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100 kW Class Electron Beam Welding Technology (Report IV)†
– Fundamental Research on Horizontal Electron Beam Welding –

Yoshiaki ARATA * and Michio TOMIE **

Abstract

A new type deflector was developed with which a high power vertical beam from the electron gun could be effectively converted to the horizontal one. To obtain a sound weld for a plate more than 100 mm in thickness, the influences of beam oscillation and material composition (especially O, N, Mn and Si) were tested in a transverse welding condition and the good welding conditions without any defects were decided. Furthermore the possibility was demonstrated to certify the full penetration welding of an ultra-thick plate more than 300 mm by the vertical upward welding with the horizontal beam.

KEY WORDS: (Electron Guns) (Electron Beam Welding) (Defects) (Hardness) (Weldability) (High Strength) (Horizontal E. B. Welding) (Vertical E. B. Welding) (All Position E. B. Welding) (Thick Plate E. B. Welding)

1. Introduction

In electron beam welding, it is essential that the electron gun should operate efficiently, and, since the gun is considerably heavy and a high degree of accuracy is required, it must in general be fixed in position or supported by a machine such as a robot. Therefore, in electron beam welding, it was heretofore said to be difficult to perform welding in various positions. The writers$^{1)}$, however, have demonstrated that welding in all positions is possible, as shown in **Fig. 1**, by developing a beam deflector. Among these positions, horizontal welding$^{2)}$ and vertical welding$^{3)}$ by means of a horizontal beam are being studied by many researchers and are starting to be put into practical use.

A horizontal beam may be produced by deflecting$^{4)}$ a vertical beam in 90 degrees with a deflector, or by using an electron gun fixed horizontally$^{5)}$. The above-mentioned horizontal electron beam welding has been found to be more effective in thick plate welding compared with ordinary flat position welding, and it is therefore frequently used in welding thick plates. We here intend to give further characteristics of horizontal electron beam welding on thick plates.

2. Evolution of Horizontal Electron Beam

An electron gun is composed of a beam acceleration chamber, a beam channel and an injection port. The electron beam emitted from the injection port reaches the part to be welded and generates plasma and thermal vapour jet as well as a beam hole there. Some of this plasma and thermal vapour jet flows back along the E.B. axis into the E.B. gun and contaminates the acceleration chamber, damaging the cathode. This effect becomes greater, the greater the increase in beam power.

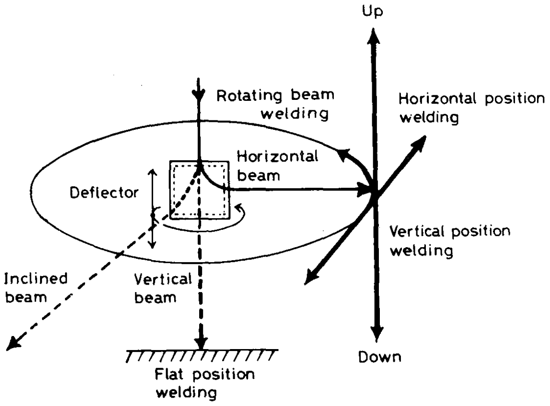

Fig. 1 All position electron beam welding method.

In the case of horizontal electron beam welding, a high power beam is usually used, and countermeasures must therefore be considered to deal with the situation. **Fig. 2**$^{6)}$ shows the contamination rate in the E.B. gun according to the deflection angle of the beam. **Fig. 2** shows the advantages of the 90° deflecting beam in relation to contamination in the E.B. gun.

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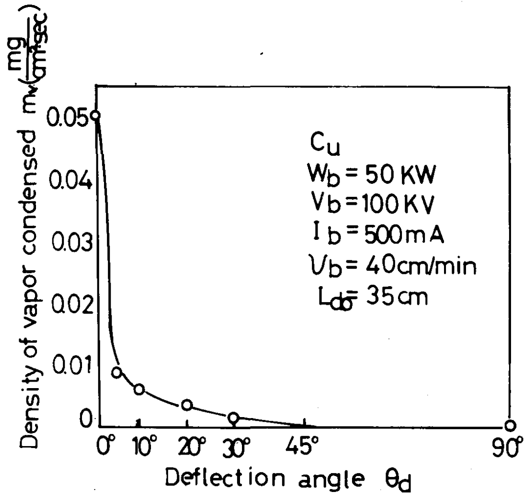


Fig. 2 Effect of beam deflection on metal vapor contaminating electron gun.

To simplify the following explanation, the above apparatus will be called Type A in this paper.

Two other methods of decreasing the contamination rate are to increase the distance (working distance) between the beam injection port and the welded part, and to alter the trajectory on the way along the beam axis. The former will be called Type B and the latter Type C.

Since these types A, B, and C all have almost indentical effects on welding, it follows that the type chosen should be the one most suitable for the particular welding conditions. Type A Welder (W_b = 100 kW, V_b = 100 kV, I_b = 1,000 mA) as shown in **Fig. 3** was used in this research, the beam condition was a_b ($\equiv D_o/D_F$) $\simeq$ 0.8 ~ 0.9, D_o = 150 mm in which D_o indicates objective distance and D_F focal Length.

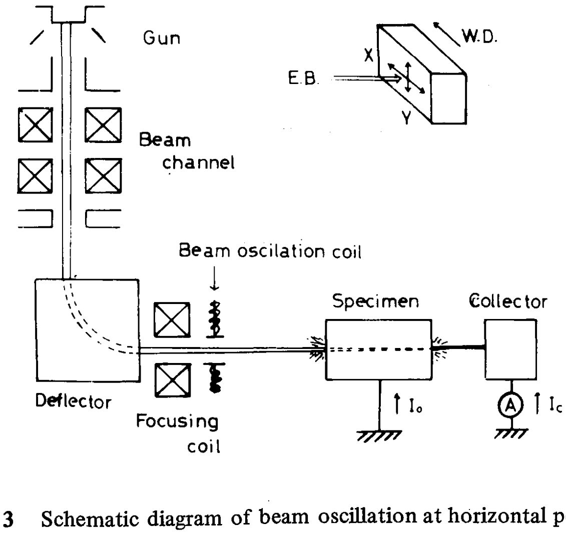


Fig. 3 Schematic diagram of beam oscillation at horizontal position. (A type welder)

3. Experimental Results and Discussions

3.1 Horizontal welding

There are basically two kinds of horizontal beam welding, i.e., welding in a horizontal position and welding in a vertical position. In the case of electron beam welding in general, shaking of the beam hole and the molten pool becomes more violent with increases in power.

