heat Input SAW

While the 4-wire SAW method is thought to be effective for heavy wall pipes as mentioned, the large heat input welding of heavy wall pipes has the following two problems.

One is the deterioration of the weld metal toughness, because weld metals of heavy wall pipes has a tendency to form coarse microstructures of low toughness owing to marked drop in the cooling rate with rising welding heat input, as shown in Fig. 7. The other is the deterioration of the external bead appearance, which is also unfavorably affected by the strong arc force in large heat input welding.

1. Weld Metal Toughness in Large Heat Input Welding
—Control of nitrogen, oxygen and boron contents in weld metal—

Boron (B) has high affinity with nitrogen (N) and oxygen (O) and is liable to form nitrides and oxides. Therefore, the soluble B content in weld metal is affected by [N] (content in weld metal) and [O],⁹⁻¹⁵⁾ which also govern greatly the condition of proeutectoid ferrite formation. As a result, the toughness of Ti-B bearing weld metal varies widely with [N] and [O]. Thus overall examination was made on the effects of [N], [O] and B on the Charpy impact characteristics of weld metal in heavy wall steel pipe.

(1) Experimental Procedure

Contents of B in weld metal, [N] and [O] were changed in a range shown in Table 4. The welding conditions were similar to the pipe manufacturing

Fig. 7. Influence of welding heat input on submerged arc weld metal toughness.

Table 4. Chemical composition ranges of submerged arc weld metals tested. (wt%)

Heat input	C	Si	Mn	P	S	Nb	V	Mo	Al	Ti	B	N	O
88 kJ/cm (32 mm ^t 1.25 mm ^t)	0.05	0.29	1.42	0.006	0.002	0.014	0.022	0.17	0.014	0.025	Tr	0.0041	0.017
	0.07	0.35	1.60	0.015	0.008	0.026	0.033	0.24	0.021	0.038	0.0074	0.0160	0.044

standard procedure for 32 mm wall thickness pipe. Variations of microalloy contents other than [N], [O] and B were considered minimal. The [N] was varied by selection of base metals, mixing of N₂ gas into the shielding gas of tack welding, and use of flux containing lime nitrogen. The [O] was changed by using fluxes of different basicity, and the B content was adjusted by selecting welding wires and using borax-bearing flux. After welding, 2-mm V-notch Charpy impact test specimens were taken from the through-thickness center position of weld metal. The notch was located at the center of weld metal and the toughness was investigated.

(2) Results and Discussion

(i) Effects of Nitrogen Content

Figure 8 shows the effects of [N] on CVE (Charpy V-notch Energy) at temperatures 0 °C (32 °F) and -40 °C (-40 °F). Within the range of 60 to 80 ppm of [N], CVE greatly changed. This trend was more conspicuous at -40 °C (-40 °F) than at 0 °C (32 °F). When [N] was 80 ppm or above, CVE decreased at a rate of 10 J for an increment of 10 ppm of [N] at 0 °C (32 °F).

The drastic change in CVE within the above-mentioned range of [N] corresponded to formation of proeutectoid ferrite. Since almost all proeutectoid ferrite disappeared at [N] of 70 ppm or below and the entire weld metal became a uniform acicular ferrite structure at [N] less than 60 ppm, excellent CVE value could be stably obtained even at -40 °C (-40 °F).

The above results reveal that a decrease of [N] is indispensable for improving the weld metal toughness.

(ii) Effect of Oxygen Content

Figure 9 shows the effect of [O] on CVE. Excellent toughness was obtained in the range of [O] within 250 to 300 ppm. Lowering the [O] content below this level caused the formation of bainitic ferrite microstructure in the weld metal due to the excess hardening effect by B,¹⁵⁾ resulting in sudden deterioration in toughness. In the high oxygen region, the soluble B which is effective in hardenability^{9,13,14)} decreases, resulting in appearance of proeutectoid ferrite at the prior austenite grain boundaries and gradual increase in nonmetallic inclusions. Weld metal toughness is, thus, deteriorated by both proeutectoid ferrite and nonmetallic inclusions¹⁵⁾ mentioned above.

The CVE decrease due to an increase of [O] was not so much pronounced as in the case of [N] as shown in Fig. 8. From the viewpoint of [O] with respect to toughness improvement of weld metal in heavy wall pipe, it would be appropriate to control [O] within a range from 250 to 300 ppm.

