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Characteristics of 500 kV Ultra-High Voltage Electron Beam Heat Source (Report II)†

— Deep Penetration by Flat Position Welding —

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Abstract

An ultra-high energy density electron beam with a beam power of 10–70 kW was successfully obtained using a 500 kV ultra-high voltage electron beam heat source. Application of the 500 kV ultra-high voltage electron beam to welding was then investigated and it was found that this beam enabled a penetration depth of 200 mm in flat position welding with a beam power of 60 kW, producing a narrow weld bead with high efficiency.

KEY WORDS: (Ultra-High Energy Density E.B.) (Ultra-High Voltage E.B. Heat Source) (Strongly Focused E.B.) (Multi-Stage Acceleration) (Electromagnetic Accelerating Unit) (Electron Beam Welding) (AB Test Method)

1. Introduction

Recently, researchers have been seeking a heat source which offers the possibility of higher efficiency, higher precision and improved functionality in the processing of metallic materials. One heat source which satisfies these requirements is a high energy density electron beam.

At the Heat Sourec Center of WRI of Osaka Univ., the authors have been developing electron beam heat sources and investigating their characteristics with regard to heat processing[1]. Through both theoretical and empirical studies, it has been found that the effect of the accelerating voltage of an electron beam is closely related to the energy density and penetration depth. In an earlier report, the authors showed that the penetration depth varies relative to the 1. 3rd power of the beam accelerating voltage, and that a high voltage type electron beam is very useful for deep penetration welding[2]. However, the beam voltage of conventional electron beam welders is limited to below 200 kV because they have only single stage acceleration and the accelerating voltage cannot be increased due to arcing phenomena. In order to overcome this restriction and to greatly increase the beam voltage, the authors developed an ultra-high voltage electron gun with a multi-stage accelerating unit. On the basis of these results, the authors designed and manufactured "500 kV ultra-high voltage electron beam heat source", the first in the world in order to generate a strongly focused ultra-high energy density electron beam[3].

In this report, the apparatus, its beam characteristics, and its deep penetration characteristics for welding application are described.

2. 500 kV Ultra-High Voltage Electron Beam Heat Source

A schematic diagram of the 500 kV ultra-high voltage electron beam heat source is shown in **Fig. 1**. It has an 11-stage accelerating type electron gun consisting of 11 electromagnetic accelerating units in series. One hundred kV is applied to the first accelerating unit and 40 kV is applied to the 2nd to 11th units. The total accelerating voltage is 500 kV. It was possible to regulate the voltage of the electron beam to within $\pm 0.5\%$ during acceleration. The first stage unit has a 2×2 mm or 2.5×2.5 mm directly heated tungsten cathode. In order to accelerate and focus the electron beam effectively, the second stage accelerating unit was equipped with an alignment coil and a focusing coil in the welding chamber.

Figure 2 shows the electron gun with the 11-stage electromagnetic accelerating unit. The electron gun is 2.5 m long and 45 cm in diameter. An 11-stage dummy resistance of 12.5 Mega ohms with 500 kV of insulation stands parallel to the electron gun. This dummy is connected in parallel with each of the elec-

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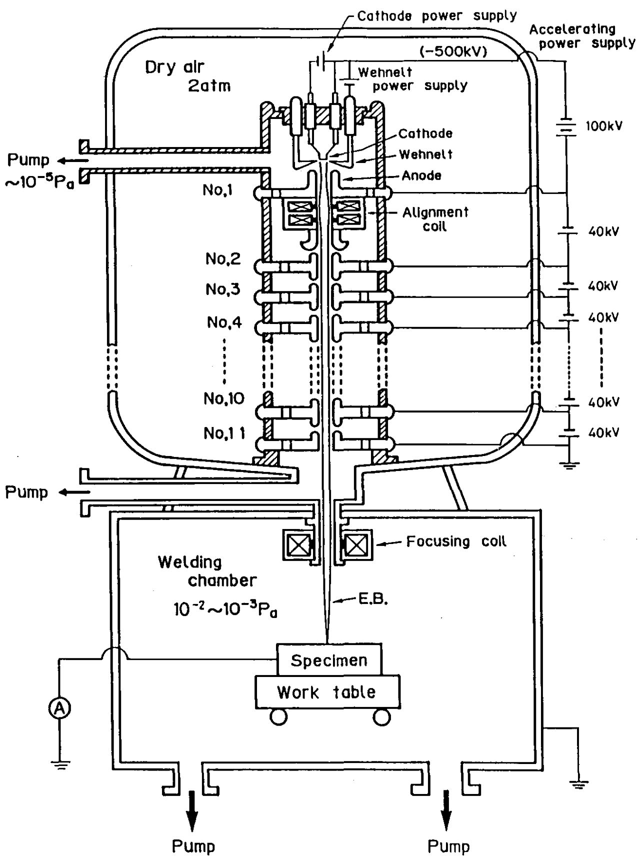

Fig. 1 Schematic diagram of the 500 kV ultra-high voltage electron beam heat source.

