Observation of Molten Metal Flow during EB Welding†

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Abstract

Observation of molten metal flow during electron beam welding was successfully carried out using a tungsten particle tracer and the transmission X-ray method. Molten metal flow was found to be strongly influenced by fluctuation of the beam hole. After excluding the influence of the beam hole, 4 simple patterns of molten metal flow were extracted.

KEY WORDS: (EB Welding) (Dynamic Observation) (Molten Metal Flow) (Tungsten Tracer) (Transmission X-ray Method)

1. Introduction

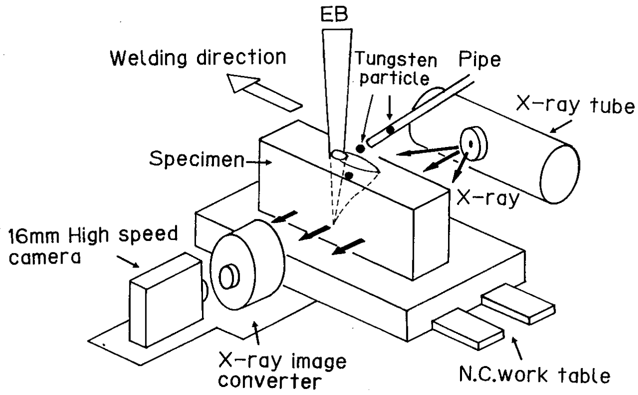
In order to clarify the phenomena which occur during electron beam welding the authors have performed experiments to observe the dynamic behavior in the molten pool. The behavior of the beam hole, particularly its front wall, has been observed by employing the transmission X-ray method[1,2] or beam hole X-ray method[3]. Through these observation the mechanism which determines the size and shape of both the beam hole and front wall and their time dependence has been analyzed. As a result, the relation between beam hole behavior and the occurrence of defects in welding was revealed.

Although the behavior of the molten metal which is also directly related to the welding characteristics and occurrence of defects, this behavior could not be clarified using the X-ray method because the absorptivity of the solid and molten metal is the same.

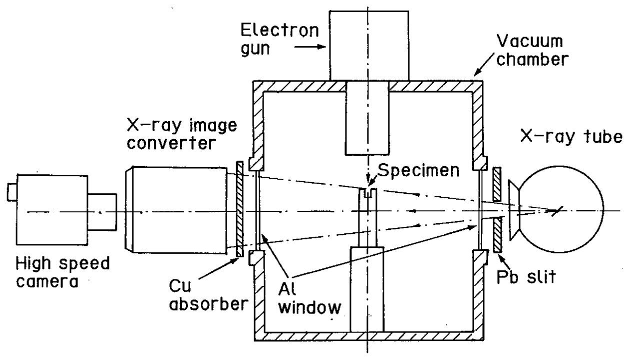
One possible way to overcome this limitation and allow visualization of the molten metal flow is to put a tracer into the molten pool which has a different X-ray absorptivity than the molten metal[4]. A tracer with a low melting temperature, however, will melt and diffuse in the molten pool. For this reason, the authors chose small particles of tungsten to use as a tracer in this report. The molten metal flow of stainless steel was visualized during EB welding by tracing the tungsten particles dropped into the molten pool using the transmission X-ray method.

2. Experimental Apparatus

Figure 1 (a) shows the schematic diagram of experimental apparatus. The X-rays emitted from the X-ray tube on the right transmit a specimen set in the center of the vacuum chamber, then impinge onto an X-ray image converter in which they are converted into visible images which appear on the fluorescent screen of the converter. These images are filmed with a high speed camera set behind the converter. During welding, tungsten particles with a diameter of 0.8 mm were dropped through a stainless steel pipe set above the specimen into the molten pool at the rear side of beam hole.



(a)



(b)

Fig. 1 Schematic diagram of experimental apparatus.

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In order to obtain an image of sufficiently high quality, some improvements were made on the experimental apparatus as shown in Fig. 1 (b). A thin aluminum plate (0.1 mmt) was used in place of the X-ray window of the vacuum chamber. An adjustable lead slit was set in front of the X-ray tube so that only the region to be melted was irradiated in order to reduce the influence of scattered X-rays which degrade the resolution and contrast of the image.

