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Tandem Electron Beam Welding (Report-I)†

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Abstract

In case of high speed welding, by using the conventional single electron beam welding method it was seen that the formation of irregular bead such as undercutting and humping is occurred under the condition that the flow of molten metal is restricted in narrow channels formed in central region of the pool cavity walls because the solidified wall had been produced on the top and bottom parts of lateral walls in the pool cavity during welding, simultaneously the pool cavity length becomes very long.

By the development and use of the TEB-welding method, we have proved the possibility of preventing the irregular bead formation, and it was clarified that the pool cavity length becomes short, while the flow of molten metal behind the pool cavity is dammed up by a new beam hole, and this flow direction of molten metal is changed toward the lateral walls associated with the solidified wall, there the molten metal is deposited on this solidified wall, and consequently the flow path of molten metal is broaden out and sound bead can be obtained even at high welding speed of 10 m/min where irregular beads appear by using the single electron beam welding method.

1. Introduction

Electron beam welding method, as is well known, has many superior characteristics such as producing a high quality and high efficiency in the welded part. And in recent years, it has been desired, still more, to increase the welding speed to reduce the welding time in production industry. High welding speed, however, introduces a serious problem of the occurrence of irregular weld bead formation such as humping and undercutting. This formation of irregular beads limits the welding speed to an economically undesirable value.

In arc welding, it has been seen that the appearance of these irregular beads is associated with the flow patterns of molten metal behind the arc[1),2)]. In electron beam welding, little investigation[3),4)] has been done with respect to the formation of these irregular beads at high welding speed, so that there is no reliable technique to prevent the occurrence of these irregular beads.

The aim of this work is to observe the formation phenomena of these irregular weld beads in detail by investigating the configuration of irregular bead formed by the electron beam in high welding speed, and to prove the possiblity of preventing the occurrence of these irregular beads by the use of the TANDEM ELECTRON BEAM WELDING method. There, the term of the "TANDEM ELECTRON BEAM WELDING" is named after that the dual electron beam is utilized in tandem and we call this, "TEB-welding"[5)] as a short name.

2. Experimental apparatus and procedure

A schematic diagram of the TEB-WELDER is shown in **Fig. 1.** Two streams of electron beam are produced by Gun-1 and Gun-2, both of them are settled compactly and EB-1 is perpendicularly applied to the surface of a specimen, while EB-2 is controlled to applied on the proper position of a specimen surface using the beam deflector.

EB-1 is used as a heat source to melt the specimen with full-penetration, and EB-2 is used to control the flow condition of molten metal. Here, the distance L_b as shown in figure, between the location of EB-1 and EB-2 on the surface of a specimen is named-for "TANDEM gap", and EB-1 is called the "leading" electron beam and EB-2 is called the "trailing" electron beam with respect to the welding direction respectively.

Each power of these beams is 6 KW max. (60 KV, 100 mA max.), and total power is 12 KW max.. Besides, its beam power is arbiturarily selected by

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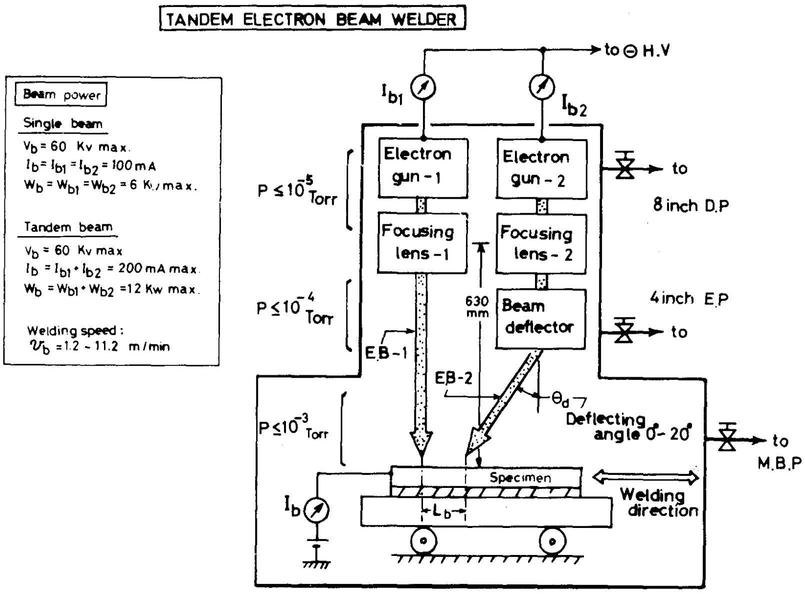

Fig. 1 Schematic diagram of TANDEM ELECTRON BEAM WELDING apparatus.

