Energy Density in Cavity during Electron Beam Welding†

Yoshiaki ARATA*, Michio INAGAKI, Tatsuhiko HASHIMOTO** and Hirosada IRIE****

Abstract

It is extremely difficult to know the energy density and its distribution in a beam hole during electron beam welding and no investigation has ever been made.

This report concerns the proposition of the method and the apparatus made as a trial to investigate them.

It proves that the electron beam which penetrates the test piece, forms the beam hole and passes through it has rather higher energy density than the original beam as the result under ordinary condition. It changes according as plate thickness. This fact also proves the "wall focussing effect".

Furthermore, it is clarified that the energy density distribution of electron beam varies in both value and shape even under the same condition of welding and it depends upon various factors of power source of electron beam and structure of electron gun.

1. Introduction

In electron beam welding, narrow and deep fusion zone is obtained because electron beam penetrates into metal through cavity which is made in metal by electron beam evaporating metal or by gas and metal vapor carring. away molten metal. In order to study the mechanism of this welding process, it is very important to know electron beam energy density in the cavity. For this reason, we developed a new apparatus and have been measuring electron beam energy density under various conditions.

In this report, the apparatus, the energy density distribution measured with this apparatus and so on are described and discussed.

2. Apparatus

Up to date, several methods and apparatuses for measuring energy density or diameter of electron beam have been proposed[1~3]. In most of these apparatuses, electron beam is cut by a plane or a rod in X Y-direction and change of current is measured, so that energy density distribution of electron beam in r-direction can not be obtained.

Recently[4),5)] new method "AB test" was developed by Arata and coresearchers in order to measure the effective diameter and also their mean energy density distribution during welding or cutting processing.

We developed a new apparatus, shown the schematic diagram in **Fig. 1.** In this apparatus, a copper disk having six tungsten rods at same interval is revolved by a D. C. motor 1 at high speed (500 to 5000 rpm). The copper disk and the motor 1 are disposed on carriage 1 and able to move in X-direction at very low speed by a D. C. motor 2. Moreover this integrated system is drived by a D. C. motor 3 in Z-direction. By means of the three motors, the tungsten rods

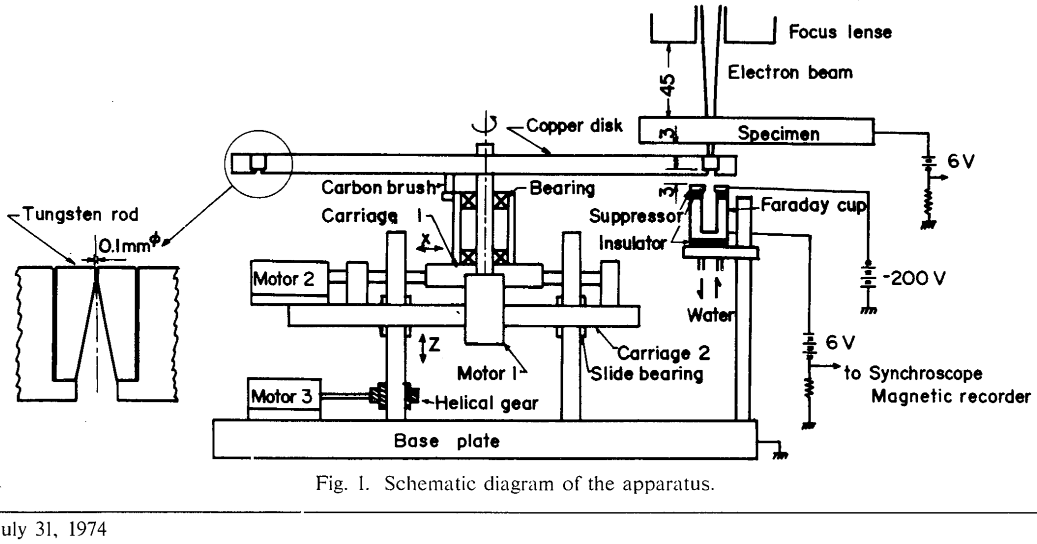

Fig. 1. Schematic diagram of the apparatus.