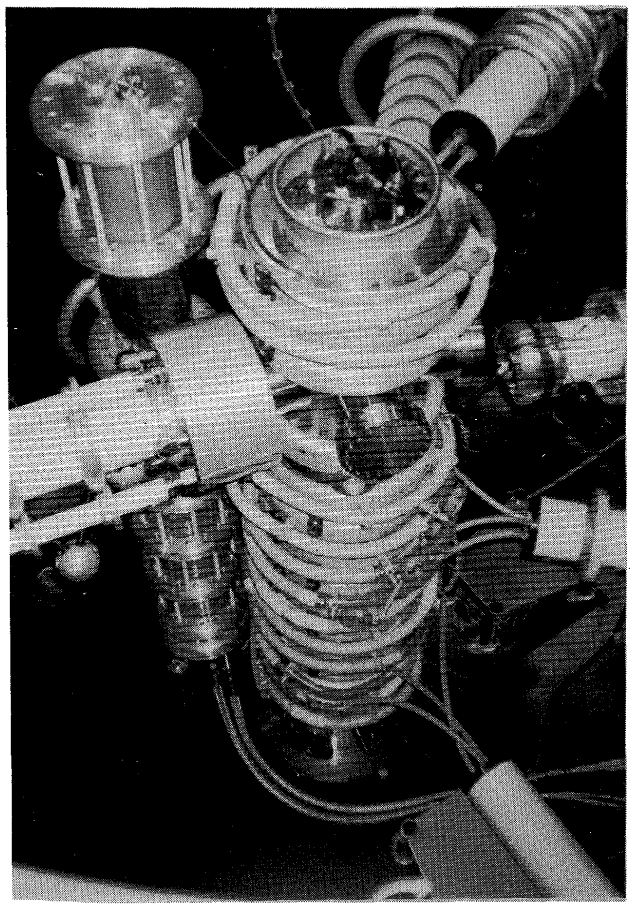

Fig. 2 Electron gun with an 11-stage electromagnetic accelerating unit.

trodes of the electron gun. It is used to adjust the output power of the accelerator, cathode and wehnelt power sources. An evacuation duct for the first stage accelerating unit and bushings which supply the accelerating voltage to each electrode are placed around the accelerating units. The gas pressure of the electron gun is 10^{-4} to 10^{-5} Pa. The electron beam emitted from the first stage accelerating unit is adjusted with the alignment coil in the second stage accelerating unit, in order to be effectively focused by the focusing coil located about 3 m from the first unit.

3. Characteristics of the Ultra-High Voltage Electron Beam

The relationship between the focusing coil current I_F and the focal distance D_F is shown in **Fig. 3** for when a 500 kV/10 kW/4 mm-in-diameter beam is focused in the welding chamber. The relationship between a focal distance of 370 mm to 460 mm and the focusing coil current is linearly proportional. Even at an output power of 20 to 70 kW, a beam diameter of 4 mm similar to a 10 kW beam was obtained at the position of the focusing coli, and the electron beam could be focused at any focal distance using the focusing coil.

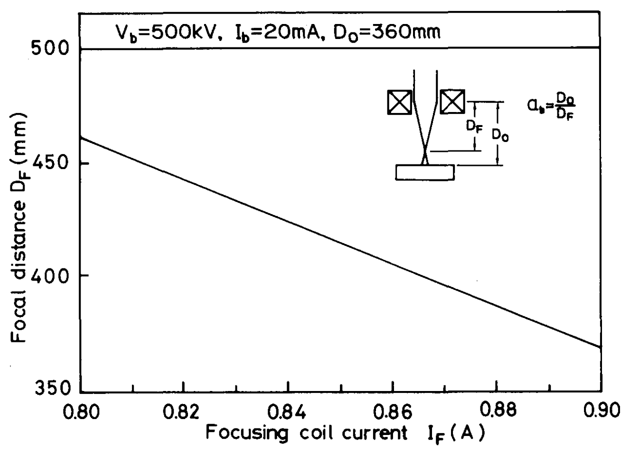

Fig. 3 Relationship between the focusing coil current and focal distance.

