WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, JANUARY 1981
Sponsored by the American Welding Society and the Welding Research Council

A Constitutive Equation for the Critical Energy Input during Electroslag Welding

Threshold energy input and threshold voltage conditions for weld penetration are used to establish a lower boundary for successful weld penetration

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ABSTRACT. The objectives of this work are to develop functional relations between electroslag welding process variables, and to investigate the process conditions under which successful electroslag welds can be produced. Functional relations are derived for:

1. Weld velocity as a function of electrode velocity and weld geometry.
2. Welding current as a power function of electrode velocity and potential.
3. Critical heat input for fusion of the base metal plates as a function of current, potential, and weld geometry.

Previous authors have used a linear relation between welding current and electrode velocity. Analysis of experimental data for welds in 4 in. (10.16 cm) thick steel plate shows welding current to be proportional to the square root of the electrode velocity, and to the cube root of the potential.

An analysis of process conditions for penetration or non-penetration of the base metal is based on the energy input per unit of plate surface area (specific energy input). Consideration of welding variables shows that the specific energy input is proportional to voltage to the 5/3 power, and inversely proportional to the welding current.

A threshold specific energy input for weld penetration is assumed at high power inputs. This is based on the fact that an increase in current at constant potential is coupled with an increase in electrode and weld pool velocities, and with a decrease in the exposure time of any point on the parent plate surface to the molten flux. At a high specific energy input the amount of heat absorbed by the base metal plate will approach a constant. Thus, an increase in current at constant potential leads to a decrease in specific energy input, and to reduced or non-penetration of the base metal plates.

At low power inputs the weld velocity is slow, and the fraction of heat absorbed by the base metal plates is substantial. An analysis of one dimensional, unsteady state heat transport yields a constant voltage threshold for weld penetration.

The threshold energy input and threshold voltage conditions for weld penetration are used to form a lower boundary for successful weld production in current-potential process space. Below this boundary the welding process will operate, but non-penetration will be observed. The two other boundaries which in close process operating space include a high power limit based on the maximum output of the welding power supply, and a minimum electrode velocity (current) below which the electrode melts by I^2R heating before reaching the flux pool. The validity of these boundaries to process operating space is demonstrated by experimental data for electroslag welds of 4 in. (10.2 cm) thick steel plate.

Paper presented at the 61st AWS Annual Meeting held in Los Angeles, California, during April 13-18, 1980.

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Introduction

Electroslag welding has been a particularly appealing process for thick-section welding because of the high deposition rate.[1-3] Paton[1] reviewed the metallurgical and process control aspects of electroslag welding in 1959, and numerous investigations and applications of the process have been made in subsequent years.[4-6]

Bridge construction and pressure vessel fabrication are two applications where electroslag welding can offer a distinct advantage with respect to deposition rate over multiple-pass welding techniques. However, utilization of the process in these areas has been hampered by welding defects such as lack of fusion of parent (i.e., base metal) plates, center-line cracking, and embrittlement of the heat-affected zone (HAZ). Culp[7] has reviewed the application of electroslag welding to bridge construction, and Okumura *et al.*[8] have examined the electroslag welding of 2¼ Cr–1 Mo pressure vessel steel.

Lack of fusion in base metal plates is one of the major defects associated with electroslag welding. The objective of this research is to investigate the control of electroslag welding process variables to determine the cause of, and find the remedy for this type of defect. The degree of fusion of the base metal plate is a function of the heat transported to the base metal plate surface. Therefore, the process variables which control heat input are of primary importance.

