Tandem Electron Beam Welding (Report VIII)†

— Control of Molten Metal Flow —

Michio TOMIE*, Nobuyuki ABE*, Xiang-Yu YAO and Yoshiaki ARATA*****

Abstract

The molten metal flow during single electron beam welding and Tandem Electron Beam welding with a deep penetration was observed using tungsten particle tracer and transmission X-ray method. The molten metal flow during single electron beam welding showed several local circulation rather than one circular flow within the whole pool. This flow related directly to the occurrence of defects. The molten metal flow pattern in Tandem Electron Beam welding was controlled with changing the parameters of the second beam. When the molten metal flow was controlled to be one circular flow in the pool, the defects were suppressed. By using the molten metal flow control effect, filler metal mixing were performed. Uniform mixing of filler metal was achieved up to 50 mm depth with proper Tandem Electron Beam welding conditions.

KEY WORDS : (Tandem Electron Beam) (Electron Beam Welding) (Molten Metal Flow)(Mixing of Filler Metal)

1. Introduction

Electron beam welding enables very deep penetration welding which is very difficult for conventional welding method such as arc welding. However, it is also well known that the specific welding defects caused by its high energy density sometimes occur such as active-zone porosity, root porosity and spiking. Tandem Electron Beam (TEB) welding has been researching to suppress such welding defects. The active zone porosity and the root porosity were suppressed in deep penetration welding of carbon steel[1]. A sound bead on carbon steel(SM41) plates with a penetration depth of about 75mm was obtained using a 30kW class TEB welding apparatus. The beam power in TEB welding of optimum condition required only ten percent increment of that of the single beam (the power of the second beam is only 1/10 of the first beam) in this experiment. This is a very superior result comparing with other methods such as oscillating or defocusing the beam, which decrease the penetration depth and increase the bead width extremely, although they sometimes suppress defects. In the previous report[1],we suggested that the molten metal flow of TEB welding was different from that of the single electron beam (SEB) welding,and this was the reason of suppressing the defects in TEB welding.

It has been known that the molten metal flow in the molten pool is one of the most important factors influencing the welding result. However, far less work has been conducted on the molten metal flow in electron beam welding with a deep penetration. In the previous report[2],we succeeded in the observation of the molten metal flow in the molten pool of relatively shallow depth (about 30 mm) using tungsten particles as a tracer and the transmission X-ray as visualizing method.

In this report, applying this method to deep penetration welding, the molten metal flow of SEB and TEB welding in deep penetration welding are observed. The mechanism of suppressing defects in TEB welding is revealed on a standpoint of molten metal flow pattern. It is also found that the molten metal flow is responsible for mixing of the molten metal. TEB welding has an ability to change the composition of the bead by mixing the filler metal effectively.

2. Observation of Molten Metal Flow in SEB Welding and TEB Welding

Figure 1 shows the typical bead cross sections of SEB welding and TEB welding. In the case of SEB welding, a neck appears at 1/3 depth in the bead cross section and many porosities are formed below this neck as shown in Fig. 1(a). These defects can be prevented using TEB welding. A sound bead was obtained with an addition of

† Received on October 31, 1988
* Associate Professor
** Graduate Student
*** Emeritus Professor

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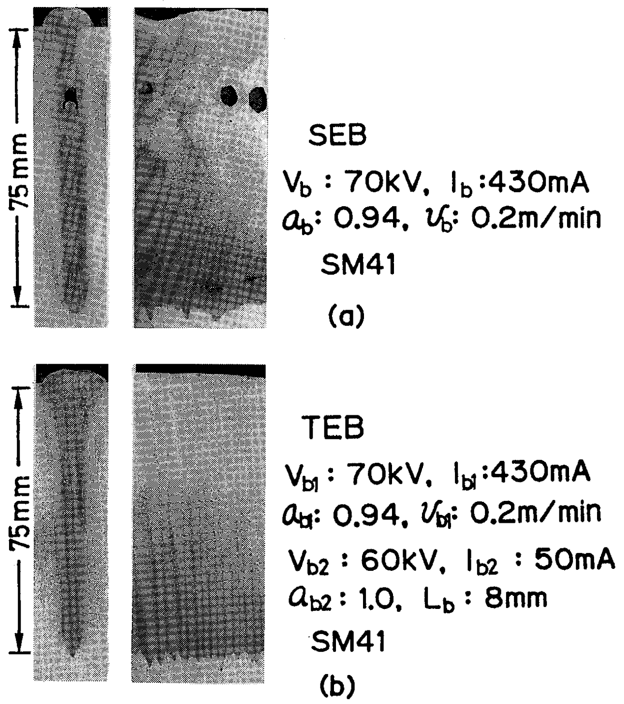

Fig. 1 Longitudinal and cross sections of bead in SEB and TEB welding
(a) SEB welding, (b) TEB welding

the second beam with a power of 3kW at Tandem Gap of 8mm as shown in Fig. 1(b).

