KAWASAKI STEEL TECHNICAL REPORT
No.10 (December1984)

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Kohzo AKAHIDE** Hiroaki FURUYA** Masahiro ISHIDA**

A circumferential SAW technique characterized by a two-electrode system and narrowly grooved joint has been developed. The welding process is applicable to butt joints of large diameter heavy wall steel pipes. The two-electrode SAW technique is especially effective in welding steel pipes of larger than 1 000 mm diameter and the welding efficiency was experimentally confirmed to be up to about 50% higher than that by the conventional single electrode. In welding a V-groove joint with steel backing, blowholes are apt to occur in the first pass bead and so their cause and countermeasure have been studied. As a result of an application of this new technique to the construction of offshore berth facilities in Taiwan, 40% increase in efficiency was attained in welding steel pipes of 1 500 mm diameter and thus its high productivity and practicality have been proved.

1 Introduction

Heavy-wall steel pipe is used in the construction of offshore structures and various other types of civil engineering and building works. In fabricating these structures, the level of welding techniques is a large factor for the quality and cost of the entire work. Therefore, it is of importance to establish welding procedures best fit to each different weld joint.

Pipe-to-pipe butt joints are typical weld joints in steel pipe structures, and submerged arc welding (hereinafter called "SAW"), gas shielded arc welding, shielded metal arc welding are used to weld these joints in flat or horizontal position or in all positions, in consideration of pipe diameter, wall thickness, quality requirements, and applied operation conditions. Since these welding operations almost unavoidably involve the bead formation on curved surfaces, the use of an efficient welding procedure is limited, and even when a generally recognized high-efficient SAW is used, the application is restricted only under a low heat input condition. Therefore, the development of efficient welding technique poses an important problem for reduction of the fabricating cost. Against this background, a study was carried out to examine the possibility of improving efficiency in the SAW process in which butt joints were made in heavy-wall pipe in the flat position by turning the pipe. At the same time, examinations were made as to the use of steel backings frequently employed in joints of steel pipe structures and as to possible measures to prevent the occurrence of blowholes in one-side welding. This paper presents an outline of these investigations and the application of the established welding process to actual work[1]; i.e., a sea berth construction work for the Hsinta Power Station of Taiwan Power Company.

2 Efficiency Improvement in Circumferential Welding

2.1 Peculiarities of Bead Formation and Concept of Efficiency Improvement

Welding efficiency can be improved by ① increasing the amount of deposited metal per unit time and ② reducing the necessary amount of deposited metal through a decrease in the cross-sectional area of the groove. In both cases, the direct effect of a reduced arc time on efficiency can be expected and a reduced slag peeling time resulting from a decreased number of passes is effective in improving efficiency. The use of large welding current condition and the application of multiple electrode system are concrete techniques associated with the method ① described above; four-electrode seam welding of large-diameter pipe[2] and four-electrode one-side welding in shipbuilding[3] are the examples. With respect to the method ②, the example of narrow-gap welding[4] can be given; attempts have recently been made to put this welding process in practical use in many fields including pressure vessels. Furthermore,

* Originally published in *Kawasaki Steel Giho*, 15(1983)4, 318–326

** Engineering Division

the effects of the two methods are aimed at in the KX-process[5] in which narrow gaps can be obtained by ensuring deep penetration using large welding current.

Unlike the butt welding in the flat position which is performed with steel plates set horizontally, beads must be formed with inclined steel plates in the circumferential welding discussed in this paper. This limits the improvement of efficiency. That is to say, beads are formed in arc welding when solidification proceeds with a balance kept between the head pressure of molten metal in the molten pool and the arc pressure. In general, the equilibrium of forces in the molten pool is appropriate for bead formation when steel plates to be welded are horizontal. In this case, smooth beads as shown in **Fig. 1(b)** are obtained. When base plates are inclined, molten metal flows in the direction of weld line in the molten pool in response to a change in the static pressure. Therefore, beads with concave center having a tendency to overlap are formed in downward welding as shown in Fig. 1(c) and those with concave toe and convex center are formed in upward welding as shown in Fig. 1(a). When circumferential welding is performed from the outside surface of steel pipe, beads are formed with the welding position changed from downward to upward. Therefore, as shown in Fig. 1(d), the bead turns out with its toe shaped in downward welding characteristics and its center in upward welding characteristics.

From the above-mentioned phenomena, it is judged to be of prime importance to conduct welding so that the inclination angle of the molten pool horizontal can be kept within a proper range*) when forming beads in circumferential welding. Therefore, there is a limit to the method of improving efficiency by which the length of the molten pool increases, i.e., the use of large welding currents and multiple electrodes to increase the deposition rate. On the other hand, the use of narrow gap groove, which allows the required amount of deposited metal to be reduced, is effective in shortening the welding time irrespective of the welding position. Incidentally, multipass welding is usually adopted in making circumferential butt joints in heavy-wall pipe. In this case, the amount of deposited metal per unit time influences efficiency, as welding is done in such a manner of building up in groove. The welding speed does not basically affect efficiency.

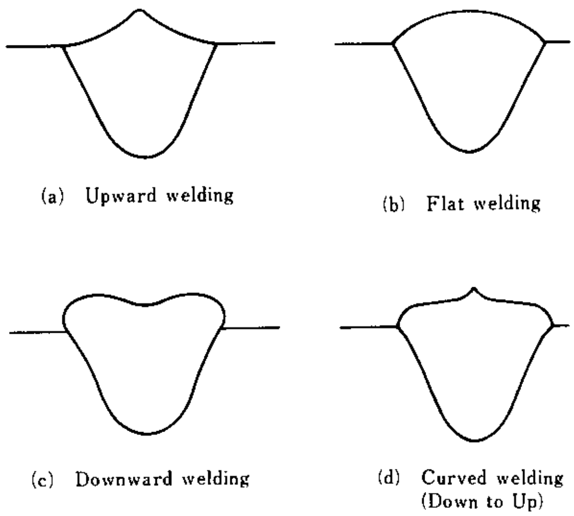


Fig. 1 Schematic illustrations of cross sectional weld bead at various welding positions

From the above-mentioned viewpoint, it is concluded that setting a maximum allowable welding current value for each pass and selecting a proper groove, i.e., a narrow groove are most effective.