A major objective for all welding processes is to control the power input per unit length of weld, since this is the major variable influencing the degree of melting of the base material, the amount of dilution of the weld metal, and the thermal history of the HAZ.[9-14] In arc electron beam and laser welding, the energy input and travel speed of the weld may be independently controlled. However, in electroslag welding, the energy input per unit area of weld and the weld pool velocity are not independent variables. For a constant voltage power supply, the current and power are both functions of the resistance of the slag pool; hence they are functions of the electrode velocity, the mechanics of electrode melting, and the nature of electrical and thermal transport at the electrode/slag interface.[1-2]

The purpose of the study discussed in this paper was to derive functional relations between the various electroslag welding process variables, and to use experimental data as well as theoretical concepts to predict conditions for sufficient penetration of the base metal as a function of voltage, current, and weld geometry. The resulting welding parameter plots would be valuable for process control. The primary objective was to select the voltage and current levels such that the energy input would be just sufficient to achieve penetration of the base metal without excessive overheating of the HAZ.

At a constant voltage, it would ordinarily be assumed that an increase in the current would provide a greater energy input per unit surface area of the weld—hence, deeper penetration into the base metal. For electroslag welding, however, such is not the case. An increase in current requires an increase in wire electrode velocity, which increases the weld pool velocity and decreases the energy input per unit surface area of weld.

As demonstrated in this paper, an increase in the current at constant voltage can shift the process from penetration to non-penetration of the base metal. This situation is peculiar to electroslag welding and is not generally understood. All concepts governing the interrelationship of electroslag welding parameters, therefore, deserve careful consideration.

Experimental Procedure

A conventional welding machine with oscillating consumable guide was used to weld sections of 4 in. (10.16 cm) thick A335 2¼ Cr-1 Mo steel plate. Hot shoes of 1¾ in. (4.44 cm) thick 2¼ Cr-1 Mo steel plate were applied to establish a 1⅛ in. (2.85 cm) opening. No starting flux was used, and an entire charge of Hobart PF-201 running flux required to establish a 2 in. (5.1 cm) flux pool depth was added at the start of the weld. Welds approximately 18 in. (45.7 cm) long were made.

Electroslag welds were produced to provide data for two principle concepts:

1. The functional relationship between current, voltage and electrode velocity.
2. The threshold or critical value of energy input required for fusion of the base metal.

Welds of constant voltage and varying electrode velocity (current), as well as welds of constant electrode velocity and varying voltage were made to generate the necessary data.

The weldments generated were subsequently evaluated with regard to penetration. The welds were cut, machined, and macro-etched to expose the fusion line on a plane perpendicular to the plate thickness. The welds were logged by means of volumetric pool velocity to correlate changes in amperage or voltage with corresponding vertical locations in the weldment. Incomplete fusion observed at the edge where the hot shoe contacted the plate could thus be correlated with changes in process parameters.

Functional Relations between Process Variables

The relations between electroslag welding process variables involve two important concepts:

1. The relation between electrode velocity and the velocity of the weld pool.
2. The mechanism of current control, and the relation between the welding current, the voltage, and the electrode velocity.

