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# Some Properties of 30 KW-Class Electron Beam for Welding<sup>†</sup>

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## Abstract

The material properties and the life time of thermionic emission type cathode which generates high power electron beam is discussed. Properties of weld bead penetration using the 30~150KV electron beam are investigated and the empirical formula for the penetration depth is introduced. Ion beam, produced by the electron beam and passing through the accelerating space of an electron beam gun, is measured, and also its properties are discussed.

## 1. Introduction

The cathode is one of the most important part of an electron beam gun and determines its capability. As desired such a thermionic emission type cathode of the high power electron beam gun can emit a large stable quantity of thermoelectrons for many hours.

The accelerating space of the welding electron beam gun is usually tainted by environment gases and "welding vapors" (which evaporate from the welded metal during welding). The spattering of the cathode material, caused by impact of ion beam produced by electron beam, is remarkable and it makes the cathode life time shorter. Then, concerning the material, the shape and the location of the cathode, many attempts or devices have been made but there is no definite conclusion. In this report, Tungsten (W) and Tantalum (Ta) were selected and discussed as the cathode material which stably generates welding high power electron beam for many hours.

Using the EB-welder with electron beam gun which was developed by the authors, the bead penetration test was carried out against SUS304 stainless steel which corresponds with AISI304 and the empirical formula for the penetration depth was introduced.

## 2. Experimental Apparatus and Materials

For the experimental apparatus, the following two types of EB-welders developed by authors were used.

A type:  $V_b = 50 \sim 150$  (KV),  $I_b = 0 \sim 50$  (mA),  $W_b = 7.5$  (KW)

B type:  $V_b = 30 \sim 60$  (KV),  $I_b = 0 \sim 500$  (mA),  $W_b = 30$  (KW)

where  $V_b$  (KV) is an accelerating voltage of electron beam,  $I_b$  (mA) is the electron beam current and  $W_b$  (KW) is the maximum beam power.

Figure 1 shows a principle drawing of electron

beam gun and beam channel in case that the work chamber can be utilized up to  $10^{-1}$  from  $10^{-4}$  Torr.

Figure 2 shows a circuit diagram.

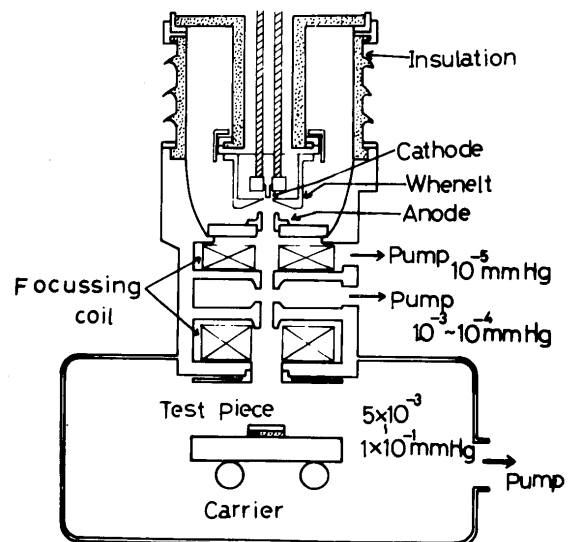


Fig. 1. Schematic diagram of EB-welder.

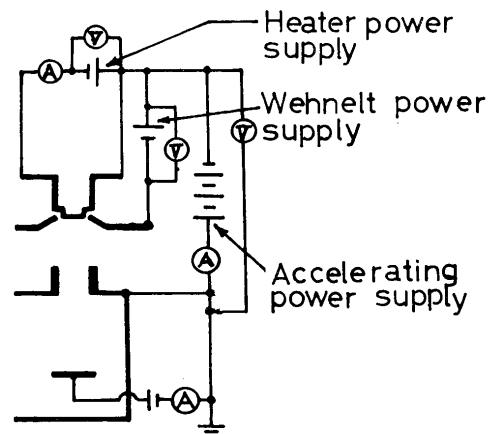


Fig. 2. Circuit diagram of EB-welder.

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The electron beam gun is a Pierce type and the open angle of whennelt is 90° and its open diameter is 6.5 mmφ. SUS304 type stainless steel was used as the experimental material.

### 3. Results and Discussions

#### 3.1 Cathode Materials

As it is well known, the following formula has been obtained. Concerning the properties of the thermionic emission type cathode material.

$$\left. \begin{aligned}
 \text{thermionic emission}^1: i_{th} &\propto e^{-V_w/V_T}, \left( \frac{\text{Amp}}{\text{cm}^2} \right) \dots\dots (a) \\
 \text{evaporation}^2) : M_{\text{vap}} &= 5.83 \times 10^{-2} p \sqrt{\frac{M}{T}} \\
 &\left( \frac{\text{g}}{\text{cm}^2 \cdot \text{sec}} \right) \dots\dots\dots (b) \\
 \text{evaporation rate} : v_{\text{vap}} &= \frac{M_{\text{vap}}}{\rho}, \left( \frac{\text{cm}}{\text{sec}} \right) \dots\dots\dots (c)
 \end{aligned} \right\} (1)$$

where T(°K) and V<sub>T</sub> [volt] indicate the temperature of the cathode material, and V<sub>w</sub> (volt), ρ(g/cm<sup>3</sup>), p and M are its work function, density, vapor pressure and molecular mass per grams respectively.

The formula (a) shows higher density thermo-electron flow is obtained by the material of higher V<sub>T</sub> value and lower V<sub>w</sub> value. The pure materials which can elevate the V<sub>T</sub> value are high melting point materials, W, Re, Ta and Mo in order, and Ta, Mo, W and Re are in order of lower V<sub>w</sub> value. It can be noticed that Mo is inferior to Ta on both the above properties, and it is better to discuss for W, Ta and Re.