In addition, a copper plate of 0.6 mm thick was placed in front of the image converter to absorb the beam hole X-rays, since they considerably reduce the resolution and contrast of the image. The specimens used were 300 mm in length and 50 mm thick. Their width was 10 mm in the direction of X-ray irradiation. The welding parameters and the X-ray irradiation conditions are shown in Table 1.

Table 1 Experimental conditions.

Material	SUS304
Beam Current (mA)	150
Accelerating Voltage (kV)	40
Welding Speed (cm/min)	30
a_b Value	1.1
X-ray Tube Voltage (kVp)	200
X-ray Tube Current (mA)	3.5
Filming Rate (fps)	100

3. Results and Discussion

Figure 2 is a sketch of a photograph obtained on 16 mm X-ray film showing the position of the tungsten particles in the molten pool. The beam hole can be seen in the center and the tungsten particles appear as black spots in the photograph.

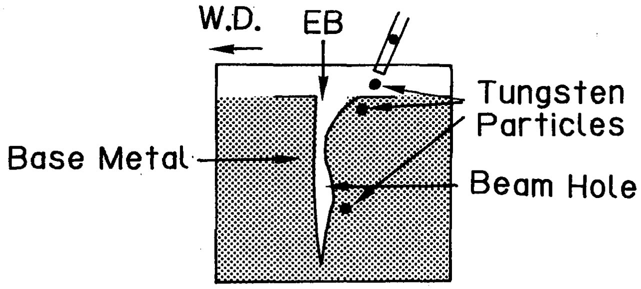

Fig. 2 Sketch of X-ray photograph.

Figure 3 shows the behavior for SUS 304 stainless steel of 0.1 second interval. The beam hole behavior is rather subdued compared with the other materials. The movement of the tungsten particles is rather complicated, however, and they move up and down in complex paths, and the particles usually remained trapped at the bottom of the molten pool as shown in **Fig. 4**, which shows an example of particle movement traced from beginning to end. In the example the tungsten particle was dropped into the molten pool near the beam hole. The broken lines show the fluctuation of the beam hole. It is thought that the complex behavior of the tungsten particles is influenced by fluctuation of the beam hole.

In order to simplify the complex trace of the tungsten particles, film analysis was performed. The X-ray images were input into a microcomputer with a digitizer in order to analyze the beam hole shape and the position of the tungsten particles. **Figure 5** shows a series of figures plotted by the computer showing the correlation between changes in the beam hole shape and the position of one of the tungsten particles at 0.1 second intervals from frame number 1 to 100. The broken line is the path the tungsten particle moving during each 0.1 second interval. It can be seen that the position of the tungsten particle is greatly influenced by the fluctuation of the beam hole. This can be seen move clearly in frames 30 and 31, where the

