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Shuichi Sakaguchi, Tadamasa Yamaguchi, Yoshifumi Nakano

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Shuichi Sakaguchi
Senior Researcher, Joining & Physical Metallurgy Lab., Heavy Steel Products Res. Dept., Technical Res. Labs.

Tadamasa Yamaguchi
Staff Assistant General Manager, Welding Rod Sales Dept., Steel Business Planning & Sales Div.

Yoshifumi Nakano
Ph.D., General Manager, Heavy Steel Products Res. Dept., Technical Res. Labs.

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1 Introduction

Tandem wire one-pass submerged arc welding (SAW) has been generally applied to the corner joint of box-shaped columns constructed of plates up to 40 mm in thickness.[1] The maximum thickness of the plates welded by one-pass SAW was increased in the latter half of 1980s with the application of a special flux containing iron powder and a 3-wire SAW method to meet the demand for higher efficiency in welding heavy section box columns. Recently, one-pass submerged arc welding has been widely adopted in box-shaped column corner joints of plates 50 mm in thickness.

The effect of the addition of iron powder to the flux and the adoption of optimum welding conditions on welding performance was investigated in this work. A flux containing iron powder KB-50 I was developed, for the high heat input welding of the box-shaped column corner joint, which has contributed to the popularization of this welding method.

This report describes the characteristics of the high heat input submerged arc welding with flux containing iron powder, the optimum conditions for tandem submerged arc welding, and high efficiency submerged arc welding technology for heavy section joints which exceed the range of application of one-pass submerged arc welding.

2 Welding Consumable for Submerged Arc Welding of Corner Joint of Box-Shaped Column

2.1 Effect of Iron Powder Addition to Flux

In SAW, iron powder has been used to increase the deposition rate and techniques which reduce welding heat input have been applied for some time. Although the techniques of scattering iron powder in the groove or attracting it to the electrode by magnetic force have been developed,[2,3] the use of iron powder as a material of the flux is more popular in Japan.

The addition of iron powder to the flux increases the deposition rate by transferring metallic iron from the flux into the weld metal. **Figure 1** shows the relationship between the iron powder content of the flux and the deposition rate, and indicates that an increase in the amount of iron powder improves the deposition rate. Thus, the use of iron powder is effective in improving welding efficiency.

As an important benefit of the addition of iron powder to the flux, the improvement of operability in high heat

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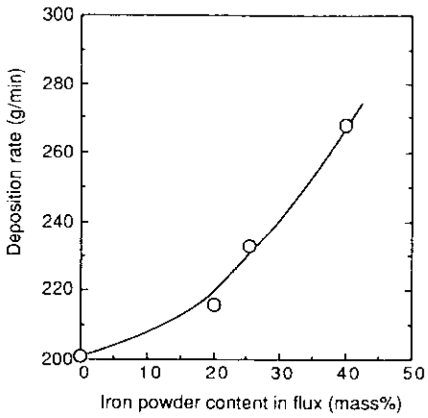


Fig. 1 Effect of iron powder content in flux on deposition rate

input welding should be noted, in addition to the improvement of the deposition rate. With conventional flux, severe eruption of gases and molten slag tends to occur immediately under the electrode at higher heat inputs. It becomes difficult, therefore, to continue welding with a high heat input of over 30 kJ/mm, leading to poor operability. The effect of iron powder addition to the flux on this eruption phenomenon was investigated by observing perspective images of the molten pool using an X-ray image amplifier.[4]

The views of the molten pool in SAW with the conventional and iron powder added fluxes, which were observed by the X-ray image amplifier, are compared in **Photo 1**. With the conventional flux without iron powder, the eruption of gases and molten slag tended to occur under the electrode with increased heat input. It was suppressed, on the other hand, by using the flux containing iron powder. Therefore, the addition of iron powder to flux effectively improves the operability of high heat input SAW by controlling the eruption phenomenon and suppressing the volume of the arc cavity, and thus expands the heat input limit. This improvement seems to be the result of an increase in the bulk density and heat capacity of the flux.[5]