(iii) Effect of Boron Content

The above examination clarified that toughness of Ti-B bearing weld metal was significantly dependent on [N] and [O],⁹⁻¹⁵⁾ particularly on the former. Therefore, an examination was made on the correlation between B content and [N] in order to obtain excellent CVE, while maintaining the [O] at nearly constant level. Figure 10 shows the test results of

Fig. 8. Influence of nitrogen content on submerged arc weld metal toughness.

Fig. 9. Influence of oxygen content on submerged arc weld metal toughness.

correlation between B content and [N], (a) for equal temperatures corresponding fracture appearance transition (*vTrs*) and (b) for equal CVE values attained at -40 °C (-40 °F) (*vE₋₄₀*).

Contents of N and B were closely related to each other in affecting toughness, and the optimum B content rose together with [N]. Even at the optimum ratio of B to [N], toughness was deteriorated, when [N] exceeded the maximum limit. Namely, *vTrs* ≤ -60 °C (-76 °F) and *vE₋₄₀* (-40 °F) ≥ 150 J (111 ft-lb) was obtained within the range of B = 0.7 · [N] ± 15 (ppm) and [N] ≤ 80 ppm, which agreed with the regions where a weld metal microstructure of uniform fine acicular ferrite was obtained.

(iv) Method for Achieving Higher Toughness of Heavy Wall Pipe Weld Metal

Firstly, the nitrogen sources and their contributions to weld metal were clarified for reducing [N]. Table 5 shows the contribution of each nitrogen source which was determined by the multiple-regression analysis, *i.e.*, by the regression coefficients. They had

a good correspondence with the dilution factors (α) at each molten part respectively. Comparison between $[N]$ estimated by dilution factors and the real $[N]$ gave the nitrogen pickup of about 20 ppm.

The effect of nitrogen in tack weld metal, N_{TWM} on that in SAW metal, N_{WM} is smaller than that of base metal, N_{BM} on N_{WM} . This effect diminished as the base metal thickness increased, but considering the fact that N_{TWM} is apt to scatter widely in the practical production, its effect cannot be ignored. While reduction of N_{BM} and nitrogen in wire, N_{wire} can be achieved in the process of steel making, N_{TWM} can be lowered by the double-channel coaxial gas shielding method which prevents the nitrogen pickup from air.

Fig. 10. Relationships among nitrogen, boron-content and submerged arc weld metal toughness.

Fig. 11. Relationship between flux basicity and weld metal oxygen content in large heat input submerged arc welding.

Secondly, lowering $[O]$ was tried by controlling the basicity of flux. Figure 11 shows the relation between B_L of several different fluxes which were trial-made for the purpose of large heat input welding and $[O]$ obtained by the 4-wire SAW method with 88 kJ/cm heat input. This figure suggests that B_L of flux should be designed to be 1.2 to 1.8 in order to obtain weld metal $[O]$ value of which ranges from 250 to 300 ppm.

2. Bead Appearance in Large Heat Input Welding
(1) Deterioration of Bead Appearance by Conventional Flux

The bead appearance by the large heat input (88 kJ/cm) welding is compared with that by the smaller (35 kJ/cm), in Photo. 2. In the large heat input welding, there appeared many wrinkles on the central part of bead and they spoiled the bead appearance considerably.

There was no ripple lines in the wrinkled part, where the equiaxed-dendrite crystallines were formed. This suggests that a very small temperature gradient

Table 5. Contributions of each nitrogen source to nitrogen content in weld metal.

Item Thick- ness	Dilution factors: α			$N_{pick-up}$ (const.)
	α_{BM}	α_{TWM}	α_{wire}	
16 mm (0.625")	0.49	0.17	0.34	22.4**
	(0.43)*	(0.14)*		(39.0)***
32 mm (1.250")	0.53	0.09	0.38	16.8**
	(0.53)*	(0.07)*		(33.0)***

* Regression coef.
** Average of estimated values by the equation in foot note.
*** Const. (ppm) by regression analysis
Foot note:

$$N_{WM} = \alpha_{BM} \cdot N_{BM} + \alpha_{TWM} \cdot N_{TWM} + \alpha_{wire} \cdot N_{wire} + N_{pick-up}$$

(N: Nitrogen content)

Photo. 2. Comparison between large heat input weld bead and relatively low heat input weld bead in the external bead appearance.

was formed¹⁶⁾ in the central part of the bead by the large heat input welding. Figure 12 is the relationship among the zone width of equiaxed-dendrite crystalline, W_E , heat inputs and the wrinkle occurrence. Because W_E decreased linearly corresponding to the decrease of heat input, it was expected to be effective for suppressing wrinkles to control W_E below 12 mm.

