Magnetic Steering of Arc and Bead Characteristics in Submerged Arc Strip Cladding

Magnetic steering experiments increase bead thickness while decreasing dilution

BY U. D. MALLYA AND H. S. SRINIVAS

ABSTRACT. Submerged arc strip cladding has been widely used when larger thicknesses of clad materials are required. Use of wider strips and higher current have all been attempted to achieve higher productivity and these have been associated with arc blow phenomena and unacceptable bead characteristics.

Investigations were carried out to study the effect of various magnetizing parameters (flux density, dwell time) and welding current on the bead characteristics, using 60-mm-wide strips of 309L stainless steel. Results of the investigation indicate very encouraging trends in increasing the melt-off rate/bead height and decreasing penetration and hence dilution by 23%. The magnetizing flux density individually did not indicate significant influence on any of the bead characteristics studied.

Introduction

Submerged arc strip cladding is one of the widely used techniques to deposit considerable thicknesses of clad material over a wide area of base metal. This is done to impart to the surface of a relatively cheap base metal the properties of the clad metal, such as corrosion resistance end wear resistance. Productivity during cladding could be increased using higher currents and wider strips (Ref. 1). However, this has been reported to be associated with difficulties such as arc blow, increased dilution and poor bead shape. Magnetic steering of the arc not only reduces the arc blow effects, but also increases the productivity and produces less and more uniform dilution.

Different process parameters must be controlled to obtain the desirable bead characteristics. This paper discusses the results of an investigation to study the sign significance of some of the magnetic parameters on bead characteristics when the arc is subjected to an oscillating magnetic field.

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Previous Work

The welding arc can be considered as a flexible current-carrying conductor which experiences a force when subjected to an external magnetic field. The welding arc can be deflected forward, backward or sideways with respect to electrode and welding direction, depending upon the direction of an external magnetic field (Ref. 2).

If an auxiliary magnetic field is superimposed, the force experienced by the arc column is proportional to (Ref. 3) the flux density of the applied magnetic field, the current in the arc, and the length of the arc.

KEY WORDS

Magnetic Steering
Bead Characteristics
Submerged Arc Strip
Strip Cladding
Flux Density
Dwell Time
Welding Current
Dilution
Oscillation
309L Stainless

A transverse magnetic field deflects the arc in the weld direction; whereas, a longitudinal magnetic field deflects the arc perpendicular to the bead. An oscillating magnetic field oscillates the arc.

Out of the various possibilities of arranging (Ref. 4) an auxiliary magnetic field with respect to the arc, deflecting the arc forward and oscillating the arc across the cladding width was found to be beneficial (Ref. 2). By forward deflection of the arc, penetration and bead height is reduced while root width is increased. The welding speed and upper limit of current for a given strip width can also be increased (Ref. 4). In the case of oscillating the arc sideways, the bead becomes wider and the penetration becomes uniform and shallow.

The penetration profile in an oscillating arc depends on the dwell time of the arc at any particular position, which is affected by the shape of the alternating current used for energizing the electromagnet. The bead boundaries can be more strongly heated by using a trapezoidal wave form of the energizing current, which results in uniform penetration across the cladding width.

Investigation (Ref. 5) with high-speed x-ray photography showed that with electrodes of larger width, the welding cavity stretches over the entire width of the electrode. With increasing width of the electrode, the number of visible metal droplets on the melted edge increases. For example, 5 droplets in 60-mm strip to 14 droplets in 150-mm strip. Each droplet corresponds to an arc along the strip width. Cross-sections of weld

beads obtained with 60, 90 and 120-mm strip electrodes using auxiliary magnetic field conditions, showed uniform and flat penetration and favorable edge formation (Ref. 6).

A study of the available literature showed that no quantitative information has been reported about the effect of magnetizing parameters on bead characteristics. Also, no data is available to compare the effect of magnetic steering on bead characteristics with those under unsteered conditions.

The present investigation studied the following:

1) The effect of magnetizing parameters, such as magnetic flux density and dwell time of the magnetic flux density, on bead characteristics while oscillating the arc across the bead width at normal and high current densities.