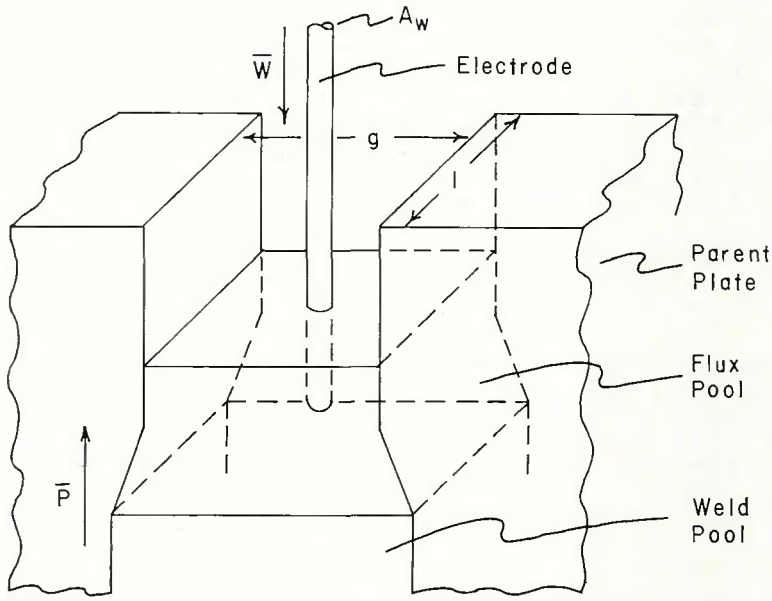

Fig. 1—Schematic representation of the electroslag welding process

Relation between Electrode and Pool Velocities

The relation between the velocity of the wire electrode and the upward velocity of the weld pool can be derived with reference to Fig. 1. The wire electrode of cross-sectional area (A_w) moves downward into the slag pool at a velocity ($\overline{W}$). The weld pool with a weld gap area (A_p) moves upward with a pool velocity ($\overline{P}$). The relation between the electrode and pool velocities can be determined by means of a volume balance:

$$\overline{P} = (F/1 - F)\overline{W} \qquad (1)$$

The fill ratio (F) is the ratio of the electrode to weld gap cross-sectional areas:

F = area of electrode cross-section/ area of weld gap

This expression would be used for cases in which the cross-sectional area of the electrode is a substantial fraction of the weld pool cross-section. For the case of electroslag welding with a wire electrode, the cross-sectional area of the electrode is very small compared to the weld gap area. In this case:

$$F/(1 - F) \simeq F \qquad (2)$$

The relation between wire and pool velocities can then be approximated by:

$$\overline{P} = F\overline{W} \qquad (3)$$

For a wire electrode radius (r_w), a base metal thickness (l) and a weld gap between the base metal plates (g), this relation becomes:

$$\overline{P} = \frac{\pi r w^2}{lg}\,\overline{W} \qquad (4)$$

Welding Current Control

Electroslag welding is generally accomplished with a constant voltage dc power supply, where the welding current is controlled by the resistance of the flux pool. Several investigators[1-3,15,16] have found a linear relation between the current and electrode velocity at fixed voltage. The present data, however, indicate that at constant voltage the current is proportional to the square root of the electrode velocity:

$$I = \beta\overline{W}^{1/2} \ (V = \text{constant}) \qquad (5)$$

Figure 2 is a plot of current vs. electrode potential for an electroslag weld made at a constant potential of 48 volts (V). The data follow the functional relationship suggested by equation (5) very well; the coefficient of determination for this particular fit is $r^2 = 0.997$. Note that the current falls off when the power output of the welding machine (37.5 kw in this case) is exceeded. Points above that limit were excluded from the data reduction analysis.

The current at a given electrode velocity is not independent of the voltage during electroslag welding, although the voltage dependence is not strong. A limited study of the relationship between current and voltage at electrode velocities between 3 and 10 cm/s indicates that current is approximately proportional to the cube root of the voltage:

$$I = \beta\overline{W}^{1/2}V^{1/3} \qquad (6)$$

Figure 3 illustrates this relation for three welds made at constant electrode velocities (two at 3.8 and one at 10.4 cm/s) with the voltage for each weld varying from 30 to 50 V. The slope of the resulting log $I/\overline{W}^{1/2}$ vs. log V plot (Fig. 3) was 0.33, and the coefficient of determination was $r^2 = 0.864$, indicating a good statistical fit.

Figure 4 is a summary plot for all experimental welds, wherein current is expressed as a function of $\overline{W}^{1/2}V^{1/3}$. A coefficient of determination for this overall data correlation was $r^2 = 0.923$, again indicating a good statistical fit for the power function, equation (6).