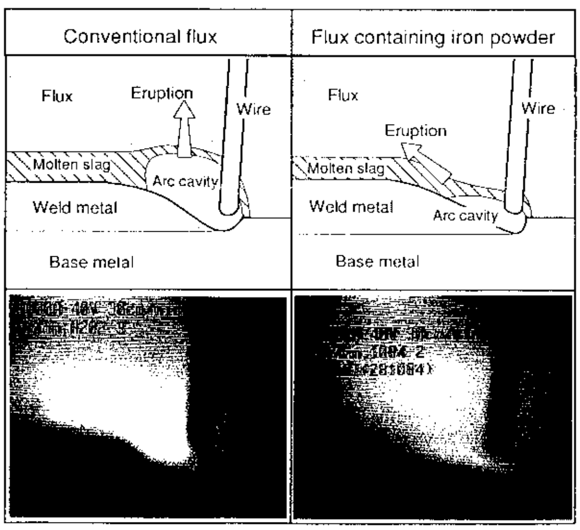


Photo 1 Effect of iron powder addition to flux on the arc suppression

2.2 Selection of Flux Composition

The appearance of the SAW bead is significantly influenced by the composition of the flux. It is generally considered that a flux having a higher melting point is suitable for high heat input welding. In this study, SiO_2, MgO, and CaO were used as the main components of the slag, as these compounds have been convention-

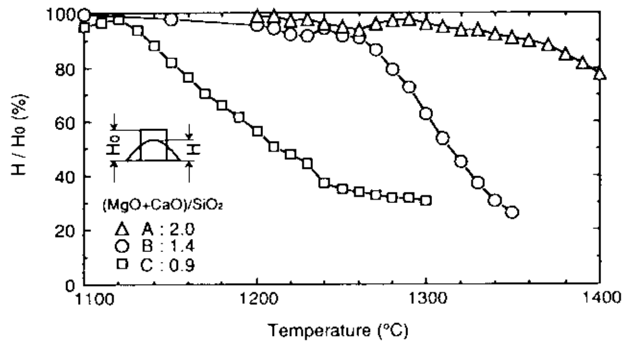


Fig. 2 Effect of the content ratio of (MgO + CaO)/SiO_2 on the melting behavior of the welding slag

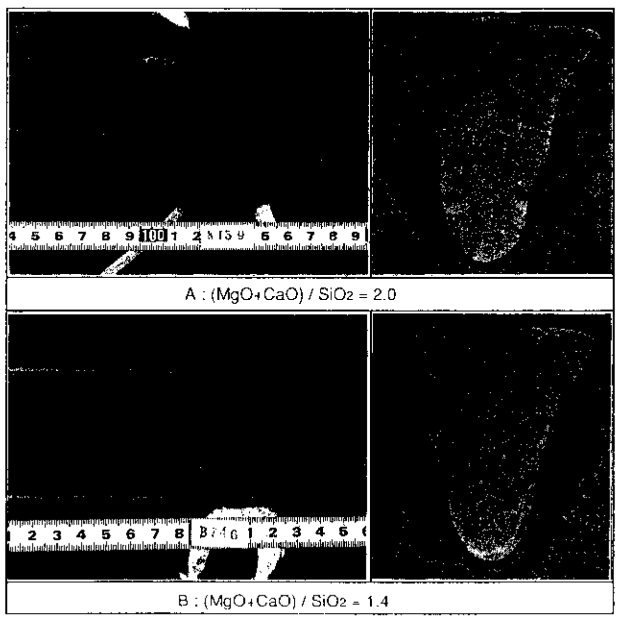


Photo 2 Effect of the content ratio of (MgO + CaO)/SiO_2 on the bead appearance (left) and cross sectional macrostructure (right)

ally used in some agglomerated fluxes. The melting point of the flux is varied by changing the ratio of (MgO + CaO) wt% to SiO_2 wt%.

