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Tandem Electron Beam Welding (Report VI)†

– Spatterless Welding of SUS 304 –

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Abstract

A new 30 kW class Tandem Electron Beam welding apparatus was developed. Its fundamental characteristics is described. The apparatus was applied to high quality welding of thin plates. High speed welding of thin plates with spatterless and low uranami bead height was achieved.

KEY WORDS: (Tandem) (Electron Beam) (Spatterless Welding)

1. Introduction

It is well known that electron beam welding, which utilizes high energy density beam has many advantages compared with conventional heat sources. It can achieve high speed or deep penetration welding which brings very low heat input and narrow deep bead. This leads high precision welding with low distortion. Therefore, electron beam welding has been employed in the fields of, for example, nuclear reactor vessels, deep submergence explorers, space rockets and so on which are required very high reliabilities. However, this high energy density, which is the merit of electron beam welding, at the same time, is the origin of specific welding defects, for example, porosities and cold-shuts in deep penetration welding or spikings in partial penetration welding or humping and spattering in high speed welding of thin plates.

In order to suppress these welding defects, Tandem Electron Beam (TEB) welding method was developed in 1975[1]. It has achieved the suppression of humping phenomena in high speed welding[2] and suppression of spiking and root-porosity in deep penetration welding of Aluminum alloy[3].

Present report describes a new 30 kW class TEB welding apparatus which was developed for thicker plates and higher welding quality than previous 10 kW class prototype machine. This new apparatus was applied to high quality welding of thin plates, whose purpose is the reduction of uranami bead height and suppression of spattering in high speed welding. At first, spattering phenomena were analyzed. Then, Tandem Electron Beam Welding Method was applied to high quality welding based on above research. Spatterless and low uranami bead height was achieved by TEB welding even in high speed region.

2. 30 kW class Tandem Electron Beam Welding Apparatus

Figure 1 shows a new 30 kW class Tandem Electron Beam welding apparatus. It has two electron guns, one (the first electron gun) has maximum output of 30 kW (70 kV, 430 mA) and the other (the second electron gun) has 6 kW (60 kV, 100 mA). As shown in the block diagram of Fig. 2, the first gun stands perpendicularly to the specimen and the second gun inclines 25° against the first gun. Two guns are positioned along the welding direction. Each electron gun evacuated by two turbomolecular pumps (each 160 l/sec) which enable stable welding conditions of 10^{-4} Pa in the gun region at the pressure conditions of below 1 Pa in the welding chamber. Each electron beam system has two focusing lenses whose

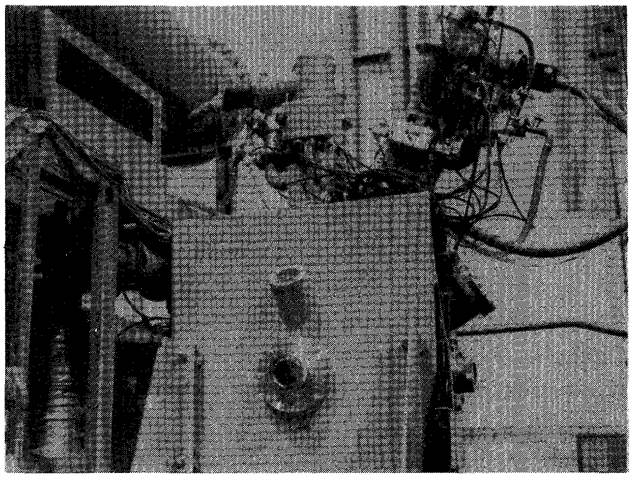

Fig. 1 A new 30 kW class Tandem Electron Beam welding apparatus.