† Received on July 31, 1974

* Professor

** National Research Institute for Metals, Japan

can be carried accurately to desired position.

At the center of each tungsten rod, a pin-hole (0.1 mm in diameter) is drilled through along the axis, as shown on the left side in Fig. 1, and electron beam can passes through the pin-hole toward the Faraday cup when the pin-hole is right under the electron beam. Position in X and Z-direction of the pin holes is monitored by potentiometers directly connected to the motors.

The Faraday cup is water-cooled and biased 6 volts with respect to ground. A suppressor electrode is disposed on the Faraday cup with an insulator and biased -200 volts with respect to ground so as to suppress secondary and thermal electrons emitted from metal or the Faraday cup. The copper disk is connected directly to ground by means of a carbon brush.

Energy density distribution of electron beam is measured by recording current captured by the Faraday cup with a synchroscope or/and a magnetic recorder connected to a resistance of the Faraday cup. As the frequency range of the magnetic recorder is D. C.$\sim$20 kHz, the revolution rate of the copper disk is arranged so that the frequency of the energy density distribution curve may be less than 20 kHz.

The alignment of the pin-hole with electron beam is always obserbed by the synchroscope. The electron beam welding machine is of type of 30 kV-500 mA welder made by Sciaky and the filament used is of circular ribbon type. Welding voltage is kept at a constant value of 27 kV.

3. Experiments

In order to know the energy density of electron beam in metal, current density of electron beam which passes through mild steels of 13, 20 or 30 mm in thickness or molybdenum rods, at each center of which a hole is drilled through, is measured and compared with those when there is no metal.

1. Characteristics of the welder

The energy density distribution of electron beam is measured under various conditions changing focussing lense current and objective distance to know the characteristics of the welder. A typical density curve measured is shown in **Fig. 2.** This is reproduced by the magnetic recorder and a photo-oscilloscope.

In this welder, the energy density distribution varies even under the same condition. This seems to be resulted from variation in the electric power of this welder, that is to say, the high voltage power source contains some ripple wave of 300 Hz due to three phase full-wave rectification and filtering of 50 Hz power source and also the filament current source

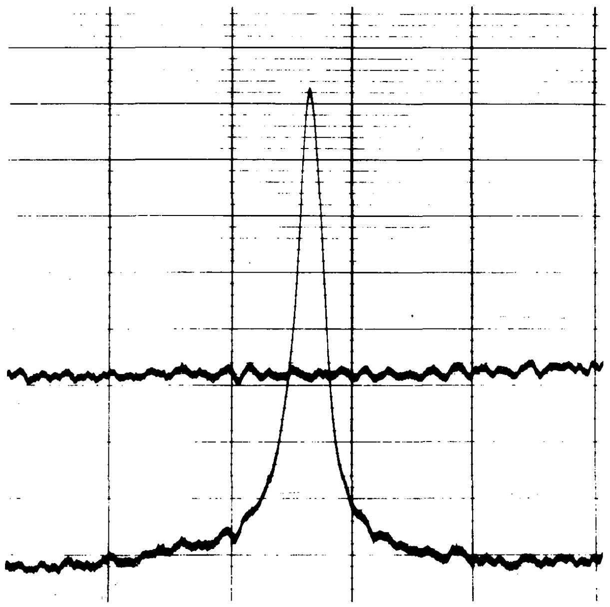

Fig. 2. Typical example of energy density curve.

contains large ripple wave of 300 Hz due to six phase half-wave rectification. So that the beam current measured by the Faraday cup contains ripple wave of 300 Hz by about ± 20 %.

