Title	Electron Beam Melting of Aluminum Alloy by Beam Oscillation(Physics, Process, Instrument & Measurement)
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Citation	Transactions of JWRI. 20(1) P.17-P.20
Issue Date	1991-06
Text Version	publisher
URL	http://hdl.handle.net/11094/6689
DOI	
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Electron Beam Melting of Aluminum Alloy by Beam Oscillation†

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Abstract

The fundamental characteristics of electron beam melting of low-melting point metals such as aluminum alloy were studied utilizing a prototype of a beam oscillation pattern input system which allows the electron beam to be freely controlled. Observations on the melting phenomena of a specimen of aluminum alloy were made at various beam currents, beam scanning frequencies and beam oscillation patterns. The optimum melting conditions, with a constant capacity evacuation system, were a beam scanning frequency of approximately 10 Hz, at which the quantity of metal vapor generated per unit time was small, and a beam output no higher than the level at which the beam penetrates the specimen. To apply the beam energy as effectively as possible, the molten surface should not be repeatedly scanned and the oscillation pattern should not result in heating the molten pool.

KEY WORDS: (Beam Oscillation)(Electron Beam)(Melting)(Aluminum Alloy)

1. Introduction

At present, electron beams are being used to melt high-melting point metals and highly reactive metals[1,2], but very rarely is an electron beam applied to low-melting point metals such as aluminum alloy. While, when some spongy active metals such as Ti or Zr are molten, there are serious problems on the supply of a feed metal to a melting vessel, that is, the yield of the molten metal is reduced due to the dispersion of droplets, or the granular molten metal is deposited on the areas around the supply port due to the dispersion of droplets or radiant heat from the molten metal.

This paper describes fundamental studies on melting of aluminum alloy with an electron beam. One of the advantages of an electron beam heat source is that the path of the beam or beam scanning can be controlled at high speeds with high accuracy using an electromagnetic system at the outlet of the electron gun. A prototype of a beam oscillation pattern input system that permits free control of the electron beam was developed, and the melting phenomena were observed when the beam was irradiated on a specimen of aluminum alloy at various beam scanning speeds and beam oscillation patterns.

2. Experimental Procedure

The chemical composition of Al-Si-Mg aluminum alloy used in the experiments is shown in **Table 1**. The size of the specimen was $\phi 30$ mm$\times$30 mm. As the heat source for melting, a 30 kW electron beam welding apparatus was used. A schematic diagram of the experimental apparatus is shown in **Fig. 1**. By inputting a specific beam oscillation pattern into a computer, the specimen in a pot was melted while the location of the beam on the surface of the specimen was varied at different preset speeds using the magnetic field of deflecting coils. To determine melting times, a C/A thermocouple was attached to the bottom center of the specimen to measure the temperature of the specimen.

At first, a simple scanning pattern was applied to investigate the effect of the scanning frequency, i.e. the scanning speed, on the melting phenomena. Electric currents I_x and

Table 1 Chemical Composition of Al-Si-Mg Aluminum Alloy used in the Experiments.

(wt%)

Al	Cu	Si	Mg	Zn	Fe	Ti
92.307	0.108	6.97	0.32	0.003	0.142	0.150

† Received on May 13, 1991

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

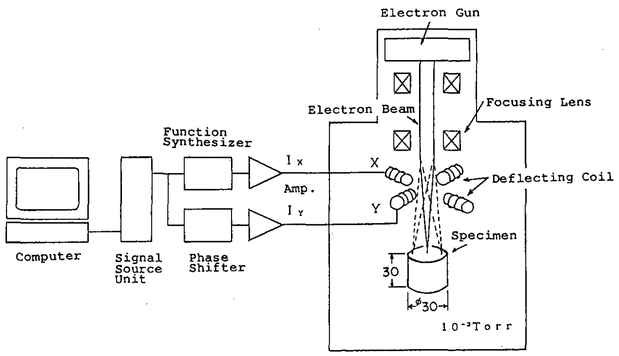

Fig. 1 Schematic Diagram of Experimental Apparatus.

I_y having a sine waveform were generated for scanning the beam at a certain frequency, and the phase difference was varied sequentially to form the oscillation patterns as shown in **Fig. 2**.

Then, the effect of beam oscillation on the melting depth and the phenomena of molten surface was studied by using the oscillation patterns shown in **Fig. 3**. The beam oscillation parameters were radial waveform, radial scanning frequency and rotational frequency. The beam speed in a radial direction was controlled by varying the radial waveform and frequency. In this report, the rotational frequency was set at 0.1 Hz.

