Effect of Accurate Voltage Control on Partial Penetration EB Welds

Direct comparison with earlier experiment shows that accurate control reduces weld variation

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ABSTRACT. The effect of accurate voltage control on the variability of weld geometry of partial penetration electron beam welds was determined. It was shown that the 95% confidence limit, for predicting weld geometry from the input parameters, is less than 10% of the response for the midpoint of this experiment. This is a significant improvement over previous work and is attributed to improved control of the accelerating voltage.

Introduction

It has recently been shown (Ref. 1) that the voltmeter on an electron beam welding machine does not accurately measure or repeatably reproduce the operating voltage. Using a technique which involves measuring the x-rays emitted when the beam hits a target, it is now possible to accurately measure and control the operating voltage. The purpose of this work was to show that accurate voltage control decreases the penetration variations, from weld to weld, seen on partial penetration electron beam welds.

Weidner and Shuler (Ref. 2) (WS) recently reported on a statistically designed five level fractional factorial experiment (Ref. 3) studying the effects of welding parameters on the weld geometry of partial penetration electron beam welds. Their welding parameters were voltage, current, focus position, travel speeds, and material composition. The weld geometry was measured as the maximum and minimum penetration and their difference, weld width, and weld depth to weld width ratio. The WS experiment showed all parameters to be significant to some degree with some parameter interaction.

Our experiment was designed so that the results could be compared to the results obtained by WS. The variable weld parameters used for this work were voltage, current, and focus position. The materials and travel speed were chosen from those used in the WS experiment. Also, the same electron beam machine and a 6 in. gun-to-work distance was used in both experiments. The experiment was a 2 × 2 × 3 complete factorial employing two values for each voltage and current and three values for the focal position. Thus, 12 welds were required for each material used. This design permitted statistical determination of the significance of the linear effects of the weld parameters, their three interactions, and the second order focus effect. It was also possible to make a comparison of weld geometry variation between our work and that of the WS experiment.

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Experimental

The values used for the weld parameters were consistent with and centered around the zero point values (contrast unit = 0) used in the WS experiment. Table 1 shows the weld parameters and their corresponding contrast units used in this study. For the data analysis, the values of the weld parameters were transformed to contrast units to reduce the residual calculating error. The materials used for this work were 6061 aluminum and 1100 aluminum (contrast units of ±5 in the WS experiment). The travel speed was 55 ipm (contrast unit = 0 in the WS experiment). The focus position was measured using a flying wire probe with sharp focus determined in

Table 1 — Welding Parameters and Contrast Units

Voltage, kV	CU	Current, mA	CU	Focal length, F (in.)	CU
105	−1	10	−1	−.75	−1
134	+1	20	+1	0	0
				.75	+1

Materials:
6061 Al (CU = + 5 in WS experiment)
1100 Al (CU = − 5 in WS experiment)
Travel speed: 55 ipm
Gun-to-work distance: 6 in.

the same manner as Sandstrom et al (Ref. 4) and Sanderson (Ref. 5). The specific quantities measured (i.e., the geometric responses) were maximum and minimum penetration (Pmax and Pmin) and weld width (W).

Another set of 12 welds was done with 1100 aluminum using a different but supposedly identical machine. This was done to determine whether or not weld parameters could be transferred from one machine to another with no change of variances for the weld geometry. Both machines were "high voltage" types capable of delivering a maximum power of 6 kW.

The samples were 3 × 3 × 0.5 in. in size and were butt welded in a fixture. After welding, the weld bead was photographed, the sample fractured longitudinally, and the fracture photographed. All photographs were taken using approximately 3X magnification. Measurements of the weld geometry were taken from the photographs. The weld width was the average of five measurements across the weld.

The energy dispersive x-ray spectrometer system, used to measure the operating voltage, consisted of a lithium drifted silicon detector, 2048 channel pulse height analyzer, associated amplifiers, and power supplies. The spectrometer was calibrated to measure operating voltages with an accuracy ±0.1 kV. Details of the spectrometer-welding machine configuration and additional details on the voltage measuring techniques can be found elsewhere (Ref. 1).

Prior to the actual welding of each sample, the voltage was set using the x-ray technique. This was accomplished by impinging the beam on a tungsten target and acquiring an x-ray spectrum. The high energy cut-off, and thus the operating voltage, was determined by observing the spectrum. The operating voltage was adjusted until the high energy cut-off was at the desired energy (voltage). After the operating voltage was set, sharp focus was obtained using the flying wire probe and then the sample was welded.

Results and Discussion

The measured responses were analyzed by standard statistical techniques. Linear regression analysis was used to fit the data with a function of the form:

$$Y_i = B_0 + B_1K + B_2M + B_3f + B_4KM + B_5Kf + B_6Mf + B_7f^2$$

where Y_i are the geometrical responses,

K = voltage in contrast units,
M = current in contrast units, and
f = focus position in contrast units.