The process of porosity formation in SEB welding was revealed using transmission X-ray method. It is found that bubbles are frequently formed at a depth of one third of the molten pool. Once it forms, it moves in the molten pool clockwise following the molten metal flow. It is trapped by the solidification surface and remained as a porosity as shown in **Fig.2**(a).

While in TEB welding, although porosities formed at the same place as SEB welding, they moves up and down very quickly. Then, they are absorbed by the beam hole of the second beam or the first beam and disappears as shown in Fig.2(b). There seems to be an different flow pattern between SEB and TEB welding.

In order to clarify the mechanism how the defects are generated in SEB welding and suppressed in TEB welding, molten metal flow was observed using tungsten particle tracer and transmission X-ray method. Filming conditions were 310kV$_p$ of X-ray tube voltage, 2mA of tube current, 200fps of film speed and 0.7 mm of Cu absorber thickness. **Figure 3** is the photos from an X-ray film showing tungsten particles' motion in the molten pool of SEB welding. After extracting the influeuce of gravity of the tracer and the beam hole fluctuation, the movement of tungsten particles is considered to indicate the molten metal flow. As seen in the photos, the molten metal flow is actually very complex and random. Many trials of tungsten particle injection were repeated in order to get an average flow pattern of the molten metal. The molten pool was divided into 2mm x 2mm small cells, and the moving direction of tungsten particles at each cell was collected in eight directions. The most frequent direction among the eight directions was determined to be the average molten metal flow direction at each cell[3]. The result is

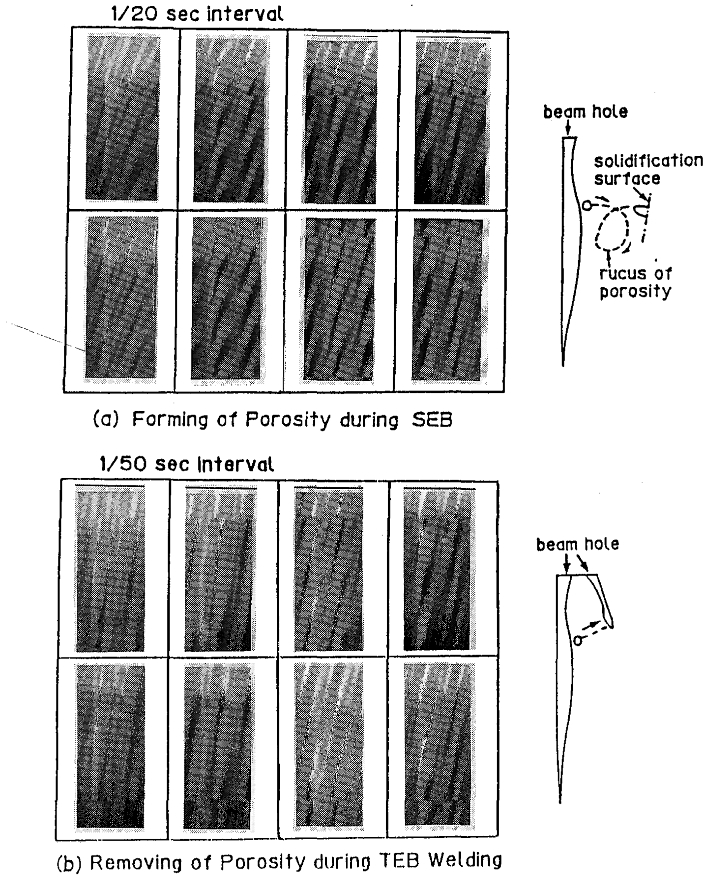

Fig. 2 X-ray photographs in SEB and TEB welding
(a) Formation of porosity in SEB welding
(b) Suppression of porosity in TEB welding