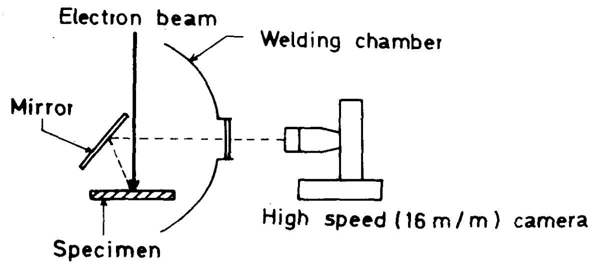

Fig. 2 Observation of flow condtion of molten metal during welding by use of High-Speed Camera with turnning mirror.

changing the beam current of each gun independently under the constant beam voltage.

Welding speed of this apparatus is in the range of 1.2~11.2 m/min, and all of experiments in this work were carried out in bead-on-plate welding. Specimen used is austenitic stainless steel, and chemical compositions of specimen are shown in **Table 1,** and size of specimen is 300 mm in length, 80 mm in width, and 1.2 and 2.0 mm in thickness.

The flow condition of molten metal was observed using by the high-speed camera with turnning mirror arranged as shown in **Fig. 2.**

3. Single electron beam welding

—Characteristics of irregular bead formation—

The crater-cavities near the molten puddle in the case of the conventional single electron beam welding are shown in **Photo. 1.** Both typical high-speed photographs and its schematic figures during welding are shown in **Photo. 2** and **Fig. 3** respectively. As shown in them, here we named a hole behind the impinging electron beam, "pool cavity" and its length, "pool cavity length L_c" and we call the region of molten metal behind this pool cavity, "main molten pool".

At a low welding speed of 3 m/min the shape of weld bead is sound, at a high welding speed of 6 m/min humping bead appears and this is a irregular weld bead. Moreover it is clear that the cavity length

Table 1 Chemical compositions of specimen used

SUS 304 Wt(%)	C	Si	Mn	P	S	Fe	Ni	Cr
1.2 mmt.	0.078	0.66	0.99	0.025	0.007	Bal.	8.66	18.18
2.0 mmt.	0.049	0.55	1.03	0.032	0.009	Bal.	9.19	18.30

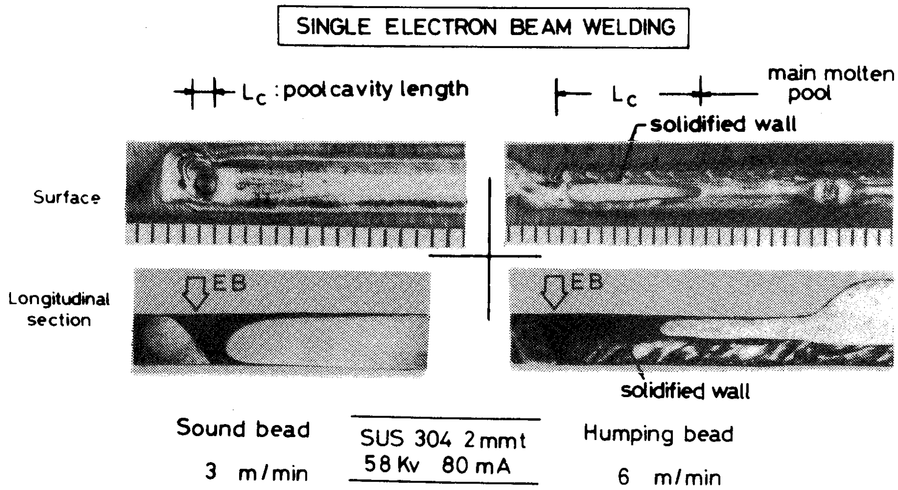

Photo. 1 Shapes of weld beads near the molten puddle using by convention single electron beam welding method with low and high welding speed.

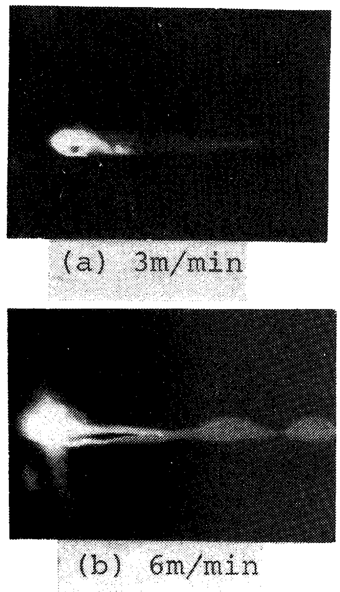

Photo. 2 (a) (b) Typical High-speed photograph during conventional single electron beam welding method. 58 kV-80 mA SUS 304 2 mmt (a) 3m/min, (b) 6 m/min.