2.2 Relationship between Welding Conditions and Molten Pool Length

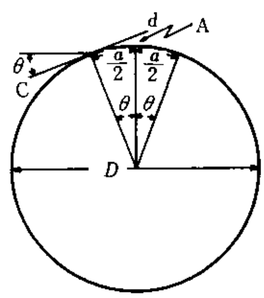
2.2.1 Single-electrode welding

When welding is performed in the inclined position, it is essential to set welding conditions that provide a small molten pool length a. Therefore, an examination is made as to the relationship between a and welding conditions. Christensen et al.[6] made an analysis of heat conduction by assuming that the arc is a moving point heat source and found the relationship between the nondimensional molten pool length λ and a welding parameter n given by Eq. (1):

$$\lambda = n \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

λ and n are defined by Eqs. (2) and (3), respectively.

* Supposing that circumferential welding is being conducted with the formation of a molten pool with a length of a so that its center coincides with the apex A of the arc of a circle, as shown in the right figure, then the angle θ formed by the tangential line $\overline{cd}$ at the ends of the molten pool with the horizontal plane is determined from the angle of the arc formed by the molten pool, i.e., $2\theta = 360\, a/\pi D$. This means that in this case, welding is conducted in the range from downward θ to upward θ. Therefore, the larger the molten pool length a and the smaller the pipe diameter D, the larger the angle of inclination θ at which beads must be formed.



$$\lambda = \frac{va}{2\alpha} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$n = \frac{qv'}{4\pi\alpha^2 c\gamma(T_c - T_o)} \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where,

a: actual molten pool length
v: welding speed
α: average heat diffusivity
q: quantity of heat (product of current and voltage)
c: specific heat
γ: specific gravity
T_c: melting temperature of steel
T_o: initial temperature of base metal

From Eqs. (1) to (3), the molten pool length a is given by Eq. (4):

$$a = \frac{q}{2\pi\alpha c\gamma(T_c - T_o)} \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Since the denominator is a heat constant in this equation, a is proportional to the quantity of heat, i.e., the product of welding current and arc voltage, and has no relation to the welding speed.

In setting welding conditions, the arc voltage is properly selected depending on the welding current and speed. The practical arc voltage ranges from about 30 to 40 V and, hence, can be regarded as constant. Therefore, the molten pool length can be treated as a value determined by the welding current. **Figure 2** shows the relationship between the welding current and the molten pool length in bead-on-plate welding experiments. It is proved that the molten pool length is proportional to the welding current and does not depend on the speed.

2.2.2 Two-electrode welding

Figure 2 also shows the molten pool length in the two-electrode arc welding, determined from the experiment, along with that of the single-electrode welding. In this case the electrode spacing is 25 mm. As is apparent from the figure, if the experimental results are rearranged by totals of current values of the leading and trailing electrodes, almost the same relationship as with