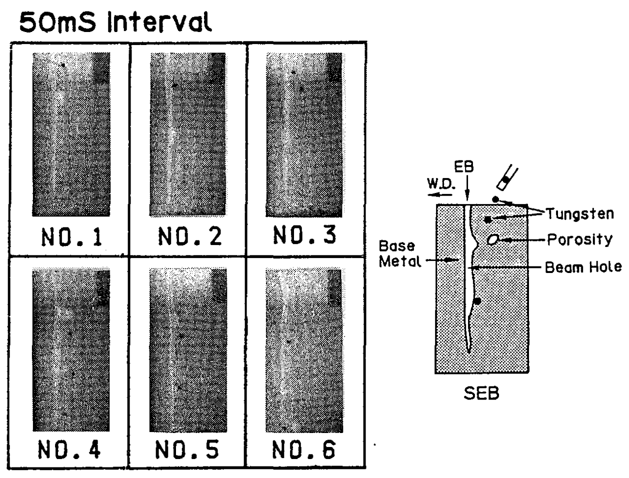

Fig. 3 Tungsten particle motion in the molten pool

shown in **Fig.4.** From this figure, it is found that the molten metal flow during SEB welding is divided into several local flows. Especially, there exists a circular flow at the middle depth of the molten pool where porosities frequently occur. On the other hand, there is no local flow at the middle depth in TEB welding. The molten pool shape becomes much different from that of SEB welding.

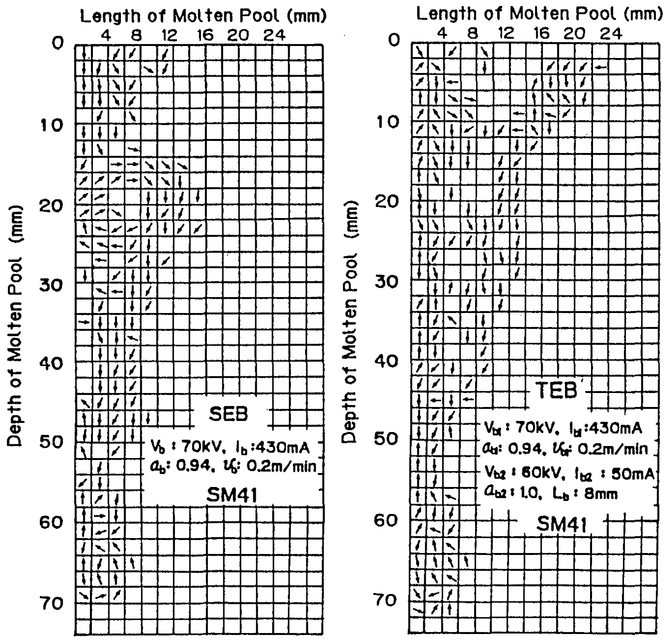

Fig. 4 Average molten metal flow pattern
(a) SEB welding, (b) TEB welding

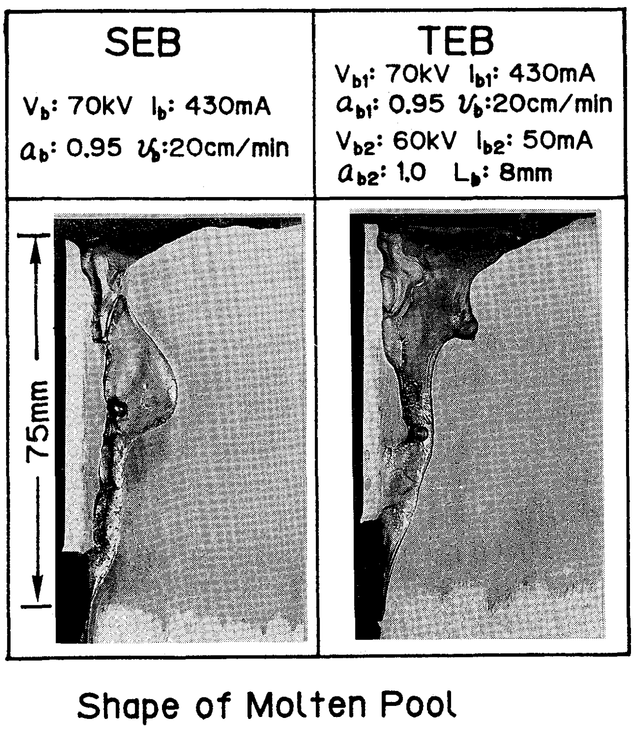

Fig. 5 Solidification wall shapes

Figure 5 shows the molten pool shapes by removing the molten metal instantaneously during welding, which have good coincidence with Fig.4. There exists a big bulge at the middle part of the pool in SEB welding, while there is no bulge and the solidification wall becomes smooth along the penetration depth in TEB welding.