By adopting a multi-stage accelerating electron gun, an ultra-high voltage electron beam could be emitted with very good focusing characteristics.

Figure 4 shows the results of the AB test[4] for the shape of the electron beam emitted into the welding chamber. In this figure, the beam voltage V_b was set at 500 kV and 150 kV at a constant beam power of 10 kW. Data obtained by other electron beam heat

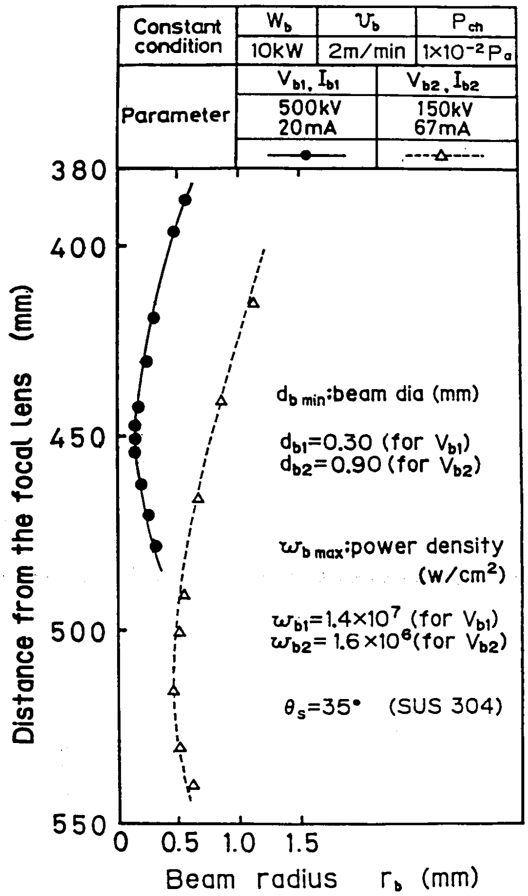

Fig. 4 Shape of the ultra-high voltage electron beam inside the heat processing chamber.

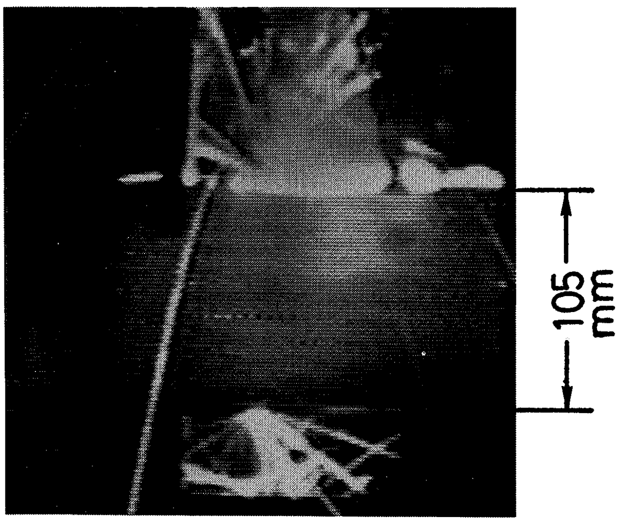

Fig. 5 Observation view during full penetration flat position welding using the 500 kV electron beam (W_b=30 kW, v_b=400 mm/min, SUS304).

sources of 150 kV are provided for comparison[5,6]. The focal position of the 500 kV electron beam was located 450 mm from the focusing coil. The minimum beam diameter was 0.30 mm, and an average power density of 14,000 kW/cm^2 was obtained. This value is 10 times higher than that of a 150 kV beam with a beam diameter of 0.9 mm and a power density of 1,500 kW/cm^2.

Figure 5 shows full penetration flat position welding being carried out on a specimen of stainless steel (SUS304, 105 mmt) by an electron beam with a beam voltage of 500 kV and beam power of 30 kW. Only spatter is spouted and the molten metal does not drop down from the bottom of the specimen. It is impossible to perform full penetration flat position welding of thick plates using an ordinary 100 kV class electron beam. Because the beam diameter of the 500 kV electron beam is so fine, the weld bead is very narrow and there is only a very small amount of molten metal, so that it enables full penetration welding of thick plates even in a flat position.