In the case of flat position welding on thick plates in particular, the shaking becomes so violent as to make welding extremely difficult.

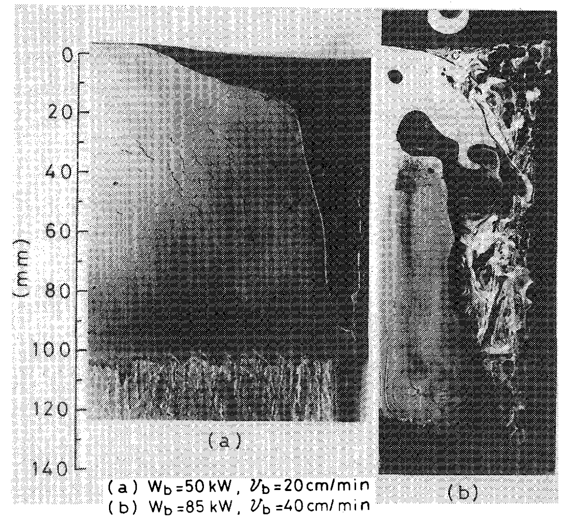


Fig. 4 Bead sections indicating condition of violently shaken molten pool during flat position welding. (θd=0)

This is clearly shown in **Fig. 4**$^{7)}$ and motion picture analysis.

The fundamental conditions for achieving good welding are: -

1) maintaining the beam-hole in a stable condition,
2) inhibiting shaking of the molten pool

These conditions will be called ConditionA.

It becomes increasingly difficult to maintain Condition A as the beam-hole grows deeper. In the case of flat position welding in particular, the influence of gravity on the molten pool must not be ignored. In the case of horizontal and vertical welding, this effect disappears, and it is possible to forecast a better result compared with flat position welding.

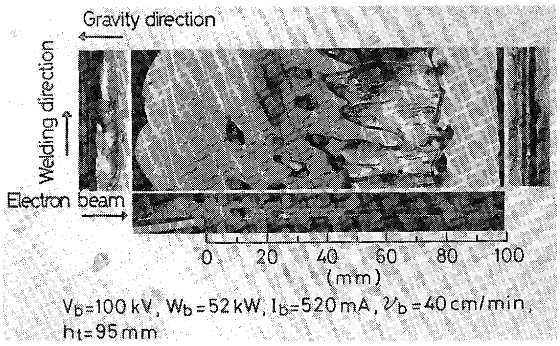
However, the drawback is that the molten pool is apt to flow outward and result in what is called "porosity" due to lack of molten metal. An example is shown in **Fig. 5** in the case of horizontal welding.

The materials used in this experiment were Cr - Mo steel (2¼Cr - 1Mo), stainless steel (SUS304), high tensile strength steel (HT50, 80) and centrifugally cast steel pipe for welded structures (SMK50) as shown in **Table 1** and thick plates of a thickness of 100 mm or more.

Table 1 Chemical composition of materials used.

Wt% ← | → ppm

Materials \ Elements	C	Si	Mn	P	S	N	O
$2^1/_4$ Cr-1Mo (CM)	0.11	0.21	0.51	0.016	0.009	63	20
$2^1/_4$ Cr-1Mo (Y)	0.12	0.15	0.49	0.011	0.010	109	30
SUS 304	0.050	0.74	1.74	0.030	0.010	360	75
HT 50	0.15	0.34	1.26	0.020	0.015	—	—
HT 80*	0.11	0.32	0.92	0.008	0.006	34	10
HT 80 (N)	0.12	0.29	1.56	0.010	0.001	75	69
HT 80 (A)	0.12	0.06	0.96	0.007	0.006	57	56
HT 80 (B)	0.12	0.10	0.94	0.008	0.005	102	47
HT 80 (C)	0.11	0.09	0.93	0.008	0.006	274	47
HT 80 (D)	0.12	0.03	0.98	0.008	0.007	46	61
HT 80 (E)	0.12	0.03	0.93	0.009	0.007	53	109
HT 80 (F)	0.12	0.03	0.90	0.007	0.006	118	271
HT 80 (G)	0.13	0.12	0.24	0.008	0.009	44	71
HT 80 (H)	0.11	0.11	1.06	0.010	0.007	57	82
HT 80 (I)	0.12	0.14	4.98	0.012	0.006	43	81
HT 80 (J)	0.11	0.03	0.92	0.010	0.010	79	63
HT 80 (K)	0.12	0.16	0.97	0.009	0.009	70	73
HT 80 (L)	0.13	1.02	0.93	0.010	0.009	66	77
SMK 50	0.15	0.30	1.03	0.016	0.023	123	28



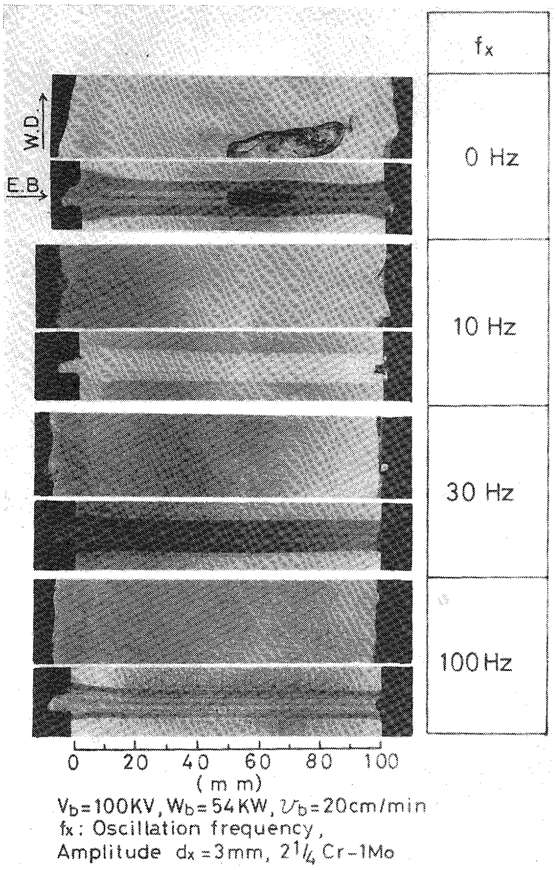
V_b=100 kV, W_b=52 kW, I_b=520 mA, ν_b=40 cm/min, h_t=95 mm

Fig. 5 Fully penetrated cross sections and appearance of horizontal position welding.

