Penetration Mechanisms of Electron Beam Welding and the Spiking Phenomenon

The x-ray pinhole movie camera technique is used to reveal beam-metal interactions and the spiking phenomenon

BY G. L. MARA, E. R. FUNK, R. C. MCMASTER AND P. E. PENCE

ABSTRACT. A refinement of the x-ray pinhole movie camera technique is used to continually monitor the EB weld process using a combination of parameters and materials. A comparison of full penetration and partial penetration welding is made, as well as an examination of the effects of beam power density. Periods of spiking are clearly revealed and a means whereby spiking might be reduced is proposed.

G. L. MARA is Research Engineer, Lawrence Livermore Laboratories, Livermore, CA. E. R. FUNK is Associate Professor, R. C. MCMASTER is Regents Professor and P. E. PENCE is Engineering Technician, Welding Department, Ohio State University, Columbus, Ohio.

Introduction

The electron beam welding process has provided a new dimension in joining technology because of its ability to generate welds with large penetration depth to width ratios, but associated with this ability are unique weld defects — cold shuts, root porosity, and spiking. These defects have been linked with the dynamic nature of the weld cavity, but prior to the development of the x-ray pinhole camera (Ref. 1), which provides for continuous monitoring of points of beam impingement, the dynamic nature of the beam-metal interactions had escaped observation. This technique is applied to a number of materials and weld parameters in order to develop a basic understanding of electron beam welding and the spiking phenomenon.

Experimental Procedure

The x-ray pinhole movie camera records the position of x-rays generated as the electron beam interacts with the material within the weld cavity during welding. Depending on the point of beam impingement, a region on the rapidly moving x-ray film (typically 1.5 m/sec) is exposed, Fig. 1. The result is a high speed "smear picture" which accurately gives time related information on points of electron beam impingement. The time information is provided by a series of timing light dots produced on the film by pulsing a neon bulb at 50 millisecond intervals. The film used to re-

Table 1 — Experimental Parameters, Objectives and Data

Weld	Material	Thickness, cm	Voltage, kV	Current, mA	Approx. beam area × 10^{-2} mm^2	Welding speed, cm/sec	Objective	Weld specimen	Beam-metal interactions
1	2024 Al	0.952	122	10	5	0.88	Record beam-metal interaction in 2024 Al	Fig. 3	Fig. 4
2	1100 Al	0.952	123	10	5	0.88	Record beam-metal interaction in 1100 Al	Fig. 5	Fig. 6
3	7075 Al	1.27	126	10	5	0.88	Record beam-metal interaction in 7075 Al	Fig. 7	Fig. 8 Fig. 9
4	7075 Al	0.952	120	10	11	0	Record effect of welding speed on beam-metal interaction	Fig. 10	Fig. 11
5	7075 Al	1.27	122	10	11	0.88	Record effect of defocusing on beam-metal interaction	Fig. 12	Fig. 13
6	7075 Al	0.952	120	10	5	0.88	Record beam-metal interactions in a full penetration weld	—	Fig. 14
7	Ti-6Al-4V	—	123	10	5	0.88	Study material effects	—	Fig. 15
8	410 stainless steel	—	120	10	5	0.88	Study material effects	—	Fig. 16
9	Mg casting alloy	—	135	5	5	0.88	Study material effects	Fig. 17	Fig. 18
10	ETP Cu	—	131	10	5	0.88	Study material effects	—	Fig. 19

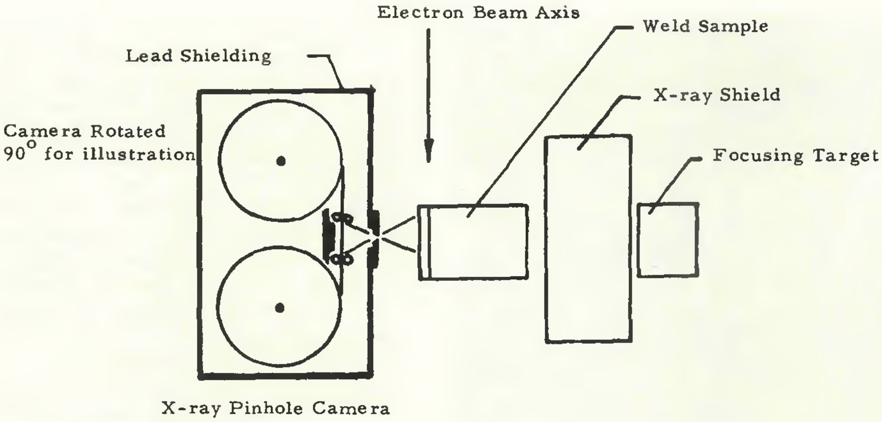

Fig. 1 — Sketch illustrating x-ray pinhole camera technique

cord the beam-metal interactions is 35 mm × 25 ft, Kodak NS-392T medical x-ray film.

