A Parametric Study of the Electroslag Welding Process

Heat input and HAZ size are found to be principally dependent on the same process variable—namely, plate gap width

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ABSTRACT. Screening experiments were conducted on electroslag welds to statistically evaluate the effect of independent process variables upon dependent process responses consisting of heat affected zone size, dilution, form factor, welding speed and heat input. The results of multiple electrode electroslag welds made with and without the use of a supplementary filler material are presented as well. Methods of reducing the size of the heat affected zone while maintaining an acceptable form factor were determined.

It can be concluded that significant reductions in heat affected zone size, with resultant improvements in weldment impact properties, are not to be expected when the heat input to the process is reduced by as much as a factor of five.

Introduction

Electroslag welding (ESW) has been of interest for many years, because it provides one of the highest rates of weld metal deposition. Unfortunately, the high heat input and the long thermal cycle inherent in the process produce a large heat affected zone (HAZ) which is subject to grain coarsening and a loss of fracture toughness. It is possible to improve the properties of an electroslag weld joint by normalization or quenching and tempering; however, this is generally impractical due to the large size of the structures fabricated by ESW.

Most previous studies of ESW have emphasized the mechanical properties or the metallurgical structure of the joint (Ref. 1-6). A few investigators have attempted to define a range of acceptable operating parameters (Ref. 7-9), but none has correlated the process parameters with the size of the HAZ.

The structure of the HAZ limits the usefulness of the process, and the structure is at least partially dependent upon the size of the region and its thermal history. For these reasons, it is desirable to develop an understanding of how the process parameters affect the HAZ size. It is hoped in this way to define a set of operating conditions which will minimize the size of the HAZ, thereby optimizing the mechanical properties of the joint.

A screening experiment was conducted to evaluate the effect of independent variables consisting of voltage, current, electrode diameter, flux composition, initial plate gap width and slag depth upon the dependent responses consisting of HAZ size, dilution, form factor, welding speed and heat input.

Experimental

The initial series of welds consisted of a Plackett-Burman experimental design (Ref. 10), which is capable of statistically evaluating the significance of each process variable. All six independent variables were tested in a series of twelve welds consisting of two values for each variable. These values are listed in Table 1.

A second series of welds were made using closely spaced multiple electrodes. Three electrodes were spaced 8.5 mm (0.33 in.) apart across the plate thickness. The plate gap was 15 mm (0.59 in.), and the plate was 50 mm (2 in.) thick. A previous model of heat generation patterns in the slag phase (Ref. 11) suggested that this electrode configuration might have a number of advantages over the common practice.

The first series of welds was made with a non-consumable electrode holder, while the second series was performed with a consumable electrode guide tube. All welds were made on 50 mm (2 in.) thick steel plate with water-cooled copper shoes bridging the plate gap. The first series of welds was performed with A516 Grade 70 steel, while the second series used A36 plate. Each plate was approximately 305 mm (12 in.) square. The initial gap between the plates was greater at the top than at the bottom in order to allow for shrinkage during the process and to provide a uniform gap width during welding. The chemical compositions of the electrodes, base metal plates and fluxes are given in Table 2.

Slag depth was the most difficult independent parameter to control. It was observed that a vigorous motion of the slag pool represented a shallow slag and that a quiescent slag pool represented a deeper slag. With experience the operator was able to control the slag depth within reasonable limits.

All weldments were sectioned both transversely and laterally. Cut surfaces were ground, polished and etched. Percent dilution, form factor, and HAZ size were measured from macrographs. Percent dilution was defined as $(A_f - A_g)/A_f \times 100$ where A_f and A_g were the fused and gap areas respectively. Form factor values, which are defined as the ratio of the width of the weld pool to its height, were measured from the solidification profiles. The HAZ was interpreted as being the innermost zone of coarse grained structure adjacent to the fusion boundary. HAZ area was measured by point counting techniques for each side of the weld, normalized to unit magnification, averaged and represented in units of square centimeters.

Results

Values of the five measured responses for each of the twelve trials of the Plackett-Burman screening design are

Table 1—Values of Factors Used in Plackett-Burman Screening Design

	High	Low
Voltage, V	50	40
Current, A	450	400
Electrode diameter, mm	3.18	2.38
Plate gap width, mm	38	19
Slag depth, mm	12.5	2.5
Flux	A	B

Based on a paper presented at the 62nd Annual AWS Convention held in Cleveland, Ohio, during April 5-10, 1981.