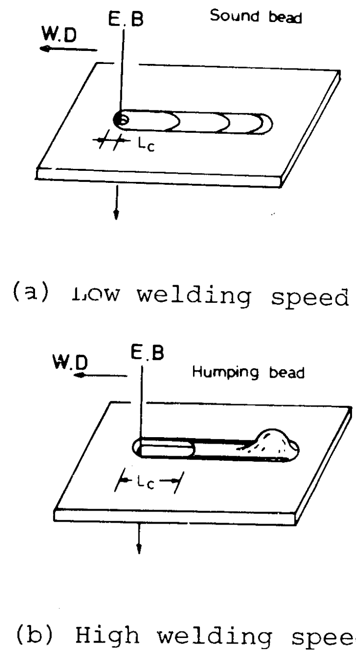

Fig. 3 (a), (b) Schematic figure of conventional single electron beam welding during welding.

L_c in the case of humping bead is longer compared with the case of sound bead since the main molten pool of humping bead goes backwards remarkably with respect to the welding direction.

While, on the photograph of the longitudinal section of humping bead it is seen that a broad solidified wall* as shown in **Photo. 2,** had been existed during welding, on the top and bottom parts of lateral walls in the pool cavity but we can find no solidified wall in sound bead. The formation process of this solidified wall along both lateral walls on each cross-section of humping weld bead is shown in **Photo. 3,** and its schematic figure is shown in **Fig. 4,** easily to realize the situation of **Photo. 3.**

Molten metal which flows along the wall surface inside the pool cavity increases gradually as molten metal advanced from (a–1) to (a–3) as shown in **Photo. 3.** On the other hand, the scale of solidified

* Here, "solidified wall" is defined to be the region where the thin layer of molten metal solidified on the top and bottom parts of both lateral walls in the pool cavity.

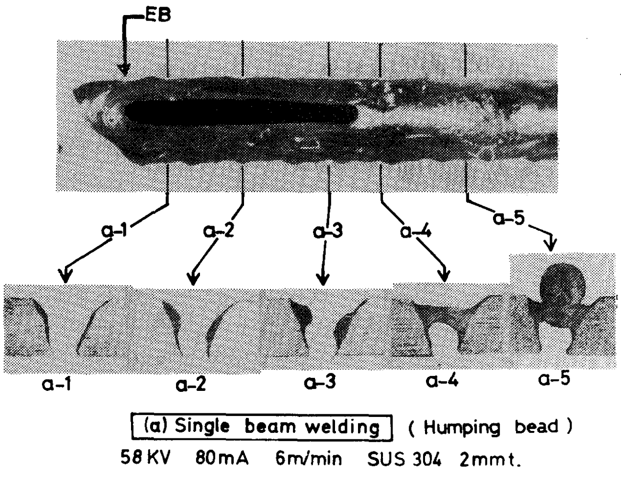

Photo. 3 Flow condition of molten metal and growing process of solidified wall along laterval walls in pool cavity of humping bead.

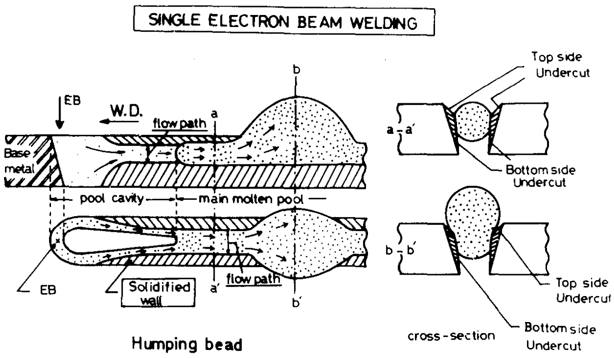

Fig. 4 Configuration of humping bead associated with broad solidified wall, narrow flow path of molten metal.

wall grows rapidly because the more molten metal goes away from the location of electron beam as a heat source and the faster molten metal is cooled. And moreover, the flow of molten metal is gathered together on the central region of pool cavity wall by the force of surface-tension of molten metal, at last these flows which exists on both lateral walls are bridged each other, there this pool cavity becomes the main molten pool.

According to these observations, it is seen that the solidified wall as shown by shadowed portion in **Fig. 4,** restricts the flow path of molten metal in narrow channels which are formed in the central region of pool cavity walls, and therefore it brings about finally undercutting in the weld bead as shown in (a–4) and a–a' cross-section of **Phto. 3** and **Fig. 4**, and its inner pressure[1] caused by the surface configuration of molten metal is higher than that of the sound bead, then as shown in (a–5) of **Photo. 3** and b–b' of **Fig. 4** the shape of weld bead consequently becomes humping.