In the case of these thick plates, however, a number of defects such as porosity appear, if a suitable beam condition is not chosen. One means of inhibiting such phenomena is to produce beam oscillation, i.e., to cause the beam to oscillate along the transverse line of welding by applying X-oscillation, or to cause it to oscillate perpendicularly by applying Y-oscillation by means of a suitable magnetic field, as shown in **Fig. 3**. As a matter of course, these oscillations are indicated by frequency f_x, f_y (H_z) and amplitude d_x, d_y (mm).

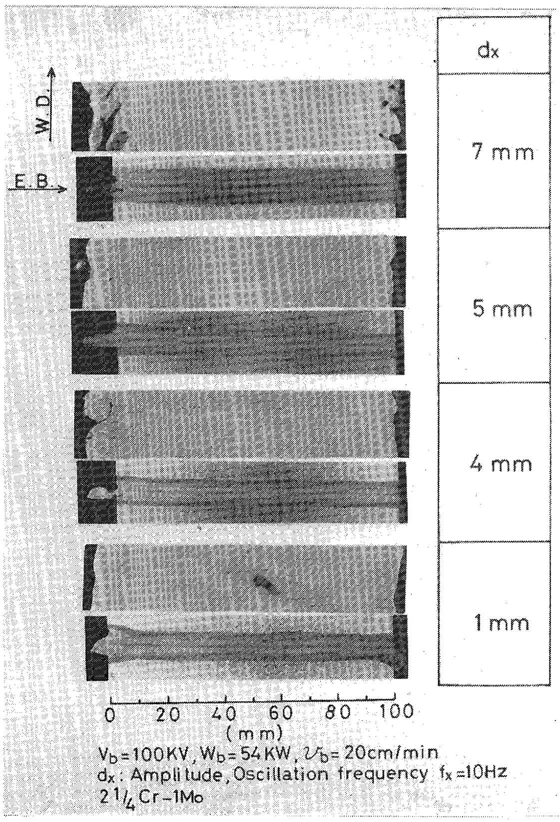
Which oscillation should be chosen or whether a compound oscillation (circular or elliptical in shape) would be suitable depends on the material. **Fig. 6** and **Fig. 7** show the effect of X-oscillation (f_x and d_x) when 100mm–thick 2¼Cr - 1Mo steel was welded at a welding speed of ν_b = 20 cm/min., the beam condition being d_x = 3 mm, W_b = 54 kW and V_b = 100 kV.

The illustrations show the condition of a bead cross section, where large porosities appeared when there was



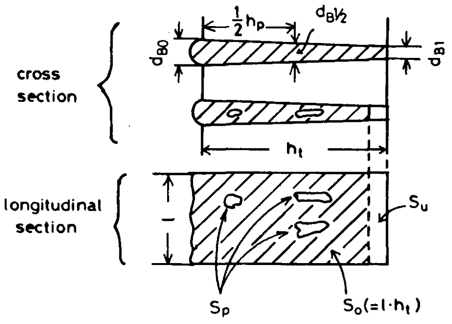
V_b=100KV, W_b=54KW, ν_b=20cm/min
f_x: Oscillation frequency,
Amplitude d_x=3mm, $2^1/_4$ Cr-1Mo

Fig. 6 Fully penetrated bead section of horizontal position welding with various beam oscillation frequency.



V_b=100KV, W_b=54KW, ν_b=20cm/min
d_x: Amplitude, Oscillation frequency f_x=10Hz
$2^1/_4$ Cr-1Mo

Fig. 7 Fully penetrated bead section of horizontal position welding with various beam amplitude.



$$R_p = \frac{S_p}{S_o} \times 100(\%)$$

$$R_u = \frac{S_u}{S_o} \times 100(\%)$$

Fig. 8 Bead defect explanation.
Note: So indicates the cross section area of the bead. (So = l · ht; l = width, ht = plate thickness) S_p indicates the area of porosity in So.
Su indicates the area of under-fill in Su. l indicates the width of the cross-section and in this case l = 40 mm.

no oscillation ($f_x = 0$), but disappeared when $f_x = 5$.

To illustrate these bead conditions more specifically, the results shown in **Fig. 9** and **Fig. 10** are obtained by using the symbols shown in **Fig. 8** and by indicating the rate of porosities and under-fill by: - porosity rate R_p (= S_p/S_o), and under-fill rate R_u (= S_u/S_o). When the value of f_x and d_x are $f_x \simeq 10$, $d_x \simeq 2 \sim 5$, conditions are optimum, R_p and R_u being limited to almost 0.

Furthermore, a condition called parallel bead may be obtained at the welded part, where the bead width is almost uniform throughout. Neither Y-oscillation nor compound oscillation of X and Y were taken up this time because they produced rather poor welding results.

In full penetration welding, the important factor is the value of $\mathcal{J}$, the beam pass rate of the beam current. ($\mathcal{J} = I_c/I_b$: I_b indicates the incident beam current, I_c indicates the collected beam current shown in **Fig. 3**. The influence of $\mathcal{J}$ values is shown in **Fig. 11**, and its range of efficacy is $\mathcal{J} \simeq 10 \sim 50$. When $\mathcal{J} \simeq 10$ and $f_x \sim 10$, the porosity disappeared though the under-fill still remained; but when $f_x \simeq 30 \sim 100$, the under-fill also almost totally disappeared (except for $1 \sim 2\%$). The relationship of f_x, d_x and $\mathcal{J}$ is most important.