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Table 2—Chemical Compositions of Base Plates, Electrodes and Fluxes Used in this Study

	C	Mn	P	Cu	S	Si	Mo	Other
A516 Grade 70	0.23	0.93	0.009	0.020	0.21	0.20	—	
A36	0.23	1.10	0.01	0.025	0.02	0.10	0.04	Ni 0.03
Electrode	0.14	2.00	0.017	0.024	—	0.03	—	
	SiO_2	MnO	CaO	MgO	Al_2O_3	TiO_2	CaF_2	Fe_2O_3
Flux A	44	10	20	10	15	0	5	0
Flux B	36	0.14	46.3	0.36	3.2	4.4	9.8	0.20
Flux C	35	5	20	10	20	0	20	0

Table 3—Response Values for First Series Screening Experiment

Trial	HAZ size, cm^2	Dilution, %	Form factor	Welding speed, m/h	Heat input, kJ/m × 10^3
1	4.69	37.4	2.20	0.73	6.31
2	4.17	50.2	5.26	0.47	8.72
3	3.57	63.0	1.52	1.22	3.04
4	4.28	49.7	2.23	1.12	4.11
5	3.28	62.5	1.44	1.42	3.27
6	4.46	45.1	4.21	0.75	5.47
7	2.61	43.8	0.71	1.29	2.56
8	3.33	31.3	2.64	0.62	5.31
9	3.60	25.2	3.84	0.63	5.88
10	3.75	68.4	3.44	1.41	2.91
11	4.37	31.3	2.87	0.70	5.23
12	3.68	50.9	2.57	1.09	3.04

shown in Table 3. Here it can be seen that the difference between the maximum and the minimum response values varies by a factor of 2 for HAZ size, 2.5 for percent dilution, 7 for form factor and 3 for welding speed and heat input.

A summary of the statistical effect and the minimum significant effect for each response of the screening experiment is shown in Table 4. If the absolute value of an effect is greater than the minimum significant effect, then the factor is considered to be significant. Responses with less than the minimum significance depend only weakly on the independent variable or else the measured values are within the experimental scatter. The magnitude and algebraic sign of the effects are important, because they determine the confidence level and the slope of the linear relationship between the response and the factor.

From Table 4 it can be seen that:

1. HAZ size increases with increasing voltage and/or gap width.
2. Percent dilution increases with decreasing gap width and/or increasing voltage.
3. Form factor increases with increasing gap width and/or slag depth.
4. Welding speed increases with decreasing gap width and/or slag depth.
5. Heat input increases with increasing gap width.

An analysis of the correlation coefficients among the five responses is shown in Table 5. There is:

1. A positive relationship between HAZ size and form factor.
2. A negligible correlation between percent dilution and either HAZ size or form factor.
3. A negative relationship between welding speed and either HAZ size or form factor.
4. A strong positive relationship between welding speed and dilution as well as between heat input and form factor.
5. A relationship between heat input and HAZ size, although the effect is not as direct as predicted by current theories of heat flow in fusion welding.

Data from the five multiple electrode experiments are tabulated in Table 6. The independent variables for these trials are shown in Table 7. It will be noted from Table 6 that, although the heat input varied by more than a factor of two, the HAZ size is essentially unchanged. The weld travel speed was nearly constant for all four combinations of current and voltage, yet the heat input changed markedly. The addition of a "cold wire" (electrically neutral) feed almost doubled the welding speed with little change in dilution or HAZ size, but produced a sharp reduction in the form factor.

Discussion

The purpose of the work described in this paper has been to study those factors which would permit a reduction in the size of the HAZ in ESW. It is generally

Table 4—Summary of the Statistical Effect and Minimum Significant Effect for Each Response with Each Independent Variable

	Independent variables[(a)]						
Response	Voltage	Current	Electrode diameter	Flux	Plate gap width	Slag depth	Minimum significant factor effects[(b)]
HAZ Size	0.578	0.298	0.192	−0.168	0.575	−0.288	0.575
Percent dilution	11.32	−3.45	4.82	2.87	−19.64	−1.57	10.15
Form factor	0.568	−0.802	0.485	0.182	1.505	−1.042	0.942
Welding speed	0.059	0.032	−0.062	0.008	−0.606	0.149	0.129
Heat input	0.095	−0.005	0.045	0.048	0.298	−0.078	0.105

(a) The significant factors are underlined.
(b) 90% confidence level

Table 5—Values of Correlation Coefficients Among Responses

Responses compared	Correlation coefficient
Form factor to HAZ size	0.5185
Dilution to form factor	−0.1796
Dilution to HAZ size	−0.1540
Welding speed to form factor	−0.6606
Welding speed to HAZ size	−0.4908
Welding speed to dilution	0.7537(a)
Heat input to form factor	0.7434(a)
Heat input to HAZ size	0.5710
Heat input to welding speed	−0.8995(a)

(a) 95% probability of significance.