Figures 3 and 4<sup>3) 4)</sup> illustrate the formula (1). Although the formula (b) and (c) are related to the life time, the formula (c) is more convenient compared with the formula (b). From these, it can be noticed that Ta is somewhat better compared with Re as the cathode material at each temperature in practical continuous usage. Moreover, Ta has more advantages over W in the manufacturing property. Therefore it seems that Ta is the best conthode material. But it is necessary to take some considerations as follows that is the accelerating chamber in the EB-welder is usually tainted and damaged by environmental gases and welding vapors. Especially, ions, produced by electron beam, are accelerated as ion beam to the opposite direction against electron beam in the accelerating chamber, impact with the cathode material and damage it. This is named "ion beam etching" or simply "beam etching". The effect of the beam etching is stronger than any other mechanism and not only makes the cathode life time short. But it damages both the stability of the electron beam power and the

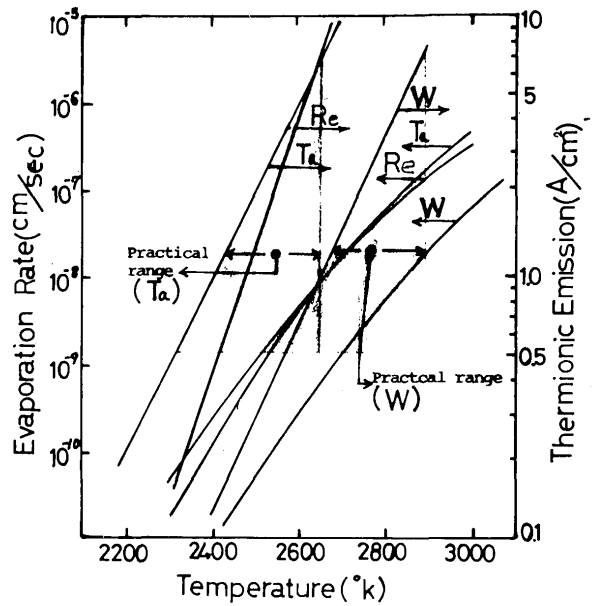


Fig. 3. Relation of evaporation rate, thermionic emission and cathode temperature.

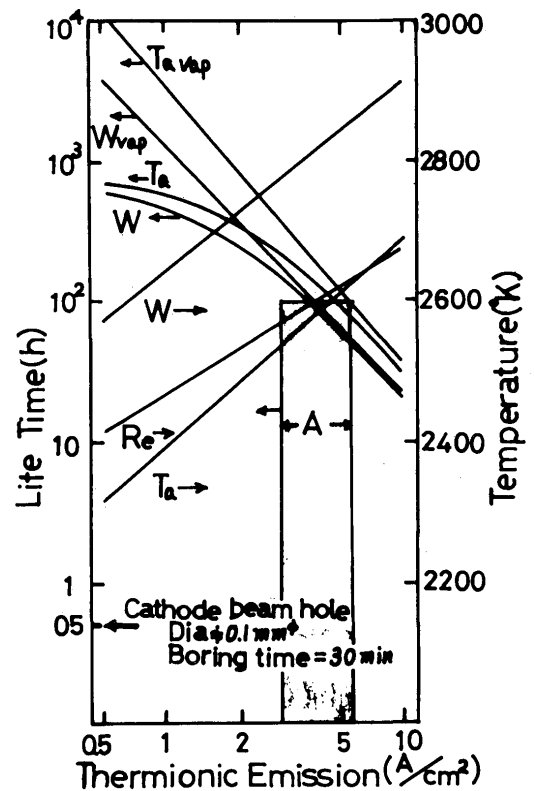


Fig. 4. Relation of life time, temperature and thermionic emission for the cathode. (A: Range used generating electron beam for 100 hours)

beam focusing. Resistance of Ta against the beam etching is inferior to W resistance.

Futhermore, required properties of the cathode material are that the mechanical strength is high and both expansion and contraction are small in the

region of service temperature. In case of the large coefficient of expansion or construction, the cathode is deformed and its fitting position is away from the original position; consequently, it is difficult to generate a stable electron beam. And in case of the low mechanical strength at the service temperature, the cathode material is apt to be deformed or to be destroyed by electromagnetic force, generated from the large electric current heating the cathode material, consequently, stable electron beam is difficult to obtain.

W is superior to Ta against both properties of the mechanical strength and the coefficient of expansion at each practical service temperature as shown in Fig. 5.<sup>5), 6)</sup>

For example, the cathode materials of W and Ta must be heated up to 2700°K and 2500°K respectively in order to obtain  $i_{th}=2 \text{ A/cm}^2$  as the beam current density, but in this case, the fracture strength of W is 4 [Kg/mm<sup>2</sup>] and the strength of Ta is 1.8 [Kg/mm<sup>2</sup>], consequently, W is 2.2 times fracture strength of Ta. Further, the coefficients of expansion of W and Ta are 6.9 and 10.1 respectively. From these, it seems that W has the most suitable properties as the cathode material of high power welding beam gun. So we used it for our developed powerful welding guns.

So far various shapes of the cathode mater have been used. The typical shapes are hair-pin type, square type (square, rectangle), spherical winding type and circle type. Circle type showed the best beam property among these types, so we used the circle type, 3 mm in diameter.

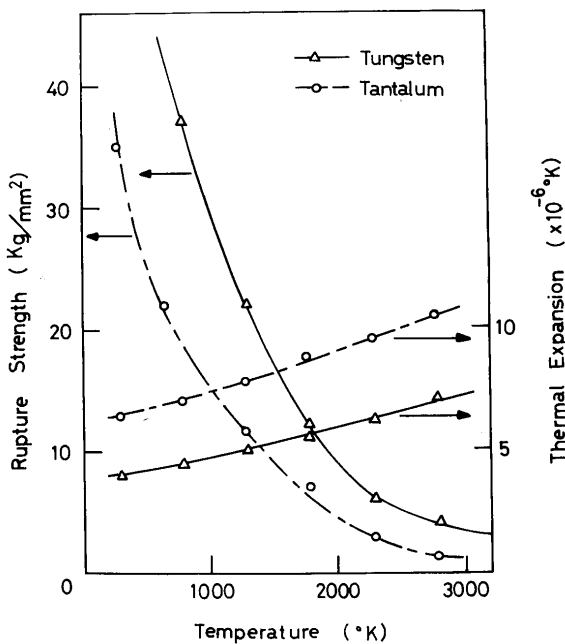


Fig. 5. Relation of rupture strength, thermal expansion and cathode temperature for W and Ta.