The factor most critical in generating high quality x-ray films is the control of film exposure, which is accomplished through the camera pinhole geometry. Too small an opening can result in an underexposed film while too great an opening causes a decrease in resolution. A cone-shaped hole with an opening at the apex varying between 0.01 and 0.10 cm depending on welding and material conditions, was suitable for generating the experimental data. Another factor critical to obtaining quality film exposure is the problem of x-ray attenuation due to the material. Since the x-rays are generated within the weld cavity, they must first travel through the sample material. As a result, most of the welds in this experiment were made with butted plates in which the plate facing the camera was very narrow, typically 1 to 2 mm (see Fig. 1).

By controlling the ratio of weld cavity to pinhole distance vs. x-ray film to pinhole distance, the record of points of beam impingement within the cavity can be magnified. In addition, the exposed x-ray films can be enlarged using standard photographic techniques; thus, the activity in a 0.5 cm deep cavity is easily enlarged to 2 cm for purposes of analysis.

The welding operations were performed using a 3 kW Hamilton-Standard Model #W1-0. Weld parameters were recorded using the meters provided on the welding machine with the exception of beam voltage which was monitored with a digital voltmeter. Travel speed was recorded using a photo-tachometer sensitive to linear movements as small as 0.2 mm.

Generating data requires setting up

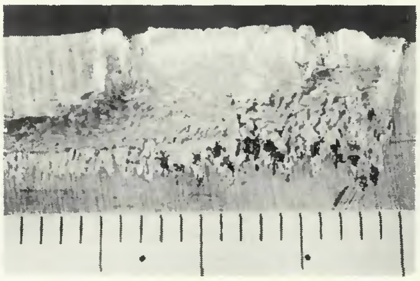

Fig. 2 — Longitudinal section through weld no. 1 (2024 Al). Rule divisions in millimeters

Fig. 3 — Portion of beam impingement record of weld no. 1. Nominal oscillation frequency, 400 cps. X1.5 (interval between timing dots, 0.050 sec)

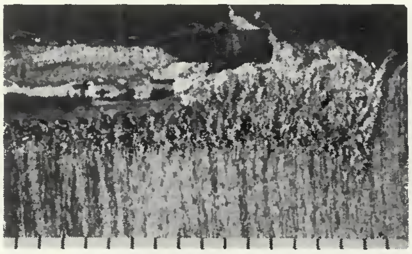

Fig. 4 — Longtiudinal section through weld no. 2 (1100 Al). Rule divisions in millimeters

Fig. 5 — Portion of beam impingement record of weld no. 2. Nominal oscillation frequency, 600 cps. X2.14 (interval between timing dots, 0.050 sec)

Fig. 6 — Longitudinal section through weld no. 3 (7075 Al). Rule divisions in millimeters

Fig. 7 — Portion of beam impingement record of weld no. 3. Nominal oscillation frequency, 400 cps. X1.5 (interval between timing dots, 0.050 sec)

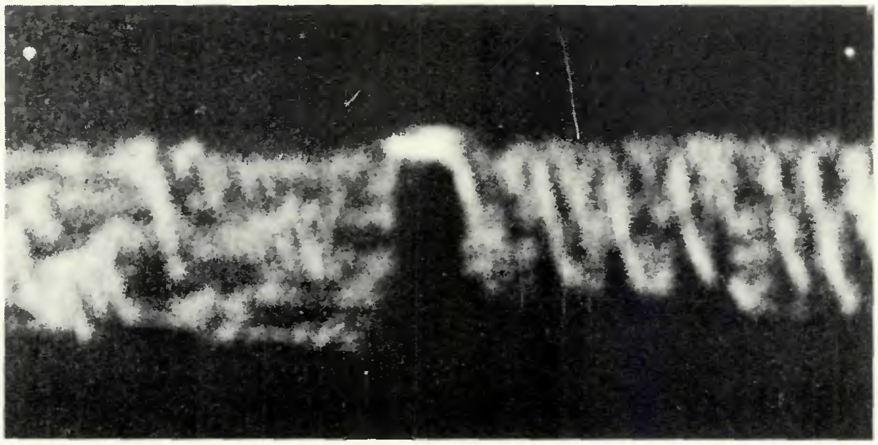

Fig. 8 — Another portion of beam impingement record of weld no. 3 showing one of the infrequent surface closure events. Nominal oscillation frequency, 400 cps. X3.15, reduced 30% (interval between timing dots, 0.050 sec)