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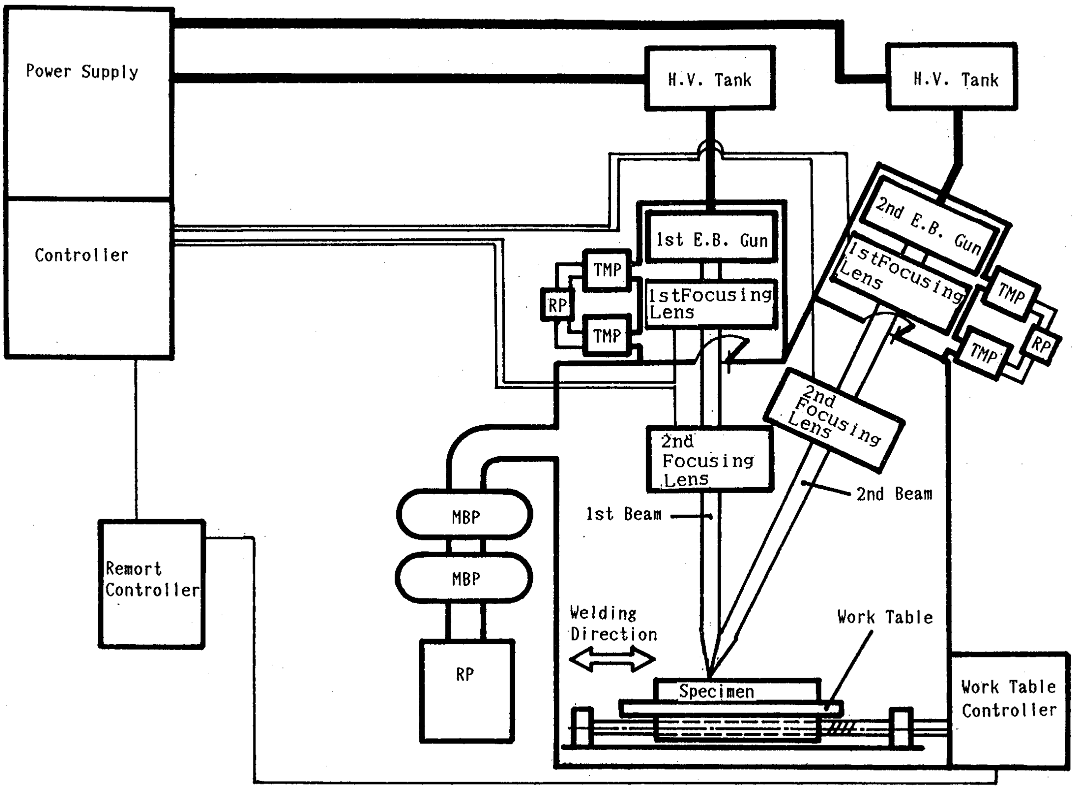


Fig. 2 Block diagram of 30 kW class Tandem Electron Beam welding apparatus.

maximum work distance is 600 mm. Usually the first electron beam (EB-1) and the second beam (EB-2) cross with crossing angle of 25° at work distance of 400 mm. This crossing point can be changed by a deflection coil just behind the second focusing lens. This deflection coil is also can oscillate the beam in very high speed, which is utilized for slit beam test or high frequency beam oscillation. A vacuum welding chamber has a volume of 0.6 m^3 (1.0 × 1.0 × 0.6 m) and eight viewing ports which enable observation of welding phenomena in all direction. It is evacuated two mechanical booster pumps (each 600 m^3 / hr) which achieve a pressure of 10^{-2} Pa. A working table inside the vacuum chamber can operate from 0.15 m/min to 7.0 m/min.

Total control system of this apparatus is shown in Fig. 2. Electron guns, focusing lenses, deflection coils and vacuum systems for electron guns are controlled on main controller. Remote controller enables coincidence control of electron beam and work table which enables high controllability.

Figure 3 shows focusing characteristics of the first and second electron beam in full power conditions measured with AB test[4] and slit method. The beam diameter of EB-1 is about 2 mm and energy density is 9.5 × 10^2 kW/cm^2. The beam diameter of EB-2 is about 0.5 mm and energy density is 7.6 × 10^2 kW/cm^2. This difference in beam diameter of two beams is caused by the difference of cathode diameter (EB-1: 4 mm, EB-2: 2 mm) and

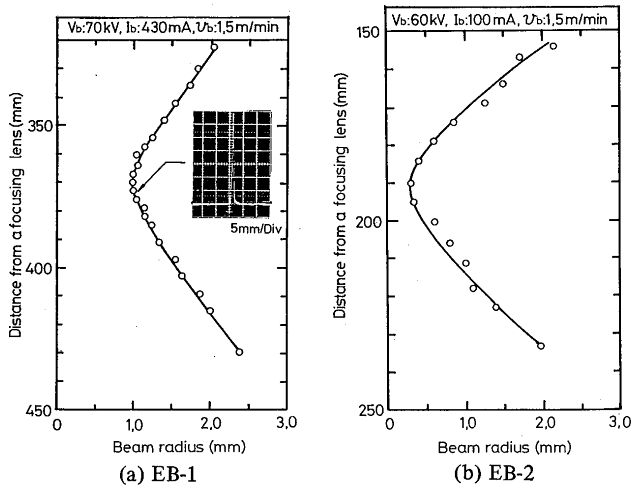


Fig. 3 Focusing characteristics of beams in full power condition.

emission current (EB-1: 430 mA, EB-2: 100 mA).