For this reason, in order to obtain the relation between the variations in electron beam energy density and in power source, wave form of energy density distribution is measured with respect to ripple wave of beam current as shown in **Fig. 3.** The wave form becomes of type (a), (b) and (c) when $\theta=\pi/2$, 0 and $-\pi/2$ respectively, where the position of the ripple wave is represented by electric angle---$\theta=\pi/2$ represents the maximum electron beam current. As this result is a typical tendency, the wave form can be of type (a) or/and (b) only under full-ripple wave by choice of lense current and objective distance.

In order to simplify the discussion, we take the condition to be able to obtain wave form of type (a) and (b) in the following experiments.

In **Fig. 4,** the relation between the peak energy density and the angle (position) of the ripple wave of electron beam current is shown. The fluctuation in the peak energy density is very large at small objective distance and decreases with this distance. The peak energy density at larger objective distance, however, still fluctuates. It tends to increase when electron beam current increases (θ approaches to $\pi/2$) and the objective distance decreases, as shown in the above figure. In **Fig. 5,** the maximum peak energy density and its diameters with respect to the objective distance is plotted.

The energy density distribution, however, will be researched in more detail with respect to variation in power source of the welder.

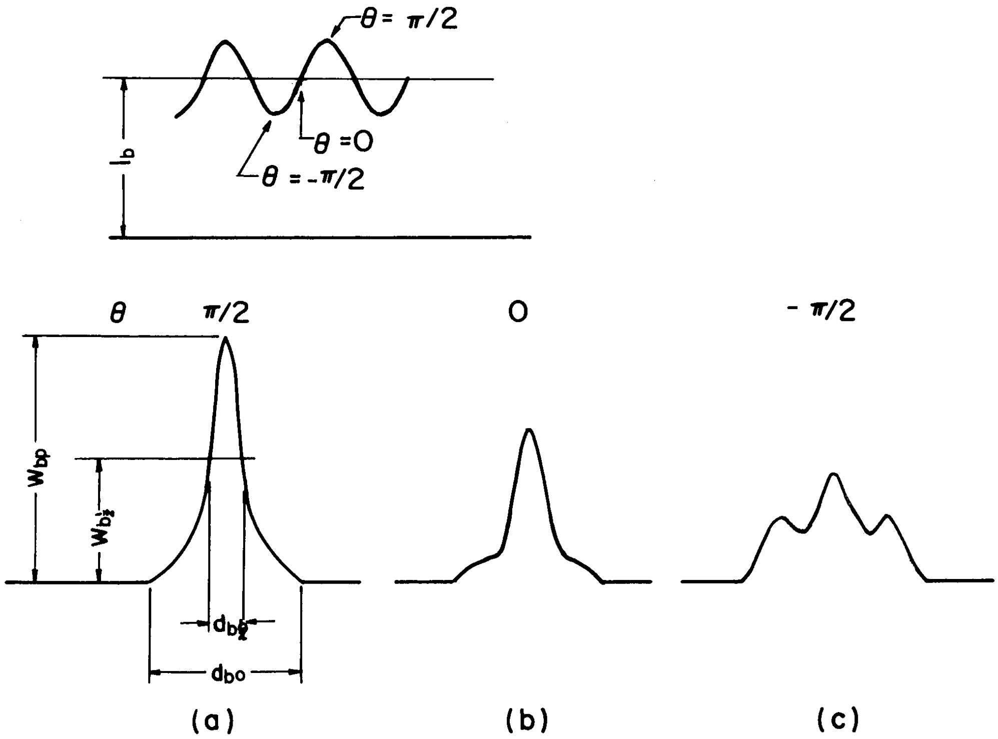

Fig. 3. Relation between shape of energy density curve and ripple wave of electron beam current.