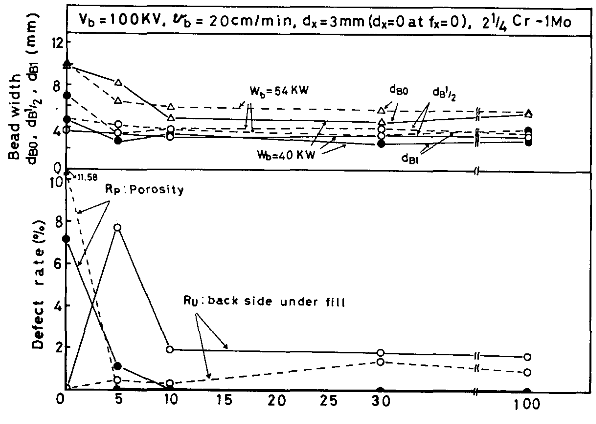


Fig. 9 Relation between bead width, defect rate and beam oscillation frequency at horizontal position welding.

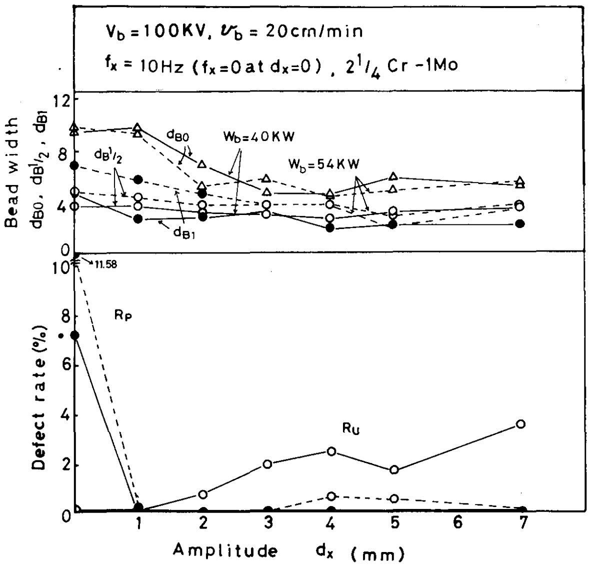


Fig. 10 Relation between bead width, defect rate and beam amplitude at horizontal position welding.

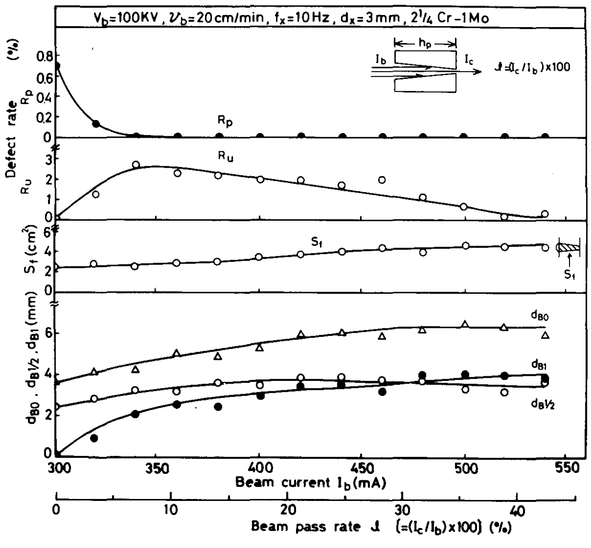


Fig. 11 Relation of Ru, R_p, S_f bead width and I_b, beam pass rate at horizontal position welding with x-oscillation beam.

The result mentioned above relates to the case where 100mm-thick plates were used. Extremely good results were obtained up to a thickness of 150 ~ 175 mm as shown in **Fig. 12**, when welding was performed under a beam condition such as $f_x = 10$, $d_x = 3$, $\mathcal{J} = 20 \sim 40$.

However, large porosities appeared when the plate thickness was increased to 200 mm. Therefore, the beam condition must be reconsidered when the plate thickness

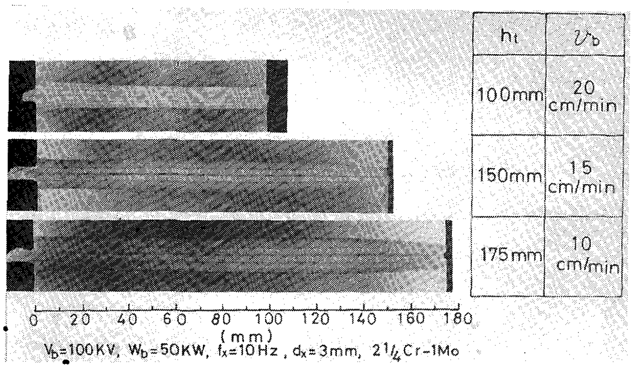


Fig. 12 Fully penetrated bead section of horizontal position welding at various plate thicknesses.

is further increased. Not only 1¼Cr - 1Mo steel, but other steels exhibited a tendency similar to the above as shown in **Fig. 13**.

It was found from the above-mentioned results that it was possible to achieve a flawlessly welded part on fairly thick plates, if the beam condition was regulated properly. There were still, however, some points that could not be solved by merely regulating the beam condition, and some problems related to the materials themselves.

The influence of the gas constituent (especially O_2 and N_2) and elements having high vapour pressure such as Mn, Si were problems common to all these materials. High tensile strength steel HT80 (see **Table 1 (A)** ~ **(L)** and **(N)**) was used, and beam conditions such as $f_x = 10$, $d_x = 3$, $\vartheta = 20 \sim 30$ and $W_b = 50$ were adopted. **Fig. 14** and **Fig. 15** illustrate the results of when the nitrogen content varied from [N] = 57 ~ 273 ppm, while the oxygen content was held almost constant [O] = 47 ~ 63 ppm.

The bead shapes appeared normal and similar in shape up to [N] $\simeq$ 100 ppm, but the bead width on the top side and the bottom side increased a little and defects appeared at around 300 ppm. This is thought to have resulted from the violent perturbation caused by the effusion of nitrogen gas.

This effect was heightened as plate thickness increased and the same defect appeared when the plate thickness was 175 mm, even though [N] = 100 ppm. The effect of the gas was brought about not only by the amount of [N] but also by the total gas amount of [N] + [O].