Welding characteristics of these beams are tested against popular structural steel SM-41 and stainless steel SUS 304. Chemical compositions are shown in Table 1. Dependence of penetration depth on a_b value and welding speed is shown in Fig. 4. In case of SM-41, maximum penetration depth is 43 mm at v_b = 1.0 m/min and a_b = 1.0, 55 mm at v_b = 0.6 m/min and a_b = 0.98 and 76 mm at v_b = 0.2 m/min and a_b = 0.94.

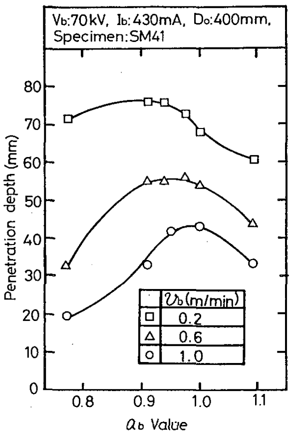
In case of SUS 304, at a_b value of about 0.94, penetration depth of 48 mm, 58 mm and 79 mm are obtained with welding speed of 1.0 m/min, 0.6 m/min and

Table 1 Chemical compositions of specimens.

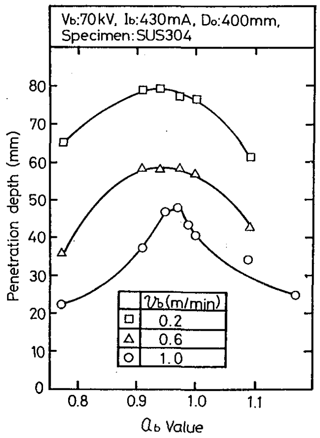
Wt (%) ← | → PPm

	C	Si	Mn	Cu	Ni	Cr	Al	Mg	Mo	Ti	Zn	Fe	P	S	N	O
SUS 304	0.05	0.74	1.74	0.12	10.9	19.5	0.015	—	0.16	—	—	Re	0.030	0.010	365	70
SM 41	0.18	0.47	0.71	—	—	—	0.050	—	—	—	—	Re	0.015	0.010	68	36

Re:remainder



(a) SM-41



(b) SUS 304

Fig. 4 Welding characteristics of EB-1.

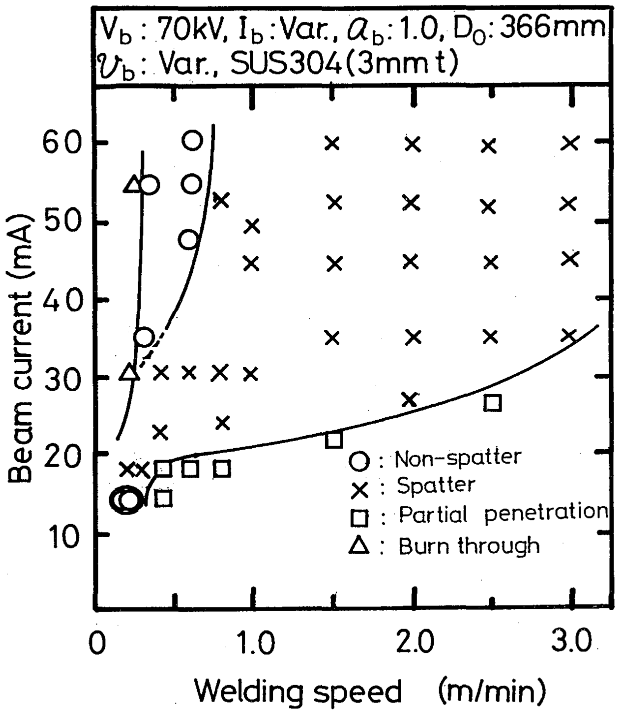


Fig. 5 Thin plates welding of single electron beam.

0.2 m/min, respectively.