the camera and test sample such that the pinhole is on line with the axis of the beam and aimed at the approximate midpoint of the expected penetration depth. The chamber is evacuated, weld parameters are set, and sequentially, the camera motor is engaged, weld sample motion initiated, and the electron beam energized. The data obtained in this manner does not lend itself to presentation since the exposed film is several meters in length, but selected sections of the film can easily generate contact prints and enlargements. Thus, beam-metal interactions are recorded and in particular, periods of spiking can be presented.

Experimental Results

In the course of this study, several engineering materials were used in conjunction with welding parameters which produced spikes. The materials and parameters are presented in Table I which also contains the experimental objective of each run in addition to listing those figures which identify weld samples and selected sections of the x-ray films. Since the earlier work with the x-ray pinhole camera technique demonstrated the ability to reveal weld penetration (Ref. 1), this work concentrates on the basic beam-metal interactions as a function of material, the influence of the welding speed, and the differences in partial vs. full penetration welding. General observations on the effects of these factors are developed from the data presented in Fig. 2 through 18 as well as techniques by which spiking might be suppressed.

The most striking fact that can be observed in all the films is that the beam-metal interactions are dynamic, even with zero welding speed (Fig. 16) and that the point of beam impingement moves at speeds as great as 6.5m/sec (Fig. 17). In addition, it is observed that this point generally works from the top of the cavity towards the bottom and decelerates as it approaches an "equilibrium" depth. Spiking events are characterized by periods of weld cavity stability in which the points of beam impingement become reasonably fixed with a significant amount of the beam's energy being expended at the weld root. The termination of a spike is signaled by the restoration of the oscillatory motion of the point of beam impingement. The characteristics of spiking events are determined by material properties and weld parameters such that the magnitude (as great as 25% of the average weld penetration) and duration (between 2.5 and 55 milliseconds) of the spikes vary. In addition, the basic phenomenon of a continually oscillating point of beam impingement is seen to be characteristic of both partial and full penetration welds (Figs. 7 & 13).

Discussion of Results

Necessary to any discussion of results is a consideration of those factors which enter into electron beam welding as unknowns. Of major importance is the stability of the beam's total power and power density. No continuous monitoring of critical weld parameters was performed; thus, line voltage fluctuations, high voltage

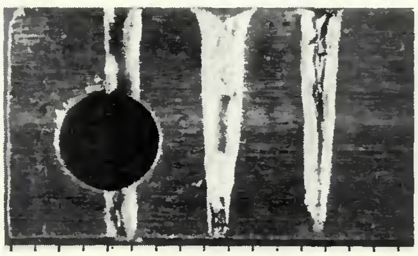

Fig. 9 — Longitudinal section through weld no. 4 (7075 Al). Rule divisions in millimeters

Fig. 10 — Portion of beam impingement record of weld no. 4. Nominal oscillation frequency, 150 cps. X1.4 (interval between timing dots, 0.050 sec)

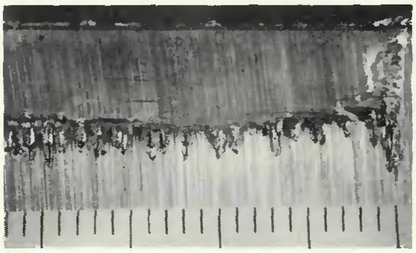

Fig. 11 — Longitudinal section through weld no. 5 (7075 Al). Rule divisions in millimeters