In this case, similar results appeared as in the case of [N]. **Fig. 16** and **Fig. 17** show the effects of gas when [N] + [O] = 107 ~ 389 ppm and, they show clearly that the increase in gas content and the thickening of the plate result in defects. Thus defects resulted even when the plates were quite thin, if the gas content was high.

The effect of Mn is quite obvious from **Fig. 18** though that of Si in **Fig. 19** is not so apparent. However, the effects of both may be expressed as a whole by the parameter;

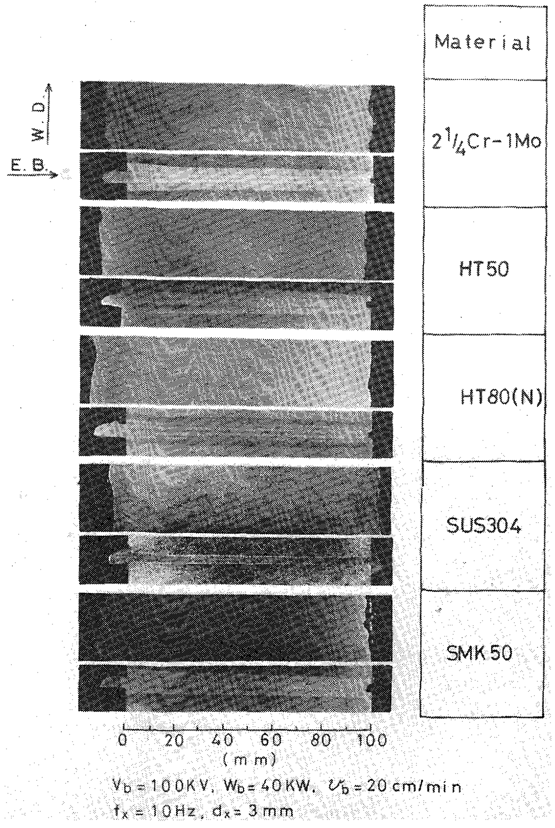


Fig. 13 Fully penetrated bead section of horizontal position welding with various metals.

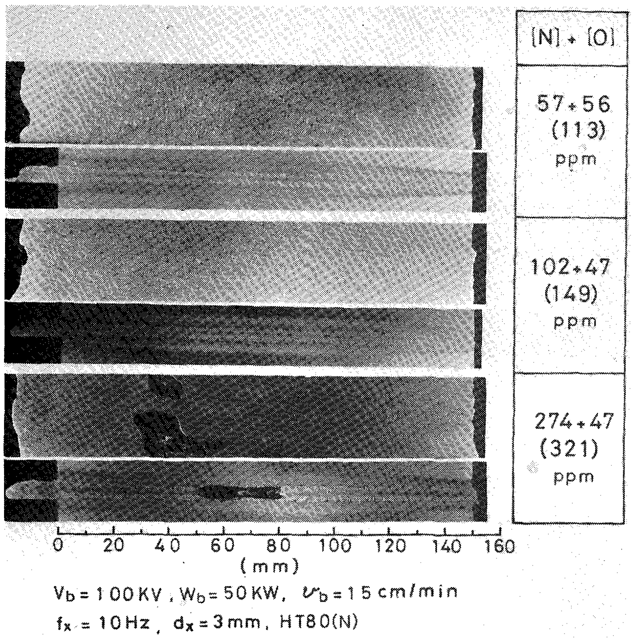


Fig. 14 Characteristics of fully penetrated bead section with variations in [N] + [O].

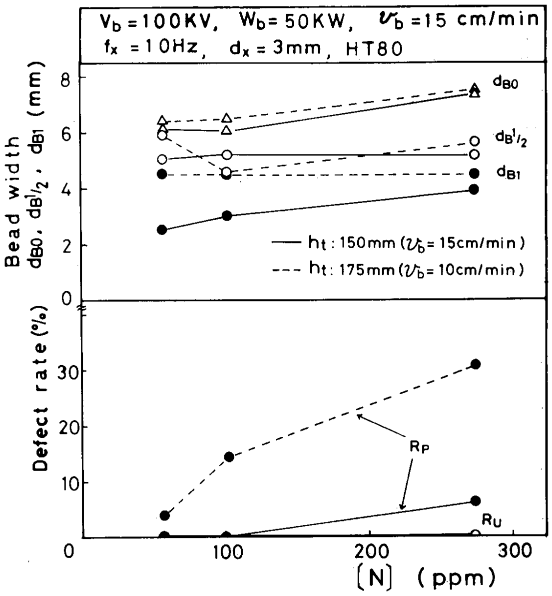


Fig. 15 Relation between bead width, defect rate and content of [N].

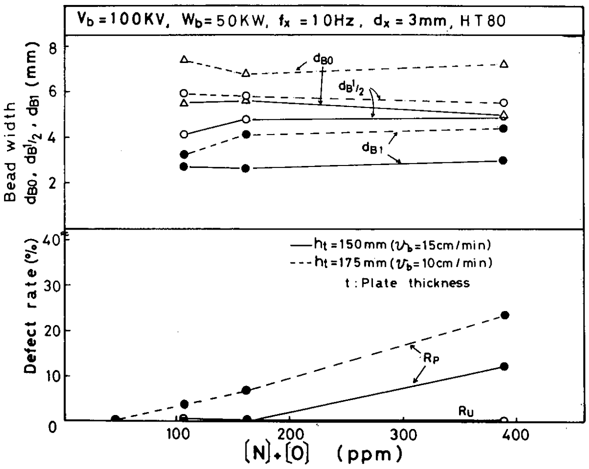


Fig. 16 Relation between bead width, defect rate and contents of [N] + [O].

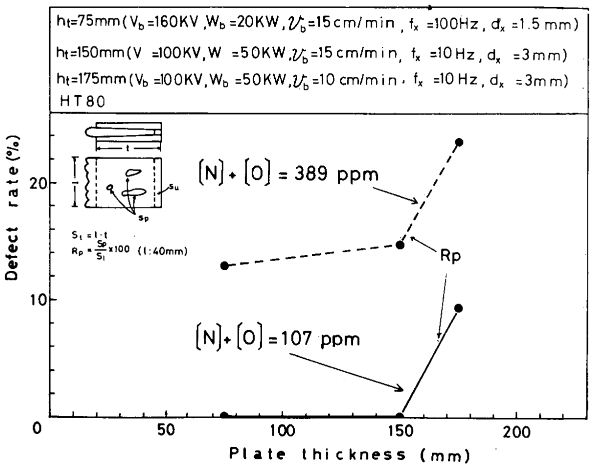


Fig. 17 Relation between defect rate and plate thickness with variation in [N] + [O].