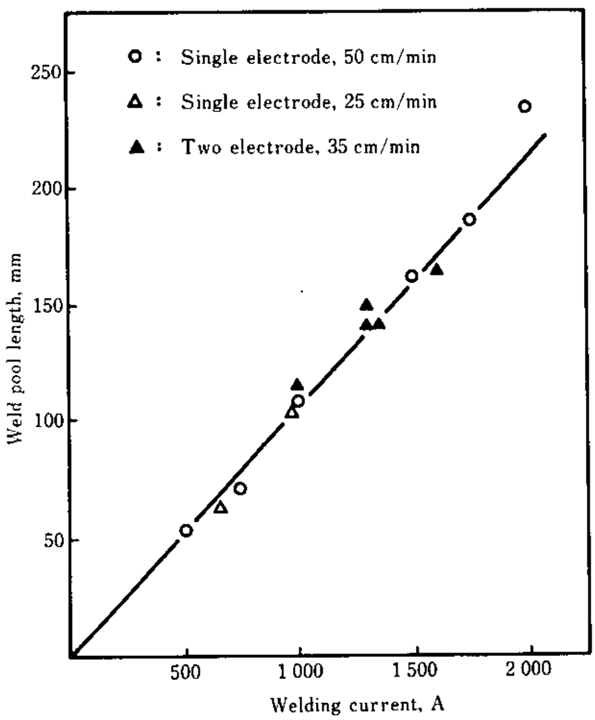


Fig. 2 Relationship between welding current and weld pool length

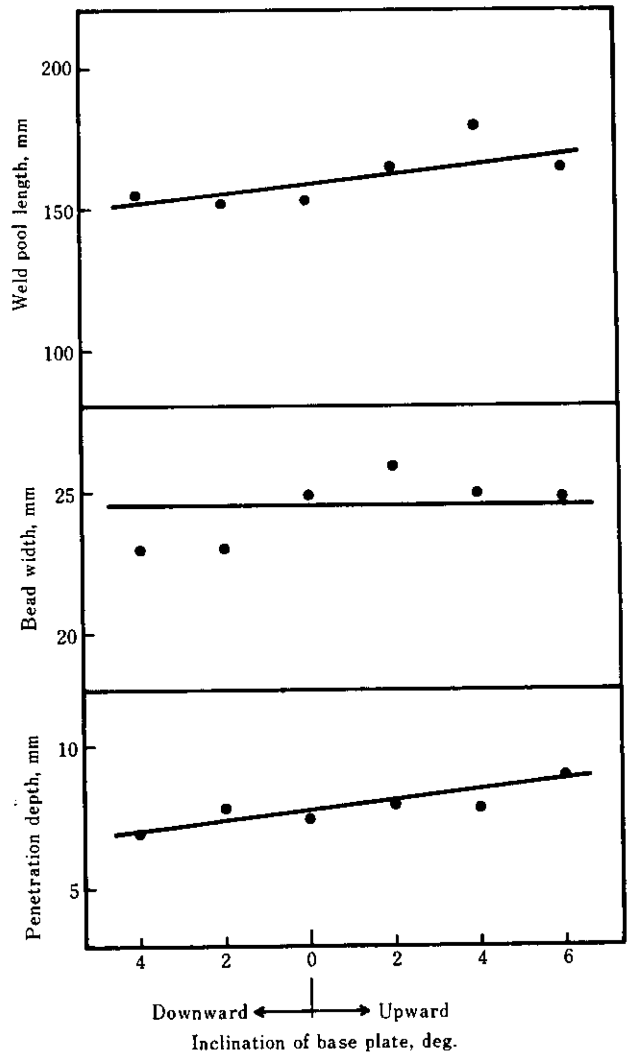


Fig. 3 Change in bead shape and weld pool length by inclination of base plate

the single-electrode welding is obtained and the molten pool length, a, can be regarded as proportional to the welding current. That is to say, when a is constant, there is no difference in current values between the single-electrode welding and the two-electrode welding. As far as this is concerned, it is impossible to find advantages of the two-electrode welding over welding in the inclined position.

When the single-electrode welding is performed under conditions of large current and high speed, welding conditions are limited with respect to the bead shape to prevent surface defects such as undercuts. In the two-electrode welding, however, ranges of conditions are wide; that is, both the current range and the speed range are about twice those of single-electrode welding. In this case, therefore, there is a possibility of efficiency improvement by the two-electrode welding. That is to say, it can be presumed that the two-electrode welding is effective in improving efficiency when large-diameter pipe is welded.

2.3 Setting of Two-Electrode Welding Conditions

2.3.1 Effect of incline angle of plate on bead shape

The above-mentioned relationship between the molten pool length and welding parameters relates to flat welding. When welding is performed in the inclined position, gravity may influence the flow of molten metal in the molten pool and consequently the length of the molten pool may change. An experiment was conducted to investigate the relationship among the molten pool length, bead shape and the incline angle of the base plate. Test results are summarized in **Fig. 3** and **Photo 1**. The molten pool length a increases with increasing angle as the welding position changes from downward to upward. However, the amount of this increase in the molten pool length is 10 mm for a change of 5°. This value is not more than 10% of the initial length. Therefore, even if values for flat welding are used as a in setting circumferential welding conditions, no great difference would be generated. On the shape of reinforcement the amount of excess weld metal is too large as shown in Photo 1 because of bead-on-plate welding. Overlaps occur in downward welding and extreme convex beads are formed in upward welding. However, if a bead with proper amount of reinforcement is formed in a grooved joint, the bead can be free of defects even under the same welding conditions. As shown in **Photo 2**, this is demonstrated by an example of experiment on a 4° downward weld.

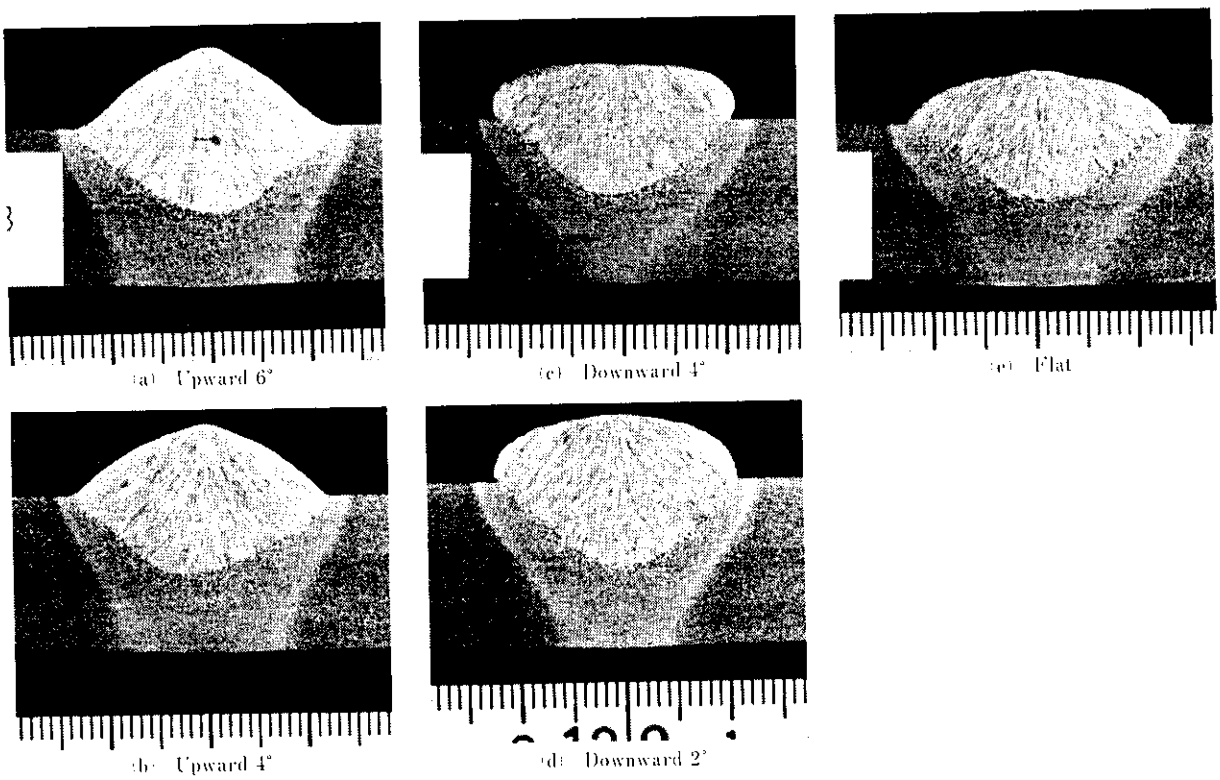


Photo 1 Variation of bead shape by inclination of base plate

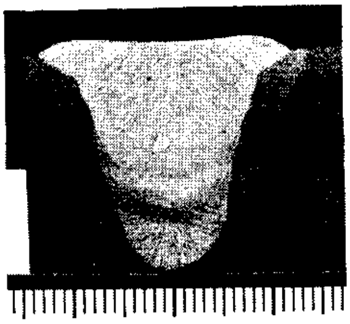


Photo 2 Bead shape of 4° downward welding with V-groove

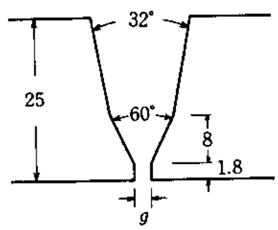
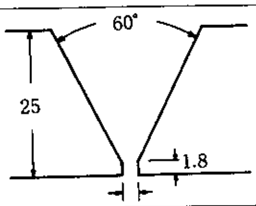
2.3.2 Estimation of circumferential welding conditions