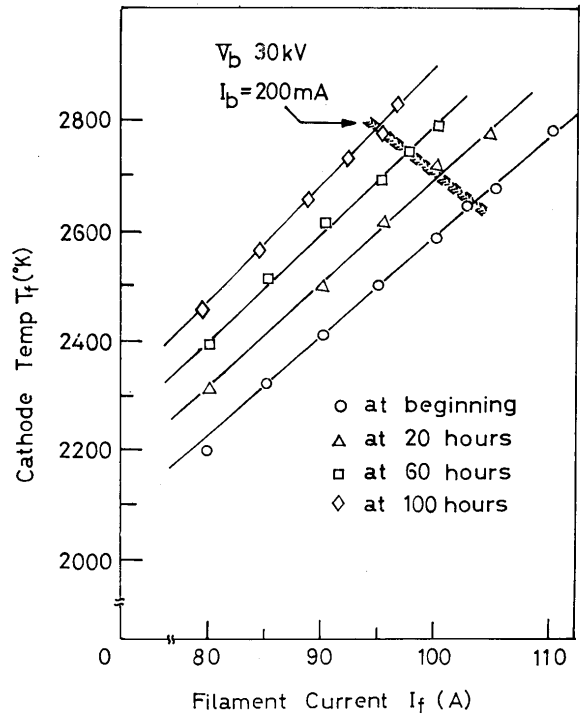


Fig. 6. Relation of cathode temperature and filament current keeping constant;  $V_b=30 \text{ KV}$ ,  $I_b=200 \text{ mA}$ .

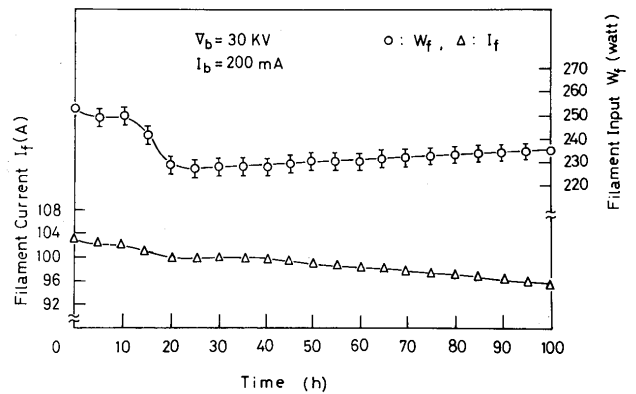


Fig. 7. Relation of filament current, input power and time. keeping constant;  $V_b=30 \text{ KV}$ ,  $I_b=200 \text{ mA}$ .

Figure 6 shows  $I_f-T_f$  characteristic curve and Fig. 7 is characteristic curve of  $I_f-T_f$ -time, where  $I_f$  is an electric current heating the cathode, that is, filament current,  $T_f$  is temperature of cathode material heated with  $I_f$  and  $W_f$  is input power required to heat the cathode material. As shown in these figure, in case that  $I_b=200 \text{ mA}$  was taken out for 100 Hr. continuously,  $I_f$  decreased gradually from 103(A) to 97 (A).

Also, small decreases on  $W_f$  and  $I_f$  were recognized after 10~20 min operation, and they remarkably decrease after 15~20 hours. This phenomenon occurs when the center of cathode material is remarkably consumed by beam etching, caused by above-mentioned ion beam. Consequently, boring

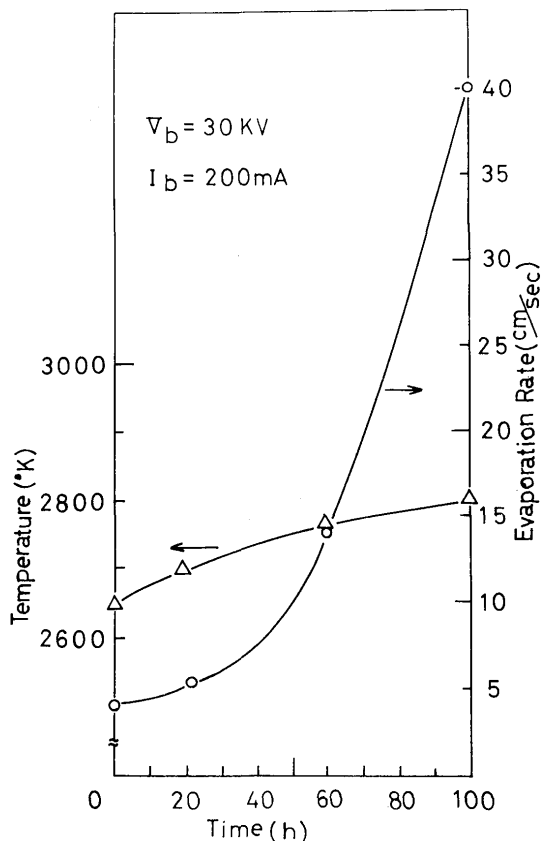
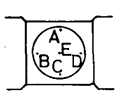


Fig. 8. Relation of cathode temperature, evaporation rate and time, keeping constant;  $V_b=30$  KV,  $I_b=200$  mA.

Table 1. One example of consumption rate of cathode.

Location Thickness (mm)	A	B	C	D*	E
$t_0$ (before use)	0.177	0.179	0.174	0.174	0.176
$t_{100}$ (after use)	0.150	0.157	0.153	0.143	0
$\Delta t = (t_0 - t_{100})$	0.027	0.022	0.021	0.031	0.176



phenomenon is caused and the effective area of the cathode decreases. After that, their curves gradually change. It seems that these phenomena are caused by a continuous decrease of the volume of the cathode material, based on the various mechanisms as shown in Fig. 8 and Table 1.

3.2 Ion Beam

It is known that the high density beam plasma is produced by the powerful electron beam at the suitable gas pressure,  $P_{ch} \geq 10^{-4}$  Torr.<sup>7)</sup>

During welding, in general, such condition of the gas pressure is fully satisfied in a work chamber and the high density beam plasma is practically formed as shown in Fig. 9.<sup>8)</sup>

Ions among the beam plasma are caught by electron beam itself and the ion motion drifting away from the beam axis is restrained. On the contrary, the drift along the beam axis is easy.