Figure 2 shows the influence of the (MgO + CaO)/SiO_2 ratio on the melting behavior of the slag made from the three experimental fluxes in the button test. Melting behavior was evaluated from the softening temperature, which was estimated as the temperature at which the height ratio of the button, (H/H_0), became 0.8. The bead appearance and cross-sectional macrostructures in tandem SAW using experimental fluxes A and B with a heat input of 41 kJ/mm are compared in **Photo 2**. The softening temperature increases with the ratio of (MgO + CaO)/SiO_2. When the flux has a high softening temperature, the amount of slag is controlled to be low, which seems suitable for keeping a good bead appearance. The ratio was adjusted here to be 1.4 or less, because the bead becomes convex and narrow if the ratio increases excessively.

3 Optimum Welding Conditions in High Heat Input Welding

Weld defects which easily occur in the one-pass SAW of thick plates with a high heat input include the lack of penetration, lack of side wall fusion, and solidification cracking. When internal defects such as lack of penetration and solidification cracks occur, hard labor is required to repair the defect, because internal defects cannot be repaired from inside the box column. Therefore, it is very important to select the optimum welding conditions to prevent such internal defects.

The penetration depth of weld metal is controlled by the welding current and speed,[6] and is affected by the condition of arc generation. Although it is important to adopt a welding current for the leading electrode which is suitable to the groove angle, the condition of the arc varies depending on the ratio of the trailing electrode current (I_T) to the leading electrode current (I_L) and the arrangement of electrodes. The welding current ratio (I_T/I_L) and the arrangement of electrodes should be carefully selected to avoid solidification cracks and lack of penetration by controlling the cross-sectional profile of the bead. The effect of I_T/I_L and the arrangement of electrodes on the cross sectional profile of the bead was examined using the welding conditions of one-pass SAW for 60-mm-thick plates as shown in **Table 1**.

Figure 3 shows the effect of I_T/I_L on the cross sectional profile of the bead. The effect of I_T/I_L was evaluated from the ratio of the bead width at a position 30 mm below the surface (W_c) to that at the surface (W). The bead width and the penetration depth were also measured. When the current ratio is small, the bead width at the mid-thickness is narrow, and thus solidification cracks and lack of penetration tend to occur more easily. These defects occur when the ratio of W_c/W is lower than 0.4. To make the ratio of W_c/W larger than 0.4, it is necessary to make the welding current ratio I_T/I_L larger than 0.70. On the other hand, the penetration depth tends to decrease slightly and the bead width tends to decrease as I_T/I_L increases. Therefore, it is preferable to select an I_T/I_L in the range of between 0.70 and 0.80.

The distance between the leading and trailing electrodes affects the molten pool. In high heat input tandem submerged arc welding with deep penetration, the arrangement of electrodes should be controlled so that

Table 1 Welding conditions used for studying the profile of weld metal

Thickness (mm)	70	
Groove angle (deg)	35	
Root face (mm)	15	
Leading electrode	2 300A 38V	2 600A 40V
Trailing electrode	1 600 2 000A 50-52V	1 650-1 900A 55V
Speed (mm/min)	210-250	220-240
Heat input (kJ/mm)	45-49	47-55

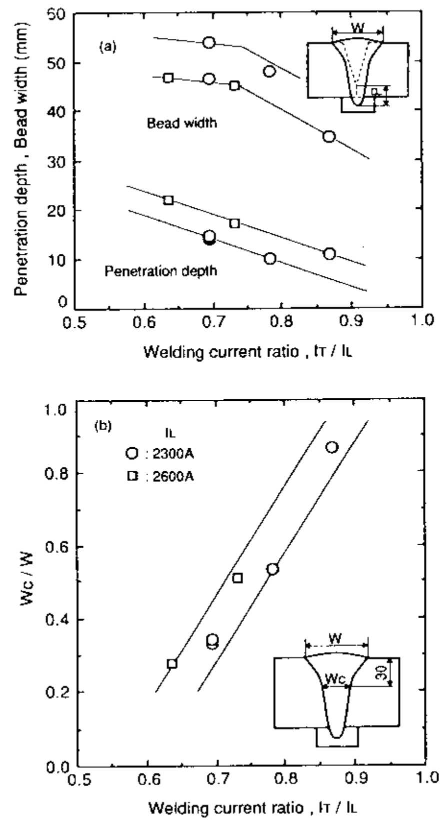


Fig. 3 Effect of the ratio of the trailing current to the leading current on the profile of the weld metal

