On the Measurement and Interpretation and Application of Parameters Important to Electron Beam Welding

Minimal drop-through and spatter is obtained on thin gage materials using low current-high voltage techniques, and low power density provides precise penetration and root control for partial penetration welds in thicker materials

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Introduction

A study of the electron beam welding process has been initiated by several AEC contracting agencies. The purpose of this study is to define the physical properties of materials and operational features of electron beam welding machines in order to better describe the characteristics of the electron beam welding process. The various agencies and organizations which have been involved in this study have used various kinds of welding equipment and diagnostic instrumentation. The Los Alamos Scientific Laboratory has been a contributor to this program in the areas of beam diagnostics and the relationship of physical properties of materials to the resultant welds. The welding machine which has been used for all of the studies described in this paper is a 7.5 kw Sciaky unit which has a maximum capacity of 30 kv at 250 milliamp. This machine is equipped with a d-c filament power supply and automatic voltage regulation.

The studies by AEC contractors have shown that, due to the variation in instrumentation on machines of the same type, it is difficult to obtain reproducible welds from one machine to another. In addition to the problem of non-reproducibility of machine settings, the study at Los Alamos has shown that the usual parameters—i.e., voltage, current, and welding speed—are insufficient to define the characteristics of an electron beam used for welding. Another parameter, beam spot size—which in turn defines energy density in an electron beam weld—must be measured in order to characterize the properties of an electron beam weld.

Development of Instrumentation for Beam Diagnostics

The problem of designing a device which can measure the current distribution in a continuous electron beam of high energy density is not a simple one. Physicists have designed devices for measuring beams of extremely high energy density; however, most of the beams have existence times of extremely short duration. The power density in an electron beam unit is of the order of $10^6 - 10^7$ watts/in.$^2$, and this power density is sustained for a significant period of time during most welding operations.

Based upon the foregoing consideration, it then becomes obvious that any device which is used for sampling the electron beam must have a very short duty cycle, i.e., it should be in the beam for a short time, or should be constructed in such a way that the high power density can be dissipated without destroying the device. The device which was designed and constructed at Los Alamos is based upon the short duty cycle criterion.

Figure 1 consists of a schematic line drawing of this device. An aluminum vane which contains various diameter tungsten wires at its extremities is rotated through the electron beam. The rotation of this vane is accomplished by an 1800 rpm synchronous
motor. The aluminum vane does not actually intersect the beam, but the W wires which are at the vane extremities do. The diameter of the W wire should be small compared to the diameter of the beam in order to obtain accurate measurements.

The current that is picked up by the wires intersecting the beam is sampled and applied to an oscilloscope. Below the wire beam probe a Faraday cup has been installed. This cup collects the total current in the beam and is a positive check on the accuracy of the meters on the machine. The collector plates, in which the beam rotates, were set at the same potential as the vane and were necessary to collect the back scattered and secondary electrons. (Unfortunately our choice for hole size in the collector plates was a bad one since electrons are back scattered at discrete angles. The solid angle generated between the rotating wire and the collector plate was such that most of the back scattered electrons escaped through the hole!)

Figure 2 consists of a composite showing several views of the actual rotating wire beam-scanner device. The upper left hand view is a side view of the device showing some of the details of construction. The base plate upon which the Faraday cup is mounted is an alloy steel cage which is necessary to provide magnetic shielding. The first measurement experiments showed that the field produced by the motor was of sufficient magnitude to disturb the electron beam. The porcelain insulators were also determined to be necessary after the initial measurements. The porcelain insulators help to balance the electrostatic field and prevent the beam from being disturbed by the rotating shaft.

The bottom view of the scanner shows the detail of the collector mounting and the magnetic shielding. The method of motor mounting is unique and allows one to use a comparatively inexpensive motor for long duration in a vacuum. The motor is water-cooled to prevent overheating. The water cooling system which was devised consists of a hollow water-cooled annular ring which surrounds the motor. The volume in between this ring and the motor has been filled with one of the low melting fusible alloys. Using this technique it is possible to dissipate all of the heat generated in the motor.

The view in the lower left hand side of Fig. 2 shows the top view of the device with the collector plates in place. The lower right hand view shows the detail of the Faraday Cup and the vane probe. Figure 3 is a schematic of the water-cooled Faraday Cup which was constructed for
Fig. 3—Cross sectional view of a water-cooled Faraday cup

Use on the Los Alamos Electron Beam weld. This cup design has proven to be adequate for collecting all the current in a 7.5 kw beam.