The ions are accelerated to the opposite direction of electron beam by receiving the same accelerating voltage as the electron beam in the accelerating space and impact strongly with the cathode material as ion beam. Such ion beam can be divided into "concentrated ion beam" which is constricted near the electron beam axis and "distributed ion beam" which is distributed widely over the beam plasma region. The former is high density and causes the violent beam etching accompanying the strong boring phenomenon against the cathode material. and the latter is low density and makes gradually the consumes the whole cathode.

Figure 10 illustrates schematically an aspect of their distribution when electron beam of  $I_b=200$  mA is emitted into the work chamber with  $P_{ch}=6 \times 10^{-5}$  Torr,

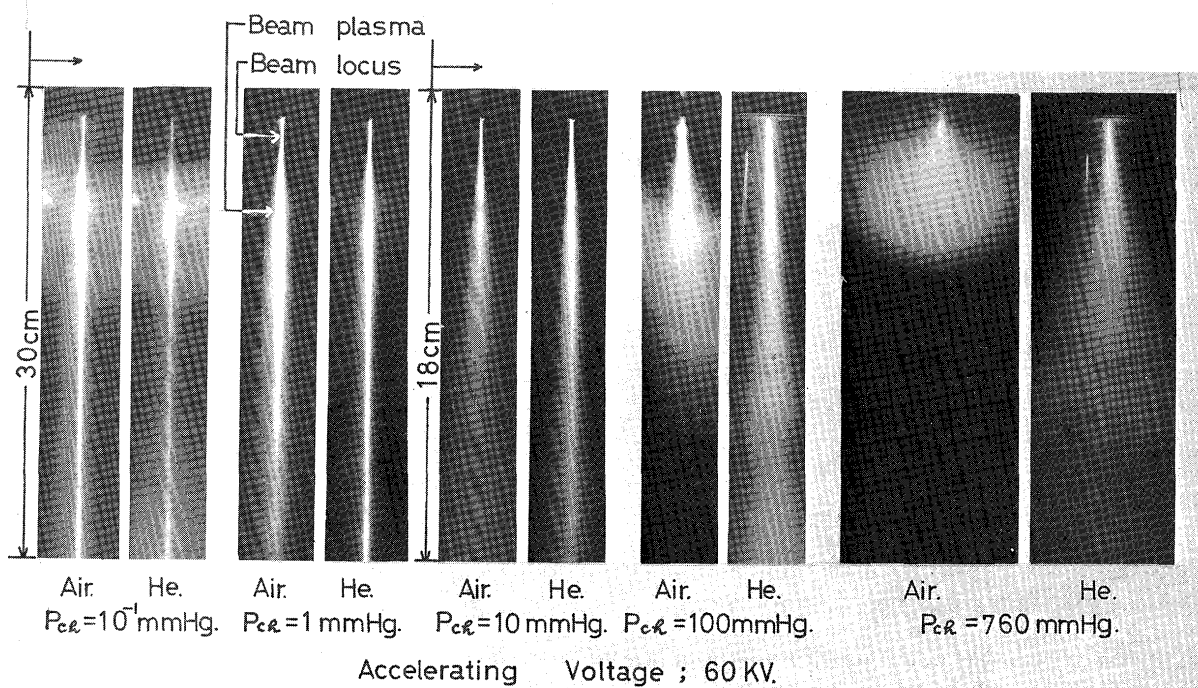


Fig. 9. Profiles of both the electron beam and beam plasma against various gas pressures ( $P_{ch}$ ).

by using the electron beam gun with beam perveance of  $G_b=2.3 \times 10^{-8}$ , and W-cathode of 0.15 mm in thickness, is fully penetrated by concentrated ion beam after 24 min. as shown in Fig. 11. Further, after 20 hours, this small hole, cathode beam hole with about 1.0 mm in diameter, is formed as shown in Fig. 12 (a).

As a result, beam etching speed ( $v_{etch} = \text{cathode material thickness/penetration time}$ ) in this case is nearly  $v_{etch} \approx 1 \times 10^{-5}$  cm/sec and the forming time of the cathode beam hole is 24 min. Therefore it can be considered that average diameter of the concentrated ion beam is nearly same, 1.0 mm  $\phi$  in this case, as this

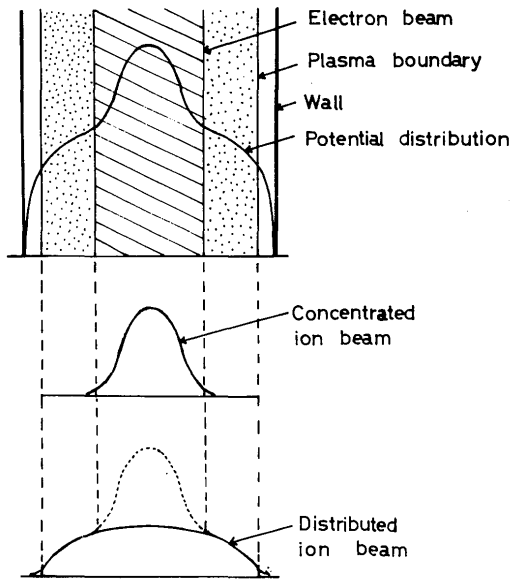


Fig. 10. Schematic distribution of both concentrated and distributed ion beam.

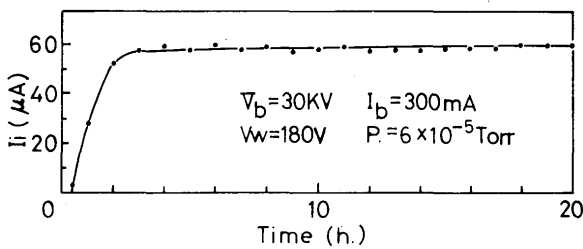
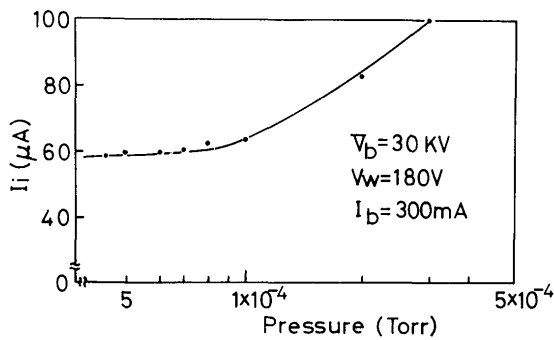


Fig. 11. Ion beam current against gas pressure in gun and elapsed time. (Ion beam appears suddenly after a certain times elapsed 24 min. due to full penetration).  $V_w (=180 \text{ V})$  is wehnelt voltage.

