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On Underwater Submerged-Arc Welding (The 1st Report)*

—The Feasibility of Underwater Welding by Submerged-Arc Welding Process—

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Abstract

Feasibility of underwater welding by submerged arc welding process has been studied. The wire US36 and the flux MF43, which has been mixed with 40 % water glass, were used. The base metal was steel for welded structure SM41 having a thickness of 9 mm.

Main results are summarized as follows:

(1) *By using the 40 % water glass mixed flux and selecting suitable welding condition, a stable welding arc can be kept under water. Then a good weld without undercut can be obtained. However, even when welding is done under the condition, which seem to be suitable, blowholes are formed in the weld metal.*

(2) *Heat insulating effect of flux for the weld zone is significant and cooling rate of the underwater weld by this process is considerably lower than those by the other processes.*

(3) *Average hardness of the underwater weld metal is about Hv160, and that of the heat-affected zone about Hv220. So a remarkably hardened zone cannot be found in the weld.*

(4) *The joint efficiency of the butt weld made by this process is 82 %. The elongation of the underwater weld is less than that of base metal.*

1. Introduction

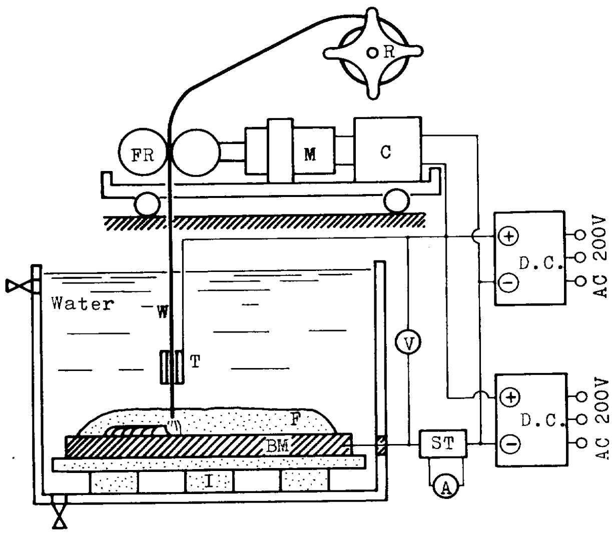
At present the interest in development of ocean is increasing in various fields. Accordingly research and development of underwater welding technique have been carried out, which is considered one of the tools for construction, reconstruction and repair of the submarine structures. Papers have been published that deal with some conventional welding processes to be applied to underwater use for comparatively good welds[1-7]. In general, however, the "wet" underwater weld is hardened by rapid cooling by water surrounding it. And it reduces ductility and toughness of the joint in cooperation with a large quantity of the hydrogen dissolved in the weld. Consequently weld crack takes place in a certain case.

In contrast to it, it may be considered that the underwater submerged arc welding process has possibility to lower the cooling rate of the weld zone by flux and slag over it and to prevent the weld from being brittle. Moreover it seems to be suitable for welding under water, where operations is very difficult, owing to easiness of mechanizing or automation. In the present situation, however, there is no systematic investigation as to applicability of this process to "wet" underwater welding.

Therefore experiments of the underwater submerged arc welding have been made under various conditions to study the influence of welding condition on welding phenomena and properties of the weld, and the feasibility of this process for underwater welding.

2. Experimental arrangement, base metal and weld materials

Fig. 1 shows the arrangement of experimental equipment. The experiments were done in city water and the surface of base metal was situated at a water depth of 100 mm. The DC electric source of drooping characteristic was used and the polarity was



BM : Base Metal R : Wire reel
W : Wire M : Moter
F : Flux C : Voltage controller
I : Insulator ST : Shunt
T : Contact tip A : Ammeter
FR : Feed roll V : Voltmeter

Fig. 1 Arrangement of equipment

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Table 1 Chemical compositions of base metal and wire (%)

	C	Si	Mn	P	S
SM41	0.17	0.039	0.92	0.014	0.024
US-36	0.14	0.034	2.11	tr.	0.010

electrode positive.

First of all, preliminary experiments were carried out to select the welding wire and the flux among those put on sale. In consequence the wire US36 and the fused flux MF43 were adopted, which produced comparatively good results. The diameter of wire was 2.4 mm.