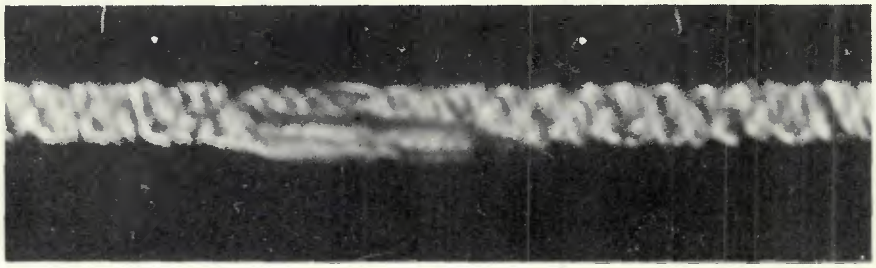

Fig. 12 — Portion of beam impingement record of weld no. 5. Nominal oscillation frequency, 220 cps. X1.58 (interval between timing dots, 0.050 sec)

ripple, filament age and position within the electron gun, and filament temperature are among those factors in the machine and its setup that could have influenced the results of an experiment of this type. It is assumed that variations did exist, but that they were within the bounds normally encountered in high voltage electron beam welding.

Another factor which presents unknowns is the effect of vaporized material on electron gun stability. Vapors and ions generated during welding are free to interact with the electron gun accelerating and grid potentials initiating possible arcing events which result in an uncontrolled beam of varying total power and power density. The effects of these complex machine-material interactions are not addressed in this work, although their possible influence is recognized. The two issues discussed above suggest that there are several uncontrolled factors which can influence electron beam welds, and depending on the degree of sophistication required for a given welding operation or experiment, these factors could be significant.

Recognizing that conditions exist which have an unknown influence on the welding of this experiment, it becomes reasonable to interpret the results. The results of this work support the existence of a weld cavity in which the back pressure created by evaporating material is the dominant cavity-producing force, while the hydrostatic head and surface tension are the significant cavity closing forces (Refs. 2, 3, 4). The dynamic interaction of these forces are responsible for the unique characteristics of electron beam welds and are at least in part revealed by the x-ray pinhole camera.

Figure 10 illustrates the basic nature of beam-metal interactions. The beam is seen to impinge within the cavity at several points, but maintains a sequence of excursions toward the base of the weld cavity. At certain points, it is clear that a large percentage of the beam's energy is being delivered at the base of the weld cavity, followed by the beam's impinging at multiple points nearer the surface. This suggests that as the beam is working in the cavity, superheated molten metal is displaced to the surface. As the hydrostatic head pressure increases, partial interception and collapse of the cavity become imminent. In addition, the metal displaced to the surface generates waves which are reflected at the weld pool periphery and return to the cavity where they are free to interact with the beam. Depending on the magnitude of such event, the material associated with the wave will be partially driven toward the cavity base and into the sides. Recognition of the beam's interaction with material near the top of the weld cavity while also impinging at points lower in the cavity suggests that the upper half of the weld cavity is usually clear and the location of only partial beam interception. Thus, the likelihood of a complete surface closure event is minimal. High speed photographic films of high voltage electron beam welds on aluminum alloys (Ref. 5) support this observation, and Fig. 8 illustrates the rather unique surface closure event which was observed

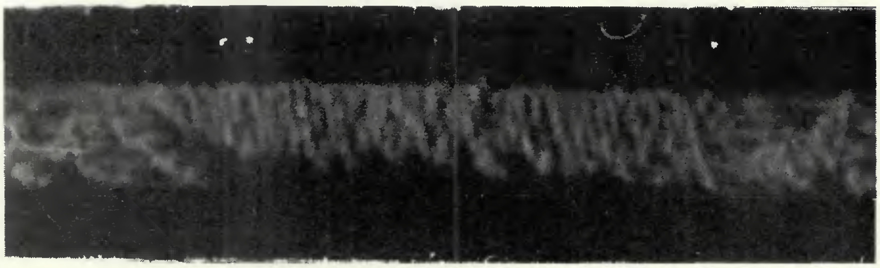

Fig. 13 — Portion of beam impingement record of weld no. 6. Nominal oscillation frequency, 200 cps. X1.5 (interval between timing dots, 0.050 sec)