An attempt is made to set circumferential welding conditions for a pipe diameter of 1 500 mm. From results of fabrication at the single-electrode welding, it is found that if the pipe diameter is of this order, the incline angle of the base plate that ensures satisfactory circumferential welding has a value determined based on the angle of arc 2θ between 10 and 12°. Supposing that 2θ is 10°, the range in which the bead is formed (corresponding to the molten pool length in the case of the single-electrode welding) is 130 mm. Since the electrode spacing is 25 mm in this two-electrode welding, it is considered that welding conditions that ensure a molten pool length of 155 mm (the sum of 130 mm and 25 mm) are suitable in terms of efficiency. Concretely, the total of the current values of the leading and trailing electrodes is calculated. From Fig. 2, a value of 1 400 A is determined.

Table 1 summarizes standard welding conditions for narrow grooves of modified Vee and conventional V-grooves based on a conservative value of 650 A in the final layer for both the leading and trailing electrodes. Case (A) presupposed that CO_2 gas shielded arc welding adopted for a sealing run, by which it is possible to obtain a depth of penetration to the steel backing. It has been confirmed that satisfactory bead shapes are ensured under these conditions not only in flat welding, but also in welding in the inclined position in the angle range from 4° upward to 4° downward.

Under the conditions given in Table 1, the efficiency improvement accomplished by the use of narrow grooves is about 12% and this effect is small because the plate thickness is 25 mm and, hence, is not so heavy. However, the use of narrow grooves is very effective in improving efficiency when the plate thickness increases. On the other hand the efficiency improvement resulting from the use of two electrodes is about 50% because the current applicable to single-electrode welding is about 900 A. Therefore, under the welding conditions set here, the expected efficiency improvement over conventional techniques is about 60% in case (B) with narrow grooves and about 50% in case (C) with ordinary grooves.

Table 1 Estimated welding parameters for pipe with diameter of 1 500 mm and thickness of 25 mm

	Joint geometry (mm)		Seal welding process	Submerged arc welding				
				Layer	Pole	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)
(A)		g : 0	CO_2 gas shielded arc welding	1st	Lead	650	29	50
					Trail	650	29	
				2nd	Lead	650	29	50
					Trail	650	29	
				3rd	Lead	650	29	40
					Trail	650	29	
(B)		g : 4	Shielded metal arc welding	1st	Lead	700	30	50
					Trail	700	30	
				2nd	Lead	700	30	40
					Trail	700	30	
				3rd	Lead	650	30	35
					Trail	650	30	
(C)			Shielded metal arc welding	1st	Lead	750	32	40
					Trail	750	32	
				2nd	Lead	750	32	40
					Trail	750	32	
				3rd	Lead	650	30	30
					Trail	650	30	

2.3.3 Confirmation of welding conditions in pipe

A full-scale model experiment on steel pipe was conducted as part of experiments concerning techniques for setting welding conditions. **Photo 3** shows steel pipes being welded for the experiment. The test pipe is made of SM-50 and has an outside diameter of 1 500 mm, a wall thickness of 25 mm and a length of 4 000 mm. Two types of groove were used. The one is ordinary V-groove with a root opening of 2 to 4 mm and an angle of 60° and the other is narrow groove of modified Vee with a root opening of 4 mm and two varied angles of 60° and 32°. Based on the results of the above-mentioned experiment on plate specimens, two-electrode welding was carried out with welding currents of 600 to 700 A and at speeds of 25 to 50 cm/min. A combination of agglomerated flux KB-120 and wire KW-50C was used as the welding material.

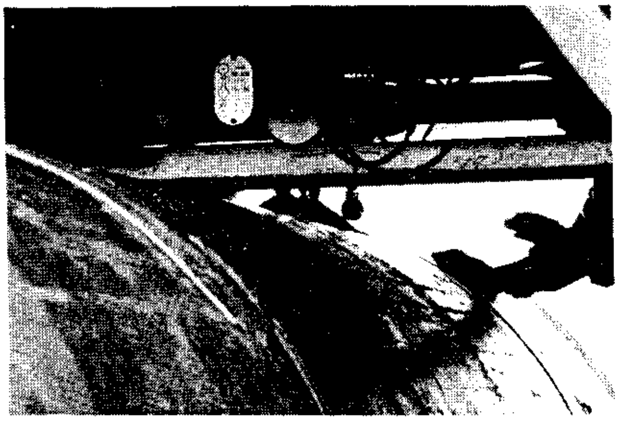
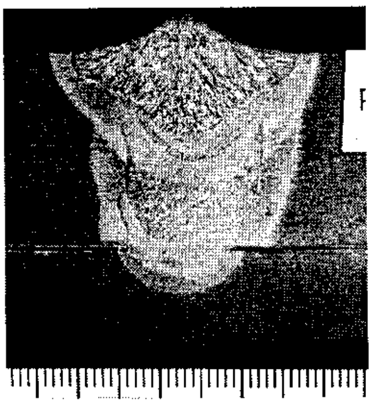


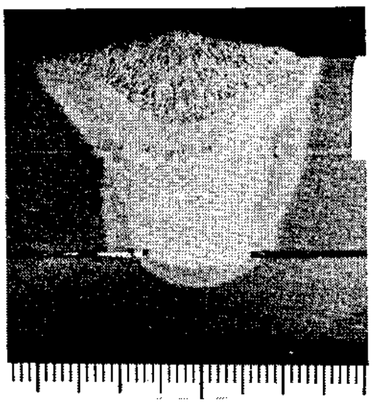
Photo 3 Circumferential welding of large diameter pipes