4. Tandem electron beam welding

(a) Principle of preventing irregular weld bead formation

By the use of the TEB, we can prevent the occurrence of irregular bead formation as schematically described in **Fig. 5.** EB-1 is used as a heat source, as was stated previously, to melt the specimen with full-penetration in much the same manner as the case of the conventional single electron beam welding. Of course, using by the single electron beam welding of only EB-1 at high welding speed the irregular bead formation appears.

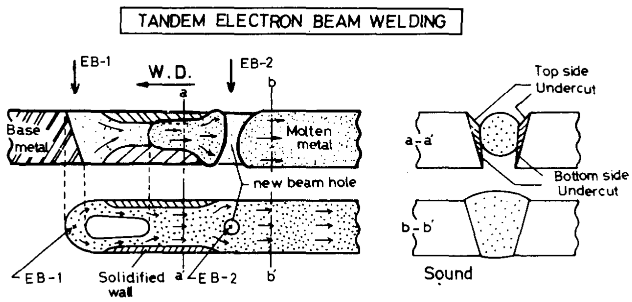

Fig. 5 Principle of preventing occurrence of irregular bead formation using by TEB-Welding method.

Then, when EB-2 of the TEB is impinged in the molten pool produced by EB-1, EB-2 generates a new beam hole as shown in **Fig. 5.** This new beam hole has a function of changing the flow direction of molten metal toward both lateral walls where the solidified wall formed by EB-1 exists, and the following phenomena arise in there; this molten metal is deposited on the surface of solidified wall which causes the irregular weld bead to occur, therefore the flow path of molten metal in the molten pool is consequently broaden out and its inner pressur is reduced compared with the case of single beam welding. In this way, the irregular bead formation can be prevented and sound bead is obtained. This is a principle of preventing the irregular bead formation at high welding speed by the use of the TEB.

(b) Important welding parameters in TANDEM ELECTRON BEAM WELDING

In the TEB-welding process, the following two welding parameters should be selected carefully in order to prevent the irregular bead formation for the purpose of controlling the flow condition of molten metal effectively in high welding speed.

(1) Location of applied trailing electron beam (EB-2) with respect to the molten pool produced by leading electron beam (EB-1).
(2) Ratio of beam power of trailing electron beam (EB-2) to that of leading electron beam (EB-1).

(1) Location of impinging EB-2

In the TEB-welding process, as shown in **Fig. 6** the location of impinging EB-2 with respect to that of EB-1 can be classified into A, B, C three regions according to the configuration of humping bead formed by the single beam welding of only EB-1.

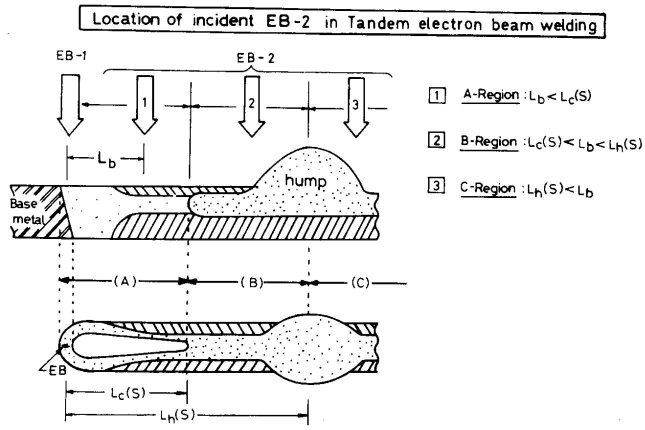

Fig. 6 Location of impinging EB-2 with respect to molten pool caused by single electron beam of only EB-1.

Here, in **Fig. 6** the location of incident EB-2 is given as the TANDEM gap L_b as was stated previously, and $L_c(S)$ is defined to be the cavity length made by the single beam welding of EB-1, $L_h(S)$ is the distance between the location of EB-1 and its hump in the single electron beam welding.

Further, $L_c(T)$ is defined to be the cavity length formed by the TEB-welding, and $L_h(T)$ is the distance between the location of impinging EB-1 of the TEB and its hump.

[1] A-Region: $L_b < L_c$ (S)

When EB-2 is applied in the hole of pool cavity formed by the single electron beam welding of only EB-1, the occurrence of irregular bead formation is not prevented and the humping phenomena only be promoted in this region as shown in **Photo. 4** and **Fig. 7** of typical high-speed photograph and its schematic figure near the molten pool, respectively. In this case the force of evaporating recoil pressure generated by EB-2 accelerates the flow rate of molten metal in the pool cavity, so EB-2 would rather make the bridging point of molten metal move toward backwards remarkably with respect to the welding direction, therefore the cavity length $L_c(T)$ is far longer than $L_c(S)$.