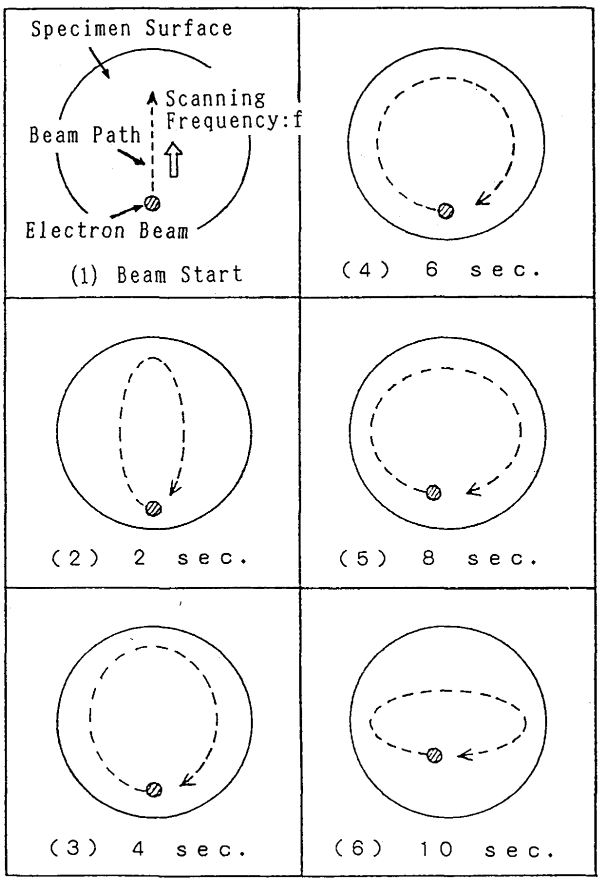

Fig. 2 Beam Oscillation Patterns to Observe Effect of Beam Scanning Frequency on Melting Phenomena.

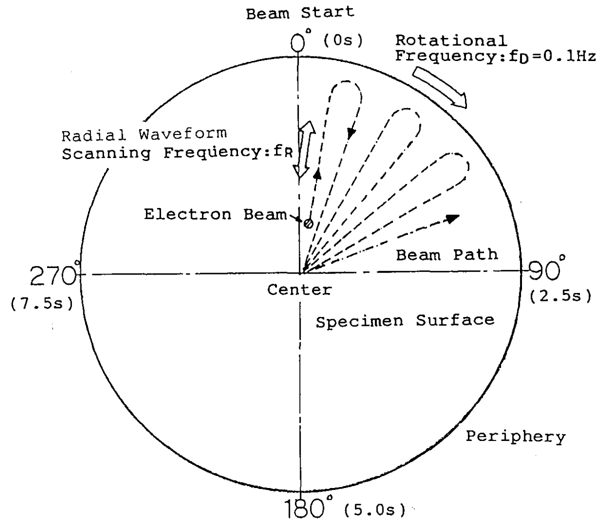

Fig. 3 Beam Oscillation Patterns to Observe Effect of Beam Oscillation Pattern on Melting Phenomena.

3. Results and Discussion

3.1 Effect of Beam Scanning Frequency

The effect of beam scanning frequency on the melting phenomena with the oscillation pattern illustrated in Fig. 2 was studied.

The relation between the beam scanning frequency f and the melting state is shown in **Fig. 4** at $V_b = 70$ kV, $a_b = 1.0$ and beam current was 50 mA, 80 mA and 100 mA. The typical results of the observation of melting phenomena using a high speed VTR are shown in **Fig. 5**. When there was no beam oscillation (scanning frequency f=0), the specimen was molten from its center, on which the beam was irradiated, to its periphery due to heat transfer as shown in Fig. 5(1). The melting time in no beam oscilla-

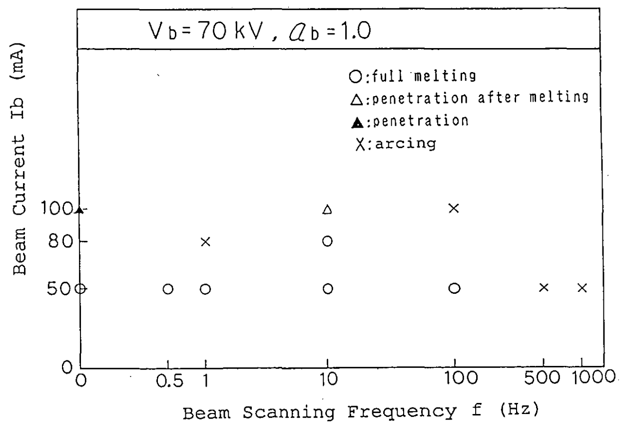

Fig. 4 Relation between Beam Scanning Frequency and Melting Condition.