Base metal used was steel for welded structure SM41 of 9 mm in thickness. Table 1 shows chemical compositions of welding wire and base metal.

3. Welding and its results

3.1 *Selection of welding conditions*

In underwater submerged arc welding, water glass No. 3 was mixed with flux as a viscous agent to prevent flux from scattering and drifting away owing to movement of water and to improve the weldability.

Fig. 2 shows the effect of water glass mixed with flux on appearance and macro-structures of welds obtained under condition of welding current 340 A and welding speed 60 cm/min, that is to say, (A), (B), (C) and (D) were obtained by using the as-received flux (without water glass), and the fluxes mixed with water glass of 20, 40 and 60 % in weight, respectively. And (E) was produced with water glass shielding.

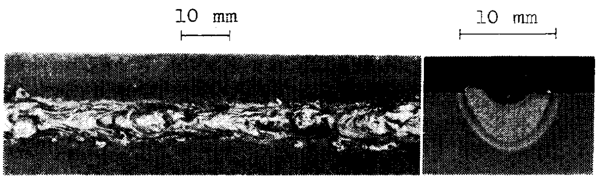
In case of (A), welding arc became unstable, which produced bad appearance of weld with undercut and many spatters. It is considered as the reason for it that flux was blown away by the gas and bubbles generated in welding and it had no effect to shield sufficiently the part being welded from the surrounding water.

In case of (B), welding arc was improved to be stable to some degree. However, the weld by it was not good. Although, in this case, water glass was mixed 20 % to prevent the flux from blowing away and to improve its shielding effect, it was not so effective.

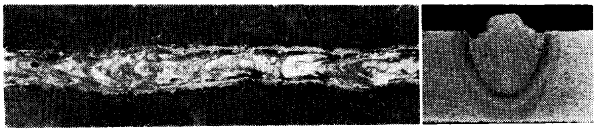
In case of (E), when welding was done by using 100 % water glass as shielding agent, welding arc became rather stable, which produced a weld with undercut and many pits on the bead surface.

In contrast with these cases, the flux, into which water glass of 30–60 % had been mixed, kept welding arc stable, and considerably good weld could be obtained. Especially, as shown in (C), welding by the flux with 40 % water glass produced a weld with a bead having regular ripples and good appearance, which had not any undercut. The reason may be considered as follows: At such a mixing rate of water glass, water glass, which prevents the flux from flowing away and produces the shielding effect by itself, and the flux MF43, which contributes to producing a good weld, both have an effective action on the part being welded.

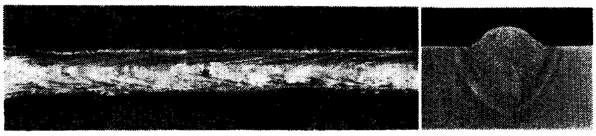
Next, welding was done using welding current of 280–400 A and the 40 % water glass mixed flux. Fig. 3 (A), (B) and (C) show appearance and macro-structures of the welds obtained by current in three varieties of amperage: too low, suitable and too high.



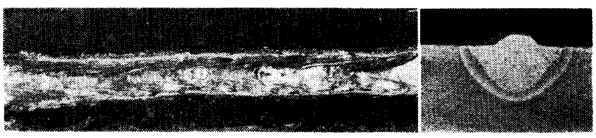
(A) Flux : MF43



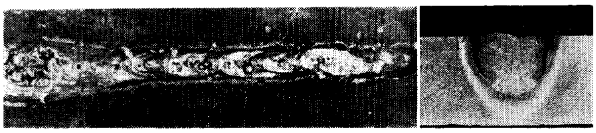
(B) Flux : 80%MF43+20%W.G.



(C) Flux : 60%MF43+40%W.G.

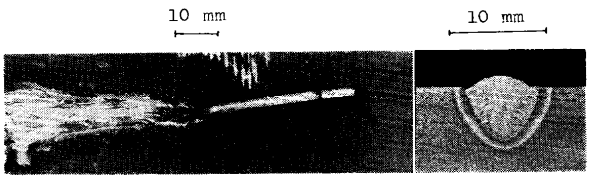


(D) Flux : 40%MF43+60%W.G.