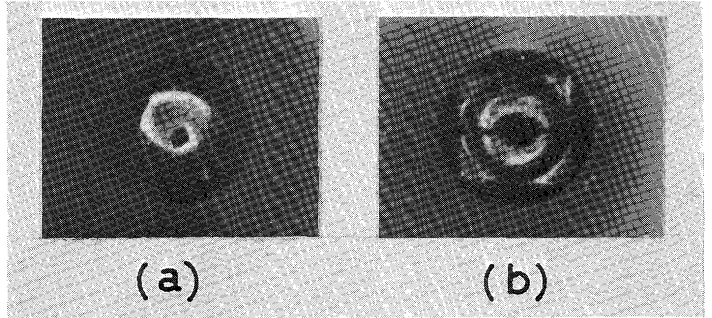


Fig. 12. Examples of beam etching against the cathode (a;  $V_b=30 \text{ KV}$ ,  $I_b=300 \text{ mA}$ , Time=after 20 hours. b;  $V_b=30 \text{ KV}$ ,  $I_b=400 \text{ mA}$ , Time=after 76 hours.)

cathode beam hole, and also cathode beam hole with 2.0 mm  $\phi$  is bored after 76 hours as shown in Fig. 12 (b).

Beam etching property is, namely, that its action concentrates near the center of the cathode in the same range as concentrated ion beam diameter and makes the cathode beam hole in a short time, and the circumference is gradually etched by the distributed ion beam. Figure 13 shows a principle drawing of measuring apparatus of concentrated ion beam and Fig. 11 shows the measured results and it was recognized that concentrated ion beam current was about 60  $\mu A$  under such conditions that  $V_b=30 \text{ KV}$ ,  $I_b = 300 \text{ mA}$ ,  $P_{ch}=6 \times 10^{-5} \text{ Torr}$ .

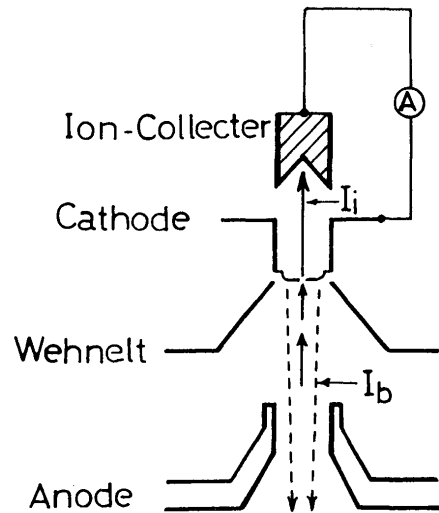


Fig. 13. Measuring method of concentrated ion beam.

### 3.3 Welding Bead Penetration

Although so far many papers<sup>9), 10), 11)</sup> were presented to search the mechanism of welding bead penetration, these are not treated systematically. General formula on the penetration depth,  $h_p$ , has been given by one of authors<sup>12)</sup> as follows.

$$h = K h(s) h(e) \dots \dots \dots (2)$$

$$\left. \begin{aligned} \text{where, } h(s) &= f(a_b, l_b, \theta_b, \theta_s) \text{ ----- (a)} \\ h(\epsilon) &= f(W_b, w_b, v_b) \text{ ----- (b)} \end{aligned} \right\} (3)$$

now, we will let

$$\left. \begin{aligned} h(\epsilon) &= \frac{W_b^{n_1} w_b^{n_2}}{v_b^{n_3}} \text{ ----- (a)} \\ &= \frac{I_b^{m_1} V_b^{m_2}}{v_b^{m_3} d_b^{m_4}} \text{ ----- (b)} \\ &= \frac{I_b^{l_1} V_b^{l_2}}{v_b^{l_3}} \text{ ----- (c)} \end{aligned} \right\} (4)$$

$h(s)$  and  $h(\epsilon)$  are called "beam shape function" and "beam energy function" respectively, because  $h(s)$  and  $h(\epsilon)$  indicate the degree of each action of the beam shape and the beam energy for the penetration. **Fig. 10** is one example illustrating the positive influence of  $h(s)$  on the penetration.

$K$  is a constant of welding materials and  $a_b, l_b, \theta_b$  and  $\theta_s$  are "beam active parameter"(active parameter), length of "beam active zone", beam convergent angle and angle of slope welding respectively as shown in **Fig. 14** and **Fig. 15**.  $n_1, n_2,$  and  $n_3$  are parameters

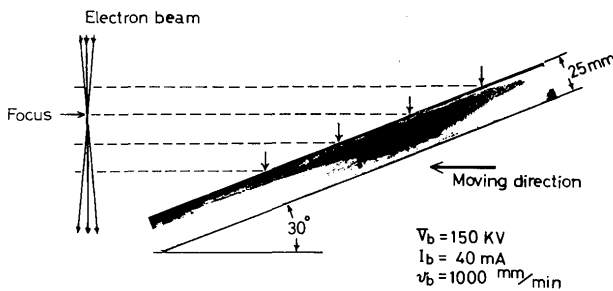


Fig. 14. Example of slope welding.