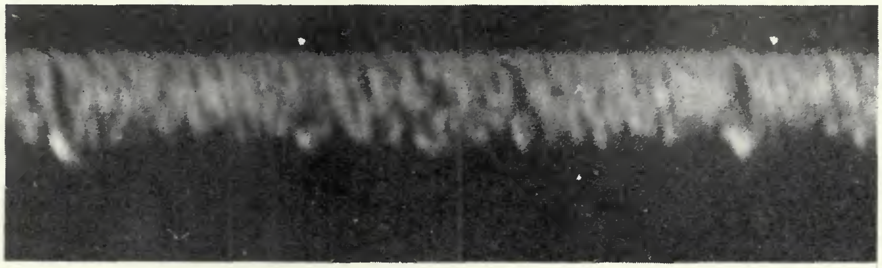

Fig. 14 — Portion of beam impingement record of weld no. 7. Nominal oscillation frequency, 435 cps. X2.73 (interval between timing dots, 0.050 sec)

Fig. 15 — Portion of beam impingement record of weld no. 8. Nominal oscillation frequency, 780 cps. X2.0 (interval between timing dots, 0.050 sec)

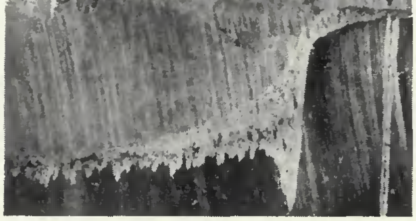

Fig. 16 — Longitudinal section through weld no. 9 (Mg casting alloy) X3.55, reduced 44%

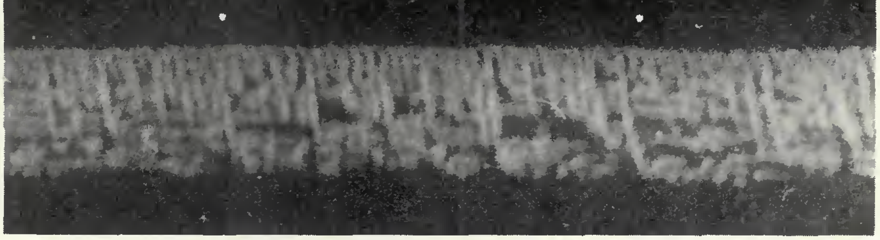

Fig. 17 — Portion of beam impingement record of weld no. 9. Nominal oscillation frequency, 650 cps. X1.67 (interval between timing dots, 0.050 sec)

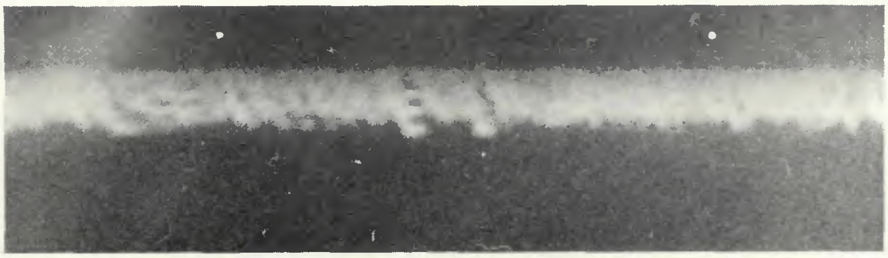

Fig. 18 — Portion of beam impingement record of weld no. 10. Nominal oscillation frequency undetermined. X5.0 (interval between timing dots, 0.050 sec)

only twice in over 50 experimental welds.

Although the top portion of the weld cavity maintains its integrity, the films suggest that there are frequent intervals when the lower portion of the cavity is free from beam impingement. During these periods, surface tension and the pressure generated by the hydrostatic head coupled with material properties determine the sequence of events. As closing forces act, the root of the cavity tends to fill with molten metal. Should the material have comparatively low thermal conductivity and reasonable fluidity, complete filling of the cavity could occur.

Another material which could dissipate the heat more readily by conduction might freeze prematurely leaving the often observed defect of weld root porosity. These same properties would influence a material's propensity to form cold shuts. Of course, the formation of root defects is not only a function of the material properties but is influenced by the weld parameters that determine the time-related energy distribution of the weld root area which is decided by the duration and frequency of beam excursions to the cavity base, and affects the very critical weld root cooling rate.

It has been noted that the x-ray films generated indicate a weld cavity whose top portion remains reasonably stable, with only the lower regions exhibiting closure events. In addition, the films suggest that the points of beam impingement follow a regular oscillatory frequency which is determined by the welding parameters and the material. This nature is evident even at zero welding speed, which suggests that as the beam works its way to the cavity base, the material displaced to the top at least partially reenters the path of the beam. As this interception occurs, the wave of molten material is accelerated towards the cavity base and partly back into the cavity wall. As one introduces the factor of a nonzero welding speed, the point of likely beam interception becomes fixed at the front of the weld cavity.