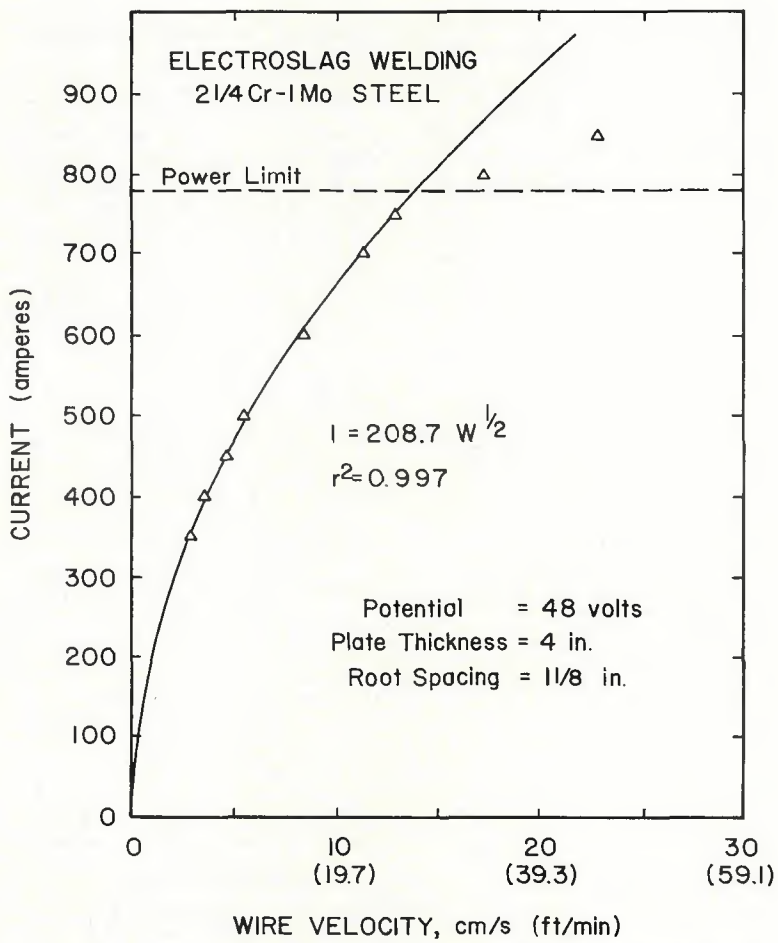

Fig. 2—Experimentally determined parabolic relationship between welding current and electrode velocity

A Constitutive Equation for Energy Input to Base Metal

The energy variable pertinent to this study is energy input per unit surface area of the weld, including the surface areas of the base metal plates and the welding shoes. Let the specific energy input (ϵ) be defined as the total energy input to the process per unit area of the weld surface:

$$\epsilon = \frac{VI\,t_e}{2\,(l + g)\,d} \quad (\text{J/cm}^2) \qquad (7)$$

where t_e = exposure time of any point on the weld surface to the molten flux pool; l = base metal thickness; g = gap between base metal plates; d = flux pool depth.

The specific energy input represents the total energy delivered by the power supply; thus, it includes heat losses as well as the heat required to melt the electrode.

Let Q be the actual energy per unit area delivered by the molten flux pool to the weld surface. This will be some fraction (δ) of the specific energy input, and it will be equal to the product of the heat flux to the weld surface (q) and the exposure time:

$$Q = \delta\epsilon = qt_e \qquad (8)$$

Equation (7) could be expressed in terms of the actual heat delivered or in terms of the heat flux, but these vari-

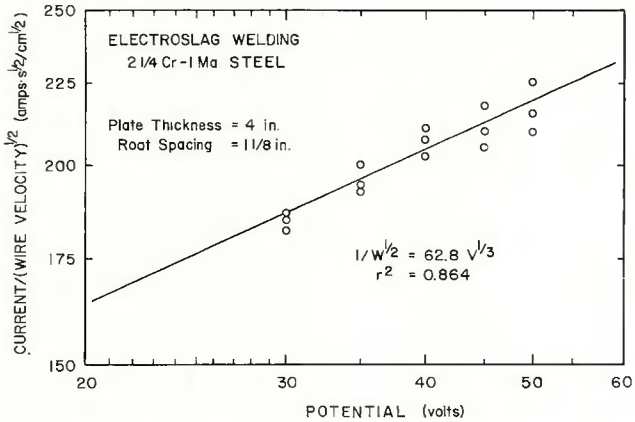

Fig. 3—Empirically determined effect of potential on electrode wire velocity-compensated welding current