2) A comparison of the bead characteristics under both steered and unsteered conditions.

Experimental Details

To produce a magnetic field in the arc zone, an electromagnet capable of developing 120 gauss at the arc zone was fitted onto the welding head with the configuration as shown in Fig. 1 A trapezoidal wave form for energizing current was preferred so dwell time could be varied without changing the frequency. A trapezoidal wave form was obtained by generating a triangular wave form from a function generator and then clipping the wave form at the required voltage. A current amplifier was used to amplify the trapezoidal wave form to get the required peak magnetic flux density. By properly choosing frequency, clipping voltage, and current amplification, it was possible to obtain the required dwell time for peak magnetic flux and peak magnetic flux density.

The following parameters were kept constant throughout the experiments: arc voltage, 28 V ±1 V; electrode extension, 40 mm; travel speed, 150 mm/min; electrode polarity, positive; magnetizing function, trapezoidal; base plate, 250 x 170 x 50 mm C 14 grade steel (ISO 2004-1970), C 0.1–0.18, Si 0.15–0.35, Mn 0.4–0.7, S 0.05, P 0.5; electrode strip, AISI 309L stainless steel, 0.5 mm thick, 60 and 30 mm wide, C 0.02, Si 0.27, Mn 1.95, P 0.01, Cr 23.7, Ni 12.8; flux, agglomerated.

The independent parameters were: current, 750, 900 and 1050 A for 60 mm strip, and 375, 450 and 525 A for 30 mm strip; dwell time of peak magnetic flux (x_2), 90, 120, 180 and 240 ms; peak magnetic flux density (x_3), 40, 60, 80 and 100 gauss.

Fourty-eight test beads were taken for each width of the strip.

The response parameters were bead characteristics. The bead characteristics were: root width,mm (Y_1); cross-sectional area of deposition, mm^2 (Y_2); average depth of penetration, mm (Y_3); average height of the bead , mm (Y_4); dilution, % (Y_5).

Figure 2 shows some of the parameters. Dilution (Y_5) is the most important parameter which affects almost every aspect of clad quality. This is a calculated parameter.

The "area method" was used to evaluate bead characteristics. The profile of the bead cross-section was projected onto a paper using an episcopic profile projector with a magnification of 10X. Areas were measured by using a planimeter.

Analysis and Discussion

Standard statistical techniques were used to analyze all experimental results. They are: 1) descriptive statistics, 2) Pearson correlation coefficients, 3) multiple regression analysis (MRA), 4) analysis of variance (ANOVA), and 5) multiple classification analysis (MCA).

By using these techniques, subjectivity in analysis and interpretation of data was eliminated. Descriptive statistics showed that the distributional characteristics and central tendencies of experimental data follows nearly normal dis-

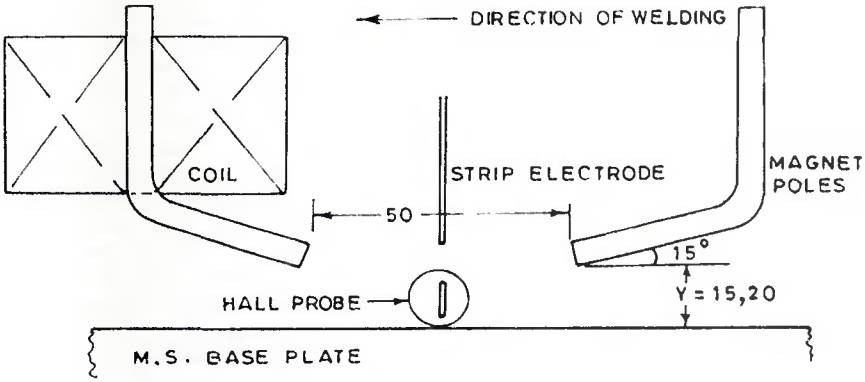

Fig. 1 — Arrangement of magnet poles for oscillating the arc across the bead.