Photo 4 shows the effect of the electrode position on the bead shape. From this photograph, it is proved that practical beads can be formed when the molten pool is within the range of position angle from 8° downward to 6° upward and that the optimum electrode position is at 4° downward at the trailing electrode. Furthermore, as is

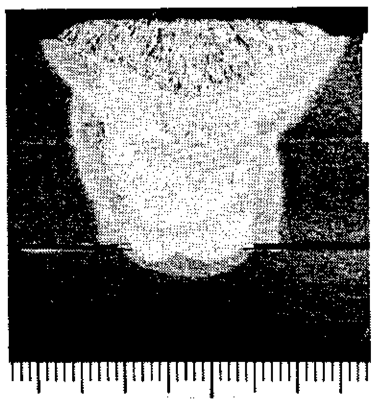


a) Flat position at trail (Weld pool : 2° downward ~ 10° upward)

b) 2° downward position at trail (Weld pool : 4° downward ~ 8° upward)



c) 4° downward position at trail (Weld pool : 6° downward ~ 6° upward)



d) 6° downward position at trail (Weld pool : 8° downward ~ 4° upward)

Photo 4 Change in bead shape of curved welding by position of electrode apparent from the photograph, beads obtained by the welding in the above-mentioned angle range are smoother than those obtained with a uniform inclination. Thus the validity of the circumferential welding conditions estimated from the experiment on welding with a uniform inclination could be confirmed for the two types of grooves.

2.3.4 Relationship between pipe diameter and welding conditions

Figure 4 shows estimated maximum welding currents as a function of pipe diameter. These current values were determined on the assumption that the incline angle of base metal is limited to 10° for the sake of keeping a good bead shape, as shown in the results of the above-mentioned experiment. As shown by the straight line, the applicable welding current can be increased in proportion to the pipe diameter and the larger the pipe diamter, the greater the efficiency improvement. However, the condition of the molten pool approaches that of a uniform inclination as the pipe diameter increases, and the allowable angle of inclination should, therefore, decrease. As shown by the dotted line, the maximum welding current curve becomes gentle gradually.

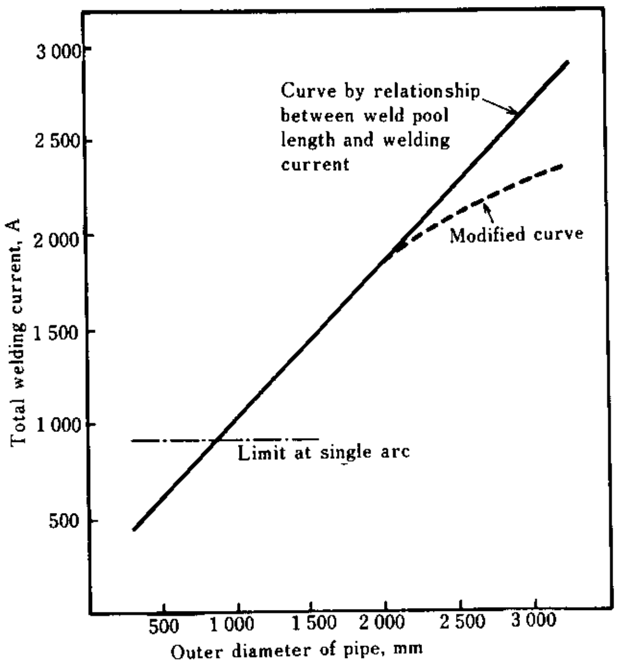


Fig. 4 Available maximum welding current estimation for various outer diameter of pipe

3 Formation and Countermeasure of Blowholes in First Layer Weld Metal

3.1 Tendency toward Blowhole Formation and Type of Blowholes

During the experiment discussed in the preceding chapter, it was found that the frequency of blowholes in the first layer is high in the two-electrode circumferential welding performed to make joints using a steel backing. Blowholes in these joints are usually generated in the root and are similar to those formed in fillet welding of primer coated steel plates[7].

Therefore, an investigation was made of the form of blowholes occurred in circumferential SAW. **Photos 5** and **6** show an example of blowhole. Photo 5 shows the macrostructure of the cross section of the bead. Photo 6 shows the macrostructure of the horizontal bead section at the root after the removal of the steel backing. As is apparent from the schematic drawings attached, blowholes about 1 mm in diameter (indicated by dotted lines) are first generated at the root. Molten metal flows into these parts and parts of them are remelted. However, the blowholes remain partially (as indicated by solid lines). From the shape of the blowholes it is inferred that the blowholes were caused by the gas (6), as shown in **Fig. 5**, expanded by weld heat in the gap between the steel backing and the base plate. As the gas escaped from the solidifying weld metal (1) into the molten weld metal (2), it made the blowholes.

In view of this formation mechanism of blowholes, it

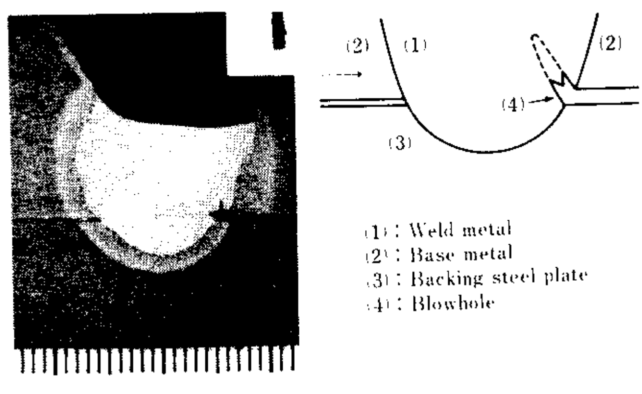
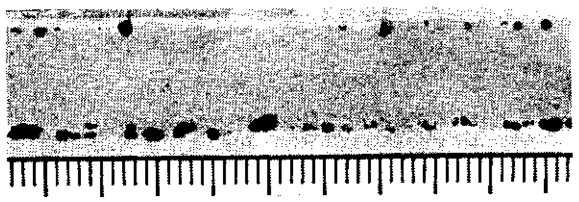