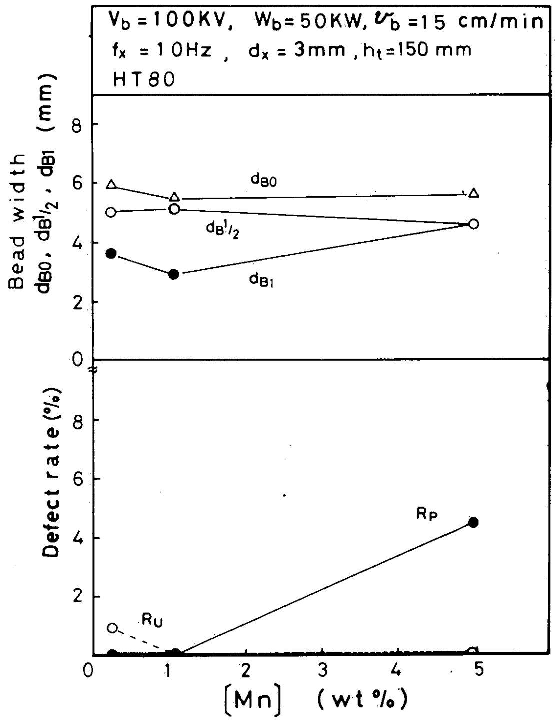


Fig. 18 Relation between bead width, defect rate and content of [Mn].

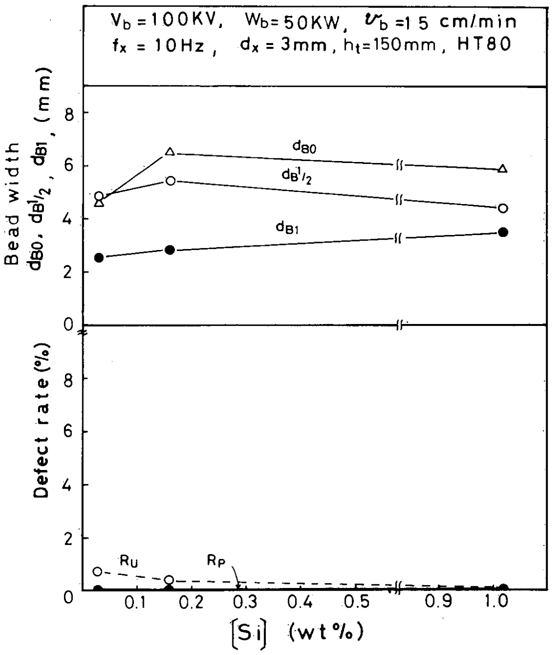


Fig. 19 Relation between bead width, defect rate and content of [Si].

$$C_R = \frac{[Si]}{[Mn][N + O]}$$

Fig. 20 shows that defects disappeared altogether at around $C_R \simeq 8$, for a plate thickness below 150 mm.

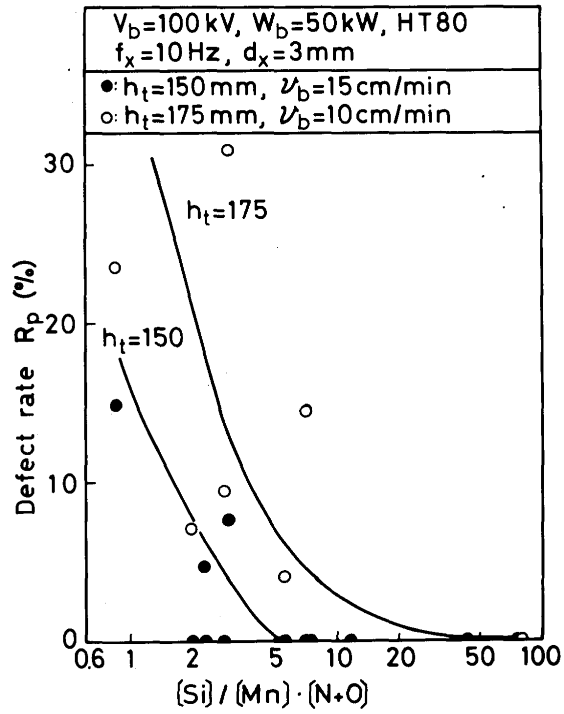


Fig. 20 Relation between defect rate [Si]/[Mn] [N+O] in steel.

The strength of welded joints is to be mentioned next. Centrifugally cast steel pipe for welded structures (SMK 50: cast while adding 50 ~ 100G) and high tensile strength steel (HT 50) show almost the same welding results, and this paper refers to the former here.

50mm-thick plates were welded under beam conditions where $W_b = 20, \mathcal{V}_b = 20$ cm/min., $f_x = 30$, $d_x = 3, \vartheta = 30$. As a result, a fracture occurred on the base metal part. The strength of the welded part was 57.9 kg/mm^2 which slightly excelled the strength of the base metal's 56.3 kg/mm^2.

In the bending test, the welded part could be bent 180° in three directions and showed no defects. The impact test was performed with the notch position at $d_{B\frac{1}{2}}$ (in the center), and the charpy was decreased at the weld bond as shown in **Table 2**. This may be improved by preheating and by using a filler metal.

The hardness is very great in the vicinity of the weld bond with a maximum hardness of $H_{max} > 300$ when the plate thickness is about 50 mm as shown in **Fig. 21**; but the hardness falls below 300 when the plate thickness is more than 100 mm due to the increase in heat input.

Table 2 Results of V-notch charpy test.