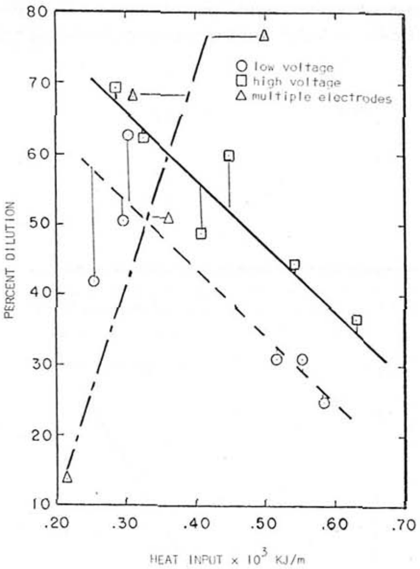

Fig. 1—Percent dilution as a function of the heat input for all welds made in this study

accepted that reducing the total heat input is the primary means of reducing the size of the HAZ. However, results for trials 2 and 4 of the screening experiment (Table 3) and trials 1 and 4 of the multiple electrode welds (Table 6) show that, as heat input is reduced by a factor of two, HAZ size may actually increase. This indicates that other factors control HAZ size and that heat input, while generally correlated to HAZ size (especially in arc welding), is not the primary variable to be considered in ESW.

Heat input was found to be principally dependent on plate gap width, while HAZ size was found to be dependent on plate gap width and welding voltage. Accordingly, a correlation between heat input and HAZ size is expected, but other factors must be considered as well.

The variation of HAZ size with welding voltage may be related to the degree of convection in the slag pool. As shown in Tables 4 and 6, increased voltage increases the dilution, suggesting a greater degree of convection and better heat transfer to the base plate.

The results in Table 5 show that there is an extremely low correlation between percent dilution and HAZ size, as well as between percent dilution and form factor. These results contradict many commonly held beliefs concerning the ESW process. HAZ size is not determined by the net heat input nor is the form factor controlled by the extent of dilution. It would appear that, by proper manipulation of the process variables, both the HAZ size and the form factor may be controlled without sacrificing dilution.

Increasing the welding voltage decreases the depth of electrode immersion within the molten slag. At constant electrode feed speeds, this requires the electrode to melt within a shorter distance, thereby creating a slag which is hotter locally and more turbulent. This increased turbulence creates a washing effect of the hot slag against the base plate walls. Hence, higher voltages promote melting of the base plates, thereby improving fusion.

The reduction in dilution associated with an increase in plate gap contradicts the work of Paton (Ref. 5) and Boag and Marshall (Ref. 7). The reduction in dilution is believed to be due to a reduction in the convection forces at the slag/base plate interface. This reduced turbulence causes a reduction in the washing effect on the base plate walls and thus a reduction in dilution. Hence, when increased dilution is necessary as in narrow gap welding, higher voltages are preferable; but when dilution is adequate, a reduction in welding voltage may decrease the size of the HAZ.

Figure 1 is a plot of percent dilution vs. heat input. For the single electrode experiments the slope of this curve is negative, but for the multiple electrode experiments the slope appears to be positive. This correlates well with data obtained by Paton and indicates that the same amount of dilution and a more uniform dilution may be attained at lower heat inputs using multiple electrodes rather than a single electrode. It appears that the use of multiple electrodes, which are closely spaced, may significantly improve the ESW process.

The observation that dilution is not affected by welding current may be due to operation within an intermediate region of electrode feed rates. Both Liby (Ref. 1) and Paton (Ref. 5) found that the dilution reaches a maximum for intermediate values of electrode feed speed. It is likely that the experiments reported here were within the flat region of Liby and Paton's electrode feed speed curves.

Welding speed is an important factor in ESW, because increased welding speeds are expected to significantly affect both the form factor and the size of the HAZ. Welding speeds are found to be most significantly affected by plate gap width and to a lesser extent by slag depth—Table 4. The increase in welding speed caused by a decrease in plate gap width can be derived from the definition of welding speed:

$$V_w = V_e (A_e/A_g)$$

where V_w and V_e are the weld travel speed and electrode feed rate, respectively, and A_e and A_g are the cross sectional areas of the electrode and the plate gap.

The form factor is an indicator of the resistance of the weld to centerline cracking. Increasing the voltage and/or reducing the current are believed to be major factors in improving the form factor. However, the results in Table 4 show that increasing the plate gap width and/or the slag depth reduces the welding speed and produces a more favorable solidification pattern in the weld pool, thus increasing the form factor.