Photo 5 Cross bead section showing blowhole occurred



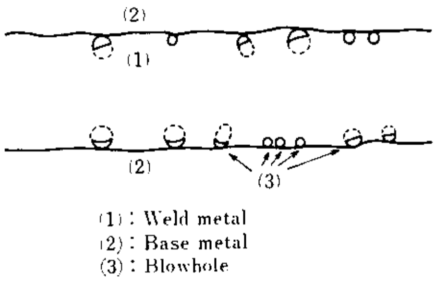


Photo 6 Horizontal bead section at root showing blowholes occurred

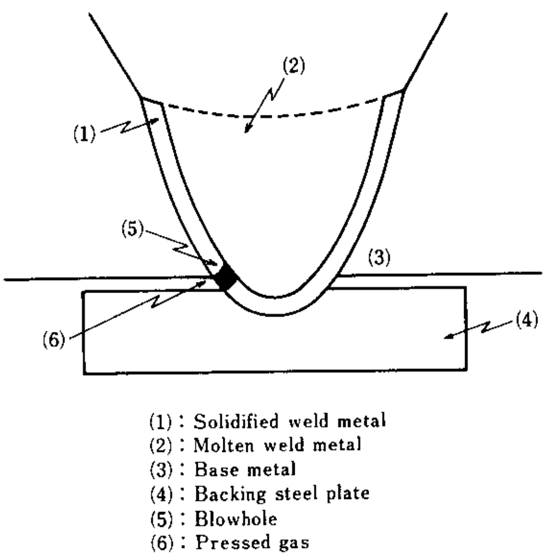


Fig. 5 Schematic illustration showing occurrence of blowhole

is necessary to eliminate gas sources such as moisture and organic matter and to reduce the pressure of generated gas in order to prevent blowholes.

3.2 Gas Sources

After it was ascertained that there is no specific relation between circumferential welding and blowhole formation, an examination was carried out using plate specimens as to the relationship between blowholes and gas sources. A combination of flux KB-120 and wire KW-50C was used as the welding material. V-grooves with an angle of 60° and a root opening of 4 mm were used. The experiment was conducted by varying the following conditions: ① moisture absorption condition of the flux, ② condition of organic matter adherence to the surface of the steel backing, ③ preheating condition and ④ gap between the base plate and the steel backing.

As a result of the experiment, the following were made clear:

(1) When preheating is performed with a gas burner, the moisture of dew condensed by the rapid cooling of the combustion gas enters the gap between the steel backing and the base plate. As a result, the tendency toward blowhole formation increases remarkably.
(2) In some cases, the above-mentioned moisture on the surface of the steel backing cannot be removed completely even if the base plate is preheated to high temperatures of about 150°C.
(3) The moisture in the flux does not so much affect the formation of blowholes of this kind.
(4) The gap between the steel backing and the base plate is effective in reducing the amount of blowholes occurred.
(5) The organic matter on the steel backing promotes the occurrence of blowholes.
(6) The frequency of occurrence of blowholes is high even when the steel backing and base plate are cleaned and preheating is performed at 200°C.

From the above-mentioned results, it is suggested that further detailed examination is necessary for establishing measures to prevent blowholes.

3.3 Measures against Blowholes Attributable to Welding Conditions

An experiment was conducted to examine the relationship between welding conditions and tendency toward blowhole formation, including the difference in the type of welding flux and a comparison between single-electrode welding and two-electrode welding. When the type of flux was changed, a small difference in the number of blowholes occurred was observed in two-electrode welding. However, it was judged that there is essentially no significant difference. The validity of this judgment can be proved by an experiment with single-electrode welding, which will be described later (refer to

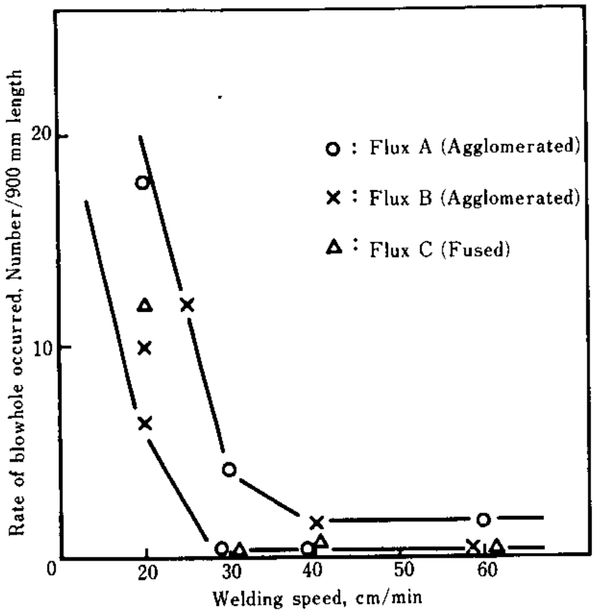


Fig. 6 Relationship between welding speed and rate of occurrence of blowhole

Table 2 Comparison of blowholes occurred by various welding parameters

No.	Welding process	Welding Speed cm/min	Heat input kJ/cm	Index of blowhole occurred*
21	Two electrode SAW	80	37	4
22		60	42	5
23		40	59	5
24		40	62	5
25		40	67	5
11	Single electrode SAW	60	27	1
12		40	34	2
13		30	39	1
14		30	42	2

* Index 1 : Number of blowhole occurred, 0 /m
2 : 1~5/m
3 : 6~10/m
4 : 10~20/m
5 : more than 21/m

Fig. 6). **Table 2** gives a comparison in the tendency toward blowhole occurrence between two-electrode welding and single-electrode welding. In this experiment, the same welding materials as in the experiment discussed in the previous subsection were used and welding was performed with organic matter caused to adhere to the steel backing in order to accelerate the formation of blowholes. In two-electrode welding many blowholes are observed under all of the different conditions, whereas the number of blowholes decreases substantially in single-electrode welding. This suggests the superiority of single-electrode welding.