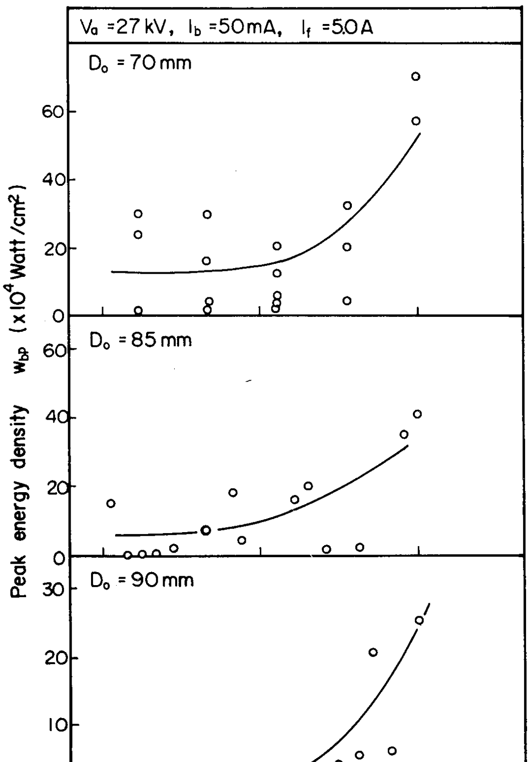

Fig. 4. Relation between peak value of energy density and angle of ripple wave of beam current.

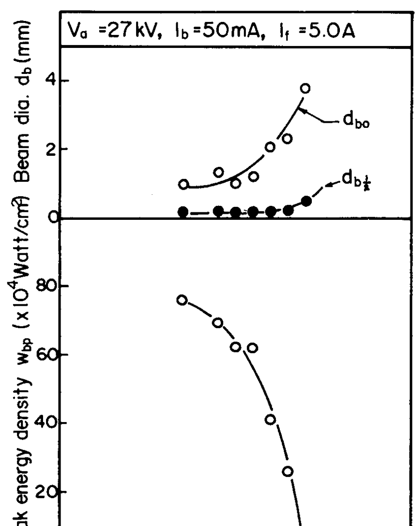

Fig. 5. Maximum peak energy density and beam diameter with respect to objective distance.

2. Energy density in cavity

In order to study the energy density in the cavity of metal, the current distribution of the electron beam impinged on and passes through mild steel at rest is measured.

In **Figs. 6** and **7,** there are shown the ratio of the peak energy density w'_{bp} to that measured in case of no metal w_{bp} and the beam diameter d'_{bo} with the welding time using mild steel of 13 and 20 mm in thickness respectively. Where the peak energy density is calculated from measured value providing that the velocity