Figure 4 shows a typical oscilloscope trace which is obtained using the beam scanner. The higher peak trace corresponds to the signal collected by the larger diameter wire in the vane. The lower peak corresponds to the signal collected by the smaller diameter wire. This difference between the two signals is a convenient check of the device since the peak current, I_p, will be directly proportional to the diameter of the wire. The abscissa represents a velocity which is measured in cm/sec and can be readily converted to a beam diameter. Thus the total current in the beam can be calculated by determining the area under this Gaussian curve.

The Affect of Variations in Operating Parameters on Beam Characteristics

The parameters which are generally used to describe the conditions in an electron beam weld are the accelerating voltage, the beam current, and the welding speed. Obviously variations in the voltage at constant current, or variations in the current at constant voltage, will have rather profound effects on the geometry of the electron beam.

Figure 5 consists of a plot of the beam current vs. beam diameter at constant voltages for several different voltages. The data plotted on these curves show that the beam diameter is linearly dependent upon the beam current for constant voltage. As one would expect, the beam diameter increases with increasing current probably due to charge repulsion effects.

Figure 6 is a plot of the beam diameter vs. the accelerating voltage for constant current electron beam welds. This dependence is obviously exponential in form. The two plots just shown demonstrate how the beam diameter, as measured, is affected by variations in the two important parameters of accelerating voltage and beam current. Schwarz1 has derived a formula for the beam diameter based upon electron optics theory. This equation says that the beam diameter is given by:

\[ d = S \frac{p^2}{V} \]

where, \( S = \) constant (dependent on gun optics); \( i = \) beam current in milliamperes; \( V = \) accelerating voltage; \( d = \) the beam diameter in 1/1000 in.

Attempts to fit the data obtained at Los Alamos to this equation have been unsuccessful. This equation indicates that the diameter is exponentially dependent on both current and voltage. By contrast, our data shows linear dependence of beam diameter with current. Empirical curve fitting has tentatively resulted in an equation of the

![Fig. 5—Beam current vs. beam diameter at constant voltage](image)

![Fig. 4—Oscilloscope trace of a 20 kv, 60 ma electron beam at sharp focus. Vertical sensitivity = 2 ma/cm; horizontal sweep speed = 5 usec/cm](image)
The following form:

\[ d \sim K \frac{V}{I_i} \]

where, \( I \) = beam current in ma; \( I_i \) = beam current at the intercept in ma; \( V \) = accelerating voltage in kv; \( d \) = diameter in \( \frac{1}{1000} \) in.; \( \alpha \sim 1.65 - 1.75; \) and \( K \sim 44 \pm 4. \)

This equation has not been finalized and hence is not described as an equality. The deviation from the theoretical equation calculated by Schwarz is not understood. Additional measurements will have to be made and fitted to curves before an empirical equation relating the beam diameter to the accelerating voltage and the beam current can be finalized.

In addition to the measurements to determine the beam diameter as a function of the current and voltage, measurements have been made to determine the degree of beam symmetry, or astigmatism. The beam measuring device described earlier was mounted in such a manner that the beam could be sampled at various positions.

Figure 7 consists of a plot showing how the beam is actually elliptically shaped when the beam is sampled in positions which are 90 deg apart. The other feature which is shown on this plot is how the beam symmetry, or spot size, changes as a function of the “gun-to-work” distance. In this case the focus was optimized (minimum beam diameter) at a 1.25 in. gun-to-work distance. The gun-to-work distance was then either increased or decreased with the resultant change in beam geometry shown in Fig. 7. The degree of symmetry which is exhibited in this electron beam weld is considered to be exceptional. The small variation from a perfectly circular geometry is probably of no consequence to the actual performance of a weld.

Figure 8 is another way of demonstrating the convergence and divergence of a sharply focused electron beam at various gun-to-work distances and using various beam power. This plot suggests that the beam diameter at gun-to-work distances which are either 0.250 in. less than or greater than the point of sharp focus are essentially identical. However, it can be shown that the variation in energy density resulting from varying the gun-to-work distance is extremely significant.

Samples of stainless steel and aluminum have been welded with the beam diameter minimized at a gun-to-work distance of 1.25 in. Welds were then made at 30 kv accelerating voltage, 250 ma beam current and 30 ipm at gun-to-work distances of 1.0 in. which corresponds to a sharp focus point above the surface of the work. The penetration which was obtained in these welds was measured by metallographic techniques. The results of these tests are shown in Table 1.

The results obtained in these measurements on aluminum are not considered to be particularly surprising, since most operators are certainly aware that a point of sharp focus below the work surface yields greater penetration. However, the penetration in the stainless steel welds was a maximum when the position of sharp focus corresponded to the gun-to-work distance.
distance. The other notable feature of these welds was that the incidence of "spiking" was least in the welds where the beam was "defocused," i.e., the gun-to-work distance was greater than the optimum focal length. Having the focal length shorter than the gun-to-work distance results in a "softer" beam which has a lower depth-to-width ratio than is obtained by the harder more sharply focused beam.