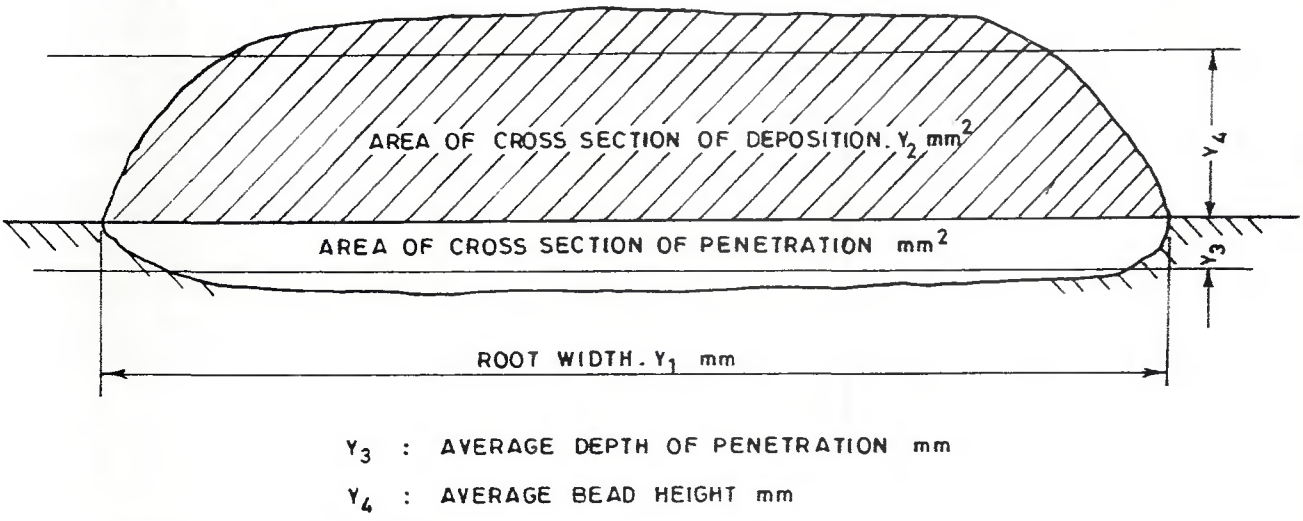

Fig. 2 — Cross-section of the bead showing response parameters.

tribution. Hence, the data was subjected to further statistical analysis to draw valid inferences.

Pearson correlation coefficients showed a strong linear relationship of response parameters (Y_1 to Y_5) with current (x_1). The remaining correlation coefficients were low, signifying nonlinearity and high dispersion of points.

Table 1 gives the summary data of stepwise forward multiple regression analysis for all response parameters (Y_1 to Y_5) for 60-mm strip. It is observed from this table that regression equations for Y_1 and Y_2 have good correlation coefficients and can be used for predicting root width and cross-sectional area of deposition. Penetration values (Y_3) can be predicted with lesser accuracy. As all these equations are based on experimental data, prediction of response parameters on the basis of these equations are subjected to limitations of experimental accuracy.

The significance of main effects and two-way interaction of independent variables on each of the response parameters for 60-mm strip was evaluated by comparing F-ratios obtained by ANOVA with those of standard statistical tables. Current (x_1) is the most significant parameter for the variation of all response parameters. There is no significant dwell time of peak flux (x_2) for the variation of response parameters. But peak flux (x_3) is significant for the variation of all the response parameters except Y_1. Two-way interactions have negligible significance for variation of response parameters.

Multiple classification analysis (MCA) gives the pattern of variation of individual response parameters with the considered levels of independent variables. The pattern is provided as the deviations from the grand mean value of a particular response parameter at each level of the independent variables seperately. This is provided in the form of tables which can subsequently be converted into plots.