Therefore, we can conclude that there is a strong circular flow at the middle depth of the pool in SEB welding, which directly related to the occurrence of the porosities. While in TEB welding, the molten metal flow can be controlled to be uniform in the pool and there is no local circular flow. This is the reason why defects are suppressed in TEB welding.

3. Mixing of Filler Metal with TEB Welding

It is difficult to mix a filler metal homogeneously by SEB welding with deep penetration. An experiment of mixing a filler wire to base metal (SM41) was performed in order to apply the molten metal flow control effect of TEB to the mixing of filler metal. **Figure 6** shows the experimental apparatus. A pure titanium wire of 1.2mm ϕ was fed toward the beam hole of the first beam at an angle of about 60 degrees at a speed of 15 cm/min. **Figure 7** shows the bead cross section of SEB welding. A lot of solidification lines appears on the medium depth of the longitudinal section of SEB weld. **Figure 8** shows the relative amount of titanium along the penetration depth, which was analyzed using EPMA, in which the titanium amount at the depth of 5mm in SEB welding is normalized to be 1.0, and the amount in base metal to be 0.0. It is obvious from Fig.8 that in SEB welding the titanium is concentrated at the upper part of the bead (above 15mm in depth), and decreased below there.

Figure 9 shows the bead cross sections when Tandem

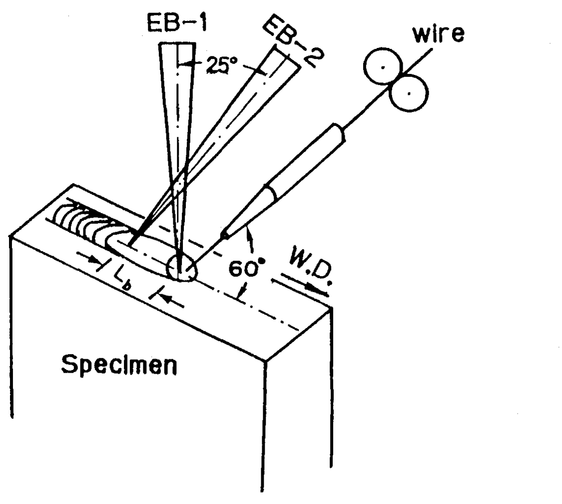

Fig. 6 Experimental apparatus for filler metal mixing

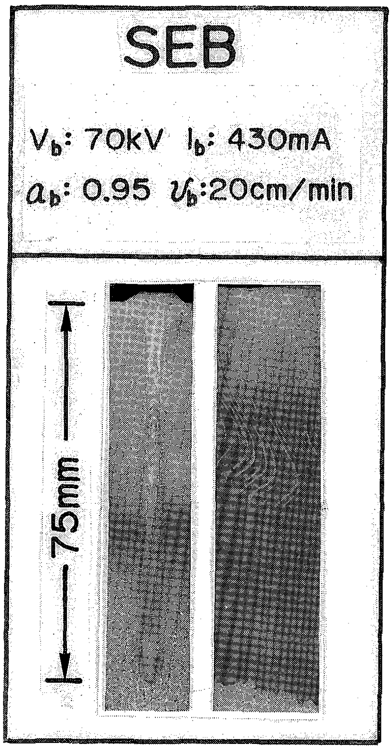

Fig. 7 Longitudinal and cross sections of SEB welding bead

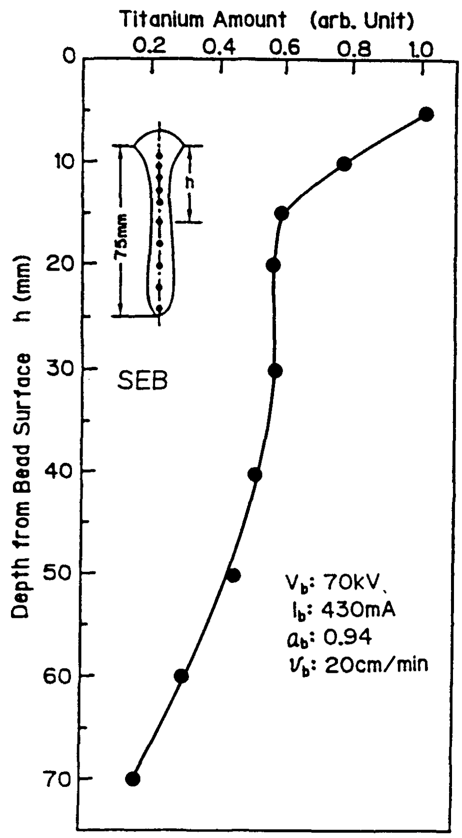

Fig. 8 Relative amount of titanium along the penetration depth in SEB welding

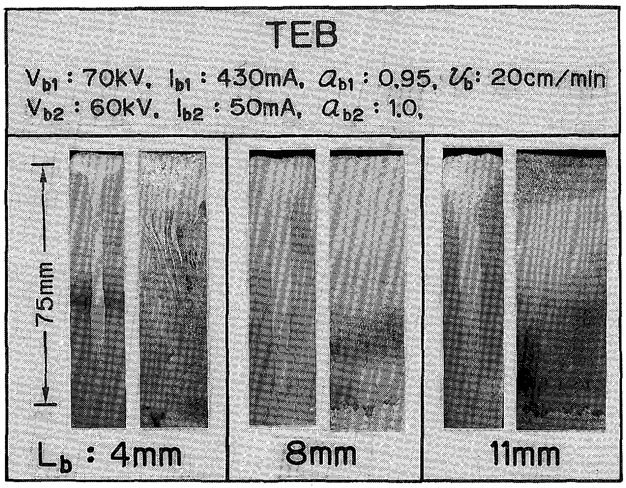

Fig. 9 Longitudinal and cross sections of TEB welding bead at various Tandem Gaps

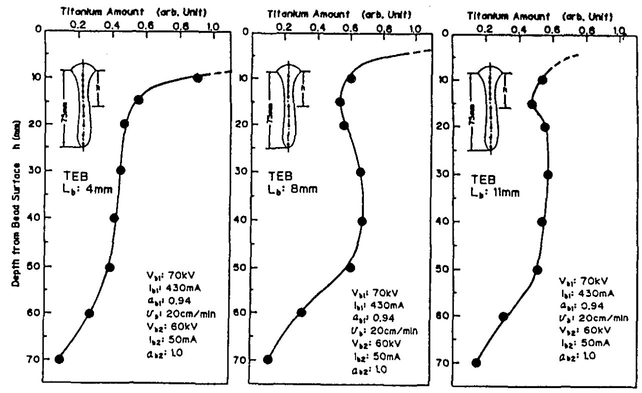

Fig. 10 Relative amount of titanium in TEB welding at various Tandem Gaps