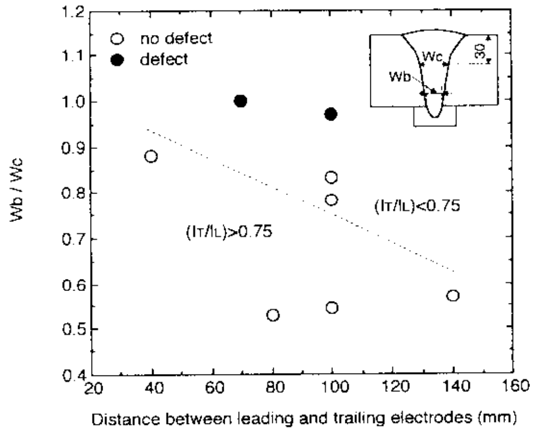


Fig. 4 Effect of distance between leading and trailing electrodes on the ratio of W_b/W_c

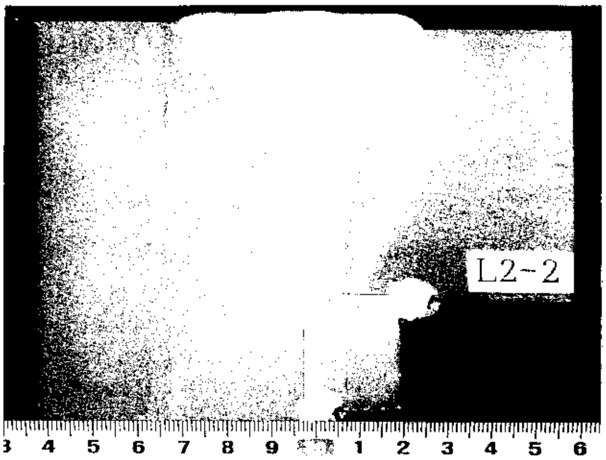


Photo 3 Cross sectional macrostructure of one pass SAW corner joint of 60-mm-thick plates

the molten pool is a semi-one pool. In other words, the trailing electrode should be located at the center of the molten pool formed by the leading electrode in order to avoid solidification cracking.[7] Susceptibility to weld defects was evaluated using the ratio W_b/W_c of the width at a position 60 mm below the surface (W_b) to that at the position 30 mm below the surface (W_c).

The influence of the distance between the leading and trailing electrodes on the W_b/W_c of the weld metal in one-pass SAW is shown in **Fig. 4**. When the distance between the two electrodes is extremely small, W_b/W_c is large, and the bead shape tends to cause pear-shaped cracks. However, since the influence of the current ratio on the cross-sectional profile is greater than that of the distance between the two electrodes, defects were avoided by selecting an appropriate current ratio.

One-pass SAW of 60-mm-thick plates is possible using tandem electrodes if proper welding conditions are adopted based on the above-mentioned examination results. The one-pass welding conditions for 60-mm-thick plate are listed in **Table 2**, and a cross-sectional macrostructure is shown in **Photo 3**.

Table 2 Welding conditions used for 60-mm-thick plates

Thickness (mm)	60
Groove angle (deg)	35
Root face (mm)	3
Leading electrode	2 300A-38V
Trailing electrode	1 800A-48V
Speed (mm/min)	200
Heat input (kJ/mm)	52
Distance $L-T$ (mm)	100

4 High Efficiency Multi-layer Submerged Arc Welding

The limit on plate thickness for one-pass SAW using tandem electrodes is about 60 mm, because there is a lower bound on welding speed for preventing weld defects such as lack of penetration. In other words, multi-pass welding is necessary with plates whose thickness exceeds 60 mm. In this case, GMAW (gas metal arc welding) has been employed before SAW. However, GMAW before SAW requires much time and labor. A new high efficiency 2-layer submerged arc welding method was therefore developed on the basis of the one-pass welding conditions described above. The most serious internal defects observed in 2-layer SAW include solidification cracking of the root pass and slag inclusion at the toe.