A radiographic method for evaluating the root quality and average penetration of welds as a function of the position of sharp focus has been devised. The aluminum samples which were welded had the welds abstracted and a static radiograph was prepared perpendicular to the weld direction.

Figure 9 is a sketch of the radiographic technique which was used on these samples. Figure 10 is a print of the actual radiographs which were prepared. The incidence of root spiking and root defects is greatest in the sample which had sharp focus below the work surface. Other interesting details of these radiographs can be seen in the very large cavities which do not extend to the weld surface which have occurred where the beam was terminated. These cavities lend support to the work performed by Tong in which he describes the mechanism for cavity formation and collapse.

Physical Properties of Materials and the Effect of Beam Parameters on Weld Characteristics

Most of the previous work on electron beam welding which has been reported in the literature has dealt with the penetration and high depth to width ratios obtainable by this process. These papers have, to a great extent, dealt with the spectacular nature of this process as opposed to some of the more practical problems of welding.

High depth to width ratios and...
minimal melt volumes are very desirable features of any weld; however, controlled depth of penetration and freedom from root defects are generally more desirable features of a weld. It can be shown that the incidence of root defects such as non-uniform penetration, cold shuts, and root porosity are aggravated by high depth to width ratio welds and by the physical properties of the materials being welded. Hashimoto and co-workers and Henry Tong have developed equations relating the physical properties of materials to their welding characteristics, especially as characterized by depth of penetration measurements. The work at Los Alamos has been performed in a similar manner on some additional materials which have varied physical properties.

The properties of a metal, or alloy which will have a profound effect on the characteristics of the electron beam weld will be thermal conductivity, heat capacity, melting point, density, and the combination of the aforementioned properties in the thermal diffusivity term. Other properties of importance are the enthalpies at melting and at transformations and the ionization potentials. The aforementioned properties do not have equal importance over the total range of possible electron beam welding variables. For example, a beam of energy density sufficient to produce melting in stainless steel, which has a comparatively high melting point and low thermal conductivity, may be insufficient to produce melting in a sample of copper which has a lower melting point, but a much higher thermal conductivity.

Table 2 consists of a tabulation of the pertinent physical properties of the metals which have been investigated at Los Alamos, Table 2 uses the format described by Hashimoto et al. and includes the equation developed by them for relating welding variables to materials properties. This equation has been solved at Los Alamos using the measured values for the beam diameter which were obtained by the flying wire probe described earlier.

This equation was solved for two variables: in one case the value for the measured diameter was used for \( \phi \) and the equation was solved in terms of \( t \), the weld penetration. In a second case the measured value of \( t \) was inserted in the equation and the equation was solved in terms of \( \phi \), the beam diameter. This particular technique yields a cross check on the validity of the equation over the range of energies considered.

One method of presenting the results of these studies is shown in Figs. 11 and 12. In these figures the measured value for \( t \) is plotted on the ordinate and the calculated value for \( t \) is plotted on the abscissa. The results which have been obtained at Los Alamos do not agree with the results predicted by the equation. A line drawn at 45 deg would, obviously, be the line which one would expect to obtain if the experimental results were in agreement with the equation.

A review of the data used by the previously cited observers has shown that the values which were used for the beam diameter were significantly larger than those measured by the flying wire probe. The values measured for aluminum are in quite good agreement with those predicted by the equation. However, the curves for the other metals and alloys of interest deviate significantly from the predict-
For the weld made at 15 kv, 125 ma and 75 ipm is identical to the energy input in different welds made at constant energy input per inch of weld. However, the geometric characteristics of the weld as defined by depth of penetration, bead width and depth-to-width ratio will be appreciably different. The problem of determining the effect of the parameters becomes a very difficult problem in three dimensional heat flow analysis. The metals which are welded at high power densities will have high depth-to-width ratio welds with a high incidence of root porosity and cold shuts. One method of improving the weld quality is to reduce the accelerating voltage, the beam current, and to decrease the welding speed. The total energy input, as expressed in kilojoules/linear inch of weld may be identical to the high voltage, high current, high speed weld. However, the weld geometry and root characteristics will be radically modified. By using this technique the total penetration is greatly diminished and the volume of metal melted is significantly reduced as compared to the welds made at higher power density.

