UCRL - 77253
PREPRINT
CONF-751012--2

LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

ELECTRON BEAM WELDING FUNDAMENTALS AND APPLICATIONS

Glenn L. Mara

Robert E. Armstrong

August 21, 1975

ADVANCED WELDING & BRAZING WORKSHOP
Society of Manufacturing Engineers
Chicago, Il, October 28-30, 1975

MASTER

ELECTRON BEAM WELDING FUNDAMENTALS AND APPLICATIONS*

Glenn L. Mara and Robert E. Armstrong

Lawrence Livermore Laboratory, University of California
Livermore, California 94550

ABSTRACT

The electron beam welding process is described and the unique mode of operation and penetration explained by a description of the forces operating within the weld pool. This penetration model is demonstrated by high speed cinematography of the weld pool on several materials. The conditions under which weld defects are formed are discussed and examples are presented.

INTRODUCTION

Electron beam welding technology, since its birth in 1950 with the work of K. Stiegerwald and Carl Zeiss, has earned a place of prominence in the field of welding processes. This position can be attributed to the unique weld characteristics which result when a focused stream of high-energy electrons impinge upon a work piece, producing a fusion joint in the material.

Before discussing these weld characteristics and their advantages and disadvantages, it is appropriate to provide some background on the operation of the electron beam welding process. In short, electrons which have been accelerated to high velocities in vacuum (typically 10^{-4} mm Hg) are focused into well-defined beams which then impinge upon the work material. The electron-material interactions which follow call for the absorption of the beam in a very thin layer. For most engineering materials this is on the order of several hundredths of a millimeter, with the incident energy being primarily converted to heat. Should the beam be well focused, the rate of heat input will exceed the capacity of the material to dissipate it by conduction. As a result, melting, vaporization, and ionization can occur. The development of vaporized material produces significant pressures on the liquid material which result in the formation of a cavity in which the electron beam acts. This explanation of electron beam operation is indeed oversimplified, but it provides the basic model which will be elaborated upon later.

The welds produced in the described fashion are generally of high metallurgical quality and exhibit outstanding mechanical properties. The metallurgical quality can be attributed to the low amount of contamination introduced, while the excellent mechanical properties are generally accounted for by the ability of the electron beam to produce deep welds with minimal heat input, (as compared with other fusion processes) and the resulting unique weld nugget geometry; i.e., narrow welds with narrow heat-affected zones. The deep welds commonly discussed in electron beam welding are better described by considering

---

*Work performed under the auspices of the U.S. Energy Research & Development Administration.

weld depth-to-width ratios, which are typically 15:1 or greater. This differs significantly from the depth-to-width ratios of most other fusion welding processes which are typically 1:1.

Another, sometimes overlooked, advantage of electron beam welding is its ability to weld dissimilar materials. Obviously, there are limitations as dictated by metallurgical factors, but the combination of a hard vacuum with the high energy density electron beam and fast cooling rates produces a unique environment in which dissimilar metal interactions that plague other fusion welding processes no longer dominate.

With the aspects of electron beam welding discussed thus far, it is possible to list several characteristic advantages of the process. These appear below.

Characteristic Advantages of the Electron Beam Welding Process

1. Exceptionally high metallurgical quality.
2. Excellent mechanical properties in many materials.
3. Minimal distortion.
4. Joining of dissimilar materials.
5. Joining of exotic engineering materials; i.e., reactive and refractory metals.
6. Penetration with high depth-to-width ratios.
7. Precise joining of miniature components.

While the electron beam welding process possesses several impressive characteristics, it is not without limitations and disadvantages. The most obvious drawback is the need for a relatively good vacuum. This fact is especially apparent if the electron beam process were to be considered for welding large vessels. Out-of-vacuum machines do exist, but generally they sacrifice some of the advantages previously cited.

Another disadvantage of electron beam welding is that the welds are not always defect free. The defects most often cited are: (1) porosity, (2) cold shuts, and (3) cracks. Porosity and cold shuts are commonly associated with the high depth-to-width ratio welds, and in general, their appearance is eliminated as the penetration depth is decreased, while cracking is more a function of metallurgical factors combined with the stresses developed during welding.