In orde to prevent solidification cracking, it is effective not only to decrease elements such as C and P, which improves crack susceptibility, but also to increase the ratio of the bead width to bead height (*W*/*P*). Therefore, the effect of the bead shape on solidification cracking was investigated by examining the root pass which was made with a heat input of 15–43 kJ/mm in a 35°V-groove. The bead shape was evaluated in terms of the penetration of the trailing arc, because the final solidification part of the bead affects solidification cracking.

The effect of *W*/*P* on the occurrence of solidification cracking is shown in **Fig. 5**. Beads in which solidification cracking occurred had a *W*/*P* ratio of 0.6 or less. It is possible to prevent solidification cracking by making the shape of the final solidification part appropriate. In practical construction, it is important to adopt a groove shape which will prevent cracking. However, the appropriate bead shape varies with the welding conditions and groove shape. The application of a double-angled groove which allows widening of the width of the first pass

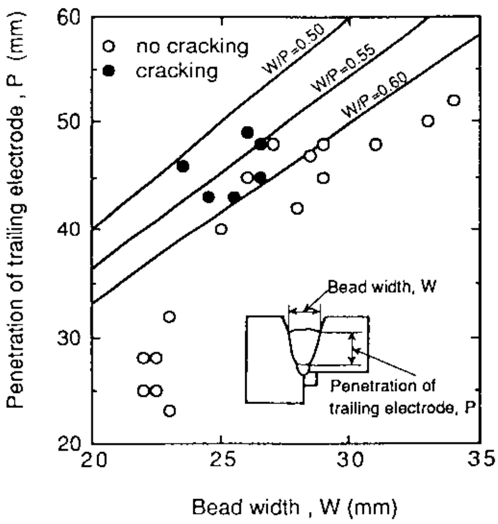


Fig. 5 Effect of the ratio, W/P, on the solidification cracking

bead while simultaneously suppressing the increase in the sectional area of the groove is effective for preventing solidification cracking.

Slag inclusions are caused by the slag which digs at the toe of the first bead and remains there without being melted by the subsequent pass. Therefore, the contact angle between the weld metal, liquid slag, and groove at the toe of the first bead is considered a very important factor. The effect of the angle of the groove on the digging depth at the first bead toe was therefore examined. **Figure 6** shows the effect of the groove angle of the second bead on the digging depth, and indicates that larger

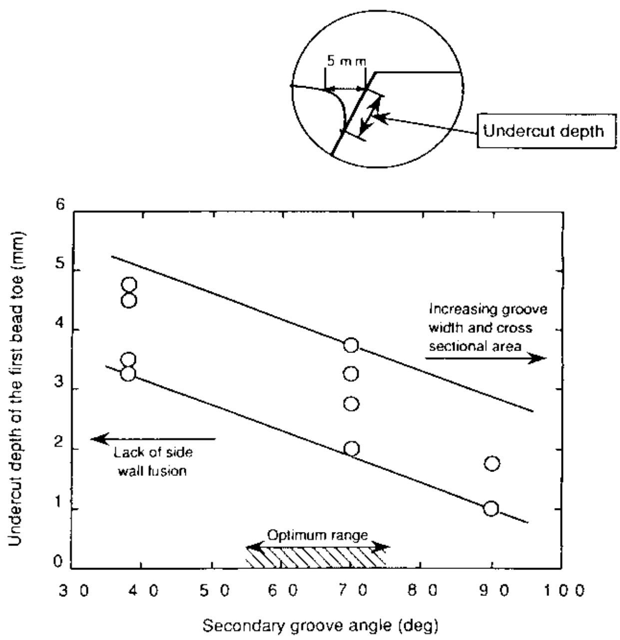


Fig. 6 Effect of groove angle on undercut depth

Table 3 Welding conditions used for 70-mm-thick plates

Thickness (mm)	70	
Groove angle (deg)	35+55	
Root face (mm)	3	
Pass	1	2
Leading electrode	2 300A-38V	1 200A-42V
Trailing electrode	1 700A-48V	1 200A-42V
Speed (mm/min)	215	195
Heat input (kJ/mm)	47	31
Distance $L \cdot T$ (mm)	100	100