4. Experimental Results of Flat Position Welding

Cross sections of the weld beads produced by flat position welding of stainless steel by a 50 kW/500 kV beam at various welding speeds are shown in **Fig. 6**. The a_b value was 0.9 and the gas pressure was 10^{-2} Pa. A deep and narrow weld bead, typically seen only in electron beam welding, was obtained at welding speeds between 400 and 1200 mm/min. Although the penetration depth increased to over 170 mm at a welding speed of 200 and 100 mm/min, the bead width widened because of the violent motion of the high temperature

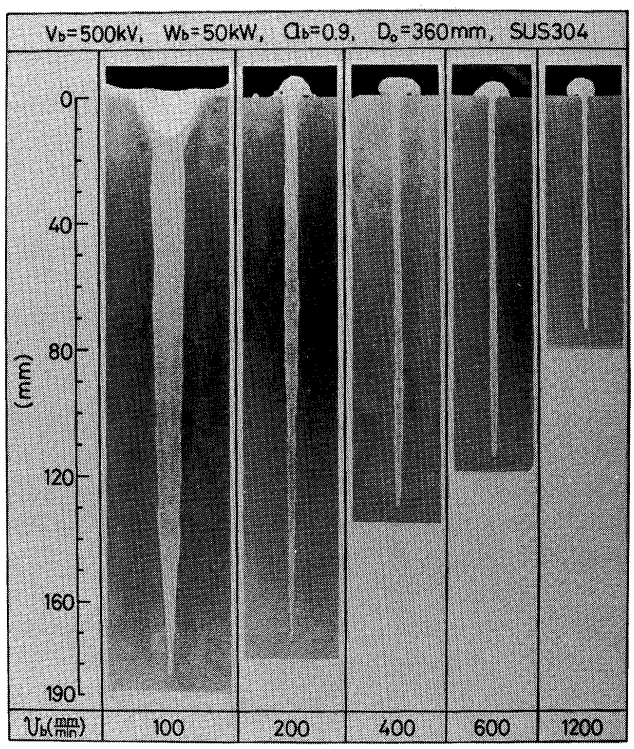

Fig. 6 Cross-sectional view of the weld beads at various welding speeds.

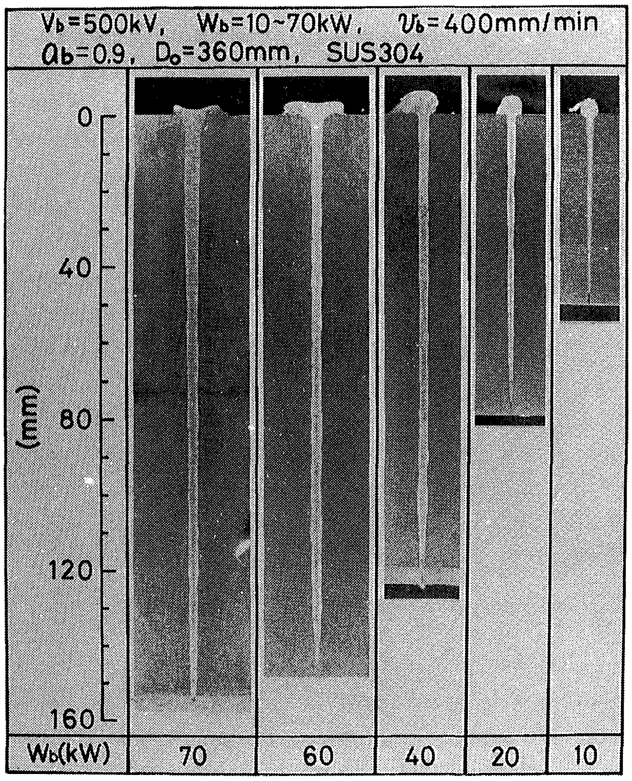

Fig. 7 Cross-sectional view of the weld beads at various beam powers.

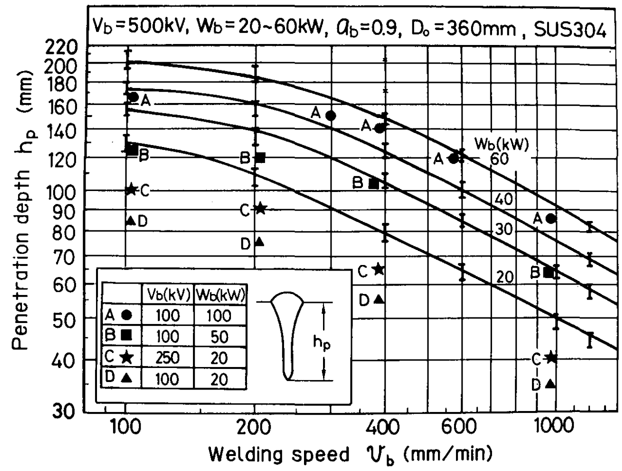

Fig. 8 Relationship between the penetration depth and welding speed for flat position welding.

molten metal around the beam hole.