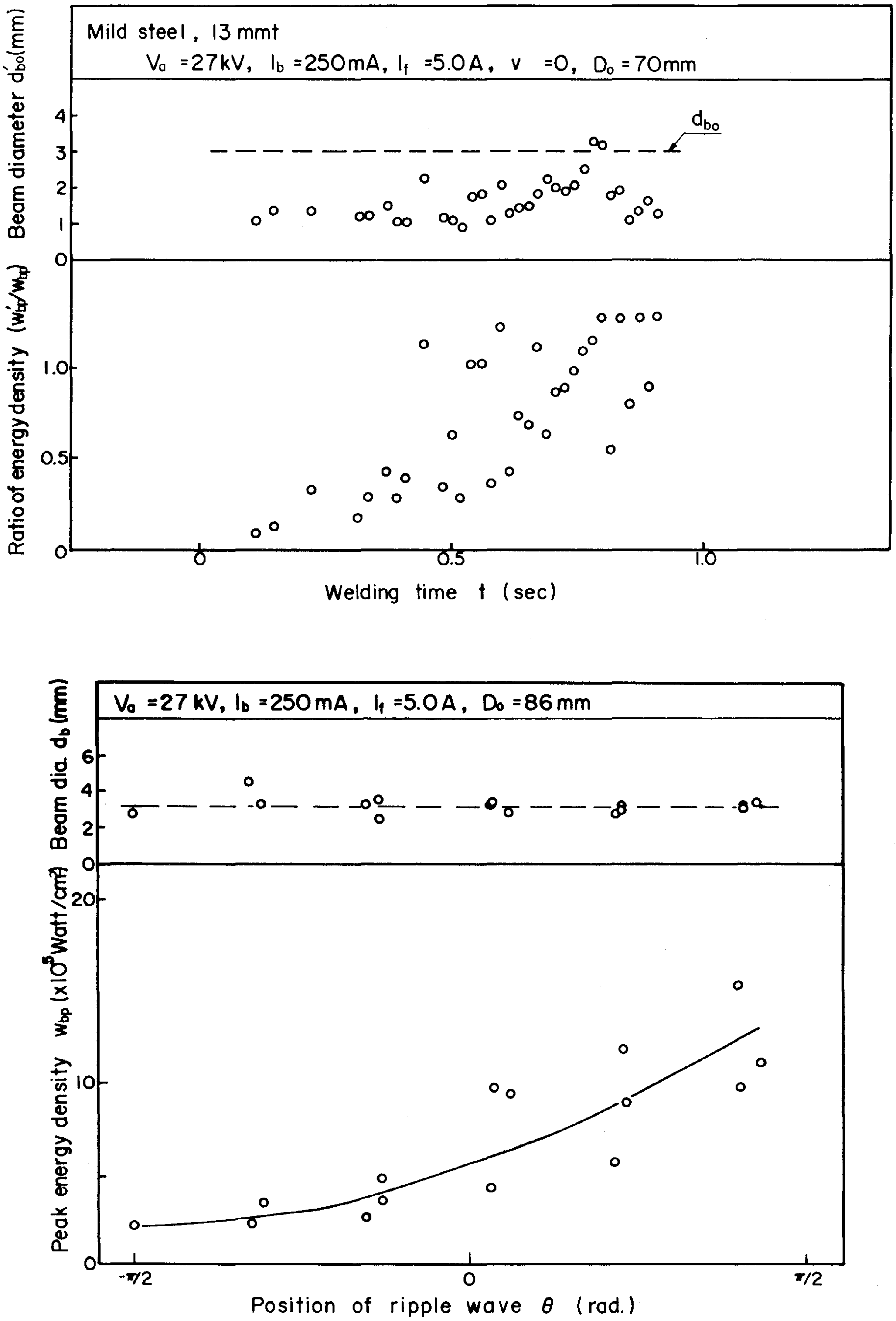

Fig. 6. Energy density and beam diameter of electron beam behind 13 mm thick mild steel (a) corresponding to that in case of no metal (b).