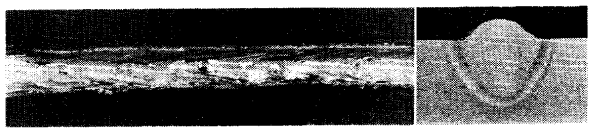


(E) Flux : No MF43+100%W.G.

Fig. 2 Effect of water glass on appearance and macro-structures of welds



(A) Welding current : 280 A



(B) Welding current : 340 A

(C) Welding current : 400 A

Fig. 3 Effect of welding current on appearance and macro-structures of welds

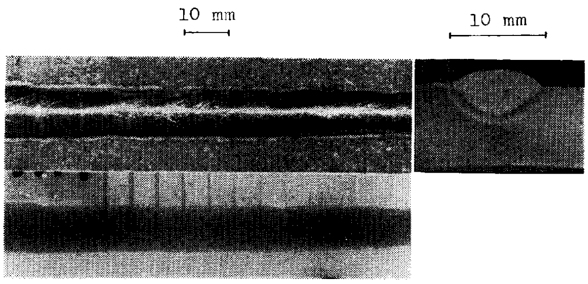
(A) is a weld by welding current of 280 A. In this case, it was difficult to keep the arc and frequently the wire made short-circuit with base metal, making the welding impossible, because arc current was too low. (C) shows the result by welding current of 400 A. In this case, it was easy to keep the arc. However, a disturbed appearance of weld and an undercut were produced, because arc current was too high. Comparing with these results, the weld obtained by the current of 320–360 A was good. Especially, when current was set at 340 A, as shown in (B), a weld of good appearance was obtained without an undercut.

The above-mentioned experiments were carried out at welding speed lower than 60 cm/min. As for the welding speeds higher than 60 cm/min, welding at such speeds has not been studied owing to the capacity limit of the experimental equipment used in this research.

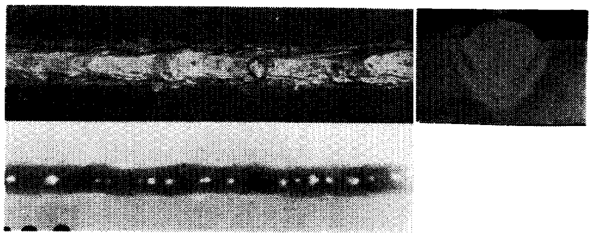
Judging from the results, hereafter the experiments shall be made under the welding condition: welding current of 340 A, welding speed of 60 cm/min, and using a 40 % water glass mixed flux.

3.2 *Comparison with welding in air*

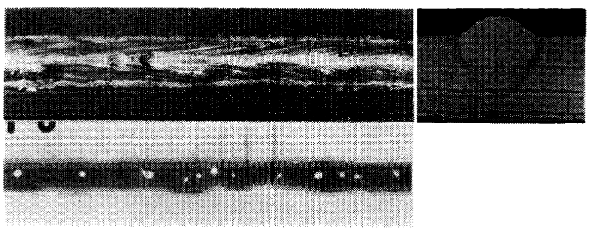
Fig. 4 (A), (B) and (C) show appearance of beads, macrostructures of the cross-section of welds and results of X-ray inspection of the welds obtained under the condition: current 340 A and welding speed 60 cm/min. The weld (A) was made in air by using the as-received flux (without mixing water glass), (B) was obtained in air by using the 40 % water glass mixed flux. (C) shows an underwater weld made by using the 40 % water glass mixed flux.



(A) In air, Flux : MF43



(B) In air, Flux : MF43+W.G.



(C) Underwater, Flux : MF43+W.G.

Fig. 4 Appearance, macro-structures and X-ray inspection of welds obtained in air and under water

From these photographs, it is clear that the weld (A) made in air is sound with smooth bead surface and no defect such as blowhole. In comparison with (A), the weld (C) made under water has blowholes of 0.5–1.5 mm in diameter in the weld metal at a rate of about two per unit length (1 cm) of weld in spite of relatively good appearance of bead. However, the weld (B), which was made in air by using the 40 % water glass mixed flux, produced the same results as the weld (C) obtained under water.

Judging from these results, it is likely that the flux mixed with water glass can shield the weld zone from the environment and the blowhole remaining in underwater weld is traced to the water included in water glass.