Table 6—Results of Multiple Electrode Experiments

Trial	HAZ size, cm^2	% Dilution	Form factor	Welding speed, m/h	Heat input, kJ/m × 10^3	Feed rate of supplementary filler material, kg/h
1	3.68	77.32	3.58	1.11	5.02	0
2	4.13	68.34	2.35	1.25	3.18	0
3	3.19	51.32	3.55	1.05	3.54	0
4	3.94	13.71	2.57	1.17	2.25	0
5	3.71	66.65	1.54	2.10	2.65	1.54

Table 7—Values of Independent Variables Used in Multiple Electrode Experiments[(a)]

Trial	Voltage, V	Current, A	Electrode diameter, mm
1	45	600	2.38
2	32	600	2.38
3	45	400	2.38
4	32	400	2.38
5	45	600	2.38, 1.59[(b)]

(a) Flux C and a 15 mm plate gap were used for all welds.
(b) The smaller diameter electrode was used as a cold wire feed into the slag bath.

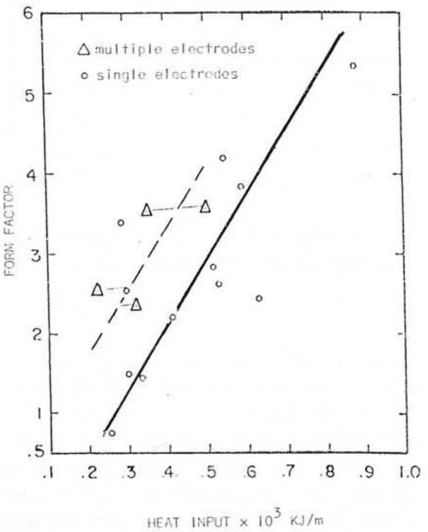

Fig. 2—Form factor as a function of heat input

Figure 2 is a plot of heat input vs. form factor. It is seen that form factor values increase with increasing heat input and that higher form factor values at lower heat inputs may be attained by using multiple electrodes. This is most likely due to the better distribution of heat when using multiple electrodes.

From the foregoing data, it is seen that the size of the HAZ in ESW can be minimized by using a minimum plate gap and a minimum voltage. The use of lower voltages, however, results in lower levels of dilution and the possibility of lack fusion defects. Figure 1 suggests that this problem may be overcome by the use of multiple or oscillating electrodes.

Decreasing the plate gap width requires the use of less viscous slags with multiple and/or oscillating electrodes to gain a uniform penetration across the face of the base plate. Unfortunately, decreasing plate gap width has a detrimental effect on the form factor. Clearly, plate gap widths should be reduced as long as the form factor is kept within acceptable limits if one is to minimize the HAZ size. Further increases in the form factor may be gained by using deeper slag pools.

Improvements in the ESW process may be made which will result in large reductions in the total heat input. However, these improvements must be made at the cost of greater process control. Reductions in heat input from standard practice of a factor of three to five are deemed practical with present techniques and equipment. However, the resulting benefits of decreased HAZ size and improved impact properties will probably not be great. Indeed, the present study has shown that variations in the operating parameters may produce large changes in the dilution, the form factor, the welding speed and the heat input, while changes in the HAZ size are relatively small. It has further been shown that the HAZ size of ESW is not a simple function of the heat input as previous theories predicted.

The use of closely spaced multiple electrodes provides several advantages. Perhaps the most important is the ability to reduce the plate gap width without sacrificing dilution.

Conclusions

From the results of some seventeen trials of the ESW process, it may be concluded that:

1. Heat input should not be considered the primary factor affecting the size of the HAZ.

2. Dilution is primarily influenced by welding voltage and plate gap width. The effect of slag depth on dilution is of lesser significance. At intermediate values of electrode feed speed the dilution is not influenced by welding current.

3. There is a weak correlation between percent dilution and HAZ size and between percent dilution and the form factor.

4. The same amount of dilution and a more uniform dilution may be obtained at lower heat inputs by use of multiple electrodes.

5. Dilution increases with increasing welding speed at a faster rate when using multiple electrodes rather than a single electrode. This is beneficial when welding with narrow plate gaps.

6. The addition of supplementary filler material was found to increase welding speed by a factor of two and reduce the form factor by a factor of two. The size of the HAZ remained constant.

7. Welding speed is most significantly affected by plate gap width and to a lesser extent by slag depth.

8. The form factor increases with increasing heat input. Higher form factor values may be attained at lower heat inputs by using multiple electrodes rather than a single electrode.

9. The form factor is most significantly affected by plate gap width and slag depth. The effects of current and voltage on the form factor are of lesser significance.

9. Heat input and HAZ size were found to be principally dependent on the same process variable, plate gap width. HAZ size is also dependent on the welding voltage.

10. In attempting to reduce the size of the HAZ, plate gap widths should be reduced as long as the form factor is kept within acceptable limits. Further improvements in the process may be gained by using minimum welding voltages, more exact joint fitup, deeper and less viscous slags, and multiple and/or oscillating electrodes.

11. Significant reductions in the HAZ size with resultant improvements in the impact properties are not expected when the heat input to the ESW process is reduced by as much as a factor of five.

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