3. Spattering Phenomena in High Speed Welding of Thin Plates

When electron beam is applied to high speed welding of thin plates, humping and undercut occur frequently. Furthermore, spattering occurs on the bottom of the specimen. This fails in uranami bead appearance and needs further mechanical treatment after welding. An uranami bead height is another problem in the structure which is difficult to make mechanical treatment after welding such as pipes and closed structures.

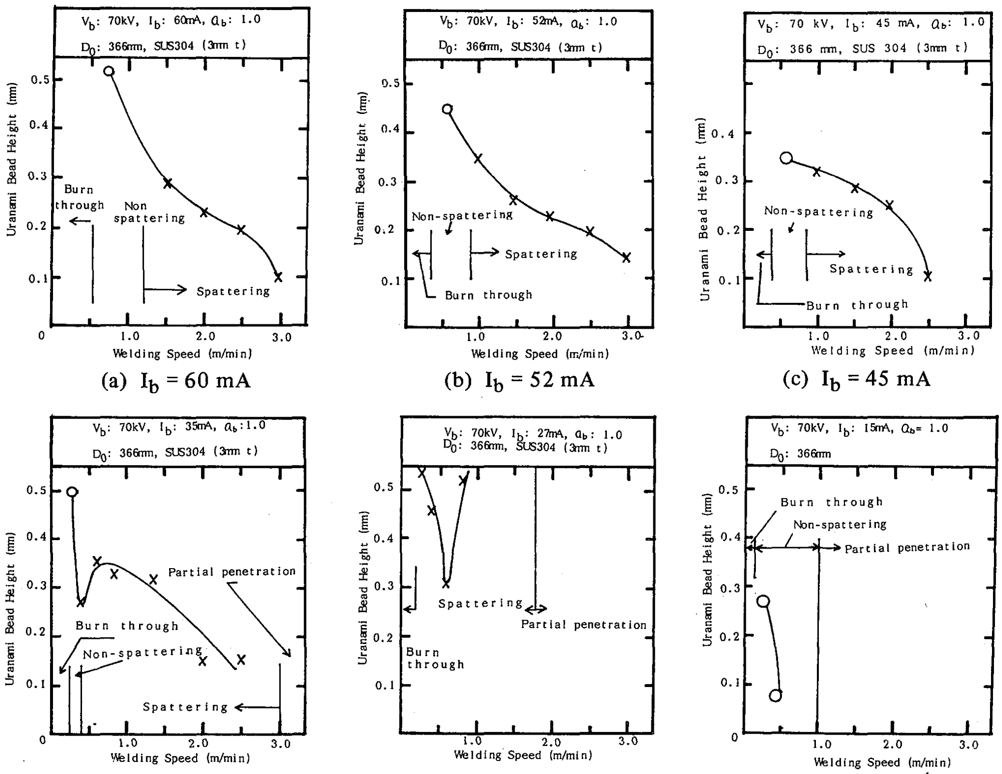
In order to suppress spattering phenomena in high speed welding and reduce uranami bead height in flat position welding, spattering phenomena were studied for single electron beam welding. Thin plates of stainless steel SUS 304 were welded on bead-on plate conditions at various beam currents and welding speeds. Beam acceleration voltage, a_b value and work distance were fixed at 70 kV, 1.0 and 366 mm, respectively. The results are shown in Fig. 5. Figure 5 shows that there are only two small regions where spattering does not occur. One is only narrow region of $v_b = 0.15$ m/min ~ 0.2 m/min and $I_b \sim 15$ mA. The other is the region of $I_b > 35$ mA and $v_b \sim 0.6$ m/min. In the region where welding speed is lower than these areas, bead burn through is occurred. On the other hand, in the region where welding speed is higher than these non-spattering areas, spattering occurs or beam cannot penetrate the plate.

Figure 6 shows the dependence of uranami bead height on welding speed against various beam currents. Over $I_b = 35$ mA, uranami bead height decrease with increasing welding speed to reach 0.1 mm. At high welding speed of nearly the limit of penetration, uranami bead height becomes very low, however, uranami bead appearance is very bad as shown in Fig. 7. At only low welding speed region, spatterless welding is achieved, however, uranami bead height is very high. On the contrast, when a beam current is 15 mA, the uranami bead height of 0.08 mm is achieved at very low welding speed.