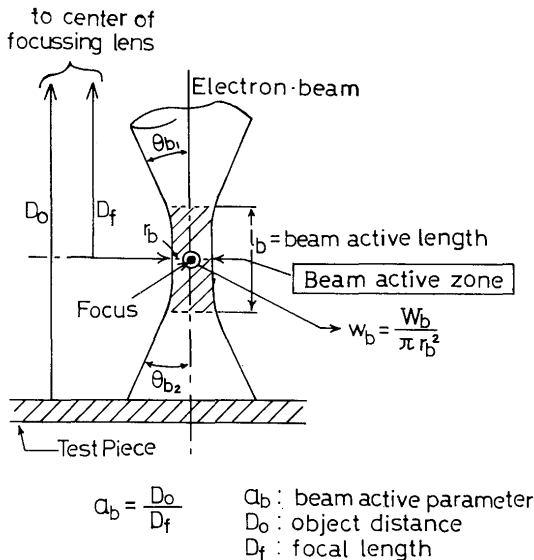


Fig. 15. Schematic diagram illustrated both shape of electron beam and many beam parameters.

which show the degree of the effects of beam power,  $W_b$ , beam power density,  $w_b$ , and welding speed,  $v_b$ , on penetration respectively.  $m_1, m_2, m_3$  and  $m_4$  are parameters which show the degree of the effects of  $I_b, V_b, v_b$  and  $d_b$  (beam diameter) on the penetration respectively. Accordingly, under such condition that  $h(s)$  maximize  $h_p$ , formula (4), (c) is adopted to obtain the most simple empirical formula for  $h(\epsilon)$ . In this case, we will let

$$K_m = K\{h(s)\}_{h_p=\max} \text{ ----- (5)}$$

It is considered that  $K_m$  value depends on the sort of the welding materials and the EB-welders (which differentiate in characteristics of the welding beam gun), because  $h(s)$  depends on the EB-welder in general. Then using the given EB-welder and such condition that  $h(s)$  maximize  $h_p$  for the given materials,  $K_m$  is constant.

Then using formulas (4), (c) and (5), formula (2) is as follows.

$$h_p = K_m h(\epsilon) = K_m \frac{I_b^{l_1} V_b^{l_2}}{v_b^{l_3}} \text{ ----- (6)}$$

To obtain  $K_m, l_1, l_2,$  and  $l_3$  in formula (6), the relation of  $h_p$  against  $I_b, V_b$  and  $v_b$  was obtained experimentally for SUS304 stainless steel under a variety of welding conditions. The results are shown in **Figs. 16 ~ 21**.

As a result, as it is obtained for both A type and

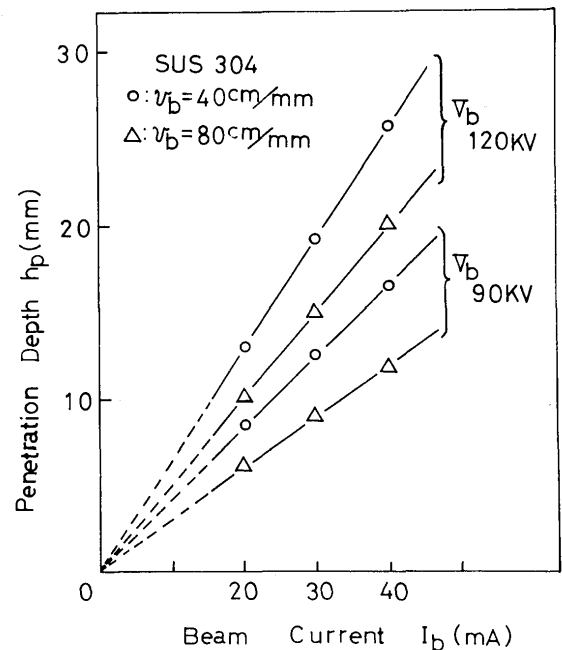


Fig. 16.  $I_b-h_p$  relation; A type-EB apparatus. (SUS304 correspond to SUS27 or AISI304)

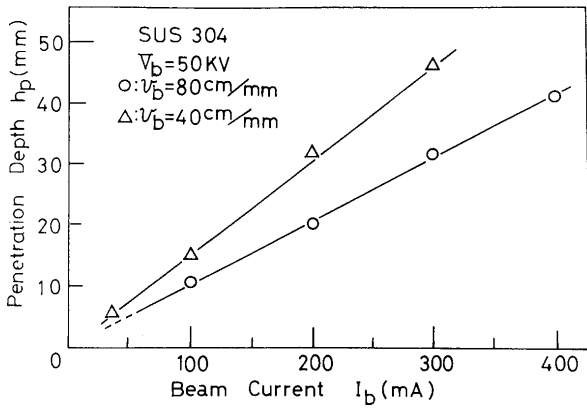


Fig. 17.  $I_b$ - $h_p$  relation; B type-EB apparatus.

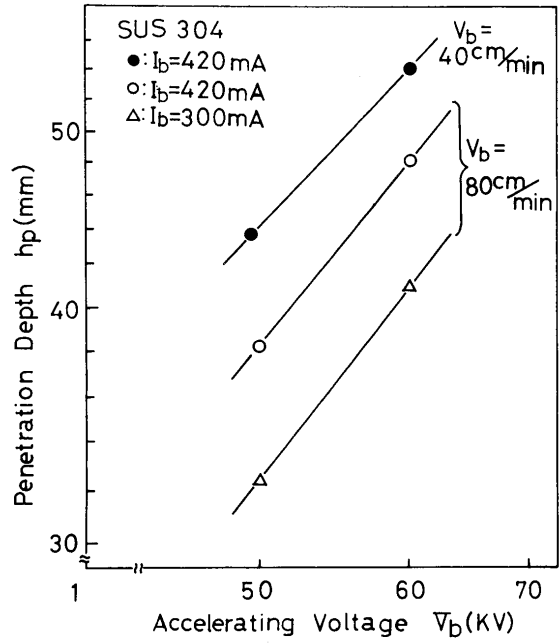


Fig. 19.  $V_b$ - $h_p$  relation; B type-EB apparatus.