There is yet another disadvantage to the electron beam welding process, which is evident in the high depth-to-width ratio partial penetration electron beam weld. This is the problem of erratic penetration, commonly termed spiking. The spiking phenomenon can be described as any significant increase in the average weld penetration for a given set of weld parameters. This increase can be as high as 25% of the average weld depth, while the frequency at which spikes occur is typically in the range from 2 to 25 spikes/cm of weld. The spiking problem has created significant interest and has motivated investigators to study the phenomenon seeking its causes and cures.

Exceptional experimental work to be discussed later has been carried out by numerous investigators, but there has been the need to develop the experimental expertise to the point that accurate, continuous observation of the electron beam welding process is possible. This, in turn, would reveal the time dependent activities of the electron beam within the cavity. Such experimental expertise now exists with recently developed techniques.[1,2] Continuous monitoring of the process coupled with predictions based on fundamental principles concerning the important energy distribution and forces within the electron beam cavity give rise to an understanding of the mechanisms which govern the formation of electron beam welds, as well as the typically encountered defects.

BACKGROUND AND THEORY

The unique ability of the electron beam to produce extremely deep and narrow welds has led to the great amount of existing experimental work regarding the process. Investigators have attacked such problems as electron scattering events, "gas focusing" due to beam-ion interactions, and forces active in the formation of the weld cavity. The results of these experiments are invaluable to the formation of new and more accurate explanations of the electron beam process.

An early interpretation of electron beam-material interactions is given by C. K. Crawford.[3] Crawford analyzes both the mechanisms of energy loss and the forces active in the electron beam cavity. From an energy standpoint, he concludes that energy losses to radiation and to ionization and excitation of evaporated atoms are negligible, while the energy required to vaporize material and the energy lost by thermal conduction are significant. His examination of the weld cavity leads him to consider four main forces: the force due to electron beam pressure, the hydrostatic force of molten metal, the surface tension force, and the force due to the back pressure of evaporating atoms.

The excellent experimental work accomplished in electron beam welding is not dominated by western investigators. Hashimoto and Matsuda[4] propose a mechanism of cavity formation based on their demonstration of important forces within the cavity. By measuring the vertical reaction force occurring during welding and accounting for this force by means of theoretical considerations, these investigators are able to reach several conclusions about the relative importance of various cavity forces. Their observation is that the predominent force which produces the weld cavity is the repulsion force of evaporated metal. The weld bead is then formed by the combination of this repulsion force, the internal pressure within the bored hole, and the surface tension of the molten metal.

As qualitative and quantitative descriptions of the electron beam welding process developed, it became natural for investigators to develop empirical relations for penetration as a function of the weld parameters. These in turn could be utilized to select optimum weld parameters when given a certain material and desired depth of penetration, or used in the reverse fashion, to determine the penetration depth from given material properties and selected weld parameters. Investigators associated with this endeavor are Dann E. Passoja,[5] T. Hashimoto and F. Matsuda,[6] and Charles Weber.[1] Despite their outstanding contributions, especially the extensive experimental work of Hashimoto and Matsuda, the need for emnirical expressions involving the typical electron beam welding parameters still exists.

Besides the development of practical expressions for parameter selection, continued advancement in the study of electron-material interactions evolved. B. W. Schumacher,[7] using the physical laws which describe the absorbtion of impinging electrons, makes several observations as to the energy required for material transformations. By establishing the conditions under which thermal mechanisms of energy loss are negligible, he is able to describe the necessary energy inputs to induce melting, phase transformations, vaporization, etc. He determines the maximum time a typical electron beam can be allowed to impinge upon a work material and yet maintain a quasi-adiabatic state, i.e., thermal properties of the material are not yet operative from an energy standpoint. This time is found to be between 0.3 and 8 μsec for engineering metals. These short time periods indicate the significant role played by the thermal properties of a material during welding, and define the basic pulse durations for electron beam machining, i.e., hole drilling.

The characteristic shape of the electron beam weld nugget is significant in explaining the electron-vapor interactions within the cavity. Experimental work in this specific area is lacking, but the literature does yield a study performed by M. Boncoeur, J. Y. Marhic, and M. Rapin,[8] in which the relationship of electron beam focusing and the resulting bead shape and dimensions are analyzed. Their experimental work shows the weld bead shape is significantly altered as the focal point of the beam is varied with respect to the surface of the weld specimen.

The results of this investigation do not provide substantial quantitative data, but the point is made that the geometry of the beam and the location of the focal spot with respect to the surface of the work material is of importance in the determination of both weld nugget geometry and depth of penetration. It becomes apparent that any analysis which treats the beam as having a defined diameter over a significant length is likely to introduce appreciable error.