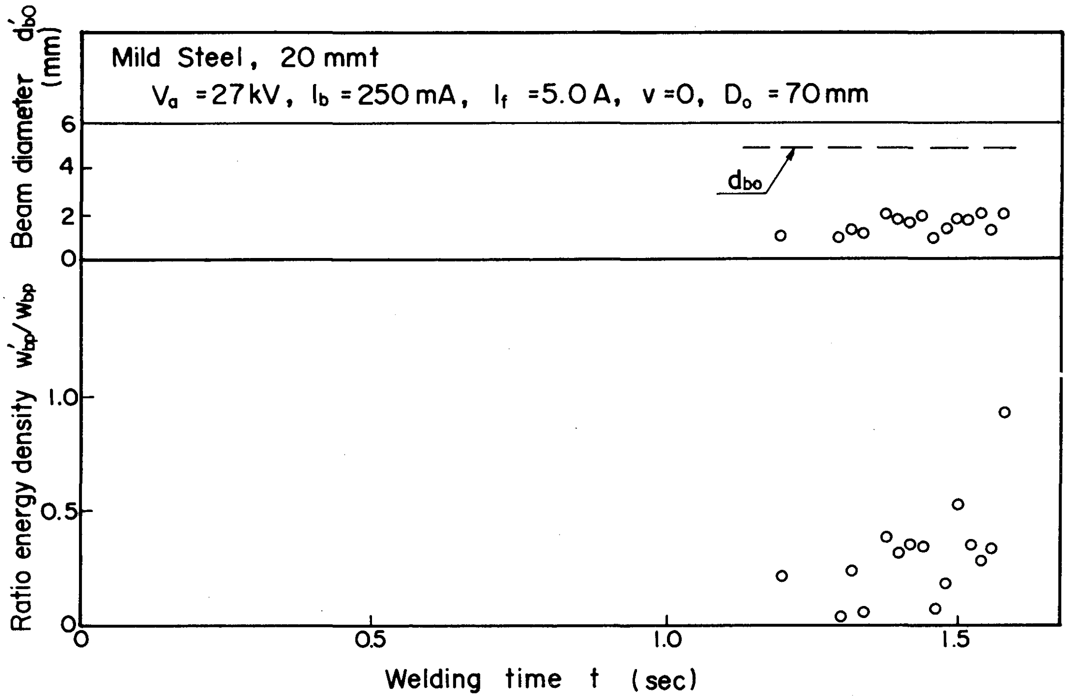

Fig. 7. Energy density and beam diameter behind 20 mm thick mild steel.

of electron is not or hardly disturbed by metal vapors and so on. And to know the value of the peak energy density w'_{bp}, the energy density w_{bp} and the beam diameter d_{bo} are shown in Fig. 6 (b) corresponding to Fig. 6 (a) as a reference.

From these figures, the energy density is much decayed at the earier time of welding. This decay seems to be due to the scattering of electron by metal vapors and gases in the cavity. As the cavity expands with time, the peak energy density increases and often becomes larger than that in case of no metal ($w'_{bp}/w_{bp} > 1$).

On the other hand, the wave form of energy density distribution is drawn in Fig. 8 and the skirt portion of it is cut off by metal.

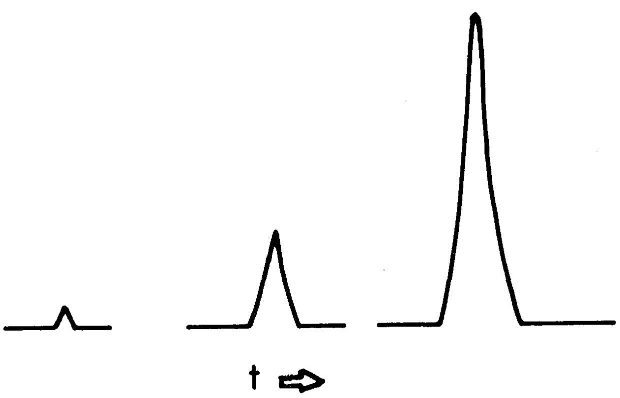

Fig. 8. Energy density distribution curve behind mild steel.

3. Wall-focussing effect

As mentioned above, the peak energy density behind metal is often greater than that in case of no metal. This phenomenon may be resulted from the "wall-focussing" effect, in a similar manner as previously observed in laser welding by one of the authors[6], that is, electron beam is reflected by the wall of the cavity and refocussed. To confirm this effect, the energy density of electron beam which passes through a hole of 1.3 mm diameter drilled through high melting point metal lest the metal should melt is measured.

Results obtained are shown in **Figs. 9, 10** and **11** using molybdenum rods of 5, 9 and 13 mm in height respectively, comparing with the case of direct measuring. In these figures, the peak energy density increases when the electron beam passes through the molybdenum rods of 5 and 9 mm height. The tendency is particularly considerable in case of 9 mm height molybdenum. Moreover, the energy density distribution curve using 13 mm height molybdenum is drawn in **Fig. 12** and the skirt portion swells. From these results, it is confirmed that there is the wall-focussing effect in the cavity.