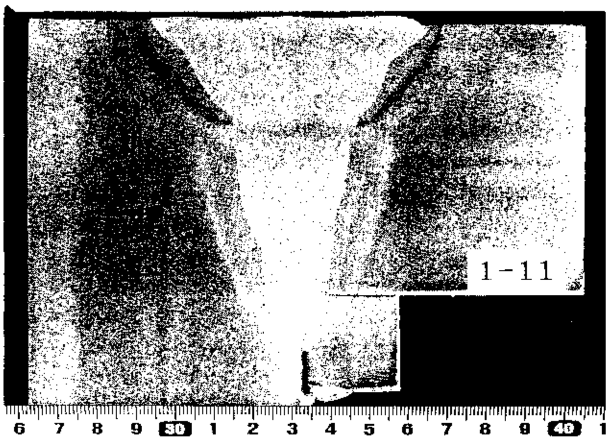


Photo 4 Cross sectional macrostructure of two pass SAW corner joint of 70-mm-thick plates

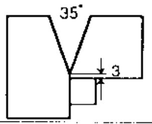
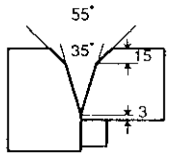
groove angles result in a shallower digging depth and are more effective for preventing slag inclusions.[8]

High efficiency welding of plates thicker than 60 mm has been materialized by adopting high heat input 2-layer SAW with a double-angled groove. Examples of 2-layer welding conditions for 70-mm-thick plate are shown in **Table 3**, and a cross-sectional view of a welded joint is shown in **Photo 4**.

5 Mechanical Properties of High Efficiency Submerged Arc Weld Metal

The welding conditions and mechanical properties of the weld metal of corner joints prepared using 60-mm- and 70-mm-thick SM490B steel plates are shown in **Table 4**. The welding consumables were the flux containing iron powder KB-50 I and a 2%Mn wire KW-50 with a diameter of 6.4 mm. The welded joints were prepared by one-pass SAW with the 60-mm-thick plate and by the 2-layer SAW with the 70-mm-thick plate. A large current was applied to the leading electrode. The test specimens were machined from the $t/4$ (t: thickness)

Table 4 Mechanical properties of weld metal made by high efficiency SAW

Thickness (mm)	Groove profile	Pass	Welding conditions	Speed (mm/min)	Heat input (kJ/mm)	YS (MPa)	TS (MPa)	El (%)	$_vE_0$ (J)
60		1	2 300A-37V 1 800A-48V	210	49	377	551	33	35
70		1	2 300A-38V 1 700A-48V	205	50	381	510	34	52
		2	1 200A-42V 1 200A-42V	209	29				

position. The tensile test was carried out using JIS Z3111 A-2 specimens, and toughness was evaluated from the absorbed energy obtained by the Charpy impact test at 0°C. The tensile strength and absorbed energy met the requirements of 490 MPa and 27 J at 0°C applied to structural members.

6 Conclusions

The characteristics of high heat input submerged arc welding with a flux containing iron powder and the optimum welding conditions for high efficiency welding has been examined. The main conclusions are as follows:

(1) The addition of iron powder to flux increases the deposition rate.

(2) The operability of high heat input welding was significantly improved by adopting a flux containing iron powder. The reason for this is that the eruption of gases and molten slag can be controlled by suppressing the expansion of the arc.

(3) The softening temperature of the slag can be adjusted by changing the composition ratio of $(MgO + CaO)/SiO_2$. The appearance of the bead made by high heat input SAW using flux with a composition ratio of 1.4 or less was excellent.

(4) The profile of the bead produced by tandem submerged arc welding can be controlled by the ratio of the current of the leading electrode to that of the trailing electrode. Solidification cracking and lack of side wall fusion tended to occur when the current ratio was low. On the other hand, the bead width and penetration depth tended to decrease when the current ratio was high.

(5) Tandem wire one-pass SAW with the 60-mm-thick plate was materialized using the flux containing iron powder and the optimum welding conditions.

(6) High efficiency, 2-layer SAW can be applied to the heavy plates whose thickness exceed 60 mm by adopting a double-angled groove.

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