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Characteristics of 600 kV Class Ultra High Voltage Electron Beam Heat Source†

Michio TOMIE*, Nobuyuki ABE* and Yoshiaki ARATA**

Abstract

An ultra-high voltage electron beam heat source with an electron gun employing multi-stage electromagnetic accelerating units was developed. The characteristics of the electron beam were studied and it was found that a strongly focused electron beam with an ultra-high average beam power density of 14000kW/cm² was successfully generated. Applicability of this ultra-high voltage electron beam to welding was investigated and it was found that this beam has high efficiency and allows to make a narrow weld bead.

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

The ideal heat source for welding is one which enables heat processing without causing thermal strain or changes in material quality. One characteristic of such an ideal heat source is infinitely high power density, but such a heat source does not exist. However, in recent years, the development and application to welding of high output electron beams, which in comparison to arc heat sources are a step closer to the ideal heat source, have begun both in Japan and abroad[1]. These high output electron beams are playing an important role in the development of new welding techniques, such as one-pass welding of metals over 10 cm thick.

The authors focused on the production of a strongly focused high power density electron beam, which is useful not only for high quality, high speed welding but also as a method of researching metallic properties such as the creation of surface layers with high functionality. To serve as the electron gun for the heat source which generate of a high power density electron beam, the authors invented a new electromagnetic accelerating unit. By connecting 13 stages of such units in series, a "600 kV class ultra-high voltage electron beam heat source" was developed for the first time in the world. This power density level had been considered difficult to realize[2]. In this report, the characteristics and welding applications of this heat source are described.

2. Outline of the Ultra-High Voltage Electron Beam Heat Source

In the case of electron beam welding, the dependence of the beam voltage V_b, the beam current I_b and the welding speed v_b on the penetration depth h_p was revealed by the authors as expressed by following empirical equation[3].

$$h_p = K_m \left(I_b \cdot V_b^{1.3} / v_b^{0.5}\right) \quad (1)$$

where K_m is a constant. The experimental conditions were in the ranges of V_b = 50 – 120 kV, I_b = 20 – 1000 mA, and v_b = 400 – 3800 mm/min. The equation takes effect in the region from several kW to 100 kW, and the penetration depth is proportional to the beam voltage raised to the 1.3 power. The results suggest that an ultra-high voltage type is excellent as an electron beam welding heat source. However, the beam voltage of conventional practical electron beam welders is in the range of 30 – 150 kV. The main reason why the maximum voltage is limited to 150 kV is that beam acceleration by the electron gun is performed with a single-stage accelerating system. If an ultra-high voltage is impressed using a single-stage accelerating system, discharge, especially arcing, occur frequently, and continuous welding is impossible.

In order to overcome this limitation, the authors developed an ultra-high voltage electron gun with a new

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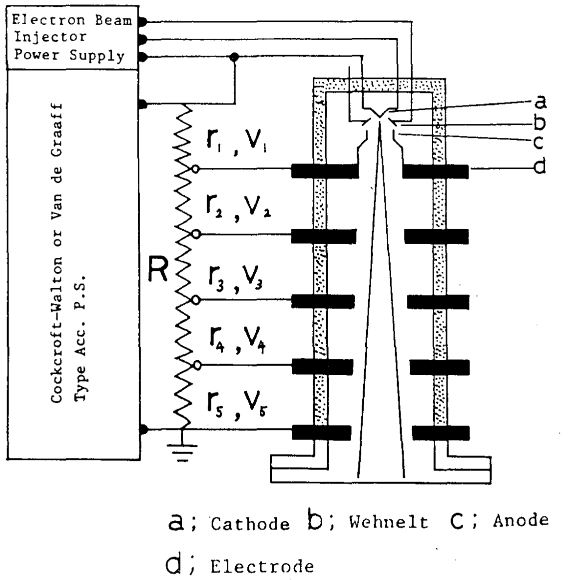

Fig. 1 Diagram of a conventional high voltage electron beam accelerator system.

multi-stage accelerating system which emits a high energy density beam. Conventional multi-stage accelerators, as shown in **Fig. 1**, are of the van de Graaff type or the Cockcroft-Walton type. As is well known, these accelerators use resistance (R) to supply voltage to each of the accelerating electrodes. Using these methods, it is difficult to produce a high output, high density beam, because runaway electrons from the beam and from the beam plasma, which is always present, flow into the electrodes, drastically changing the accelerating voltage. As a result, the discharge or changes in the shape of the accelerating beam occur which make these methods unsuitable for the production of a stable high density electron beam.