4. Conclusion

The energy density distribution of electron beams varies in both value and shape even under the same condition of welding and it depends upon various

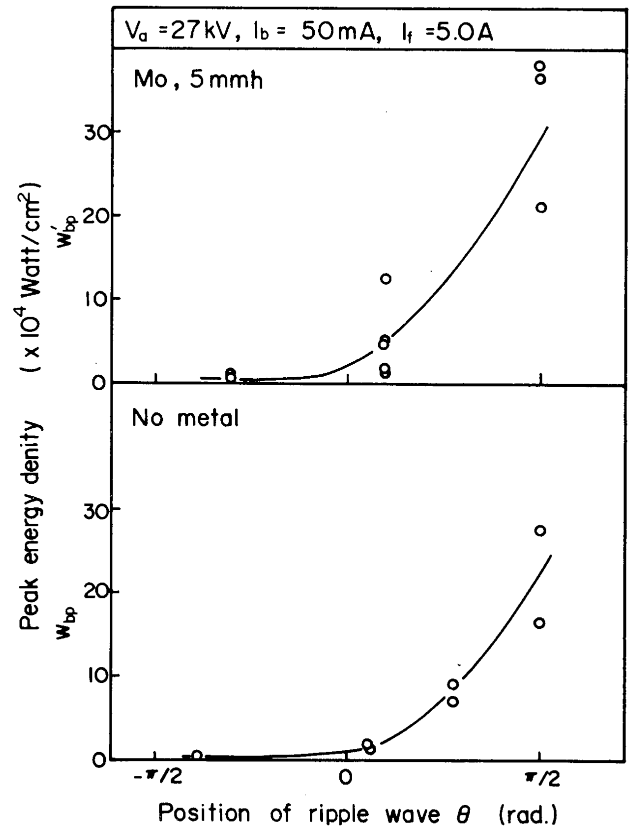

Fig. 9. Energy density of electron beam under 1.3 mm diameter hole of Mo rod of 5 mm height.

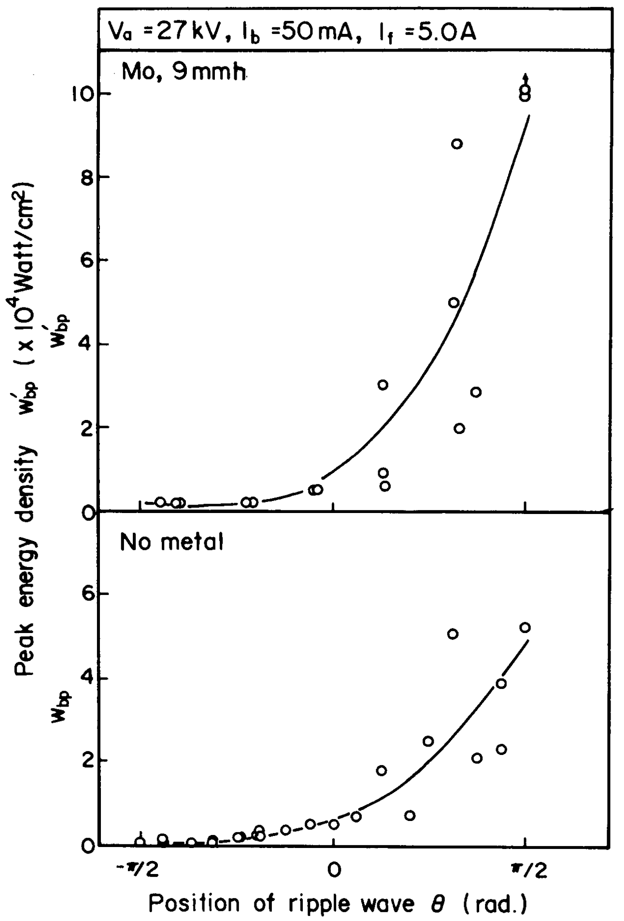

Fig. 10. Energy density of electron beam under 1.3 mm diameter hole of Mo rod of 9 mm height.