Therefore, an investigation was made into the relationship between welding conditions and blowhole occurrence in single-electrode welding. Figure 6 summarizes changes in the frequency of occurrence of blowholes caused by changes in the welding speed. The welding current and arc voltage were varied in the range from 600 A, 30 V to 850 A, 35 V depending on the welding speed so as to obtain a proper depth of penetration. The figure suggests a clear correlation between the welding speed and the number of blowholes. Contrary to the generally understood correlation that the higher the welding speed is, the more blowholes tend to occur, it is found that many blowholes are formed at low welding speeds. The critical welding speed is 30 cm/min and blowholes are frequently formed at lower speeds. With respect to the relationship between welding heat input and blowholes, there is a tendency that the number of blowholes increases as the heat input increases. However, this relationship is not so clear as the relationship between the welding speed and the number of blowholes.

3.4 Relationship between Blowholes and Welding Conditions

When the experimental results discussed in the previous subsection are taken into consideration with the formation mechanism of blowholes, the realtionship between blowholes and welding speed can be estimated as follows. As shown in **Fig. 7**, blowholes are formed during the solidification of weld metal, and the formation of blowholes depends on the relative relationship between the strength *S* of weld metal that varies in the solidification process and the pressure *P* of the gas existing between the steel backing and the base metal. As schematically shown in **Fig. 8**, although both *P* and *S* increase with the lapse of time, blowholes are formed when *P* exceeds *S*, and at that instant *P* decreases. The relationship between *P* and *S* varies depending on welding conditions. In **Fig. 9**, an increase in the welding speed accelerates an increase in *S* and, inversely, decelerates an increase in *P*; therefore this is an effective measure to prevent blowholes. In two-electrode tandem SAW, the solidification of weld metal proceeds only when the trailing electrode has passed. Therefore, the strength curve of solidified metal shifts greatly to the longer time side. However, an increase in the gas pressure proceeds after the leading electrode passes, and this is assumed to be the reason why blowholes become apt to occur.

As mentioned above, single-electrode welding in an appropriate welding speed range is effective in prevent-

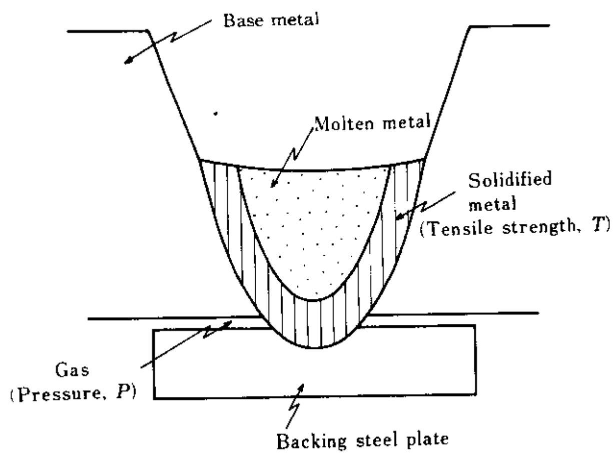


Fig. 7 Schematic illustration showing bead formation

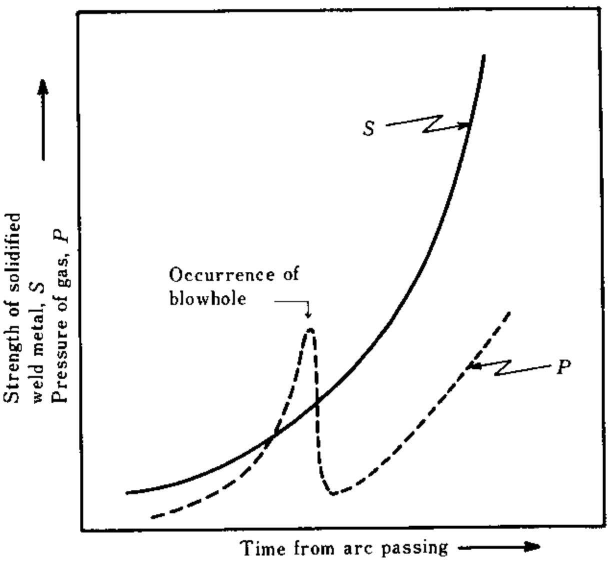


Fig. 8 Time curves of solidified weld metal strength and gas pressure at root during welding

ing blowhole occurrence in the first layer when performing circumferential welding only from the outside using a steel backing. Therefore, two-electrode welding aimed at an increase in efficiency should be applied to the second and the following layers. It is necessary to modify the welding conditions given in Table 1 in this respect.

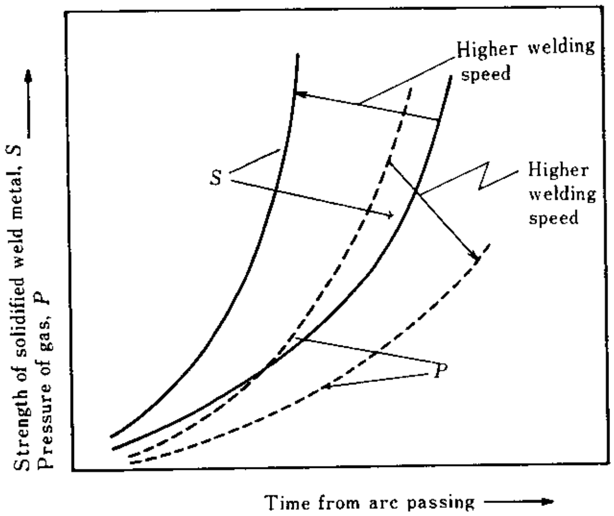


Fig. 9 Change in time curves of solidified weld metal strength and gas pressure by welding speed