	No.	Charpy(2mmV,0°C)
Weld metal	1	5.6 kg-m
	2	22.1 kg-m
Bond	1	2.2 kg-m
	2	3.2 kg-m
HAZ.	1	10.2 kg-m
	2	9.6 kg-m

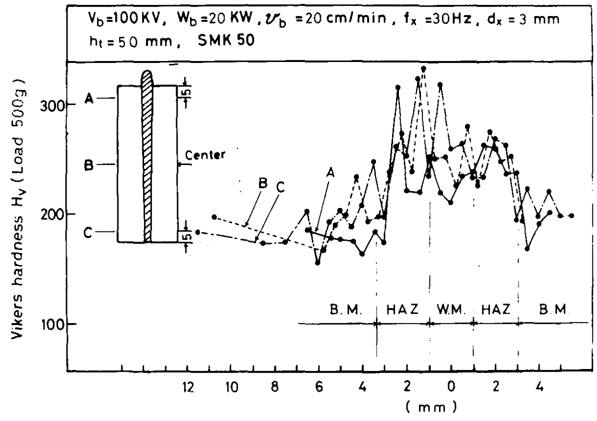


Fig. 21 Hardness curves from horizontal position welding. (50mm^t)

Even 50mm-thick plates showed hardness of $H_{max} \sim 280$, and there was hardly any dispersion of hardness when it was preheated at a temperature of around 150°C. The hardness may be lowered to that of the base metal by using a filler metal.

3.2 Vertical upward welding

Of all welding positions, vertical upward welding is most suitable for welding heavy thick plates because it is least influenced by the molten pool. Welding was performed according to this method in this instance.

Fig. 22 shows photographs of bead cross sections of vertival upward welding performed on plates of various thicknesses of high tensile steel HT80 (N) using an A type welder.

This welding method has the great advantage of producing high-grade beads whose penetration depth becomes greater in proportion to the power. **Fig. 23** shows the effect of beam currents on the bead width and

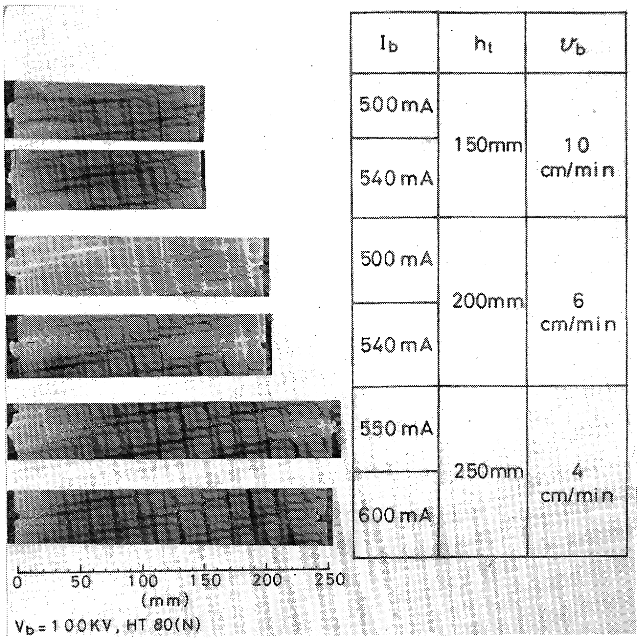


Fig. 22 Bead sections of vertical upward position welding with various plate thicknesses.

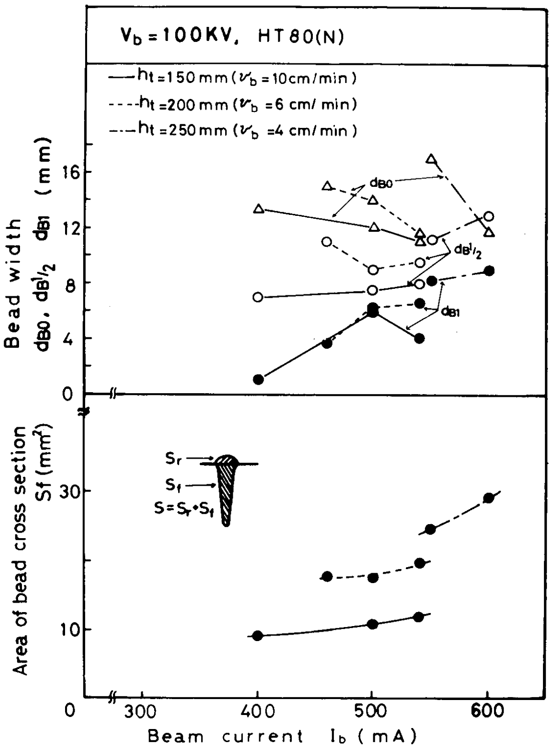


Fig. 23 Relation between bead width, melting area of weld bead and beam current at vertical upward position welding.

on the cross section area of beads produced on various plate thicknesses. It was found that a uniform crossectional bead width (called a band bead) could be obtained all along the area even when using heavy thick plates, when a suitable beam condition was provided.

Fig. 24 and **Fig. 25** show the effects a chemical composition has on these bead shapes, and they indicate that the effect is negligible.

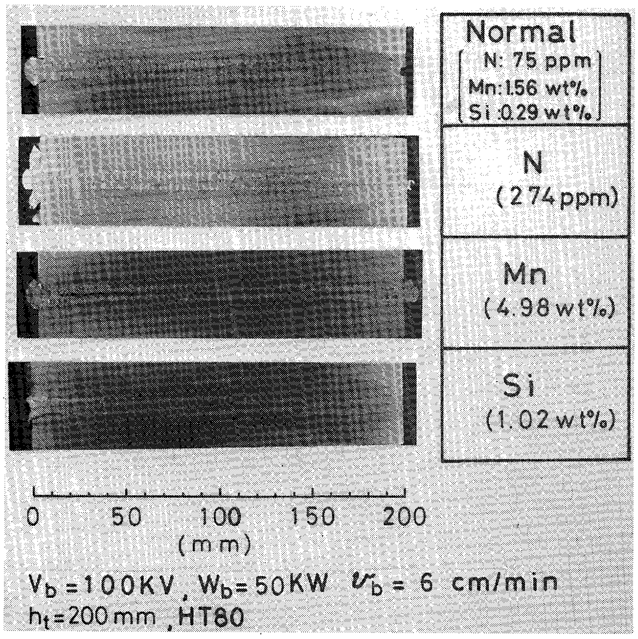


Fig. 24 Bead sections of vertical upward position welding with verious element contents.