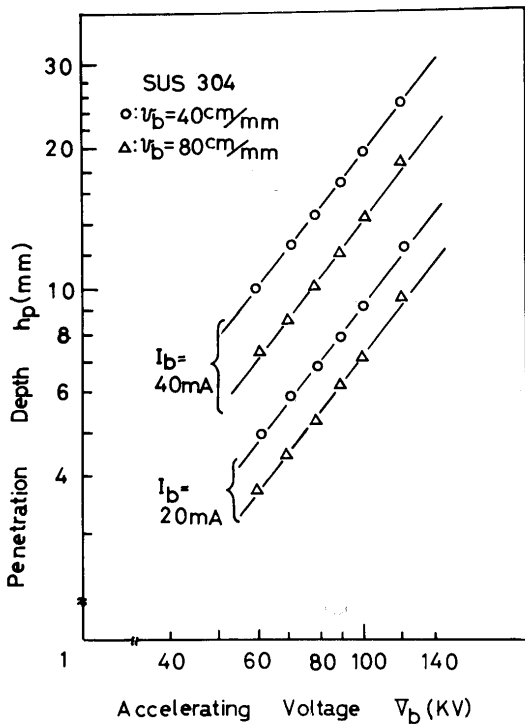


Fig. 18.  $V_b$ - $h_p$  relation; A type-EB apparatus.

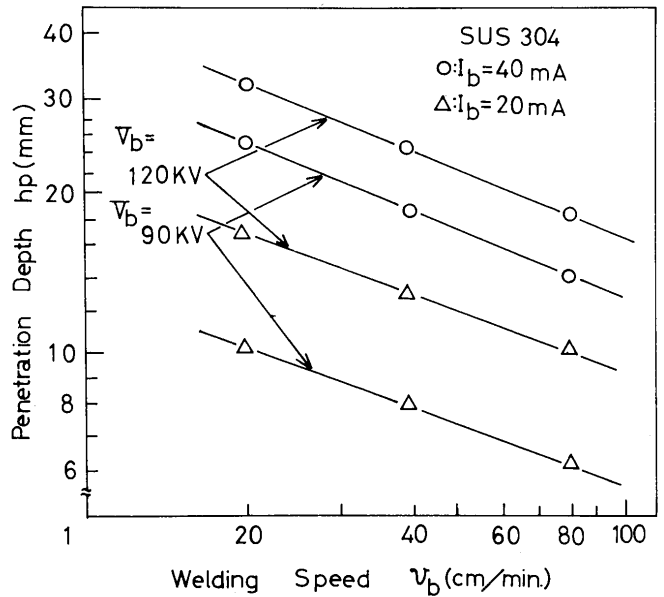


Fig. 20.  $v_p$ - $h_p$  relation; A type-EB apparatus.

B type that  $l_1=1$ ,  $l_2=1.3$  and  $l_3=0.5$ , the following formula establishes within experimented range.

$$h(\epsilon) = \frac{I_b V_b^{1.3}}{v_b^{0.5}} \text{----- (7)}$$

$$\left. \begin{aligned} h_p &= 7.93 \times 10^{-3} \frac{I_b V_b^{1.3}}{v_b^{0.5}} \quad (\text{A type}) \text{----- (a)} \\ &= 5.51 \times 10^{-3} \frac{I_b V_b^{1.3}}{v_b^{0.5}} \quad (\text{B type}) \text{----- (b)} \end{aligned} \right\} \text{(8)}$$

As described above, it is also proved in eq (7) that  $K_m$  depends on both of the materials and EB-welders. Then using EB-welders of A type and B type for SUS-304 stainless steel, it was obtained such as  $K_m=7.93 \times 10^{-3}$  and  $5.51 \times 10^{-3}$  respectively.

Therefore the empirical formula of  $h_p$  becomes as follows.

**Figure 22** shows the relation between calculated value from formula (8), (a) and measured value, and it shows close agreement. Also the calculated result from formula (8), (b) agrees well with the measured value as shown in **Fig. 23**.



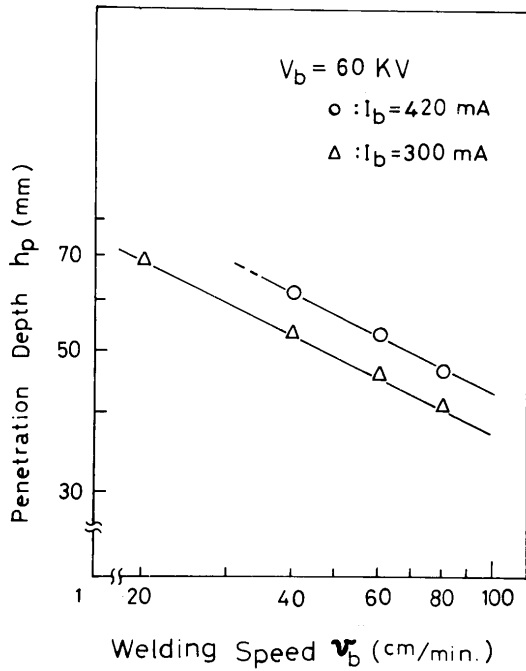


Fig. 21.  $v_b$ - $h_p$  relation; B type-EB apparatus.

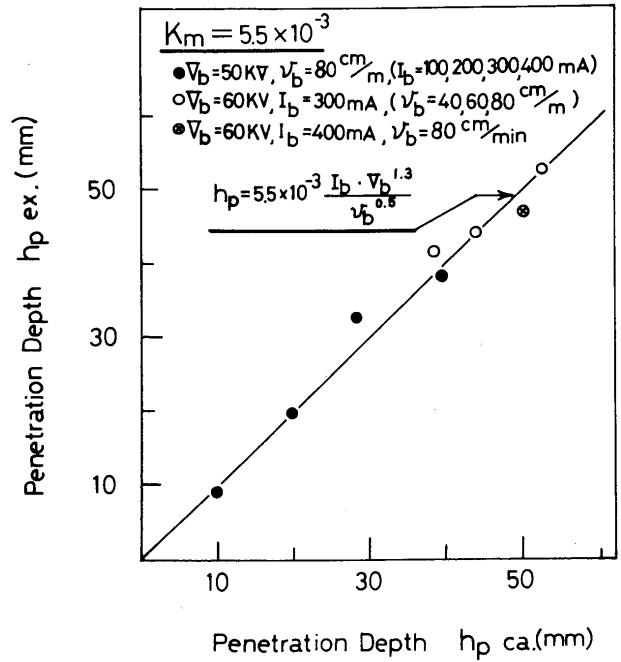


Fig. 23. Correlation between calculated penetration depth and actual depth in case of B type apparatus.