The proposed activity of cavity formation by several authors provides the groundwork for an interesting series of experiments which involve the insertion of tracer materials at various levels in the work-piece. Upon completion of the welding operation, the distribution of the dissimilar material in the weld nugget is analyzed and found to be distributed quite uniformly throughout the weld. The investigators responsible for one such series of experiments are P. Shahinian, J. T. Atwell, and E. J. Brooks.[9]

To this point, relatively little attention has been paid to the discussion of erratic penetration while considerable energy has been expended developing the basis of electron beam cavity formation. Developing significant background on this topic is necessary, since any discussion of erratic penetration will necessarily depend upon the basic physical principles underlying cavity formation.

One investigator in the field of electron beam welding, H. Tong,[10] suggests that cavity oscillations and "cavity closure" events are significant, and a model of penetration analogous to the behavior of projectiles entering a fluid is developed. The mechanism of electron beam penetration developed is one in which the cavity oscillates along with the point of electron beam impact. This gives rise to an explanation of how some typical electron beam weld defects are produced, for as closure events take place and in the cooling rate is sufficiently rapid, contaminant gases might not have time to be convected to the surface, thus giving rise to porosity. Similarly, a cold shut might be formed as molten metal falls into a solidified cavity without sufficient superheat to permit fusion to occur.

In summary, several arguments and models of cavity formation have been presented along with force considerations held to be of importance by various investigators. These serve to outline the basis for the penetration mechanism of electron beam welding.

A review of the beam energy considerations indicates that the energy losses to ionization and radiation are negligible, while the energy required to melt and vaporize material and the energy losses due to thermal properties are significant. With respect to thermal effects, one can state that for extremely short beam pulses, i.e., several microseconds, the mechanism of heat loss by thermal conduction is not operative. Obviously, for longer pulses and especially for continuous beam operation, thermal properties of the material become a significant factor.

An examination of the forces operating in the cavity suggests that the back pressure exerted by the evaporating atoms, the hydrostatic force, and the surface tension force are significant cavity forces, while electron beam pressure and magnetic forces do not appear to be important. One finds the back pressure of evaporating atoms to be the significant "cavity maintaining" force, while surface tension and the hydrostatic force of molten metal are "cavity closing" forces.

Earlier experimental work suggests that the cavity is in a state of dynamic equilibrium and that the electron beam impinges at different levels or oscillates within the cavity.

Utilizing the observations and experimental evidence that have been established, a summary in the form of several assumptions develops. These assumptions are stated as follows:

1. The cavity is in a state of oscillation in which the point of electron beam impingement is continually changing.

2. Material parameters of significance are thermal conductivity and the energy required to vaporize the material.

3. The predominant cavity producing force is the force developed by the back pressure of evaporating atoms, while the surface tension and hydrostatic pressure tend to collapse the cavity. The pressure exerted by the electron beam seems to be of secondary importance.

4. Dynamic cavity closure mechanisms arising from the motion of the molten metal can be a significant factor.

A hypothetical model for electron beam penetration which utilizes the presented background information can now be developed. Initially, the beam impinges upon the material and the back pressure of evaporating atoms begins forming the cavity. As the beam approaches the critical depth, which can also be described as the average depth, the cavity becomes dominated by those forces tending to close it. At shallower depths, the cavity maintaining forces are predominant. The notion suggested here is that the complete penetration mechanism is based on a very unstable sequence in which cavity closing forces and cavity producing forces dominate alternately with a constant critical equilibrium depth (and balance of these forces) never being realized. To elaborate on this theory further, a description of the proposed series of events occurring within the cavity is in order. The beam "bores" toward the critical depth which continually increases the magnitude of the closure forces; however, the beam is unaware of the impending closure event. Finally, these forces become of sufficient magnitude to begin closure of the cavity, but only in the lower recesses. Material intersects the beam, and the sequence begins again. In addition, the violent action of the fluid surrounding the cavity suggests that the magnitude of each closure event is subject to fluctuation as well as the time at which the closure occurs. Indeed, it is likely that the dynamic action of the weld pool will continually introduce "swells" near the top of the cavity which will periodically "pinch" or enter the path of the beam. Because these events may not be as severe as those in the lower regions of the cavity, the radial pressure within the weld as well as the force due to evaporating atoms generated during this minor event, will often be of sufficient magnitude to quickly restore the cavity to its full open configuration. Thus, it is suspected that minor closure events will continually be operative, but the formation of a complete closure which will successfully fill the cavity requires an appreciable amount of material to intersect the beam, and is unlikely. Continuous monitoring of the points of beam impingement support this contention.[11] This discussion suggests that there is no well-defined balance between those forces tending to close the cavity and those tending to maintain it, rather, the one event initiates the other, and the mechanism of penetration seems to be the result of highly unstable forces which, by their nature, do not achieve a well-definable state of equilibrium.