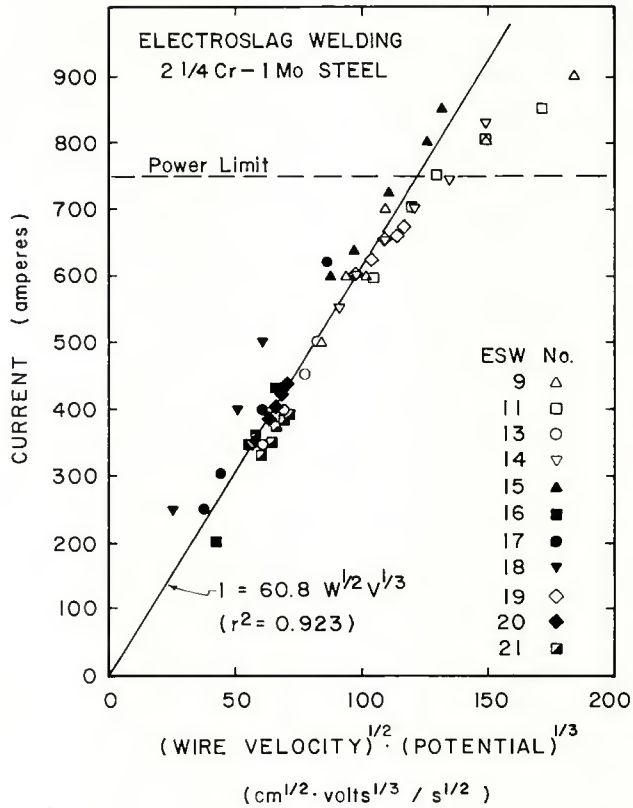

Fig. 4—Summary plot of the electroslag welding results fitted to empirically determined relationships between the welding current, electrode velocity and potential

ables are difficult to evaluate experimentally. For a dc welding process, the specific energy input can be evaluated from the product of measured current and potential.

The exposure time of the weld surface to the flux pool is equal to the depth of the flux pool divided by the weld pool velocity ($\overline{P}$):

$$t_e = d/\overline{P} \qquad (9)$$

By substituting equations (4), (6), and (9) into equation (7), the specific energy input can be expressed as a function of voltage, current, and weld geometry:

$$\epsilon = \left[\frac{lg\,\beta^2}{2\pi r_w^2\,(l+g)}\right]\frac{V^{5/3}}{I} \qquad (10)$$

This is termed the constitutive equation which relates the specific energy input to welding process variables.

Careful examination of equation (10) shows that at constant voltage the specific energy input decreases with increasing welding current, a result which might not be intuitively expected. Recall, however, that an increase in welding current is obtained by increasing the electrode velocity. This, in turn, increases the weld pool velocity, decreases the exposure time of any point on the weld surface to the molten flux, and thus decreases the specific energy input.

Process Conditions for Weld Penetration

The major objective for weld process control is to predict the process conditions under which penetration can be achieved without excessive melt back or overheating of the heat affected zone. This requires a determination of the minimum, or critical, specific energy input (ϵ^*) required for fusion of the base metal surface.