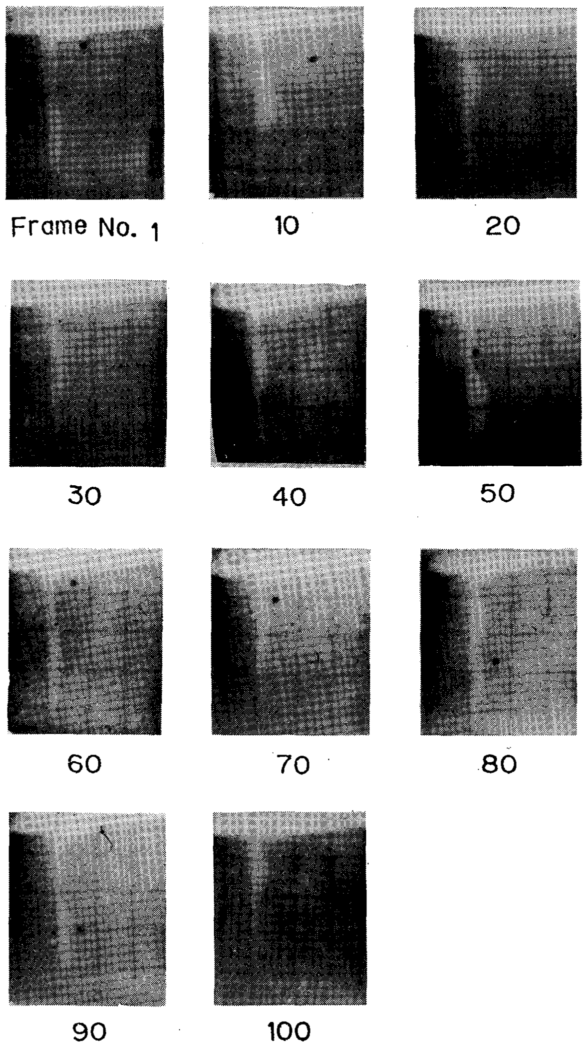

Fig. 3 Photographs reproduced from an X-ray movie showing a tungsten particle's motion in the molten pool of SUS304 in 0.1 second interval.

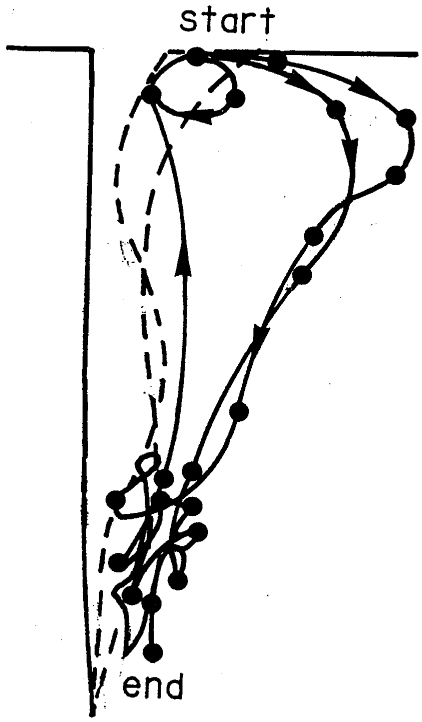

Fig. 4 An example of trace of a tungsten particle plotted in 0.05 second interval.

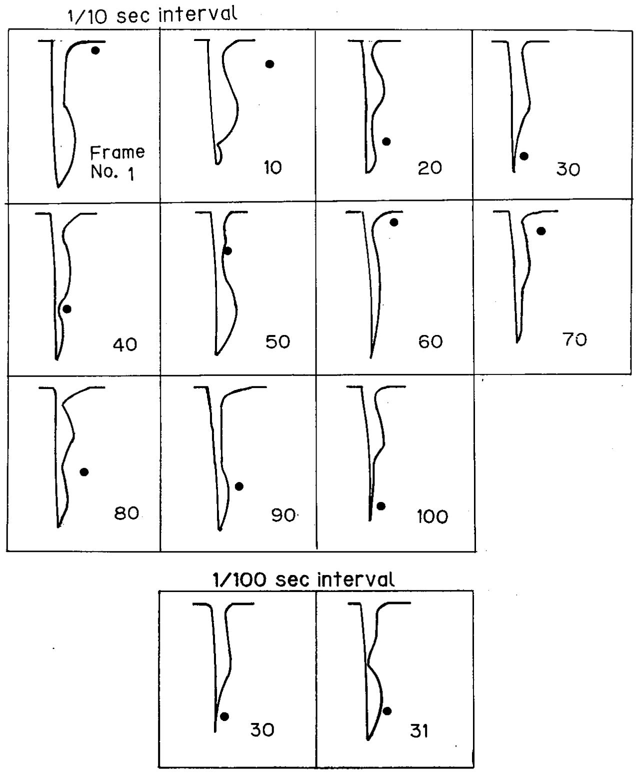

Fig. 5 Correlation between changes in the beam hole shape and the position of one of the tungsten particles.