After these regression equations were obtained, comparison of the data from 1100 aluminum welded on two different machines showed that the standard deviation was significantly larger for one machine. Since the voltage measuring technique permits accurate voltage control and the flying wire permits consistent setting of the sharp focus position independently of the welding machine, the current measurement is the most likely cause of the difference seen in the standard deviations. Also, the Student's T-test of the coefficients in each equation showed current to be the most significant variable in all cases. Thus, comparison of the data obtained from identical welds using identical material on two different machines indicates primarily that current measurement may be a significant problem. Because of this uncertainty, no further comparisons were made between welding machines and only the data obtained on the same machine that was used by Weidner and Shuler is considered.

The data obtained from two different materials welded using the same weld parameters on the same machine that was used for the WS experiment were also compared. The F-test was used to test the hypothesis that the standard error for corresponding responses was the same (i.e., standard error of Pmax for 1100 aluminum = standard error of Pmax for 6061 aluminum, etc. for Pmin and W).

In all cases, this hypothesis was accepted. The coefficients in the regression equations for corresponding responses were then tested using the hypothesis that corresponding coefficients were the same (i.e, for Pmax from 1100 aluminum and Pmax from 6061 aluminum, B_0 (1100Al) = B_0 (6061 Al), B_1(1100 Al) = B_1(6061 Al), . . . B_7(1100 Al) = B_7(6061 Al), etc. for Pmin and W). In all cases this hypothesis was rejected at the 95%

Table 2 — Equations of Geometric Responses for 1100 and 6061 Aluminum

Material	Equation	St'd Dev'n	Response = parametric equation[a]
1100 Al	1	±0.019	Pmax = 0.1734 + 0.032K + 0.115M + 0.027KM
	2	±0.0128	Pmin = 0.133 + 0.022K + 0.078M + 0.019KM
	3	±0.0087	W = 0.1032 + 0.0088K + 0.025M
6061 Al	7	±0.0112	Pmax = 0.23 + 0.033K + 0.093M − 0.01f + 0.051KM + 0.01Kf
	8	±0.0173	Pmin = 0.17 + 0.036K + 0.062M + 0.018KM
	9	±0.0045	W = 0.0975 + 0.006K + 0.011M − 0.0048Mf

(a) K = voltage (contrast units), M = current (contrast units), and f = focal length (contrast units)

Table 3 — Values of the Responses at the Midpoint of the Equations for this work and that of Weidner and Shuler (Ref. 2)

			This Work			Results of WS experiment		
Material	Equation	Response	Solution of eq at midpoint	St'd Dev'n	Variation, %	Solution of eq at midpoint	St'd Dev'n	Variation, %
1100	1	Pmax	0.1734	±0.019	±10	0.204	±0.051	±25
	2	Pmin	0.133	±0.0128	±10	0.146	±0.034	±23
	3	W	0.1032	±0.0087	±8	0.122	±0.013	±11
6061	4	Pmax	0.23	±0.0112	±5	0.278	±0.051	±18
	5	Pmin	0.17	±0.0173	±10	0.183	±0.034	±19
	6	W	0.0975	±0.0045	±5	0.107	±0.013	±12

confidence level. This test shows that the weld geometry is material dependent. This conclusion was also made in the work reported by Weidner and Shuler.

After the tests were done, the Student's T-test was used to examine each coefficient of the initial regression equation for significance. The regression analysis was then repeated using only independent variables for which the coefficients were known to be significant at the 95% confidence level. The results of the final analysis are shown in Table 2.

Table 3 shows the standard deviation values and the values of the equations at the midpoint of our work and for that obtained by the WS experiment. Since the equations are all different for the measured responses, only the variances about the regressions were examined. This was done using the F-test and in all cases they are statistically different and thus differences in the variabilities between our work and that of WS are real. Also shown in Table 3 are the standard deviations as percentages of the value of the response at the midpoints of the equations. This table shows that the maximum variation seen in this work is 10% of the value of the response at midpoint of the equations. In all cases there is less variability for this work than that done previously. Thus, we have shown that accurate voltage control reduces weld geometry variations.

Aside from the fact that increased control of the voltage decreases variations in weld geometry, for a given welding machine, it is significant that this will not produce the same variations when different machines are used. Since beam current was the most influential variable found for this work and also that of WS, it is the most probable source of the variations. Some of the variability from machine to machine can probably be removed by more frequent and accurate current calibration.

Concurrent with this it will then be important to know and be able to achieve similar electron density distributions. To a limited extent, the flying wire probe can be used to produce similar electron densities. However, for our work the probe was only used in one dimension and the actual beam diameter was not measured. Further studies should be done using a probe sampling in two dimensions of the plane normal to the beam and the beam diameter should be measured as well as some measure of total beam current. These quantities are essential to control power density and beam orientation on the weld joint.

In conclusion we can say that accurate voltage control does decrease weld variations. Additional work must be done to reduce variations further, as well as to permit transfer of machine parameters. A more thorough knowledge of machine parameters will then aid in evaluating penetration models.

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