Figure 8 summarizes these results. There are two spatterless welding zone. One is the area of low power (~ 15 mA) and low speed. The other is the area of low welding speed (~ 0.6 m/min). An uranami bead height of 0.08 mm was achieved in the former region. In the latter region, an uranami bead height of below 0.35 mm cannot be achieved. Although higher welding speed can decrease uranami bead height easily, there are always spattering and bad bead appearance.

Figure 9 shows the dependence of uranami bead height on a_b value for above two regions. Spattering is suppressed over $a_b = 1.0$, however, uranami bead height does not decrease below 0.1 mm.

Finally, in order to achieve spatterless and low uranami bead height by single electron beam welding, it is neces-



(a) I_b = 60 mA (b) I_b = 52 mA (c) I_b = 45 mA

(d) I_b = 35 mA (e) I_b = 27 mA (f) I_b = 15 mA

Fig. 6 Welding speed dependence on uranami bead height.

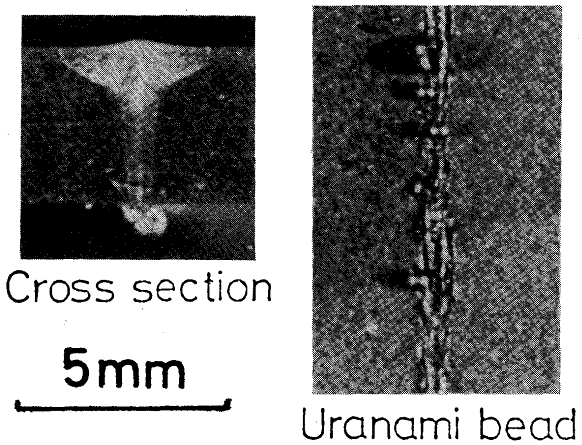


Fig. 7 Uranami bead appearance of high speed welding.

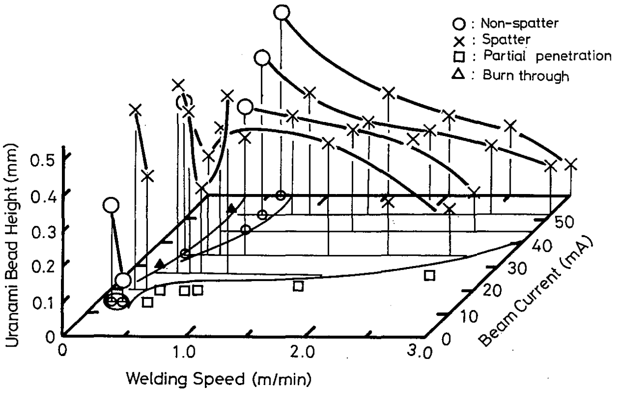


Fig. 8 Welding characteristics of single electron beam welding of thin plates.

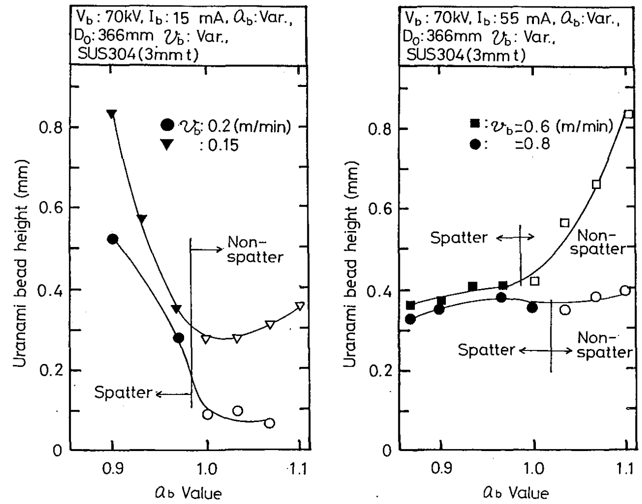


Fig. 9 a_b value dependence on uranami bead height.

sary to use low power electron beam with very low welding speed than for usual thin plates welding. These welding parameters mean that the merit of electron beam welding is spoiled.

4. Suppression of Spattering by TEB Welding Method

In order to suppress this spattering phenomena in high welding speed region, TEB welding method was applied. Because low uranami bead height is achieved at high welding speed region, it is expected that TEB welding method can suppress the spattering with stabilizing the motion of the beam hole and the molten metal.