3. Strongly Focused Electron Beam Heat Source with Multi-Stage Accelerating Units

The multi-stage accelerating electron gun reguires the introduction of the following new concepts and functions not found in conventional accelerating guns:

1) The absorption of current which charges up the electrodes and maintenance of the stability of the impressed accelerating voltage, in order to prevent the occurrence of abnormal voltage between the accelerating electrodes.
2) An optimum structure for the accelerating electrodes at each stage, including the beam injector.
3) Shielding and prevention of the occurrence of a magnetic field, which might alter the beam axis, during the beam's multi-stage acceleration. A method of strong focusing is also required for induction and generation of a high density beam.

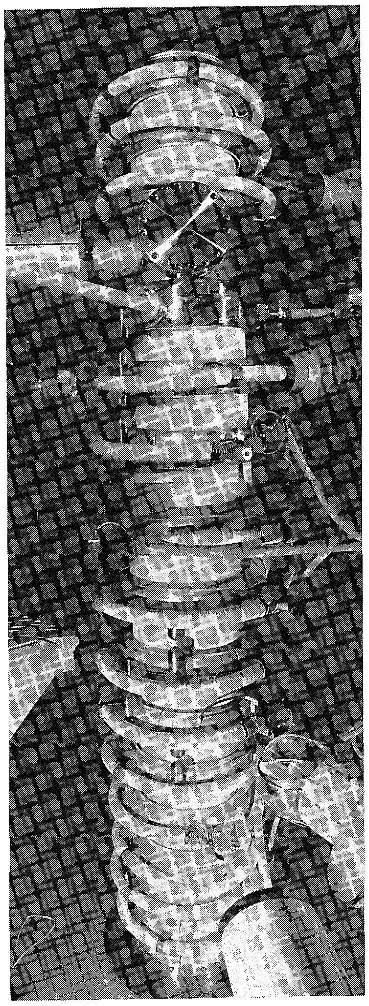

Fig. 2 Electron gun with a 13-stage electromagnetic accelerating unit.

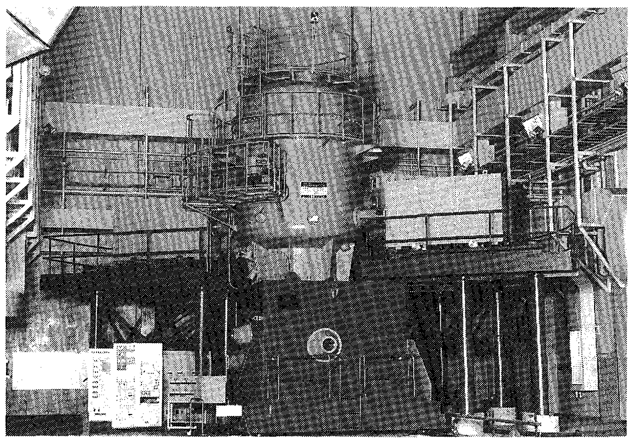

Fig. 3 600 kV class ultra-high voltage electron beam heat source.

Figure 2 shows a 13-stage electromagnetic accelerating unit electron gun designed and manufactured to fit the above conditions.

Figure 3 shows the 600 kV class ultra-high voltage electron beam heat source apparatus with the 13-stage electron gun. A maximum ultra-high voltage of 600 kV (accelerating voltage in the first stage: 100 kV, in stages 2–13: 41.7 kV) is applied (steady beam voltage during heat processing is 500 kV) to the electron gun, which is set inside an insulated pressure vessel filled with dry air at a gauge pressure of 2 atmospheres. The vacuum of the electron gun is on the order of 10^{-5} Pa. The capacity of the chamber for welding and other heat processing is $23.5 \mathrm{m}^3$, with a maximum vacuum of 10^{-4} Pa. A work table with X, Y and Z axes and a beam deflector for preventing intrusion of metal vapor into the electron gun during heat processing are built into the chamber. The electric power sources for acceleration are arranged around the pressure vessel. **Figure 4** shows a block diagram and an acceleration principle chart for the power circuit of the heat source. The power circuit consists of 13 independently controlled accelerating power supplies in 7 packages, a magnetic lens power supply, a power supply for beam generation (beam injector power supply), and a microcomputer and optical link system to facilitate precise control of these power