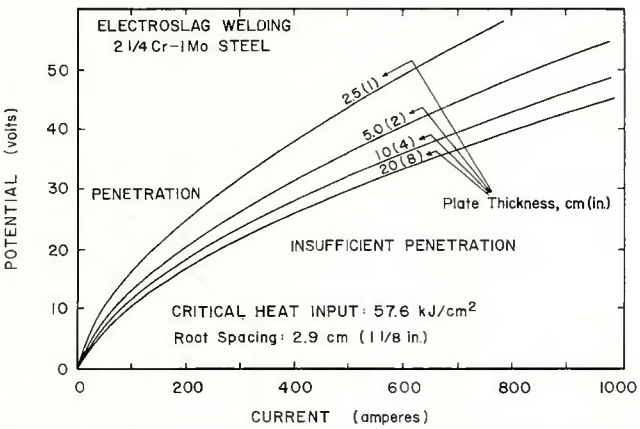

Fig. 5—Critical energy input as a function of plate thicknesses for penetration during electroslag welding of 2¼ Cr-1 Mo steel

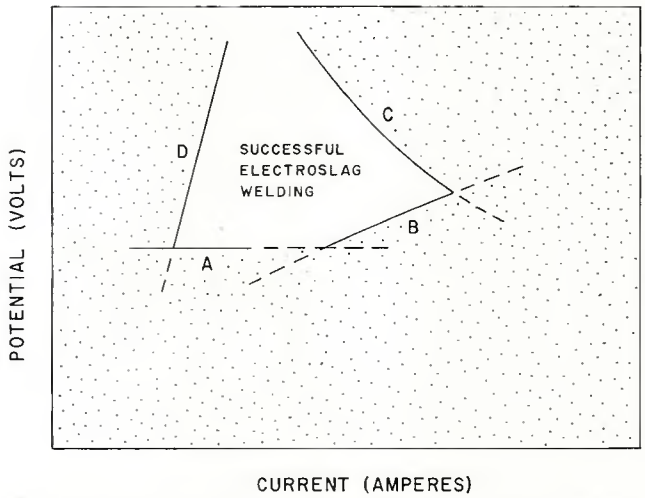

Fig. 6—Schematic illustration of the electroslag welding process boundaries for successful penetration: A—threshold potential, B—critical energy input, C—maximum power supply output, D—minimum electrode velocity

High Power Levels

At high power levels the process approaches steady condition, in which the energy input, the depth of penetration of the base metal plates, and the heat losses are constant. The situation is similar to that of steady state ablation, where a constant heat flux to the surface produces a constant melting velocity.

Under steady welding conditions the constitutive equation represents the heat input to the base metal necessary to maintain the process at steady state, and the critical specific energy input (ϵ^*) represents the threshold or minimum energy input per unit weld surface area to achieve fusion of the base metal surface. At specific energy inputs less than the critical value, the process will operate, but the weld pool will not fuse to the base metal plates.

Figure 5 is a graphical interpretation of the constitutive equation in voltage-current coordinates, for a constant value of the specific energy input. This value is an empirically derived specific energy input of 57.6 kJ/cm², which represents the experimental minimum required for base metal fusion. The curves are drawn for several base metal thicknesses.

At a constant current, equation (10) predicts that the required voltage will increase as the plate thickness decreases. A decrease in weld pool cross-section at a constant electrode feed rate will raise the weld pool velocity, and lower the exposure time of any point on the base metal surface to the molten flux pool. Thus, a higher voltage will be required to bring the base metal surface to the melting point. Figure 5 indicates that a current increase at constant potential can shift the process from penetration to non-penetration of the base metal plates.

Low Power Levels

At low power input levels, the weld pool will be moving slowly. It might be expected that a considerable amount of heat will flow into the base metal plates during passage of the flux pool. Equation (10) and Fig. 5 indicate that adequate weld penetration can be achieved at very low power levels. This is clearly not the case; therefore, heat conduction to the base metal plates must be taken into account.