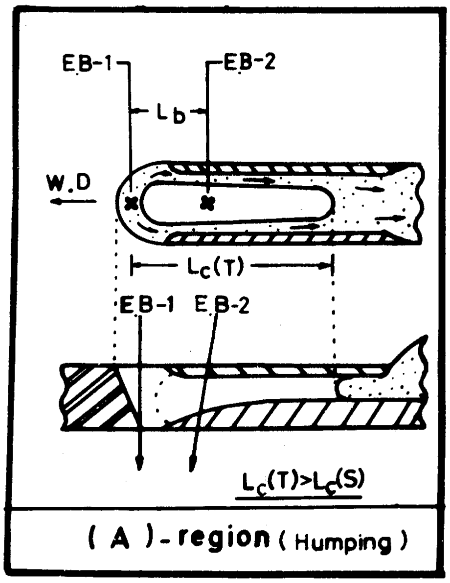

Fig. 7 Schematic figure of A-Region during TEB-Welding.

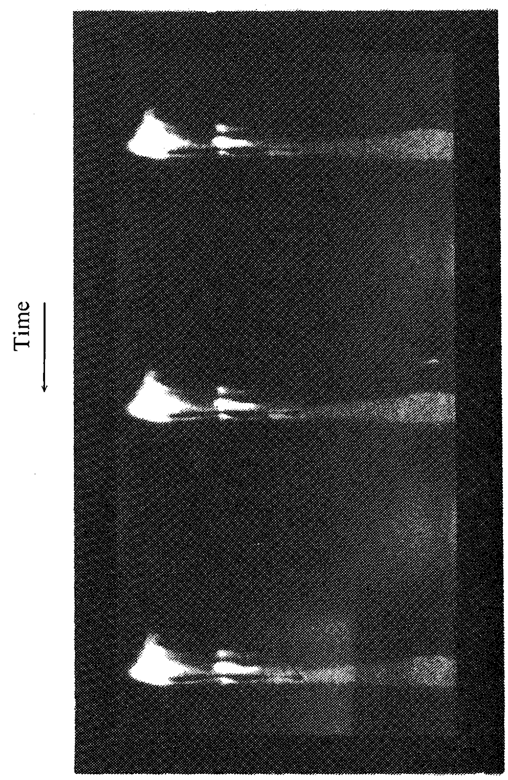

Photo. 4 Bead formation in A-Region during TEB-Welding. 58 kV-80 mA (EB-1), 58 kV-20 mA (EB-2) Lb=4mm 6 m/min SUS304 2 mmt (1800 pfs).

[2] B-Region: $L_c(S)<L_b<L_h(S)$

A typical high-speed photograph and schematic figure near the molten pool in B-Region are shown in **Photo. 5** and **Fig. 8** respectively.

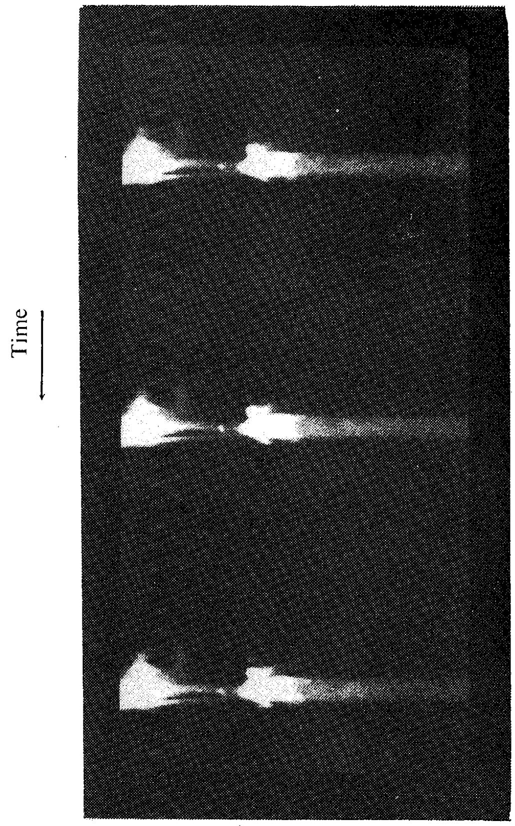

Photo. 5 Bead formation of successful preventing process in B-Region during TEB-Welding. 58 kV-80 mA (EB-1), 58 kV-20 mA (EB-2) Lb=7 mm 6 m/min SUS304 2 mmt (1800 fps).