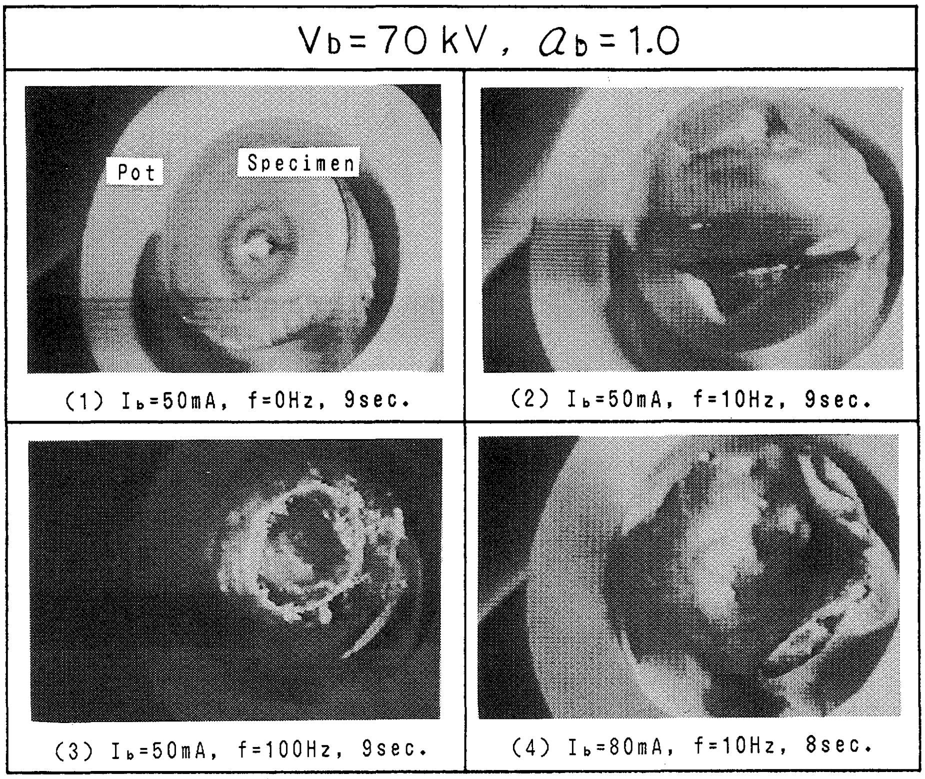

Fig. 5 Melting Condition with Beam Oscillation.

tion was 21 seconds.

When the beam was oscillated with the same beam current of 50 mA and the scanning frequency was increased to 1 Hz and 10 Hz, the melting time was reduced to approximately 15 and 10 seconds respectively. When the scanning frequency was 10 Hz and the beam current was increased from 50 mA to 80 mA and 100 mA, it was found that the molten metal tended to move away from the point irradiated by the beam to the outer circumference as shown in Fig. 5(2) and (4).

With a beam current of 50 mA and a scanning frequency of 100 Hz, there was severe spattering during melting as shown in Fig. 5(3) and a large quantity of metal vapor was generated. With a scanning frequency of over 500 Hz, arcing was caused inside the electron gun at the initial stage of melting and the beam was stopped. This was presumably caused by rapid expansion of the molten area within a very short time as the scanning frequency was increased, so that a large quantity of metal vapor was generated per unit time.

Based on these observations, with the constant capacity of the evacuation system, the optimum scanning parameters are a scanning frequency f of approximately 10 Hz, where only a small quantity of metal vapor is generated per unit time, and a beam current I_b less than the level at which it penetrates the specimen.