Gap is changed from 4mm to 11mm. **Figure 10** is the relative amount of titanium along the penetration depth. It is seen that the bead cross section of Tandem Gap of 4mm shows the feature of SEB welding, and the relative amount of titanium is almost the same as that of SEB welding except the upper part of the bead where the amount of titanium is somewhat reduced. When Tandem Gap is 8mm, the relative amount of titanium along the penetration depth is almost the same up to a depth of 50mm. It is obvious that this is the effect of molten metal flow control by TEB. When Tandem Gap is 11mm, the relative amount of titanium at the upper part further reduced, but that of the middle and lower parts are nearly the same as that of 8mm gap condition. It seems that Tandem Gap is also a very important parameter in mixing phenomenon.

Figure 11 shows the bead cross sections when the beam power of the second beam is changed from 50mA to 95mA. **Figure 12** shows the relative amount of titanium along the penetration depth. The homogeneity of the filler metal mixing is almost the same at a beam current of 50mA, 80mA and 95mA of the second beam. **Figure 13** shows the comparison of the mixing patterns between SEB and TEB wedling. It is obvious that TEB welding can mix much amount of titanium to deeper part than SEB welding.

4. Conclusion

The molten metal flow during SEB welding and TEB welding with a deep penetration was observed using tungsten particle tracer and transmission X-ray method. After extracting the influence of gravity of the tracer and beam hole fluctuation, flow pattern of the molten metal was obtained. The molten metal flow during SEB welding was divided into several local flows. On the other hand, there was no local circular flow at the middle depth of the molten pool during TEB welding.

It was also found that the molten metal flow can be changed by TEB. Titanium filler metal was mixed uniformly to the depth of 50mm by proper TEB welding conditions.