The pattern of variation of root width (Y_1) with X_1, X_2 and X_3 are plotted in Fig. 3 for 60-mm strip. From the figure, it is seen that as X_1 increases Y_1 also continously increases. In submerged arc welding (Ref. 7), as the current increases, the size of the arc cavern also increases, which is reponsible for an increase in root width. Also, as current increases, the melting rate increases and metal is deposited on the base plate. The molten metal spreads over a large area resulting in increased root width.

A slight increase in root width is observed by increasing X_2 and X_3. Peak magnetic flux (X_3) determines the amount of deflection of the arc, and dwell time of peak flux (X_2) determines the duration for which the arc is deflected in any particular direction. When the arc is deflected away from the strip edge, the cavern probably also deflects in the corresponding direction, thereby allowing the molten metal to spread over a larger width.

The purpose of the present work was to study to what extent the magnetic steering affected the bead characteristics compared to unsteered conditions. Experiments were conducted at the same three levels of current, under unsteered conditions. The mean root width at three levels of current under unsteered conditions is denoted by Y_1 (O) and has been marked in Fig 3. It is seen from the figure that the grand mean value of Y_1 under steered conditions is more than Y_1 (O). Also the root width at all levels of X_2 and X_3 is more than Y_1 (O), which is an indication of the improvement in root width under steered conditions.

Figure 4 shows similar MCA plots for a cross-sectional area of deposition (Y_2). As current (X_1) increases from 730 A to 1050 A, Y_2 also continuously increases. It is well known that as current increases melting rate increases, which increases the amount of deposited metal on the base plate. Consequently, Y_2 also increases since the speed of welding is kept constant.

The variation of Y_2, which lies within ±3.3% of grand mean value (of 302.7 mm^2) as X_2 is increased from 90 to 240 ms, is not significant, This fact is also confirmed by ANOVA.

So far as peak magnetic flux (X_3) is concerned, no definite trend in variation of Y_2 is observed as X_3 is increased from 40 to 100 gauss. The variation of Y_2 is within ±6% of the grand mean value.

It has been reported by the same authors elsewhere (Ref. 8) that electrode melting rate is sensitive to voltage fluctuations in the case of short arc length (meso-spray phenomena). In the present case, experiments were carried out at a set voltage of 28 V that varied between 27 and 29 V. During a given weld run, only X_3 was changed, keeping X_2 and X_1 constant. Hence variation of Y_2 may be attributed to the variation in welding voltage rather than to the chang in X_3. Thus, it may be concluded that the change in X_3 from 40 to 100 gauss did not have any significance influence on Y_2.

As in the case of root width, the mean value of cross-sectional area of deposition (Y_2) at the three levels of current