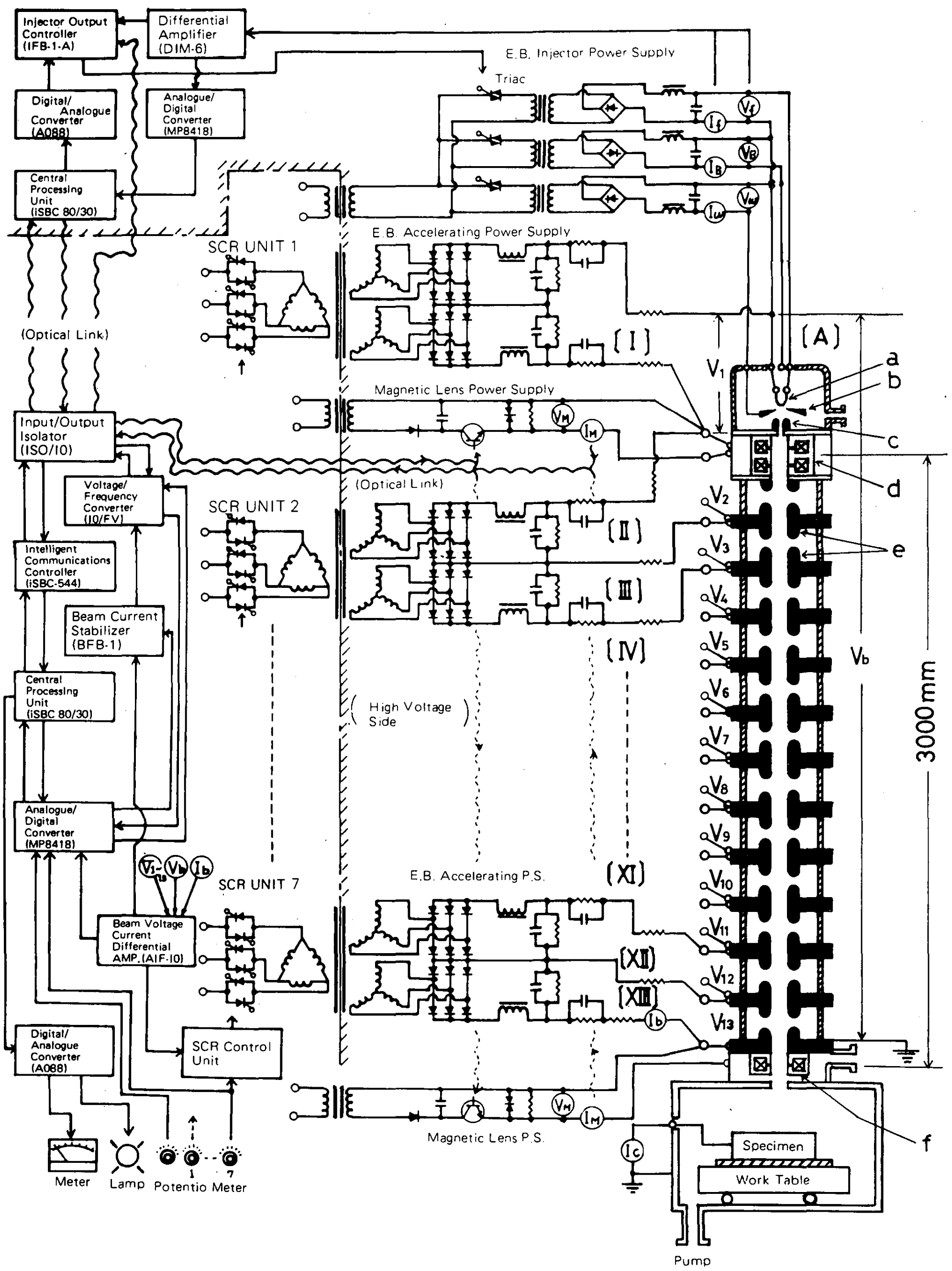

Fig. 4 Schematic diagram of the power supply circuit system and the 600 kV ultra-high voltage electron beam heat source. (a: Cathode, b: Wehnelt, c: Anode, d, f: Magnetic lens, e: Accelerating electrodes)

supplies. It was possible to regurate the voltage of the electron beam within ±0.2% during acceleration.

4. Characteristics of the Ultra-High Voltage Electron Gun

In order to evaluate the heat processing characteristics of the electron beam, it is important to know the functional characteristics of the ultra-high density beam emitted from the electron gun, such as the position of the focal spot, density and shape.