3.3 *Mechanical properties of weld*

Micro-Vickers hardness (load : 500 g) in the cross

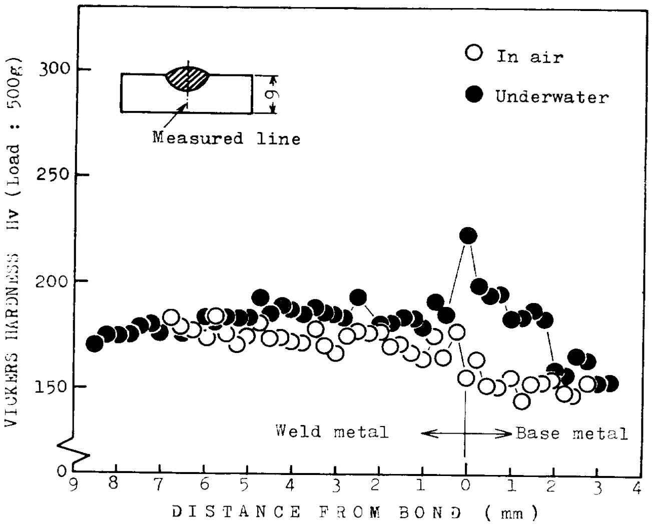
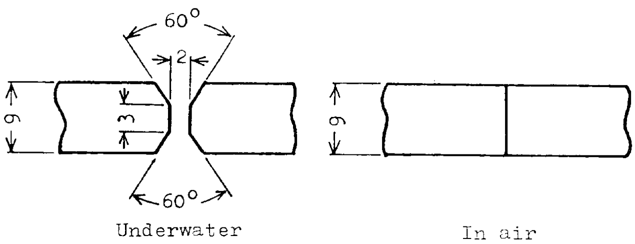


Fig. 5 Hardness distribution of welds

Table 2 Examples of welding conditions

Environment	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)
In air	340	27 – 30	60
Underwater	340	35 – 36	60

Note : Wire : US36
Flux : 100%MF43 (In air)
60%MF43 + 40%W.G. (Underwater)

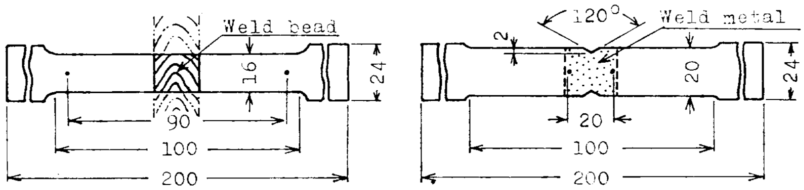


Edge preparation

Table 3 Mechanical properties of welds

	Welded joint			Weld metal		
Environment	Ultimate strength (kg/mm^2)	Elongation (GL=90mm) (%)	Location of fracture	Ultimate strength (kg/mm^2)	Joint efficiency (%)	Elongation (GL=20mm) (%)
In air	44.2	27.9	Base metal	55.4	108	16.1
Underwater	43.8	20.9	Base metal or weld*	42.2	82	8.0
Base metal	44.7	35.1	——	51.2	100	25.3

* Joint efficiency of specimen fractured at weld : 95 – 98 %



(Welded joint) (Weld metal)

Dimensions of specimens

section of underwater weld is shown in Fig. 5, which is compared with that of the weld obtained in air. From the figure, it is understood that there is no remarkable difference between the hardness of the underwater weld metal and that of the weld metal made in air. On the contrary, the hardness of heat-affected zone in the underwater weld is lightly higher than that in the weld made in air, that is, the former is about Hv220 and the latter Hv160. However, this level of hardness of heat-affected zone poses no problem in putting the underwater weld to practical use.

Table 2 shows an example of butt welding conditions by two pass welding from each side of the base metal. The joint design is shown in Table 2.

Table 3 shows results of tensile test of the welded joints made under the conditions shown in Table 2. The specimens for tensile test were cut out of the middle part of the weld at 4 cm or more off the starting point of welding and the crater, where welding had been done in a thermally quasi-stationary state. The results tabulated at the left column in the table show that the parallel specimens having a width of 16 mm, which had been prepared from the as-welded joint made in air, were broken at the base metal. And most of underwater welded joints, with some exceptions, were broken at the base metal. Next, tensile strength of the weld metal was measured using a specimen with a V-notch of 2 mm in depth such as shown in Table 3. The results, tabulated at the right column in Table 3, show that the weld metal obtained in air has a sufficient joint efficiency of 108 % and that made under water has a low value of 82 %.