Table 1 — Summary of Stepwise Multiple Regression Analysis of 60-mm Strip

SL No.	Dependent Variable	Step No.	Independent Variable Entered	Regression Equation	Mult. Corr. Coefficient R	Variation Explained: % Variation $R^2 \times 100$	Variation Explained: To Be Accounted By	Balance Variation: % Variation	Balance Variation: To Be Accounted By
1	Y_1 Root width mm	1	X_1	$Y_1 = 45.798 + 0.020\ X_1$	0.889	79.1	X_1	20.9	X_2,X_3,RES
		2	X_2	$Y_1 = 45.350 + 0.020\ X_1 + 0.0028\ X_2$	0.891	79.4	X_1,X_2	20.6	X_3,RES
		3	X_3	$Y_1 = 44.90 + 0.02X_1 + 0.0028X_2 + 0.0064X_3$	0.893	79.7	X_1,X_2,X_3	20.3	RES
2	Y_2 Cross-sectional area of deposition square mm^2	1	X_1	$Y_2 = 54.44 + 0.276\ X_1$	0.788	62.1	X_1	37.9	X_2,X_3,RES
		2	X_2	$Y_2 = 43.20 + 0.276X_1 + 0.071X_2$	0.794	63.0	X_1,X_2	37.0	X_3,RES
		3	X_3	$Y_2 = 70.4 + 0.276X_1 + 0.071X_2 - 0.39X_3$	0.819	67.1	X_1,X_2,X_3	32.9	RES
3	Y_3 Penetration mm	1	X_1	$Y_3 = 0.049 + 0.0017X_1$	0.626	39.2	X_1	60.8	X_2,X_3RES
		2	X_2	$Y_3 = 0.12 + 0.0017X_1 - 0.00044X_2$	0.631	39.8	X_1,X_2	60.2	X_3,RES
		3	X_3	$Y_3 = -0.011 + 0.0017X_1 - 0.00044X_2 + 0.0018X_3$	0.643	41.4	X_1,X_2,X_3	58.6	RES
4	Y_4 Average height of bead mm	1	X_1	$Y_4 = 2.98 + 0.0018X_1$	0.272	7.4	X_1	92.6	X_2,X_3,RES
		2	X_2	$Y_4 = 2.50 + 0.0018X_1 + 0.003\ X_2$	0.341	12.1	X_1,X_2	87.9	X_3,RES
		3	X_3	$Y_4 = 2.80 + 0.0018X_1 + 0.003\ X_2 - 0.004X_3$	0.367	13.4	X_1,X_2,X_3	86.6	RES
5	Y_5 Dilution %	1	X_1	$Y_5 = 17.58 + 0.0079X_1$	0.236	5.6	X_1	94.4	X_2,X_3,RES
		2	X_2	$Y_5 = 18.84 + 0.0079X_1 - 0.008X_2$	0.262	6.9	X_1,X_2	93.1	X_3,RES
		3	X_3	$Y_5 = 15.25 + 0.0079X_1 - 0.008X_2 + 0.05\ X_3$	0.384	17.7	X_1,X_2,X_3	85.3	RES