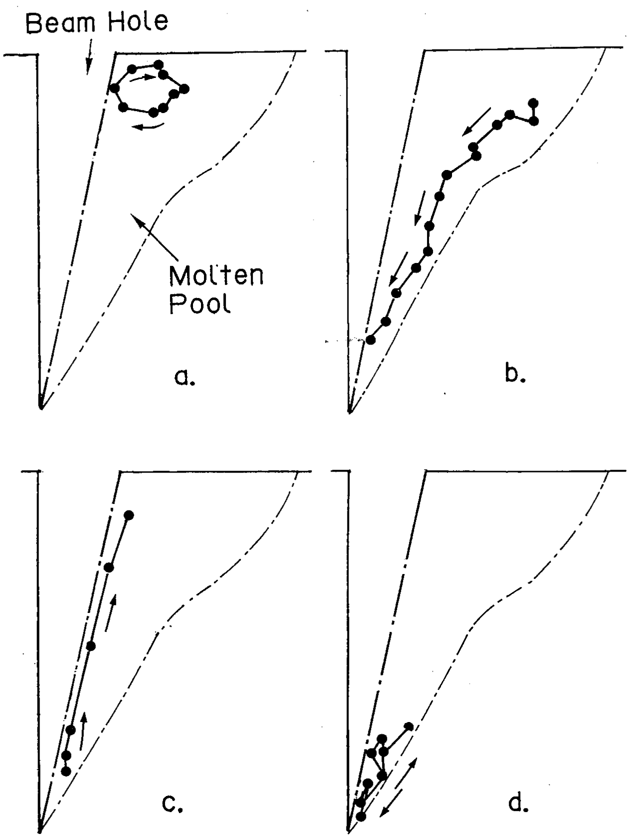

Fig. 6 Trace of tungsten particle after subtraction of beam hole fluctuation.

movement is shown over an interval of 0.01 second. Although the beam hole greatly expands in size and the tungsten particle seems to move a long distance, it actually remains near the rear surface of the beam hole and only moves slightly upwards relative to the rear surface of the beam hole. The motion of the tungsten particle is thus considered to be a mixture of the particle's motion as influenced by the fluctuation of the beam hole and the molten metal flow itself.

In order to remove the influence of beam hole fluctuation, the distance from the rear wall of the beam hole to the tungsten particle was calculated by computer and plotted for every picture taken at 1/100th of a second. **Figure 6** shows the results of this procedure. After subtracting for beam hole fluctuation, the path of the tungsten particle becomes greatly simplified. Analyzing the traces of tungsten particles, it is found that there are 4 simple patterns of molten metal flow. **Figure 7** (a) shows a slow rotational flow in the upper part of molten pool. As shown in Fig. 7 (b), there is also a flow pattern in which there is flow from the rear of the upper part of the molten pool to the lower part, gradually nearing the beam hole. A third flow pattern is a very fast upward flow near the rear wall of the beam hole, as shown in Fig. 7 (c). In this pattern, when the tungsten particle moves away from the rear wall, it moves downward following the downward flow shown in Fig. 7 (b). Finally, in the bottom part of the molten pool, the particle describes a very complicated path near the beam hole, where it is usually trapped as shown in Fig. 7 (d). This

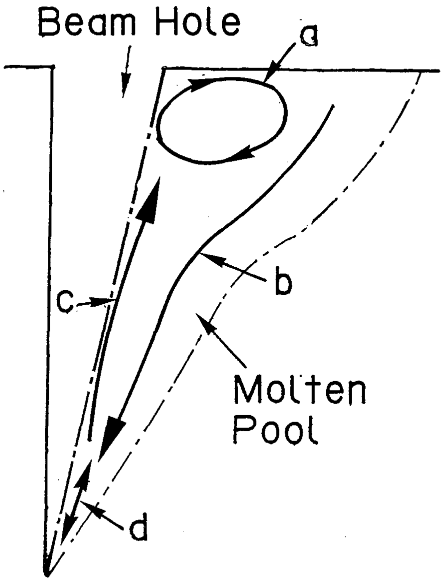

Fig. 7 Molten metal flow patterns.

means that there is only a small amount of molten metal in that area.

4. Conclusion

Observation of molten metal flow during electron beam welding was successfully performed for stainless steel by tracing tungsten particles using the transmission X-ray method.

The motion of the tungsten particles in the molten pool was found to be greatly influenced by the fluctuation of the beam hole. In order to clarify the apparently complicated behavior of the particle, film motion analysis was carried out to cancel the fluctuation of the beam hole. The molten metal flow without the influence of beam hole fluctuation could then be classified into 4 simple patterns; a simple circulating pattern at upper part of the molten pool; a fast downward flow at the rear of the molten pool; a very fast upward flow near the rear surface of the beam hole; and a violent flow near the bottom of the molten pool.

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