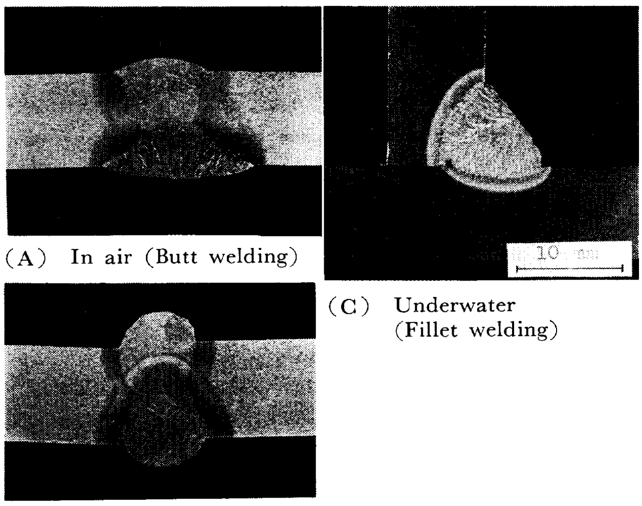
Elongation of both the weld metals obtained under water and in air is lower than that of the base metal. And especially elongation of the underwater weld metal is half of that made in air. It seems that blowholes in the weld metal, as shown in Fig. 4, are the cause of decrease of joint efficiency and elongation of the welded joint.

3.4 *Structure of weld*

Fig. 6 (A), (B) and (C) show macro-structures of butt welds by two pass welding and fillet weld. In every case, good welds with sufficient penetration can be obtained without defects such as undercut, slag inclusion and so on.

Fig. 7 (A) – (F) show micro-structures of the underwater butt weld by two pass welding and the base metal. The specimens used in Fig. 6 and 7 were made under the welding conditions shown in Table 2. They show micro-structures of weld metal by the second pass welding (A), bond of the second layer (B), heat-affected zone ((C) and (D)), the first pass weld metal reheated by the second pass welding (E) and base metal (F).