Thus, welding progresses in a fixed sequence of beam excursions in which a large measure of the beam's energy is expended down the front of the weld cavity and at frequencies of 150 to 650 cps for the runs of this experiment. The molten metal is displaced from the front to the rear with the cavity stability maintained except for the lower portions which the films indicate as being free of beam impingement for discrete intervals.

These observations indicate that for high voltage welding there is no appropriate oscillation frequency that applies to the complete weld cavity, since only the base region undergoes complete closure events. It is possible, however, to suggest the existence of a cavity base activity which follows at a regular frequency.

In addition to the nature of beam-metal interactions, the films graphically present the conditions under which spiking occurs. Spiking events are seen to be periods in which the points of beam impingement are reasonably fixed with a significant portion of the beam's energy being delivered at the cavity base producing the additional penetration. These events were observed to have durations varying between 5 and 55 milliseconds depending on parameters and the material. During this period, the oscillatory nature of the point of beam impingement breaks down, and there exists only limited interception of the beam either by material from the front lip of the cavity due to the welding speed or from the wave reflections of molten metal from the rear of the weld pool.

Thus, spiking events are characterized by periods of near equilibrium in which, for a brief instant, the back pressure of evaporating atoms which maintains the integrity of the fluid walls, is in delicate balance with the forces of surface tension and the hydrostatic head. On the other hand, the non-equilibrium condition in which the cavity generating forces and the cavity closing forces do not reach a balanced state appears responsible for uniform penetration.

These observations suggest techniques by which spiking might be reduced. First, the fact that the point of beam impingement can be characterized by a natural oscillatory frequency suggest that the judicious selection of a pulsing sequence to accommodate this action might serve to maintain the beam's action so as to eliminate those periods of cavity equilibrium which characterize the spiking event. Thus, a reasonable first approach would be to select a beam on-time sufficient to allow the beam to penetrate to the cavity base followed by a beam off-time long enough to ensure partial interception of the beam by the advancing weld cavity front, yet short enough so that the significant weld pool solidification and the associated defects would not result.

An example of this approach might be as follows. A given weld condition whose natural oscillation frequency is 150 cps would suggest a beam on-time which is the reciprocal of this number or 6.7 milliseconds. The optimum beam off-time would have to be determined experimentally.

Another approach to the minimization of spiking would be to optimize the welding speed so as to encourage the maintenance of the oscillation of the point of beam impingement, by the advance of new material from the front lip of the cavity at the optimum time.

Another significant factor which evolves from the films is the observation that the basic beam-metal interaction with its associated oscillation frequency is operant in both full and partial penetration welds. The only difference comes about from the additional venting of the cavity and energy heat input loss which occurs as the beam exits from the material. Immediately, the internal pressure drops which enhances the collapse of the weld cavity triggering the interception of the beam by both the cavity closing forces and the advance of metal due to the welding speed.

Conclusions

1. It has been shown that the x-ray pinhole camera technique is capable of generating an accurate and continuous record of beam-material interactions, thereby revealing at least in part the cavity related phenomena involved in electron beam welding, including the spiking event.

2. Uniform weld penetration is characterized by a continually oscillating point of beam impingement which maintains periodic excursions from near the top of the cavity to the cavity base.

This oscillation is most likely maintained by the regular interception of the beam by advancing material due to the welding speed, the forces of surface tension and the hydrostatic head, and the dynamic wavelike motions within the weld pool.

3. Spiking is revealed to be the result of a breakdown of this oscillatory nature, in which, for short intervals, the points of beam impingement become reasonably fixed and the weld cavity stable. This allows for a significant portion of the beam's energy to be dissipated at the weld root resulting in increased penetration.

4. The suppression of spiking might likely adopt an approach in which an appropriate pulsing schedule is developed which would maintain the oscillatory nature of the point of beam impingement and discourage the near equilibrium condition characteristic of the spiking event. Another approach, although more difficult to put to practical use, might be the selection of a welding speed to "fit" the weld parameters in an effort to optimize the periodic interception of the beam.

5. The basic mode of penetration is the same for both partial and full penetration high voltage electron beam welding. In both cases, the point of beam impingement undergoes continual oscillation within the weld cavity.

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