The occurrence of the spiking phenomenon now lends itself to description. It has been proposed that material near the top of the cavity periodically tends to intersect the electron beam. Depending on the magnitude of the cavity closing event, interception of the beam will be more or less successful. Normally, a quantity of metal will intersect the high-speed electrons and immediately the beam will begin to vaporize a portion of it forcing the volume of metal to the base of the cavity (this action accounts for the thorough mixing encountered in electron beam welding). This type of beam-material interaction typically governs the electron beam process; occasionally, however, the intersection of the beam does not occur successfully. The molten metal begins its "crowding" and "pinching" of the beam, but fails to cut it off. The result is the establishment of a "pressure bottle" which allows the cavity to exist for a longer period of time, establishing the environment for increased penetration and spike production, the depth of which will be established by the beam power density while the spike width will be determined by the time for which the open cavity can be maintained.

In summary, it is proposed that the forces acting within the cavity are not directed toward the establishment of an equilibrium situation. The mechanism of penetration proceeds in an unstable manner in which the lower regions of the cavity are successively cleared and filled with little tendency to maintain a balanced state. Interestingly enough, the electron beam process begins to approach the equilibrium condition during the spiking phenomenon, for it is during these periods that the cavity forces are maintained in a near-balanced configuration.

With these factors in mind, the high-speed movies of the electron beam welding process which will now be presented should be more enlightening and dramatically reveal the effects of beam-metal interactions.

BIBLIOGRAPHY

1. "Penetration Mechanism of Partial Penetration Electron Beam Welding", Master's Thesis, Charles Weber, Master's Thesis, Ohio State University.

2. "Suppression of Spiking in Partial Penetration EB Welding with Feedback Control", Welding Journal, T.P. O'Brien, F.E. Pence, E.R. Funk, and R. C. McMaster, August 1974, Research Supplement pp. 332s-338s.

3. "Electron Beam Machining", Introduction to Electron Beam Technology, Charles K. Crawford, ed. Robert Bakish, John Wiley and Sons, Inc., New York, 1962, pp. 342-343.

4. "Penetration Mechanism of Weld Bead in Electron-Beam Welding", Transactions of National Research Institute for Metals, T. Hashimoto and F. Matsuda, VII, No. 5, 1965, pp. 183-185.

5. "Penetration of Solids by High-Power Density Electron Beams, British Welding Journal, D. E. Passajo, XIV, January 1967.

6. "An Equation for Calculating Optimum Welding Condition in Electron-Beam Welding", Transactions of National Research Institute for Metals, T. Hashimoto and F. Matsuda, IX, No. 1, 1967.

7. "Power Density Limits for the Particle Penetration Laws and the Onset of Energy Phenomena in Electron Beam Targets", Electron and Ion Beam Science and Technology, Third International Conference, B.W. Schumacher, ed. R. Bakish, The Electrochemical Society, Inc., New York, 1968, p. 80.

8. "The Influence of Electron Beam Focusing on the Shape and Dimensions of Welds in the Electron Beam Welding Process", Electron and Ion Beam Science and Technology, Third International Conference, M. Boncoeru, J.Y. Marhic, and M. Rapin, ed. by R. Bakish, The Electrochemical Society, New York, 1968, p. 371.

9. "Metal Mixing During Electron Beam Welding", Electron and Ion Beam Science and Technology, Third International Conference, P. Shahinian, J.T. Atwell, and E.J. Brooks, ed. by R. Bakish, The Electrochemical Society, Inc., New York, 1968, p. 389.

10. "A Dynamic Interpretation of Electron Beam Welding", Welding Journal, H. Tong and W.H. Giedt, June 1970, Research Supplement, pp. 260s-263s.

11. "Penetration Mechanisms of Electron Beam Welding and the Spiking Phenomenon", Welding Journal, G.L. Mara, E.R. Funk, R.C. McMaster, and P.E. Pence, June 1974, Research Supplement, pp. 246s-251s.