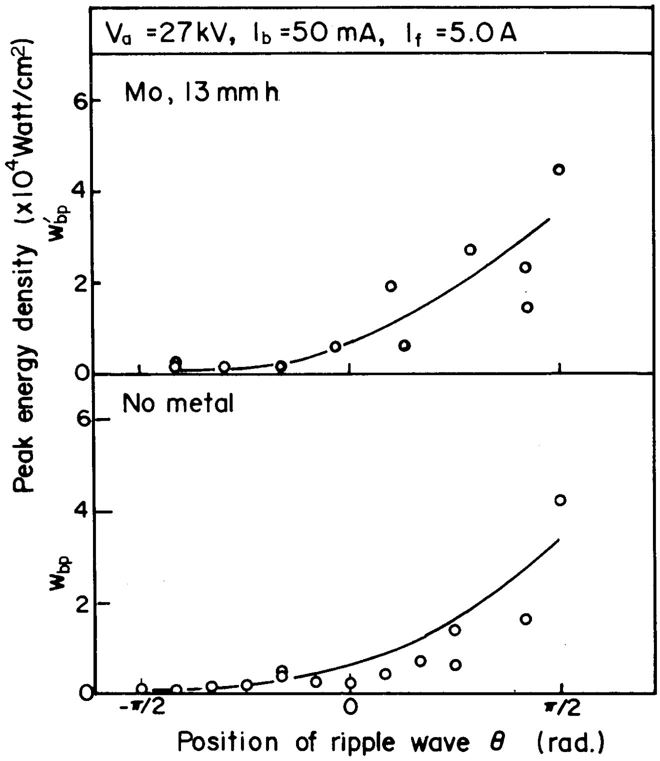

Fig. 11. Energy density of electron beam under 1.3 mm diameter hole of Mo rod of 13 mm height.

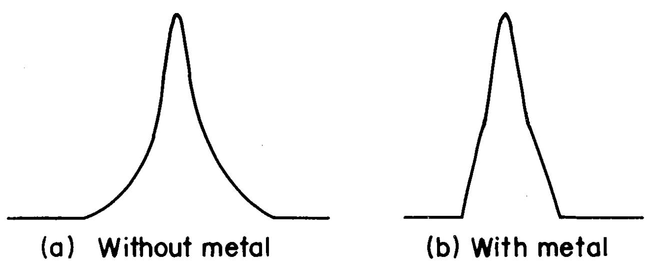

Fig. 12. Energy density distribution using 13 mm height Mo rod.

factors of power source of electron beam and structure of electron gun.

The electron beam in cavity of metal is scattered by metal vapors and gases and at the same time refocussed by the wall-focussing effect.

Acknowledgement

The authors thanks to Mr. I. Yamamoto and Mr. T. Yokogawa, Data Treatment Laboratory, Metal Physics Division, NRIM, for their helpful advices in data treatment of this research.

Nomenclature

V_a ; Accelerating voltage. (Beam voltage)
I_b ; Beam current
I_f ; Focussing lense current
v ; Welding speed

D_o ; Objective distance; the distance between the center of the focussing lense and the impinging point on the workpiece
W_b ; Energy density of electron beam
w_{bp} ; Peak energy density
$w_{b1/2}$; Half value of peak energy density
d_{bo} ; Beam diameter
$d_{b1/2}$; Beam diameter at $w_{b1/2}$
θ ; Position of ripple wave of beam current represented by electric angle

References

1) A. Sanderson; British Welding Journal, Vol. 15, No. 10, p. 509 (1968).
2) D. J. Sandstrom, et al; Welding Journal, Vol. 49, No. 7, p. 293s 1970).
3) P. Dumonte, et al; IIW Boc. IV-131-73 (1984).
4) Y. Arata; Journal of Japan Welding Society; Vol. 41, No. 11 (1972).
5) Y. Arata, K. Terai, H. Nagai and T. Hattori: JWRI, Vol. 2, No. 2 (1973); IIW Doc. IV-114-73, (1973).
6) Y. Arata and I. Miyamoto: Trans. JWRI, Vol. 2, No. 2 (1973).