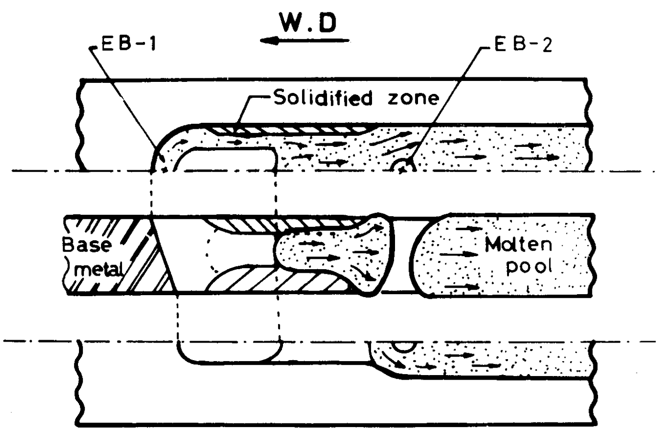

Fig. 8 Process of successful preventing iregular bead in B-Region during TEB-Welding.

When EB-2 is impinged on the surface of main molten pool between the end of pool cavity and its hump produced by the single electron beam welding of only EB-1, the shape of weld bead is sound. In this region, as the flow of molten metal caused by EB-1 is dammed up effectively by the newly generated beam hole of EB-2, the flow direction of molten metal is changed toward both lateral walls where the solidified wall produced by EB-1 exists, besides the backward movement of molten metal is restricted and this pool cavity $L_c(T)$ becomes shorter than $L_c(S)$, while the perturbation of pool cavity is decreased, and humping phenomena and any irregularity no occur in there, as shown in **Photo. 5.**

An example of sound bead produced by the proper controlling the flow of molten metal by EB-2 is shown in **Photo. 6** with each various cross sections of crater-

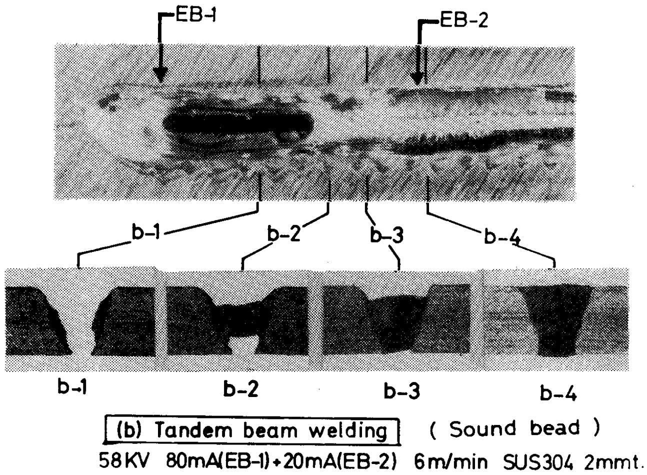

Photo. 6 Example of sound bead produced by proper controlling flow of molten metal by EB-2 in B-Region using by TEB-Welding method. Lb=7 mm.

cavity during the TEB-welding. In the lateral walls of crater cavity as shown in **Photo. 6,** the solidified wall on the cross section (b–1) and (b–2) appears with same formation process as (a–1)~(a–3) shown in **Photo. 2** of the single beam welding.

But on the cross section (b–3) in front of the location of impinging EB-2 the molten metal flows in the bottom side of bead, and behind of that of inpinging EB-2 the top side of bead is smoothly filled up with the molten metal as shown in (b–4), there a sound bead is completed without humping and undercutting. On the other hand the flow path of molten metal on (b–4) is broader compared with that on (b–2).

[3] C-Region: $L_b>L_h(S)$

A typical high-speed photograph and schematic illustration near the molten pool in C-Region are shown in **Photo. 7** and **Fig. 9.** In this case, when EB-2 is applied at a little farther than $L_h(S)$, where the molten metal formed by the single beam welding of only EB-1 is not solidified yet.

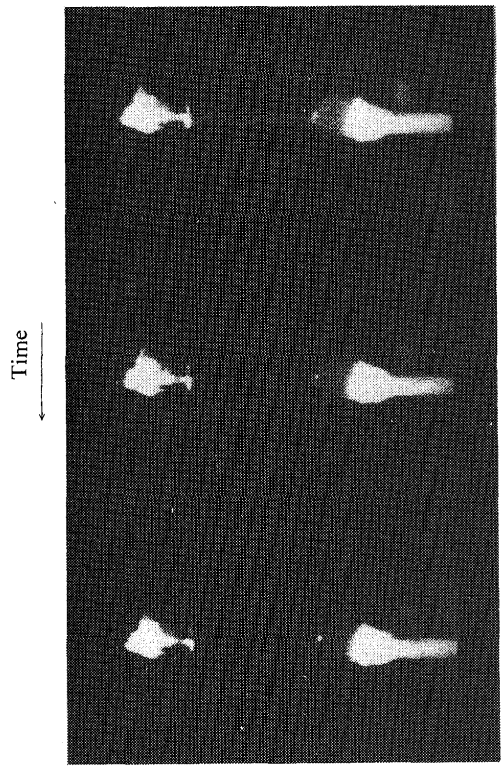

Photo. 7 "Swelling" phenomenon in C-Region during TEB-Welding. 58 kV-80 mA (EB-1), 58 kV-20 mA (EB-2) Lb=16 mm 6 m/min SUS304 2 mmt (1800 fps).