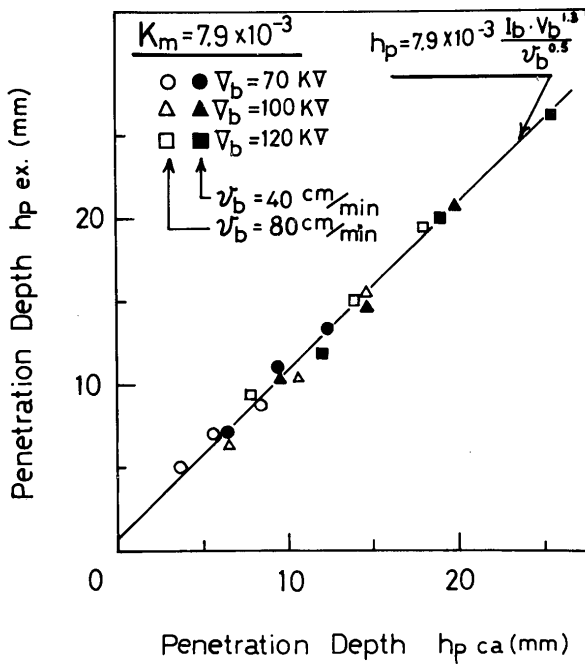


Fig. 22. Correlation between calculated penetration depth and actual depth in case of A type apparatus.

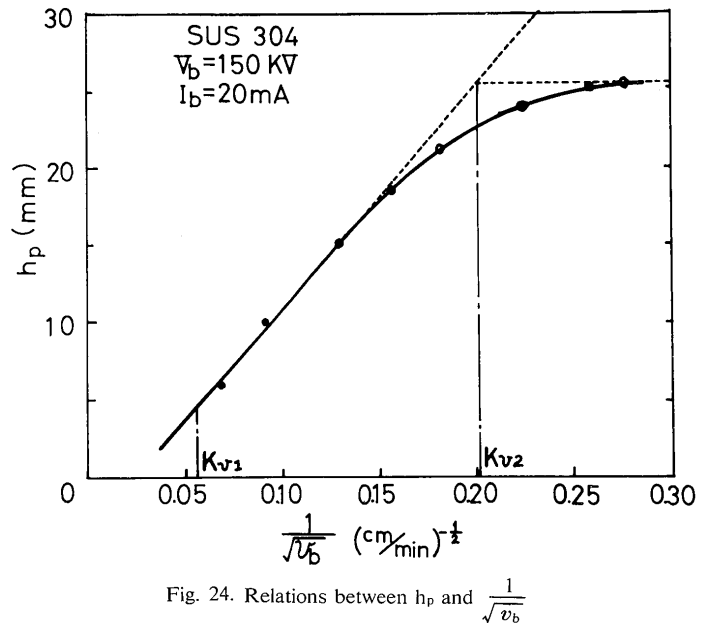


Fig. 24. Relations between  $h_p$  and  $\frac{1}{\sqrt{v_b}}$

However it is noticed that formulas (6) and (8) can only apply within a region  $K_{v1}$   $K_{v2}$  where  $h_p$  is almost proportional against  $1/\sqrt{v_b}$  as shown in Fig. 24, moreover  $K_{v1} \doteq 0.05$  and  $K_{v2} \doteq 0.2$  are obtained in case of SUS304, without regard to the change of weld conditions in most cases. We introduce general formula which can apply in more wide range covered all over the experimented region as shown in Fig. 24. We see that

$$h_p = h_{p0} \left( 1 - e^{-\frac{K_0}{v_b^l}} \right) \text{----- (9)}$$

Where  $h_{p0}$  is  $h_p$  in  $v_b=0$ ,  $K_0$  and  $l$  are constant. If  $v_b$  becomes large ( $1/v_b^l$  is small) and  $K_0/v_b^l \ll 1$  in formula (9), we see that

$$\begin{aligned} h_p &= h_{p0} \left\{ 1 - \left[ 1 + \left( -\frac{K_0}{v_b^l} \right) + \frac{1}{2!} \left( -\frac{K_0}{v_b^l} \right)^2 \right. \right. \\ &\quad \left. \left. + \frac{1}{3!} \left( -\frac{K_0}{v_b^l} \right)^3 + \dots \right] \right\} \text{----- (a)} \\ &\doteq h_{p0} \left\{ 1 - \left( 1 - \frac{K_0}{v_b^l} \right) \right\} = \frac{K_0 h_{p0}}{v_b^l} \text{----- (b)} \end{aligned} \text{--- (10)}$$

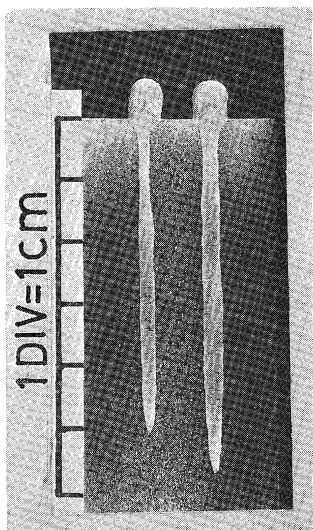


Fig. 25. Bead section at maximum penetration using B type EB-welder  
 (left side ;  $I_b=320$  mA,  $V_b=60$  KV,  $v_b=40$  cm/min )  
 (right side;  $I_b=420$  mA,  $V_b=60$  KV,  $v_b=40$  cm/min)

Here, letting  $l=0.5$ , it is recognized that approximate formula (10), (b) agrees with (6) or (8).

**Figure 25** shows the respective typical bead section photographs at max. penetration part in case that  $I_b=420$  mA and 320 mA against  $V_b=60$  KV and  $v_b=40$  cm/min using B type EB-welder.

#### 4. Conclusion

Obtained conclusion is as follows:

- 1) It was expressed that tungsten, W, is superior as cathode material of the powerful welding electron beam gun.
- 2) W-cathode properties of circle type were investigated and it was shown that the cathode of 30 KW-class electron beam gun which has the life time over 100 Hr. can be obtained.

- 3) Ion beam properties in an electron beam gun were described and beam etching action of the ion beam for cathode material was investigated.
- 4) General formulas for welding penetration using powerful electron beam up to 30 KW-class were given and the empirical formulas were introduced.

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