(2) Development of Highly Basic Fused Type Flux for Large Heat Input Welding

It was expected to be effective for reducing W_E to produce a steep thermal gradient by which the equiaxed-dendrite crystals could hardly be formed so that attention was paid to the heating effect of the slag,¹⁷⁾ which would be affected by its thickness on bead.

The relation between SiO_2/CaO , which is the ratio of SiO_2 content to CaO content in flux, and the slag height, H_s , is shown in Fig. 13. In this case, the amounts of components except SiO_2 and CaO were considered to be almost same. The cross-sectional views of slags are shown in Photo. 3. An interesting relation between W_E and H_s was observed whereby W_E decreased suddenly corresponding to the sudden increase of H_s when SiO_2/CaO was about 1.0. From the viewpoint of suppressing wrinkles, the condition of $\text{SiO}_2/\text{CaO} \leq 0.98$ should be maintained to control W_E

below 12 mm. When SiO_2/CaO was nearly equal to 0.74, however, the welding became extremely unstable as suggested by the dragon's back of slag. From Fig. 13 the lower limit of SiO_2/CaO value was set at 0.88 as the mean value between 0.83 and 0.92 because the bead appearance was judged to be getting worse when $\text{SiO}_2/\text{CaO} = 0.83$. Photograph 4 shows the example of bead appearances by 150 kJ/cm welding in some SiO_2/CaO conditions.

Based on above studies, the fused type flux for large heat input welding was developed, considering other components, mainly CaF_2 , and its B_L value was about 1.3.

Finally, the weld metal with the excellent toughness was obtained in large heat input welding as shown in Fig. 14, such as $\text{CVE} \geq 100 \text{ J}$ at -60°C .

IV. Conclusions

In this paper, the progress in both productivity and weld quality attained by use of the 4-wire SAW method is reported. The conclusions are as follows:

(1) The 4-wire SAW method which was optimized in the point of current phase and the current ratio enhanced the manufacturing of UOE steel pipes with a 10~30 % improvement in productivity and con-

Fig. 12. Influence of welding heat input on W_E (width of equiaxed-dendrite crystalline zone).

Fig. 13. Relationship among the slag thickness (H_s), W_E and SiO_2/CaO .

Photo. 3. Change of the cross-sectional view of slags with SiO_2/CaO .

SiO ₂ /CaO ratio	Weld bead appearance
1.12
0.94 (Good)
0.72

Photo. 4. Change of the external bead appearance with SiO₂/CaO.

Fig. 14. Comparison of the Charpy transition curves of welded joints between the result of this study and the conventional.

siderable suppression of slag inclusion.

(2) Oxygen content in weld metal did not depend on the number of electrodes of SAW method but depended greatly on the staying time in the molten pool, τ , (=crater length/welding speed) with hyperbolic correlation. From this result, disadvantages of speedup by the 4-wire SAW method to weld metal toughness were not observed.

(3) The optimum ratio between boron content and nitrogen content which gives the best toughness to weld metal in large heat input welding, was found to be $B=0.7 \cdot [N] \pm 15$ (ppm) for $[N] \leq 80$ ppm.

(4) For reducing the nitrogen content in weld metal, the contributions of nitrogen sources were clarified to be equivalent to their dilution factors and the order of the influence were found as N_{BM} , N_{wire} , and N_{TWM} .

(5) A fused type flux with high basicity was developed, which has excellent performances in both lowering oxygen content in weld metal to 250~300 ppm and suppressing the deterioration of bead appearance even in 150 kJ/cm welding by considering its B_L value and SiO₂/CaO.

(6) Excellent weld metal toughness, such as CVE ≥ 100 J at -60°C , was achieved in large heat input welding.

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