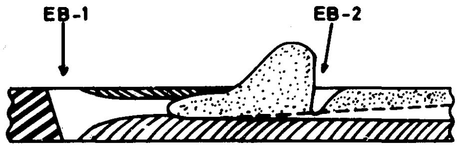

Fig. 9 Explanation of "Swelling" phenomenon peculiar to TEB-Welding in C-Region.

The solidified wall is only partially filled with the molten metal, and the cavity length $L_c(T)$ is nearly equal to $L_c(S)$ because the backward movement of main molten pool can not be obstructed.

Besides, in this region the "Swelling" phenomena appear, which causes an irregular weld bead peculiar to the TEB-welding. This "Swelling" phenomena occur as follows; the hump made by EB-1 meets the beam hole of EB-2 during this humping is moving backwards with respect to the welding direction with almost same velocity as the moving speed of specimen, and this beam hole of EB-2 restricts the movement of this hump in front of EB-2 also this hump remains with EB-2 during welding. While, when the molten metal of this hump increases gradually with time until the beam hole of EB-2 can not hold the mass motion of this hump, the hump is destroyed and simultaneously breaks away from the restriction of EB-2. This process is repeated periodically as described above and is named-for "Swelling" phenomena.

In summarization, **Photo. 8** shows typical shapes

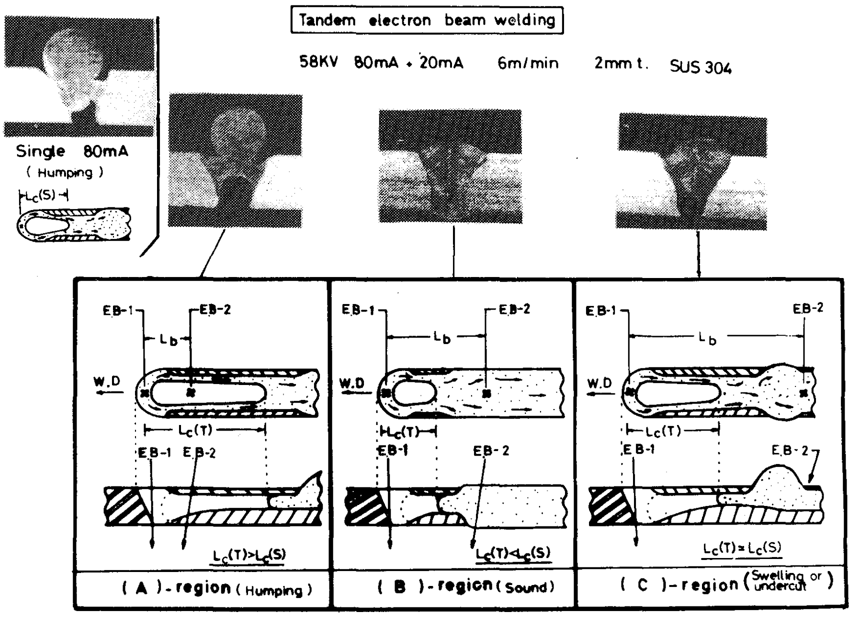

Photo. 8 Bead shapes in A, B, C-Region using by TEB-Welding.

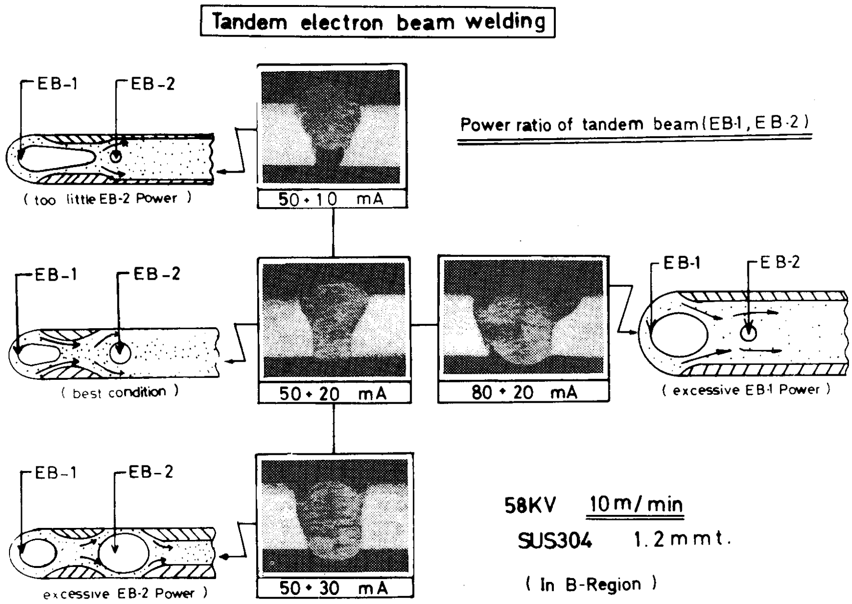

Photo. 9 Influence of power ratio of TEB on bead formation in each B-Region.