The influence of heat conduction by the base metal plates can be investigated by utilizing well developed solutions to the time dependent heat transport equation. Carslaw and Jaeger[17] give a solution for one-dimensional heat conduction in a plate subjected to a constant surface heat flux. This solution can be rearranged to give an expression for the minimum time (t_m) required to bring the plate surface to its melting point:

$$t_m = \frac{\pi\, k\rho\, C_p\, (T_m - T_o)^2}{4q^2} \qquad (11)$$

where q = heat flux into base metal surface; ρ = density; k = thermal conductivity; C_p = specific heat; T_o = starting temperature; T_m = melting temperature.

An expression for the heat flux can be obtained by combining equations (7) and (8).

$$q = \frac{\delta V I}{2\,(l + g)\, d} \qquad (12)$$

Equating the exposure time with the melting time (equations (9) and (11)), and substituting equations (4), (6), and (12), an expression is obtained which describes the welding conditions necessary for fusion of the base metal surface:

$$V = \left\{ \frac{k\rho\, C_p\, d[\pi\, r_w\, (T_m - T_o)\, (l + g)]^2}{l g\, \beta^2\, \delta^2} \right\}^{3/8} \qquad (13)$$

This relation is independent of current and provides a threshold or minimum voltage for weld penetration. Thus, unsteady state heat flow into the base metal plates eliminates the possibility of making welds at very low power levels; it thus provides an additional constraint to the constitutive relation given by equation (10)—Fig. 5.

Process Operating Space

The relationship of the critical energy input to potential, current, and electrode velocity provides appropriate information necessary for obtaining a weld of good integrity. Figure 6 represents a schematic of the boundaries to process space within which successful welds can be produced. Boundary A represents the voltage threshold for base metal plate fusion at low power inputs. This is imposed by non-steady state heat conduction into the base metal plates—equation (13).

Boundary B represents the constitutive equation for weld penetration at higher power levels—equation (10). This boundary provides both a lower limit on welding voltage for good penetration, and an upper limit on current or electrode velocity at a constant voltage. The upper limit on current reflects the fact that an increase in the weld velocity decreases the exposure time of the base metal surface to the flux pool.

In addition to boundaries A and B, which are imposed by conditions necessary for weld penetration, there are two other boundaries imposed by equipment and process geometry. Boundary C represents the maximum power output of the welding power supply. Thus, it is a practical limit on the available power. Boundary D represents a limit on the electrode velocity at which the wire electrode melts by I^2R heating during passage between the end of the guide tube and the flux pool. At electrode velocities lower than this the process becomes discontinuous.

Boundaries A through D enclose a process space within which successful welds can be produced. Outside of these boundaries the process may appear to operate well, but adequate penetration of the base metal plates will not be achieved. Within the process space, metallurgical reasoning

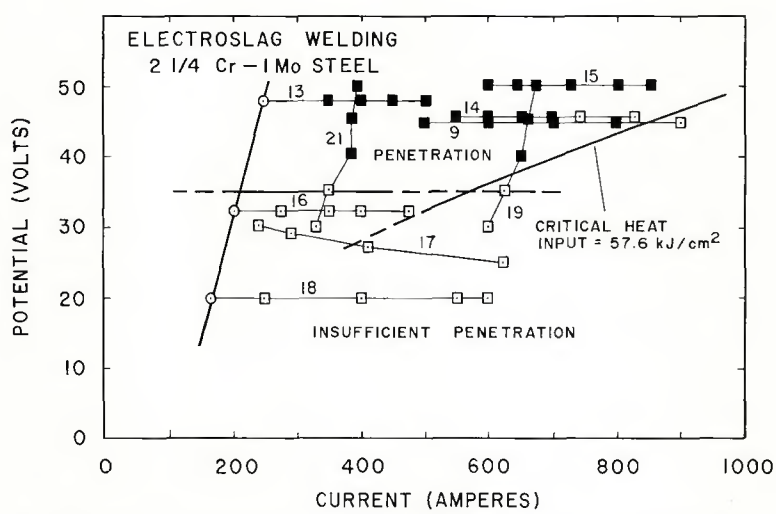

Fig. 7—The penetration results for electroslag weldments of 4 in. (10.16 cm) thick 2¼ Cr-1 Mo steel plate. Closed squares denote adequate weld penetration of the base metal plate; open squares denote insufficient penetration

dictates operation as close to the two lower boundaries as possible. This will minimize the total heat input to the base metal plates, the width of the HAZ, the depth of the weld pool, and the size of the mushy zone between the liquidus and solidus isotherms.