In the weld metal by the second pass welding (A),

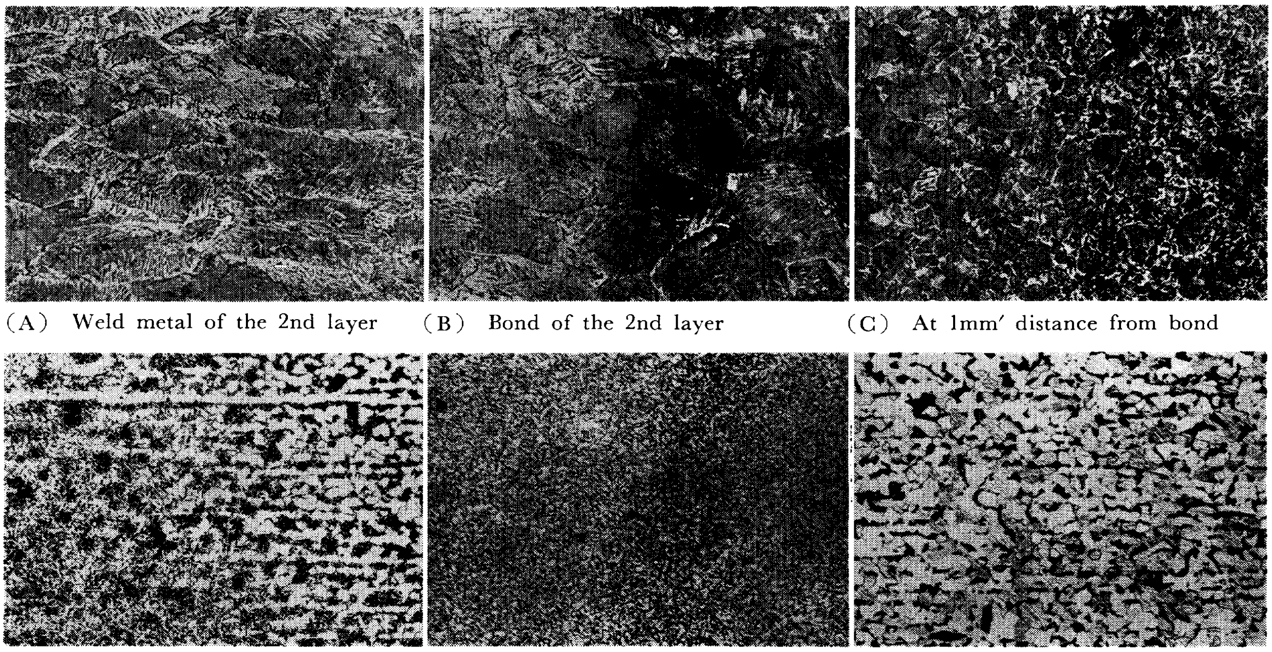


(A) In air (Butt welding)

(C) Underwater (Fillet welding)

(B) Underwater (Butt welding)

Fig. 6 Macro-structures of welds



(A) Weld metal of the 2nd layer (B) Bond of the 2nd layer (C) At 1mm′ distance from bond

(D) At 1.8mm′ distance from bond (E) Weld metal of the 1st layer (reheated) (F) Base metal

Fig. 7 Micro-structures of base metal and weld $\left(\times 150 \times \frac{2}{3}\right)$

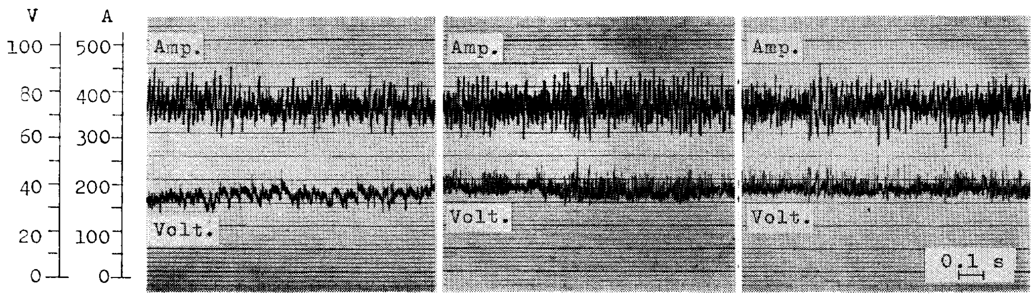
the structure consists of bainite, pearlite, and a little ferrite at the grain boundary. In the part (B) adjacent to the bond, a coarse network of ferrite, which is composed of bainite, pearlite and a little martensite, is observed. At 1.0 mm distance from the bond (C), the structure becomes finer and consists of fine ferrite and pearlite. At 1.8 mm distance from the bond (D), a structure with ferrite and spheroidized pearlite is observed. Structure of the base metal (F), composed of ferrite and pearlite, is contiguous to the structure (D). In the first pass weld metal (E), which has been reheated by the second pass welding, a fine structure, which consists of fine ferrite and pearlite, is observed.

4. Stability of welding arc

Fig. 8 (A), (B) and (C) show oscillograms of current - voltage to denote the stability of underwater welding arc, where (A) shows case of welding in air using flux without mixing water glass, (B) case of welding in air using the 40 % water glass mixed flux and (C) case of underwater welding using the 40 % water glass mixed flux.

In welding (A), arc voltage shows a relatively regular fluctuation at intervals of 0.05 s. In contrast with it, in underwater welding (C), a fluctuation of arc voltage is observed at very short intervals, but a regular fluctuation, such as shown in (A), is not found. Therefore, underwater arc seems to be rather stable. It is considered that a difference in voltage fluctuation between welding in air and that under water is caused by a change in type of metal transfer, which is influenced by arc atmosphere. And metal transfer rate is estimated at about twenty droplets per second from voltage fluctuation shown in (A), and it is considered that metal transfer in this case is a globular type. Comparing with it, the metal transfer rate in underwater welding is about 150 droplets per second by actual measurement. The reason may be considered that welding arc under thermal pinch effect is constricted by the mixed water glass with flux and the type of metal transfer changes to a spray type.