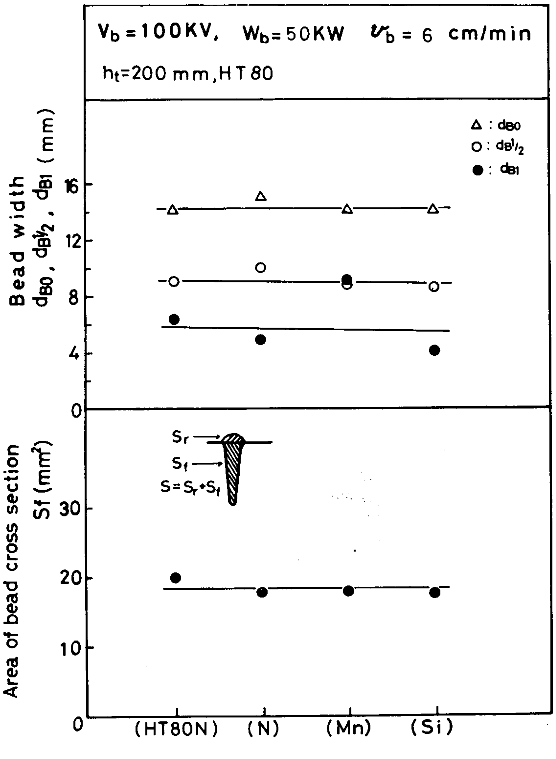


Fig. 25 Relation between bead width, melting area of weld bead and changing of elements in steels at vertical upward position welding.

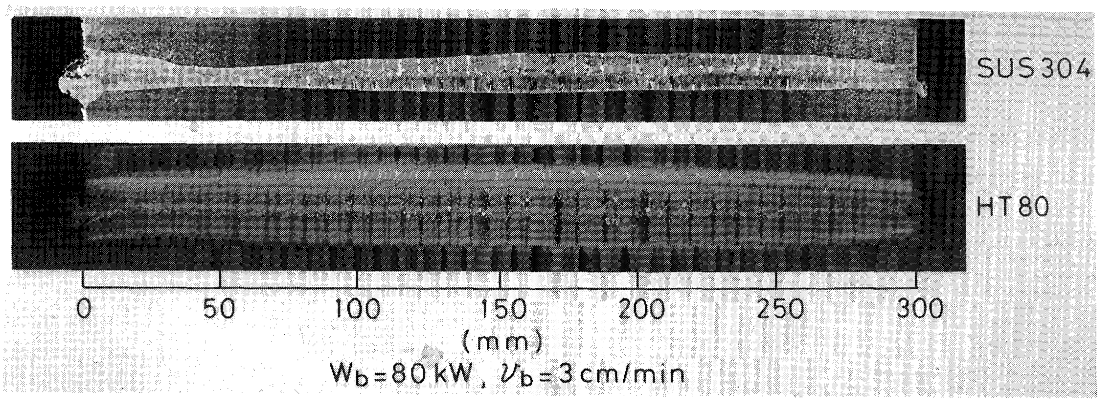


Fig. 26 Bead sections of vertical upward position welding.

N, Mn, Si were chosen as the chemical components. HT80 (C), HT80 (I) and HT80 (L) in **Table 1**, which contain the largest amount of the respective components, and ordinary HT80 (N) were used and compared. It was proved that these chemical compositions had little effect on bead shape. Only HT80 (I), however, which contains Mn 4.98%, caused a slender shrinkage due to lack of liquid metal caused by the over-flowing of molten metal on account of high vapour pressure. HT80 (C), which contains a large quantity of N, showed no defects in vertical upward welding and no difference compared with ordinary HT80 (N) was detectable, but defects appeared in the case of horizontal welding.

Fig. 26 shows the results obtained by welding 300 mm-thick HT80 (N), SUS 304 plates at W_b = 80kW, $\mathcal{V}_b$ = 3cm/min.

It may be induced from the above results that the fundamental condition for obtaining a high-grade bead with thick plates is to set up a beam condition which satisfies the above-mentioned A condition, thus devising a way to obtain a narrow band bead.

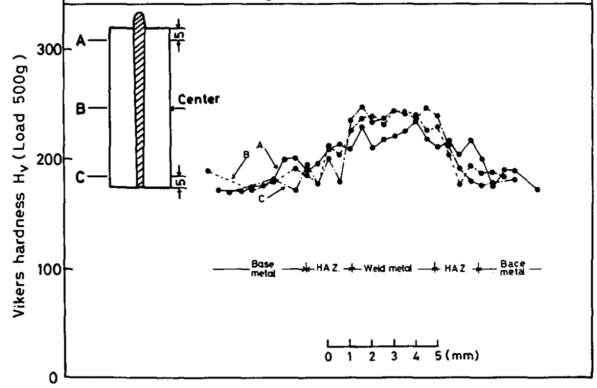


Fig. 27 Hardness curves of vertical upward position welding without X-oscillation.

Vertical upward welding, compared with all other welding positions, not only satisfies this condition the best, but also shows a lower maximum hardness (Hmax) at the welded part as seen in **Fig. 27** than the others and little dispersion. Furthermore, these values are not changed by oscillation.

4. Conclusion

1. A horizontal beam was produced by 90°-deflection of a 100kW class vertical electron beam. By using this beam an effeicient horizontal and vertical welding was performed successfully for a plate thickness of more than 100 mm.
2. A horizontal welding without any defects was possible with a low frequency (10-100 Hz) beam oscillation method in X-direction. The proper beam pass rate ranged 10-50% (for a plate thickness of more than 100 mm).
3. When the gas compositions of [N] and [N] + [O] were both below 100 ppm, a sound weld was obtained. Some defects appeared when [Mn] was commingled more than several percentages.
4. For a plate thickness below 150 mm, no defect was observed at around 8 of the composition parameter C_R as show in **Fig. 12**.
5. In case of a vertical welding at W_b = 80 kW, a full penetration welding of a plate of 300 mm in thickness was possible with a penetration depth two times deeper than in the case of a vertical welding.

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