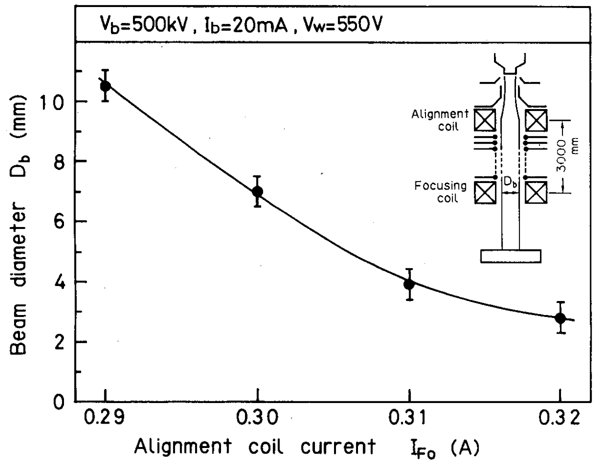

Fig. 5 Relationship between alignment coil current and beam diameter at the focusing coil.

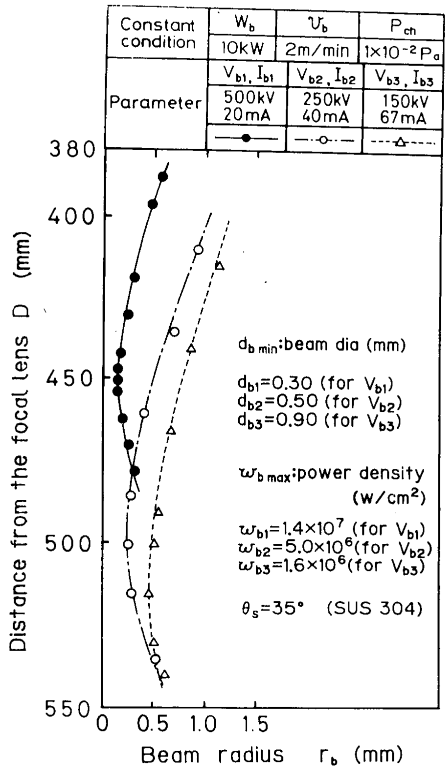

Fig. 6 Shape of the ultra-high voltage electron beam inside the heat processing chamber.

In this experiment, in order to accelerate the electron beam effectively through multiple stages and to create high energy density beam, two stages of magnetic lens (an alignment coil and a focusing coil) was used for beam focusing as shown in Fig. 4. The distance between the magnetic lenses was 3 m. **Figure 5** shows the relationship between alignment coil current I_{FO} and the beam diameter D_b near the focusing coil for a 500 kV beam. A columnar beam of D_b = 4 mm with good focusing characteristics was obtained at I_{FO} = 0.31 A. This beam was focused with the magnetic lens and emitted into the heat processing chamber. The beam shape was measured using the AB test method[4]. The results are shown in **Fig. 6.** The experimental conditions were a chamber pressure of 10^{-3} Pa, beam power of 10 kW and beam voltage of 500 kV, 250 kV and 150 kV. The beam focusing point at 500 kV was placed about 450 mm from the center of the focusing coil. The minimum beam diameter was 0.3 mm.

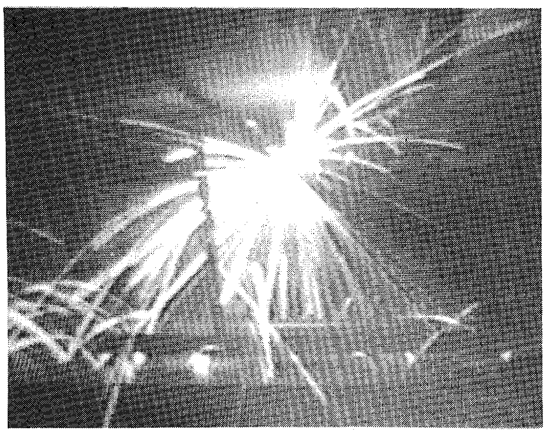

Fig. 7 Inclined welding with 500 kV electron beam.

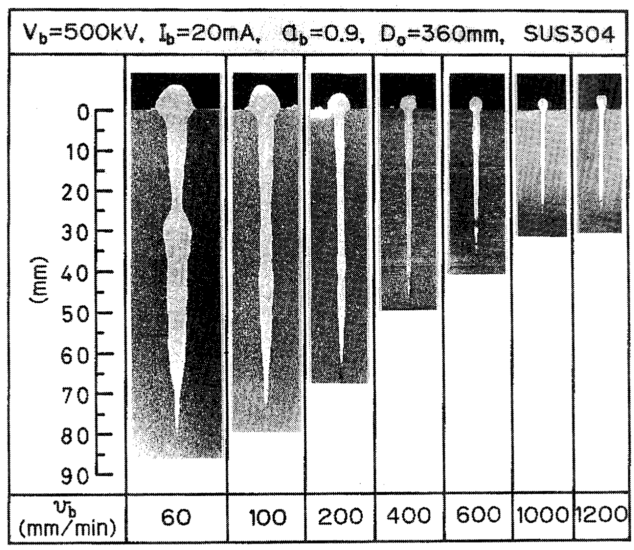

Fig. 8 Cross-sectional view of weld beads at various welding speeds.