Moreover, judging from the fact that oscillogram (B), recorded in welding in air by using the water glass mixed flux, has the same current - voltage charac-



(A) In air Flux : MF43 (B) In air Flux : MF43+W.G. (C) Underwater Flux : MF43+W.G.

Fig. 8 Effect of environment on arc stability teristic as that (C) obtained under water, it is likely that underwater weld zone is completely shielded by the water glass mixed flux from the surrounding water.

It becomes clear that as for stability of underwater arc this process has no problem in keeping welding arc stable by using the 40 % water glass mixed flux.

5. Thermal cycle

Fig. 9 shows thermal cycles at bond line and the parts at distance of 0.9 mm and 3.0 mm from bond line, respectively, when underwater bead welding was done on SM41 steel plate (200×150×9 mm). These curves were recorded in the manner shown in the previous paper[5]. To compare with these cycles, thermal cycle at bond in welding in air is given as the dotted line in the same figure. Table 4 shows cooling time from 800°C to 500°C and from 800°C to 300°C, and cooling rate at 500°C at bond line, where weld heat input is 13–14 KJ/cm.

From these curves, for instance, cooling rate at 500°C at bond line in underwater welding is found to be 23°C/s and it is understood that the rate is higher than that in air, that is, 10°C/s. However, this cooling rate is remarkably low, comparing with that in underwater gravity arc welding by the same weld heat input, about 140°C/s[5] and that in underwater plasma welding by relatively higher weld heat input, about 100°C/s[8].

Thus it is definitely shown that cooling rate of underwater submerged arc welding is remarkably low.

This result corresponds qualitatively to the fact that hardness of heat-affected zone has relatively low value, as shown in Fig. 5.

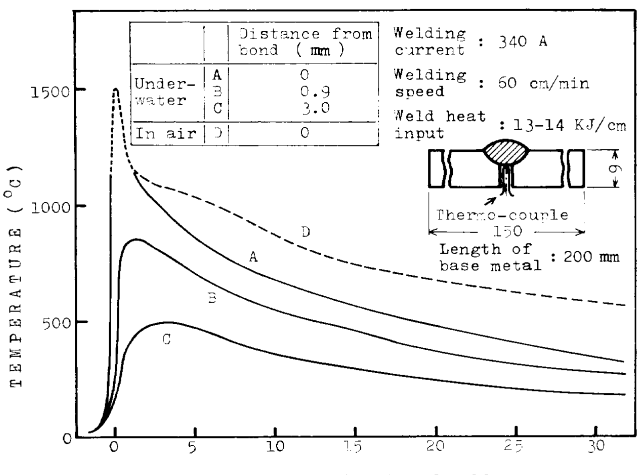


Fig. 9 Thermal histories of welds

6. Conclusions

Feasibility of underwater welding by submerged arc welding process has been studied. The wire US36 and the flux MF43, which had been mixed with 40 % water glass, were used. The base metal was steel for welded structure SM41 having a thickness of 9 mm.

Main results are summarized as follows:

(1) By using the 40 % water glass mixed flux and selecting suitable welding condition, a stable welding arc can be kept under water. Then a good weld without undercut can be obtained. However, even when welding is done under the conditions, which seem to be suitable, blowholes are formed in the weld metal.

(2) Heat insulating effect of flux for the weld zone is significant and cooling rate of the underwater weld by this process is considerably lower than those by the other processes.

(3) Average hardness of the underwater weld metal is about Hv160, and that of the heat-affected zone about Hv220. So a remarkably hardened zone cannot occur in the weld. This result corresponds qualitatively to a relatively slow cooling rate at the weld.

(4) The joint efficiency of the butt weld made by this process is 82 %. The elongation of the underwater weld is less than that of base metal. The reason may be the blowholes generated in the weld metal.

This report deals with the applicability of submerged arc welding process to underwater welding. Details of welding phenomena, prevention of blowhole formation, and moreover applicability of this process to underwater welding under higher water pressure and so on will be reported in the near future.

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Table 4 Effect of environment on cooling time and cooling rate at bond line

Environment	Cooling time (s)		Cooling rate at 500°C (°C/s)	Weld heat input (kJ/cm)
	800-500°C	800-300°C		
In air	26	103	10	13
Underwater	12	22	23	14

Note : Thickness of base metal : 9 mm
Welding current : 340 A
Welding speed : 60 cm/min

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