Figure 13 is a drawing of three welds made in stainless steel at constant energy input per inch of weld. The parameters were varied from 30 kv accelerating voltage, 250 ma beam current, a welding speed of 53 imp and a beam diameter of ~ 0.032 in. on the first weld; to 20 kv accelerating voltage, 145 ma beam current, 20.5 ipm and a beam diameter of ~ 0.035 in. on the second weld; to 10 kv accelerating voltage, 50 ma beam current; 3.7 ipm and beam diameter of 0.045 in. for the third weld. All of these welds were made at a constant energy input of 8.5 kilojoules/in. Obviously they do not possess the same characteristics insofar as geometry is concerned. In fact, it appears that the mechanism of melting is significantly different for the first two sample welds. The welds which were made at 30 and 20 kv accelerating voltages have high depth to width ratios and the mechanism of melting appears to be different. The mechanism of melting at this level of power density has been well described by Tong as penetration by cavity formation.

The sample which was welded at 10 kv has a weld geometry which lends itself to analysis by more classical methods of heat flow analysis. The power density of these particular welds was 9.33 x 10^3 KW/in.2 for the weld made at the highest power, 3.02 x 10^2 KW/in.2 for the weld made at the intermediate power level, and 3.15 x 10^2 KW/in.2 for the weld made at the lowest power level. This weld made at the lowest power level has a power density which is almost two orders of magnitude less than the power density for the weld made at the highest power level.

These data strongly indicate that the weld quality is more sensitive to energy density, or power density, which must imply a knowledge of the beam spot size, than to any of the...
other variables which are usually used to describe welding parameters. The experience at Los Alamos suggests that there is a threshold power density above which spiking and excessive root defects and cold shuts will develop. Welds made below this level of power density will have a lower depth-to-width ratio and a lower incidence of root defects. This power density threshold appears to occur at approximately 1.2 mw/in.² This power value may at first appear to be quite high. However, when one considers the area of a typical electron beam, it becomes quite apparent that the power in the beam is of enormous proportions.

An additional set of experiments have been performed at Los Alamos in an effort to further substantiate the metallographic evaluations described earlier. The experiments involved flash radiography of material which was being welded at different power levels. Figure 14 consists of a photograph of the Field Emission Corp. flash X-ray unit which has been “married” to the Sciaky 7.5 kw electron beam unit at Los Alamos. The X-rays which are emitted from the flash X-ray unit are collimated through the steel tube shown on the face of the welding machine and allowed to irradiate the work which is located near the welding unit centerline. The exact technique used insofar as intensifier screens, time delay, pulse time, pulse energy, etc., are described in a paper by L. E. Bryant of the Los Alamos Scientific Laboratory.⁷

The experiment which was performed using the flash radiographic technique involved two different materials and three different levels of power density. The power densities which were chosen were considered to represent the two different modes of melting which are produced in electron beam welds. The high power density welds produce penetration by the “cavity penetration” mechanism described by Tong.⁸ Figure 15 consists of a sketch which was reproduced from a series of flash radiographs which were made on a plate of aluminum. These welds were made at high levels of power density which were 27.5 kv and 250 ma. The weld area designated no. 1 shows an area where complete cavity collapse has occurred and the bottom of the weld contains a cold shut root defect. The other areas show partial collapse, or molten metal instability in various portions of the cavity. Area no. 5 shows a cold shut with partial cavity collapse.

Figure 16 is a conceptual sketch of the flash radiographs which were made on a bar of aluminum using the low power density technique. The parameters used in these welds were 15 kv accelerating voltage and 130 ma beam current. The nature of the progressing weld puddle is significantly different from that which has been observed in the specimen welded at high power density. The mechanism of melting as shown by both flash radiograph and metallography is significantly different. The penetration mechanism appears to be caused by a conduction process rather than by a cavity formation process. The fact that the progressing molten metal pool is below the work surface implies that a significant amount of beam down pressure exists.

Conclusions

A number of conclusions have been drawn from the work which has been performed at Los Alamos, both as a result of the experiments previously described and from experience with the fabrication of piece parts. A summary of these conclusions follows:

1. For thin gage material (0.030 in. or less) minimal drop-through and weld spatter is obtained using low voltage-high current welding techniques. These welding parameters automatically establish broad focus low power density welding condition.

2. The problem of root porosity and cold shuts is aggravated by high depth-to-width ratio welds in materials of high thermal conductivity. High power density appears to aggravate the problems of “spiking” due to the cavity formation inherent to the process.

3. Precise penetration and control of root characteristics in partial penetration weldments of thicker materials can be best achieved using multipass procedures in which the power density is kept low.

4. The mechanism of melting in electron beam welds appears to be strongly dependent upon the power density of the electron beam. High power density welds produce melting by the cavity penetration technique and low power density welds appear to produce melting by a conduction mechanism.

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