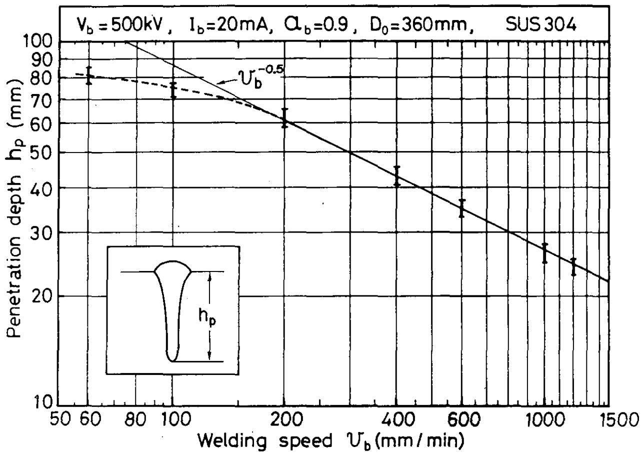

Fig. 9 Relationship between welding speed and penetration depth. ($h_p \alpha v_b^{-0.5}$: $v_b \geqslant$ 200 mm/min)

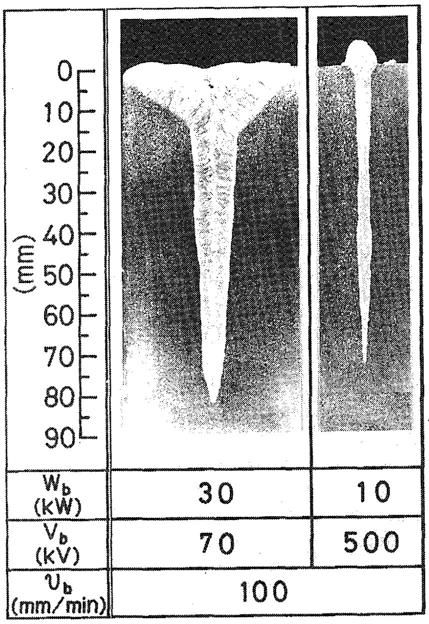

Fig. 10 Comparison of cross sections of beads using 70 kV (W_b = 30 kW) and 500 kV (W_b = 10 kW) electron beams.

An average beam power density of 14000 kW/cm^2 was obtained under these conditions much higher than can be achieved by conventional electron beams for welding.

Figure 7 shows full penetration inclined welding being carried out on a comb-shaped AB test specimen with 4 mm/9 mm thickness at a welding speed of v_b = 2000 mm/min. As the energy density of the electron beam was increased, heating, melting, boiling and splashing of the irradiated material occurred more quickly and explosive, intense spattering of the molten metal was observed.

Figure 8 shows typical cross-sections of weld beads at various welding speeds using a 500 kV beam. The welding conditions were W_b = 10 kW, P_o = 10^{-3} Pa, a_b value = 0.9, and v_b = 6 – 1200 mm/min. The specimen was stainless steel. **Figure 9** shows the relationship between the welding speed and penetration depth. At a welding speed of 200 mm/min or more, it is found that h_p is proportional to v_b raised to the –0.5 power as shown in the experimental equation (1), which was obtained through detailed experiments by the authors.

Figure 10 shows a comparison of bead cross-sections produced by electron beams with beam voltages of 70 kV (W_b = 30 kW) and 500 kV (W_b = 10 kW). The 500 kV beam can penetrate to a depth of 70 – 80 mm with only one third the beam output of a 70 kV beam.

5. Conclusion

Ultra-high voltage high power density electron beams are very effective for high precision, high quality welding of thick metals. To generate such an electron beam, the authors invented a new electromagnetic accelerating unit and developed a 600 kV class ultra-high voltage electron beam heat source utilizing 13-stage accelerating units.

Investigation of a strongly focused electron beam accelerated to an ultra-high voltage of 500 kV revealed that focusing to a beam diameter of 0.3 mm is possible at a beam power of 10 kW, obtaining a beam with an ultra-high energy density of 14000 kW/cm^2, a density not achievable with conventional electron beams for welding.

By studying the application of such an ultra-high voltage electron beam to welding, it was found that a narrow and sound weld bead with deep penetration could be obtained at a welding speeds over 100 mm/min.

Acknowledgment

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