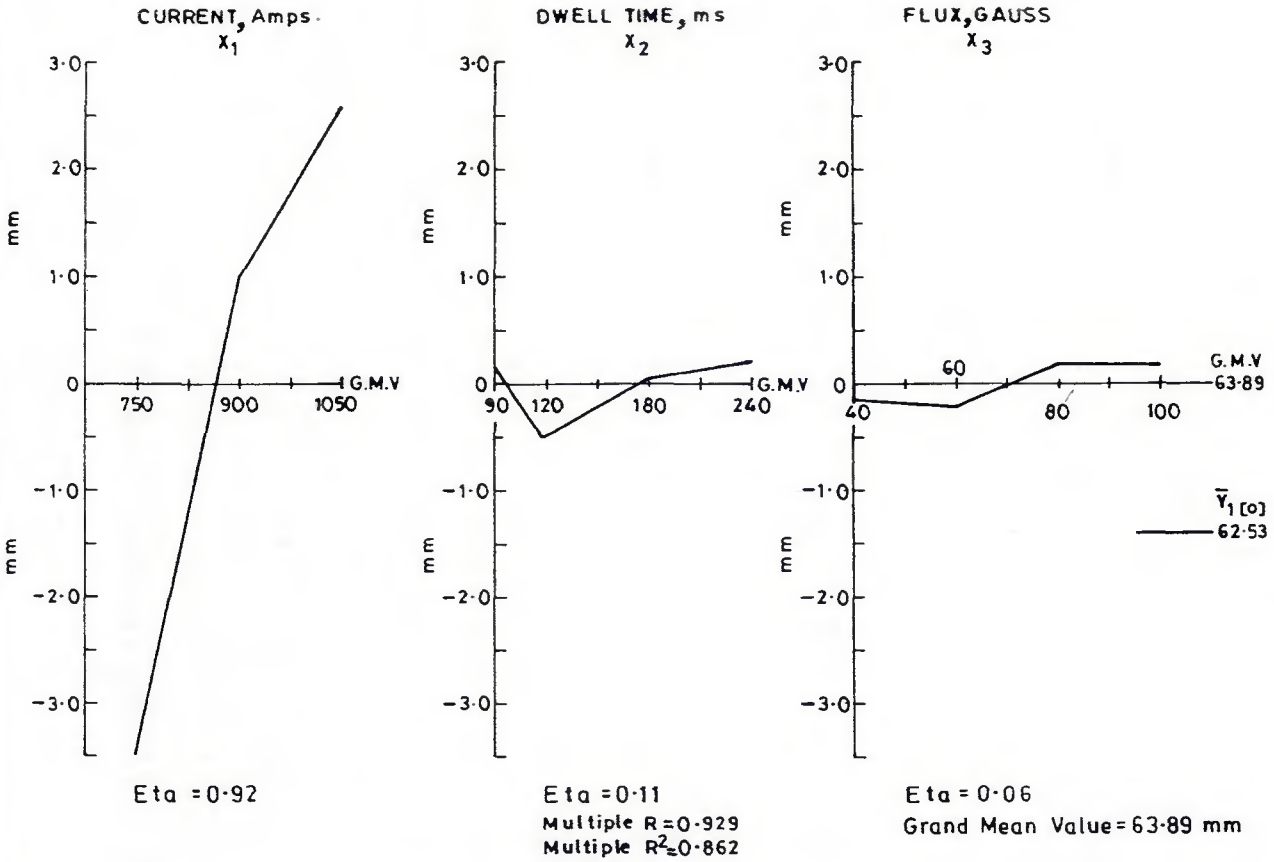

Fig. 3 — Deviations of category mean values from grand mean value of root width, mm (Y_1), 60-mm strip.

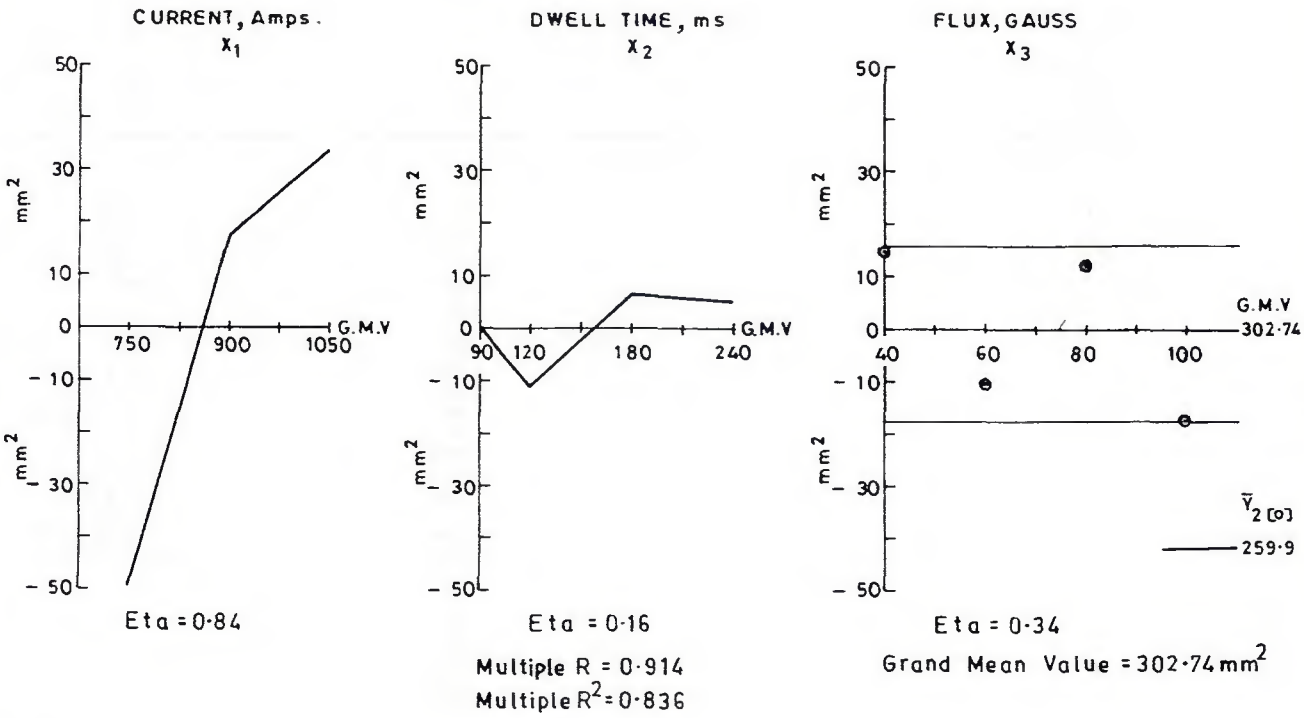

Fig. 4 — Deviations of category mean values from grand mean value of cross-sectional area of deposition, mm^2 (Y_2), 60-mm strip.