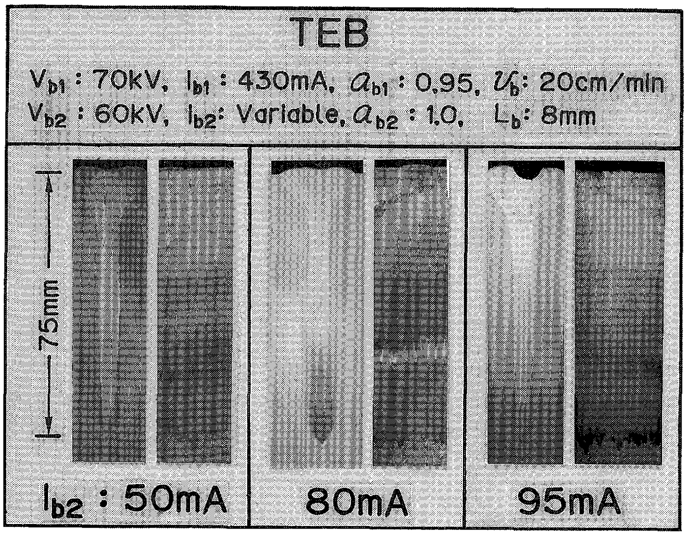

Fig. 11 Longitudinal and cross sections of TEB welding bead at various second beam powers

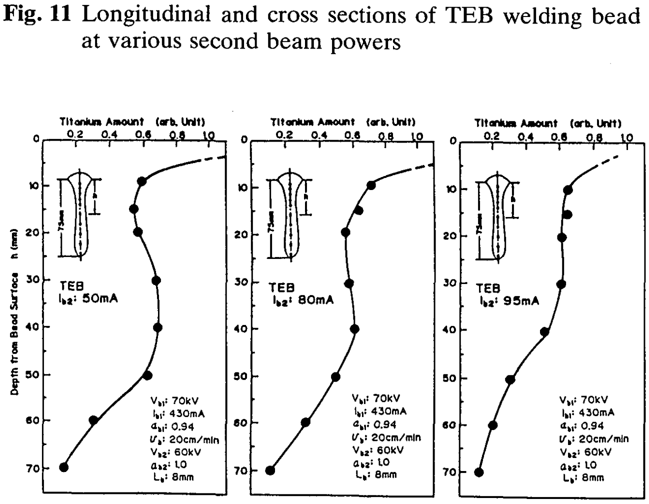

Fig. 12 Relative amount of titanium in TEB welding at various second beam powers

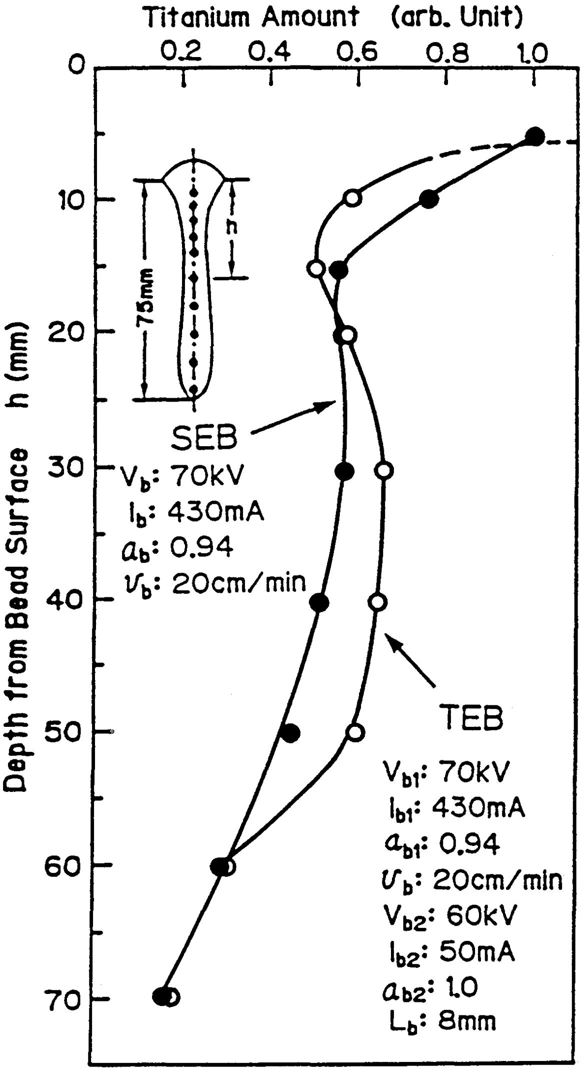

Fig. 13 Comparison of titanium amount along the penetration depth between SEB and TEB welding

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