Figure 7 shows cross sections of the weld beads obtained in flat position welding by a 500 kV beam with a power of 10 to 70 kW. The welding speed was a constant 400 mm/min and the a_b value was 0.9. Even when the beam power was increased, a well-type bead with a narrow bead width was obtained. An effective penetroparameter $\tilde{P}_p$ of 40 or 50 was obtained (The penetroparameter is the ratio of the penetration depth to the effective bead width).

Figure 8 shows the relationship between the penetration depth and the welding speed in flat position welding using a 500 kV beam with a beam power of 20, 30, 40 and 60 kW. The maximnm penetration depth was 200 mm at 60 kW. Marks A through D, indicating data obtained by other welders at different beam voltages and powers, are provided in the box for comparison[1)6)]. The maximum penetration depth obtained in flat position welding with a 100 kV/100 kW beam generated with the welder which the authors developed in the 1970's was 160 to 170 mm at a welding speed of 100 mm/min, as indicated by mark A. Using a 500 kV beam, the same penetration depth was obtained at a power of only 40 or 50 kW. Comparing the penetration depths obtained using 100 kV/50 kW, 100 kV/20 kW and 200 kV/20 kW beams —indicated by marks B, C and D—, it is clear that a 500 kV beam of the same power can achieve much deeper penetration.

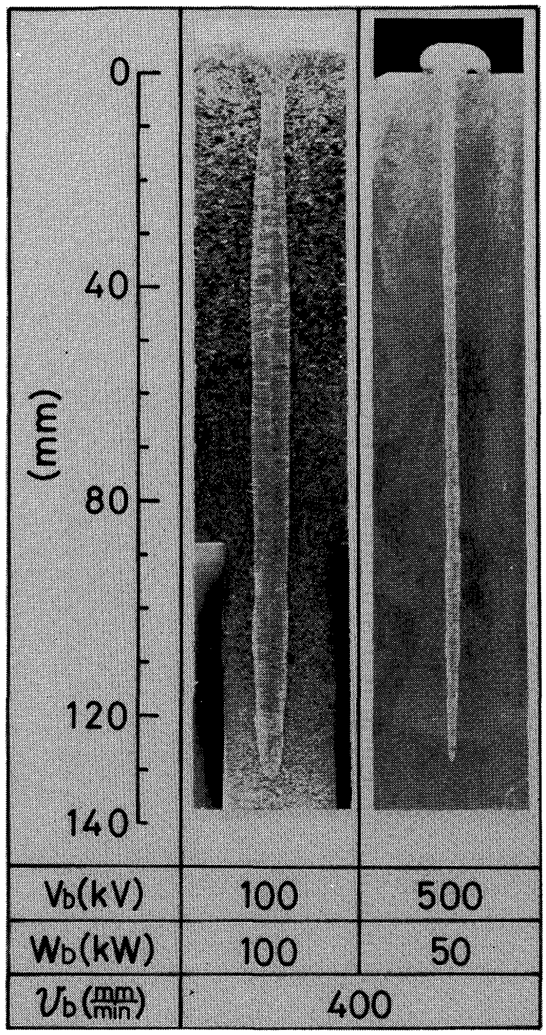

Fig. 9 Comparison of the cross sections of beads using 100 kV/100 kW and 500 kV/50 kW electron beams.

Figure 9 shows a comparison of the bead cross sections obtained in flat position welding using a 100 kV/

100 kW beam and a 500 kV/50 kW beam at a welding speed of 400 mm/min. The material was SUS304 stainless steel. The average bead width of the 500 kV beam was only 2/5 that of the 100 kV beam, and the power required for achieving the same penetration of 130 mm was only half that of the 100 kV beam. Thus, an ultra-high energy density beam displays high efficiency and excellent deep penetration characteristics in flat position welding.

5. Conclusion

A 500 kV ultra-high voltage electron beam heat source was developed and a strongly focused ultra-high energy density electron beam with a beam power of 10–70 kW was successfully obtained. By studying the application of this ultra-high voltage electron beam to welding, it was found that a narrow, sound bead with deep penetration even in flat position welding could be obtained at welding speeds over 100 mm/min. For example, a penetration depth of 200 mm (SUS304, a_b=0.9, D_o=360 mm) was achieved in flat position welding at 100 mm/min with a 500 kV/60 kW electron beam.

Furthermore, comparing the 130 mm penetration depth in flat position welding with a 100 kV/100 kW electron beam at v_b=400 mm/min, the 500 kV beam could penetrate to the same depth with a power of only 50 kW, only half the power of the 100 kV beam.

Acknowledgments

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