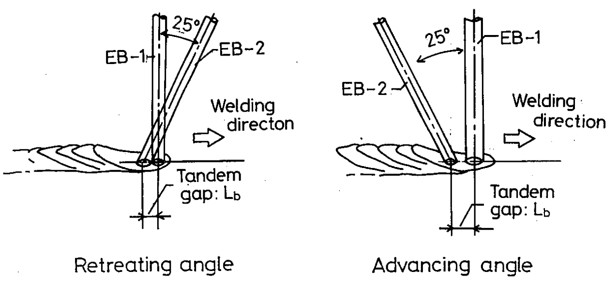


Fig. 10 Tandem configuration of two beams.

Figure 10 shows the positioning of beams against specimen in TEB welding. The distance between EB-1 and EB-2 on specimen's surface is defined as Tandem gap L_b. At first, EB-1 and EB-2 are crossed on the surface of specimen (that is, Tandem gap L_b = 0.0) and the power of the second beam and a_b value were changed. The power of the first beam was determined 30 mA and 45 mA which are the value around penetration limit at welding speed of 3 m/min, because smaller heat input decreases bead width and uranami bead height. Uranami bead height and spattering phenomena are shown in Fig. 11. Under

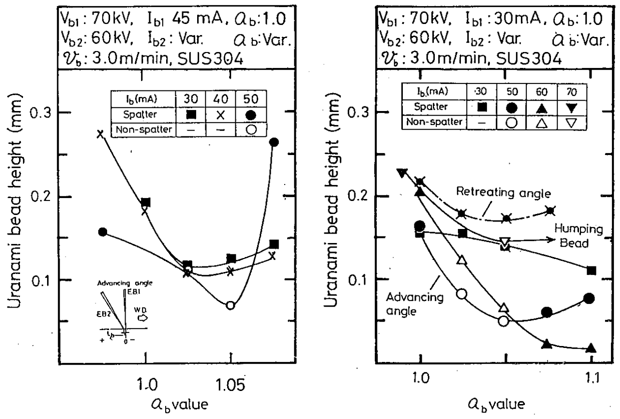


Fig. 11 Dependence of uranami bead height and spattering phenomena on a_b value and second beam current.

the conditions of I_{b1} = 45 mA, I_{b2} = 50 mA and a_b = 1.05, spattering is suppressed and uranami bead height of 0.08 mm is achieved. Furthermore, conditions of I_{b1} = 30 mA, I_{b2} = 50 mA and a_b = 1.05 achieve uranami bead height of 0.05 mm without spattering. Typical example of bead crosssection and appearance are shown in Fig. 12. Welding heat input of this conditions is 1 $\times 10^3$ J/cm, which is lower than the best condition of single electron beam welding of 2 $\times 10^3$ J/cm. Although

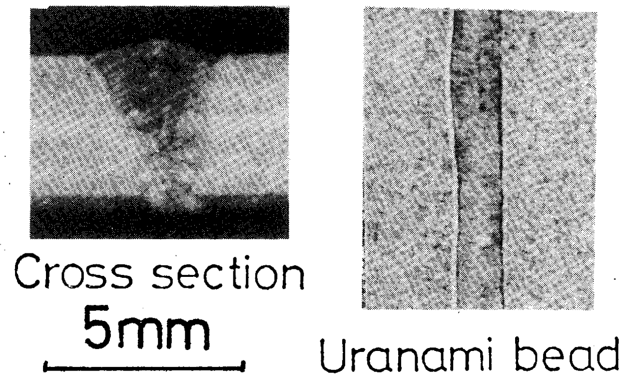


Fig. 12 Bead crosssection and appearance of TEB welding.

single electron beam can also achieve the same uranami bead height without spattering at only very low welding speed of 0.15 m/min, TEB can realize it even at a high welding speed of 3 m/min. Furthermore, the bead cross-section of TEB welding is better than single electron beam welding. Although the bead crosssection of single electron beam welding looks like that of arc welding, the bead crosssection of TEB welding shows nearly parallel bead appearance.

5. Conclusion

A new 30 kW class Tandem Electron Beam welding apparatus was developed. It was applied to high speed welding of thin plates in high welding speed. Although single electron beam can achieve low uranami bead height of 0.1 mm without spattering at very slow welding speed of 0.15 m/min, TEB welding can achieve 0.05 mm without spattering even at a high welding speed of 3 m/min. Heat input for the best condition of TEB welding is half lower than SEB welding.

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