3.2 Effect of Beam Oscillation Pattern

In order to melt the specimen more rapidly and uniformly, the oscillation pattern illustrated in Fig. 3 was applied. The radial beam speed was varied for the three waveforms shown in **Fig. 6** to change the energy density distribution applied to the specimen in order to investigate the effect of beam oscillation pattern on the melting phenomena. The beam irradiation conditions were as follows: acceleration voltage $V_b = 70$ kV, beam current $I_b = 20$ mA, $\alpha_b = 1.0$, radial frequency $f_R = 10$ Hz, rotational frequency $f_D = 0.1$ Hz, and the beam rotation was one cycle. The specimen was then cut at a point of 180° from where the beam was started to observe the melting profile for that section. As

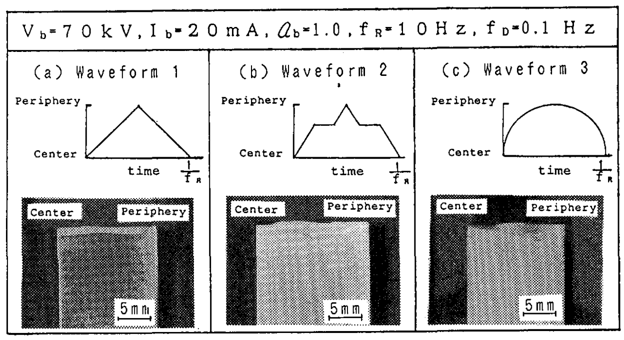

Fig. 6 Relation between Radial Waveform and Melting Profile.
(a) Waveform 1
(b) Waveform 2
(c) Waveform 3

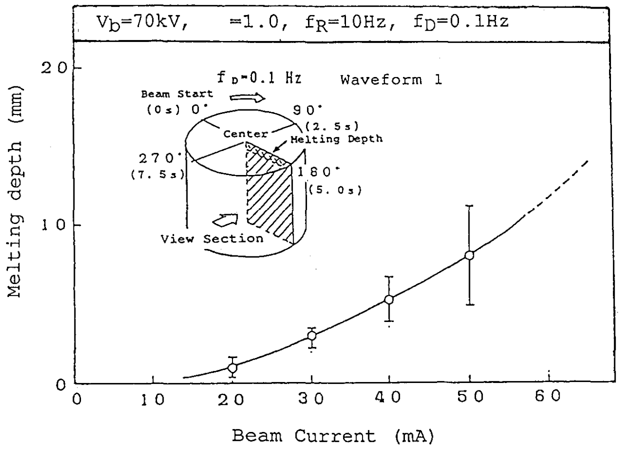

Fig. 7 Relation between Beam Current and Melting Depth.

shown in Fig. 6, for Waveform 1 in which the radial beam speed was constant, a uniform melting profile was obtained, while for Waveform 2 in which the beam resided for a time after moving two-thirds of the distance from the center of the specimen, there was deeper melting at this location. For Waveform 3 in which the beam speed decreased as it approached the periphery, the melting became deeper at these outer areas. Thus, the beam speed corresponds well with the melting profile, so it is possible to freely control the melting depth by inputting a suitable waveform.

Using Waveform 1, which made a uniform melting depth, the radial scanning frequency f_R was varied from 5 Hz to 10 Hz and 20 Hz, and the molten surface was observed. When the scanning frequency was 5 Hz and 10 Hz, the molten surface was relatively flat and smooth, but when it was increased to 20 Hz, the molten surface became significantly disturbed. Using Waveform 1, the beam current was varied at a scanning frequency of 10 Hz to investigate the effect on the melting depth. As shown in **Fig. 7**, the melting depth was increased linearly as the beam current was increased from 20 mA to 50 mA. At the beam irradiation conditions of acceleration voltage $V_b = 70$ kV, beam current $I_b = 50$ mA, $a_b = 1.0$, radial frequency $f_R = 10$ Hz and rotational frequency $f_D = 0.1$ Hz, spattering was not observed and the molten surface during the melting was always stable.

If the oscillation patterns in Figs. 2 and 3 are compared, the beam hole was successively filled with molten metal in the Fig. 2 oscillation pattern, where the beam repeatedly heated the surface of the molten pool and could not penetrate deeper without a large quantity of metal vapor. On the other hand, in the Fig. 3 Oscillation pattern, the circumferentially moving beam always melted the undissolved areas of the surface of the specimen, where the beam could penetrate deeper than in the former pattern.

In order to achieve rapid melting without spattering, it must be required to select an oscillation pattern in which the beam can penetrate the specimen sufficiently utilizing its energy effectively to the melting.

4. Conclusion

The melting phenomena were investigated when the aluminum alloy specimen of $\phi 30$ mm $\times 30$ mm was irradiated with an electron beam at various beam scanning speeds and beam oscillation patterns.

Main conclusions obtained are as follows:

(1) The optimum scanning parameters are considered to be a scanning frequency of approximately 10 Hz, where only a small quantity of metal vapor is generated per unit time, and a beam current less than that at which the beam penetrates the specimen.

(2) To make effective use of the beam energy for melting, the beam should not scan repeatedly over the molten surface and should not heat the surface of the molten pool too much.

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