of weld beads in A, B, C-Regions by the use of the TEB-welding method.

(2) Beam power ratio of TANDEM ELECTRON BEAM

In this section, another important welding parameter, namely the beam power ratio of the TEB will be described here. In this experiment, welding speed is selected at a very high speed of 10 m/min using thinner metal plate of 1.2 mm thickness.

Their experimental results are shown in **Photo. 9** with schematic figure near the molten pool during the TEB-welding in each B-Region. In this situation, the conventional single electron beam welding, of course, only make a humping bead formation, but when the TEB is used the occurrence of irregular bead formation is prevented and sound bead can be obtained.

In this case, the best condition of beam power ratio to obtain a sound bead is 50 mA 58 KV and 20 mA 58 KV for EB-1 and EB-2 as shown in **Photo. 9.** When EB-2 power is a little low of 10 mA 58 KV than the best condition under a constant EB-1 power of 50 mA 58 KV, the solidified walls on the top and bottom parts of lateral walls produced by EB-1 are not filled up with the molten metal completely, therefore the broad undercutting remains, particularly on the bottom part of weld bead. While, when EB-2 power is a little large of 30 mA 58 KV over the best condition under a constant EB-1 power of 50 mA 58 KV, the solidified wall appears newly again on the lateral walls of bead near the location of impinging EB-2 since the diameter of beam hole of EB-2 enlarges more of the distance between both lateral walls containing the solidified wall caused by EB-1, then the shape of weld bead is irregular associating with undercutting on the top part of specimen.

Next, we change the power of EB-1 under a constant EB-2 power of 20 mA 58 KV. When EB-1 power is larger of 80 mA 58 KV than the best value of 50 mA 58 KV. Indeed, the beam hole of EB-2 can change the flow direction of molten metal formed by EB-1, but they are not enough to fill the solidified wall because the width of bead produced by EB-1 power is larger compared with the beam hole diameter of EB-2, this welding situation is similar to the case of the beam power ratio of 10 to 50 mA (58 KV) with respect to the surface of specimen, and the undercutting formation can not be prevented. As described above, the power ratio of the TEB is a very important welding parameter to prevent these irregular bead formation.

5. Conclusion

In this study, the formation phenomena of the irregular weld beads are observed by the investigating the configuration of molten pool near the pool cavity, and the new welding method for preventing the irregular bead has been developed and named, "TANDEM ELECTRON BEAM WELDING" method. Moreover, the process of preventing the occurrence of the irregular bead is investigated.

Results obtained are stated as follows;

(1) When the conventional single electron beam welding method is used for the high speed welding of a thin metal plate, the irregular beads such as humping and undercutting appear.

The irregular bead formation is occurred under the condition that the flow of molten metal along the lateral walls in the pool cavity is restricted in narrow channels which are formed in central region of pool cavity walls because the occurrence of the solidification of molten metal had existed at the top and bottom parts of these walls during welding, simultaneously the length of pool cavity becomes very longer compared with that of sound bead and the pool cavity is perturbed.

(2) When the TANDEM ELECTRON BEAM WELDING method is used, the occurrence of irregular bead formation can be prevented and sound bead is obtained without humping and undercutting even at high welding speed of 10 m/min where irregular bead formation appears by the use of the conventional single electron beam welding method.

The process of preventing the occurrence of these irregular weld beads is as follows; the flow of molten metal behind the pool cavity formed by the leading electron beam (EB-1) is dammed up by a generated beam hole of the trailing electron beam (EB-2), and the flow direction of molten metal is changed toward the both lateral walls where the solidified wall exists, there this solidified wall is filled up with the molten metal, and consequently the flow path of molten metal is broaden out and sound bead is obtained. While the length and perturbation of the pool cavity is reduced.

In practice, the important welding parameters of the TEB-welding are the location of the trailing electron beam (EB-2) impinged with respect to the configuration of molten pool caused by the leading electron beam (EB-1), and the ratio of beam power of trailing electron beam (EB-2) to that of the leading electron beam (EB-1).

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