Figure 7 is a plot of experimental data for a number of electroslag welds made on 4 in. (10.16 cm) thick, 2¼ Cr–1 Mo steel plate. Welds were made both at constant potential over a range of electrode velocities, and at constant electrode velocity over a range of potentials. The objective was to produce single welds which crossed the boundaries of process operating space between penetration and non-penetration. The squares show locations where voltage and electrode velocity were held constant for a sufficient period to achieve stable welding conditions. The closed squares indicate conditions under which penetration of the base metal was achieved, and the open squares indicate non-penetration.

Based on these data, an empirical critical heat input of 57.6 kJ/cm² is required for weld penetration at higher power levels. At low power levels, the threshold voltage for penetration is experimentally found to be about 35 V. The fraction of the total power input which is required to heat the base metal plates to the melting point (δ) may be found by substituting the threshold voltage into equation (13). At a penetration threshold of 35 V and low electrode velocities, about 45% of the total power input is used to heat the base metal. The minimum electrode velocity required to prevent electrode melt-off is shown at the left-hand side of Fig. 7. This boundary provided a minimum operating current limit for welds 13, 16, and 18. Below this limit the wire electrode melted off between the guide tube and the surface of the flux pool, and the process became discontinuous.

Welds 16, 17, and 18, as well as a portion of weld 21, were made below the low power voltage threshold for weld penetration. In these cases the process operated as normal, but the weld pool did not penetrate the base metal. Weld 19 illustrates the case of non-penetration below the critical heat input at higher power levels. This weld was run at a constant electrode velocity with the voltage increased in steps, and the process conditions stabilized at each step. Penetration was not achieved until the critical heat input had been reached.

Welds 9 and 14 were run at constant voltage. They represent the case of a maximum current or electrode velocity for weld penetration. These welds were made in opposing directions of current change, i.e., weld 9 was made beginning at low current and progressing to high current, while weld 14 was made beginning at high current and progressing to low current. Thus, little preheating occurred in weld 14, and insufficient penetration persisted to lower current values than would normally be expected.

Conclusions

1. Functional relations have been developed between the various electroslag welding process variables. In particular, the specific energy input per unit area of the base metal surface was expressed as a function of current, potential, electrode velocity, and weld geometry. The specific energy input was shown to decrease with increasing current and electrode velocity at constant potential.

2. Relations for the minimum or threshold heat flux necessary for fusion of the base metal plates have been developed based on welding process and on heat transport considerations. These relations together provide a lower boundary for process operating space in potential-current coordinates. Above this boundary successful welds can be produced.

3. Additional boundaries to process operating space are provided by power and process continuity considerations. The maximum power is limited by the capacity of the welding power supply. The minimum electrode velocity (minimum current) is controlled by I^2R heating of the wire electrode between the guide tube and the flux pool surface. Below this threshold velocity the electrode melts off before reaching the flux pool, and the process becomes discontinuous.

4. Experimental data were obtained for welds of 4 in. (10.16 cm) thick steel plate. These data demonstrate, in principle, the validity of the proposed boundaries to process operating space. The welding process may be operated outside these boundaries, but adequate fusion of the base metal plates will not be obtained.

Acknowledgments

This research was sponsored by the Department of Energy's Fossil Energy Materials Program. The assistance of our colleagues, D. L. Olson and J. E. Jones, and of P. E. Dempsey and W. Clay of Stearns Roger Corporation is gratefully acknowledged. Steel for this research was provided by the Stearns Roger Corporation.

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