4 Application of Circumferential Welding Techniques to Construction Work

The welding process established was applied to the construction of a coal unloading sea berth for the Hsinta Power Station of Taiwan Power Company[1] when site welding work was executed from August 1981 to March 1982. Improved welding efficiency was aimed at with weld quality ensured at the same time by adopting single-electrode welding for the first layer and two-electrode welding for the second to final layers. In this construction work, an experiment was carried out to confirm the relationship between welding conditions for the first layer and formation of blowholes and satisfactory results were obtained; that is, as a result of the X-ray film test in accordance with JIS (Japanese Industrial Standards), 98% of 48 joints made by single-electrode

Table 3 Steel plates for mock-up test

Steel	Yield strength (kg/mm^2)	Tensile strength (kg/mm^2)	Elongation (%)	Chemical composition, %					
				C	Si	Mn	P	S	Nb
ASTM,A572-45 (25 mm t)	37.5	49.7	30	0.15	0.21	0.90	0.020	0.006	0.009
ASTM,A572-55 (36 mm t)	42.3	57.5	25	0.15	0.24	1.57	0.020	0.004	0.026

Table 4 Welding consumables used

SAW wire	KW-50 C (4.0 mm ϕ)
SAW flux	KB-120 (12×200 mesh)
Covered electrode for tack welding	KS-76 (4.0 mm ϕ)

Table 5 Tensile strength of welded joints

Steel	Yield strength (kg/mm^2)	Tensile strength (kg/mm^2)
ASTM	41.1	53.2
A572-45	40.9	53.2
ASTM	–	59.8
A572-55	–	59.1

welding at a speed of 30 cm/min and 100% of 16 joints made similarly at 40 cm/min were rated as JIS first class. Moreover, the mechanical properties of the welded joints were satisfactory. As shown in **Tables 3** to **6**, the joints possess appropriate strength and high ductility. If the conventional single-electrode SAW had been applied to this work, 0.5 pipe/day (on average 3 joints/pipe) would have been attained. With the technique applied, pipe fabrication was at the rate of 0.7 pipe/day. This corresponds to an efficiency improvement of 40%. Thus the high efficiency of this welding process was ascertained.

As mentioned above, it was possible to prove the effectiveness of the two-electrode SAW in actual work which was established for the butt welding of large-diameter steel pipe.

5 Conclusions

To improve the efficiency of circumferential butt welding of steel pipe, an examination was made as to the applicability of a two-electrode submerged arc welding technique. The establishment of this technique was aimed to apply this technique to actual work. Principal results obtained are summarized in the following.

(1) In circumferential welding, there is a limit to the applicable molten pool length relative to the pipe diameter in terms of bead formation. This limits the improvement of efficiency. It was shown that the molten pool length increases in proportion to the welding current and does not depend on the welding speed.

(2) In the two-electrode welding, the molten pool length varies in proportion to the sum of current values of the leading and trailing electrodes. The larger the pipe diameter is, the more effective becomes this welding process, although its application to circumferential joints in small diameter pipe is limited.

For example, a 50% improvement in efficiency over single-electrode welding can be expected with a pipe diameter of 1 500 mm.

(3) The larger the wall thickness is, the more effective becomes narrow-groove welding in improving efficiency. In case of 25 mm in thickness, however, the effect of this process reduces to a relatively low of about 10%.

(4) A high-efficiency submerged arc welding technique

Table 6 Absorbed energy of welded joint (kg · m)

Steel	Notch position		Testing temperature (°C) −20	(Ave)	0	(Ave)
ASTM A572 -45	Face	WM	7.4, 6.1, 5.3	(6.3)	9.3, 10.0, 11.3	(10.2)
		Bond	19.0, 10.8, 20.0	(16.6)	17.7, 14.0, 17.6	(16.4)
		HAZ	9.9, 19.1, 19.1	(16.0)	11.0, 21.5, 20.5	(17.7)
		BM	11.0, 16.7, 16.3	(14.6)	20.0, 23.2, 20.7	(21.3)
	Center	WM	5.4, 5.5, 6.4	(5.7)	9.8, 8.7, 8.7	(9.1)
		Bond	16.1, 11.0, 16.0	(14.4)	12.2, 14.8, 19.7	(15.6)
		HAZ	16.1, 16.1, 14.4	(15.6)	21.5, 24.1, 22.0	(22.6)
		BM	12.1, 16.1, 13.9	(14.0)	18.4, 17.3, 19.2	(17.3)
ASTM A572 -55	Face	WM	4.0, 4.3, 5.1	(4.5)	6.0, 6.0, 7.0	(6.3)
		Bond	5.0, 2.2, 5.9	(4.4)	9.1, 19.8, 19.7	(16.2)
		HAZ	14.4, 18.9, 8.2	(13.8)	27.1, 25.3, 19.6	(24.0)
		BM	21.2, 16.1, 13.6	(16.9)	29.1, 29.5, 29.0	(29.2)
	Center	WM	4.0, 4.1, 4.7	(4.3)	10.4, 9.3, 5.9	(8.5)
		Bond	3.1, 3.2, 4.1	(3.4)	4.4, 4.1, 13.6	(7.3)
		HAZ	4.1, 6.9, 3.1	(4.7)	17.9, 11.6, 11.0	(13.5)
		BM	5.6, 5.6, 6.4	(5.9)	8.7, 7.7, 8.1	(8.1)

with two-electrode, which can be applied to circumferential welding for large diameter steel pipe such as 1 500 mm,.was established.

(5) The frequency of blowhole occurrence in the first layer is high in welded joints using a steel backing. These blowholes are considered to be formed due to the expansion of the gas existent in the gap between the steel backing and the base metal near the root.

(6) Blowholes of this kind are more liable to occur in two-electrode welding than in single-electrode welding. Furthermore, in the case of single-electrode welding, the lower the welding speed is, the higher the frequency of blowhole occurs. Therefore, single-electrode welding at a high speed is effective in preventing these blowholes.

(7) The blowhole formation conditions can be estimated from the relative relationship between the gas pressure and the strength of weld metal at high temperature.

(8) The established two-electrode circumferential submerged arc welding technique was applied to the sea berth construction work for the Hsinta Power Station of Taiwan Power Company and its high efficiency was proved.

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