under unsteered conditions is denoted by Y_2 (O). It could be seen from Fig. 4 that the grand mean value of Y_2 under steered conditions is higher than Y_2 (O) by about 16.5%. This shows that the melting rate of the strip increases significantly under steered conditions.

Under steered conditions, the arc experiences a sideways force causing the arc to move forward and backward along the strip width. The arc traverses a longer distance along the strip width than the momentarily stationary arc existing under the unsteered condition. This may be expected to result in a greater area of the strip cross-section experiencing the arc action, resulting in increased melting rate of the strip.

Penetration is the depth which the base plate is melted. Figure 3 shows the deviation of penetration values (Y_3) from the grand mean at different levels of X_1, X_2 and X_3, individually.

As the current increases, the arc force increases, which in turn increases the digging action of the arc on the base plate. Hence, penetration increases with current. No significant variation in Y_3 is observed as X_2 is increased from 90 to 240 ms.

As in the case of Y_2, no definite trend in variation of Y_3 is observed as X_3 Increases from 40 to 100 gauss. Depth of penetration is also sensitive to voltage fluctuations in the meso-spray region. In the present case, the variation in Y_3 lies within ±12% of grand mean value of 1.55 mm. Variation in Y_3 may be attributed to voltage fluctuations rather than to the variation of X_3. Thus, it may be inferred that an increase in X_3 from 40 to 100 gauss does not have any influence on penetration.

The mean penetration at all three levels of current under unsteered conditions is denoted by Y_3 (O).

It Is seen from Fig. 5 that the grand mean value of penetration under steered conditions is about 22% less compared to Y_3 (O).

Penetration depends on the digging action and dwell time of arc at any given point on the base plate. Magnetic oscillation of the arc is somewhat analogous to mechanical oscillation of a welding head (Ref. 9). With the oscillation of the arc, dwell time of the arc at any particular point on the base plate is reduced, which decreases the depth of penetration. Under magnetic steering, the arc always bends sideways and hits the base plate at an angle, reducing the digging characteristic of the arc force.

The reduction of penetration at high current values in strip cladding under magnetically steered conditions is the most important benefit of magnetic steering. Reduction in penetration reduces dilution, which reduces the contamination of the clad metal with the base plate. MCA Plots of Y_4 and Y_5 were similar to those of Y_2 and Y_3.

Most of the research in submerged arc strip cladding is directed toward the reduction of dilution together with an increase in productivity. Magnetic steering of the arc reduces the dilution by about 23% and increases the bead height by about 14%. This improvement in bead characteristics is significant and is sufficient incentive for adopting magnetic steering in industrial practice.

Conclusions

It is possible to use 40% higher current density 35 A/mm^2) than normal current density (25 A/mm^2) under magnetically steered conditions, with acceptable bead characteristics.

With electrode positive, oscillating the welding arc perpendicular to the welding direction results in the following improvements in the bead characteristics compared to unsteered conditions:

1) Root width increases by an average of 2 mm. This result is in agreement with the findings of earlier research investigations.

2) Melting rate is increased by 15%. Consequently, either the width or the thickness of the deposit could be increased by 15%. Average depth of penetration is reduced by 20%.

3) Average bead height is increased by 15%.

4) Dilution is reduced by 23%. This is the major improvement as reduction in dilution increases the alloy content of clad metal for given strip and base plate compositions.

Increase in dwell time of peek magnetic flux from 90 to 240 ms does not bring about any significant change in bead characteristics.

No significant improvement in bead

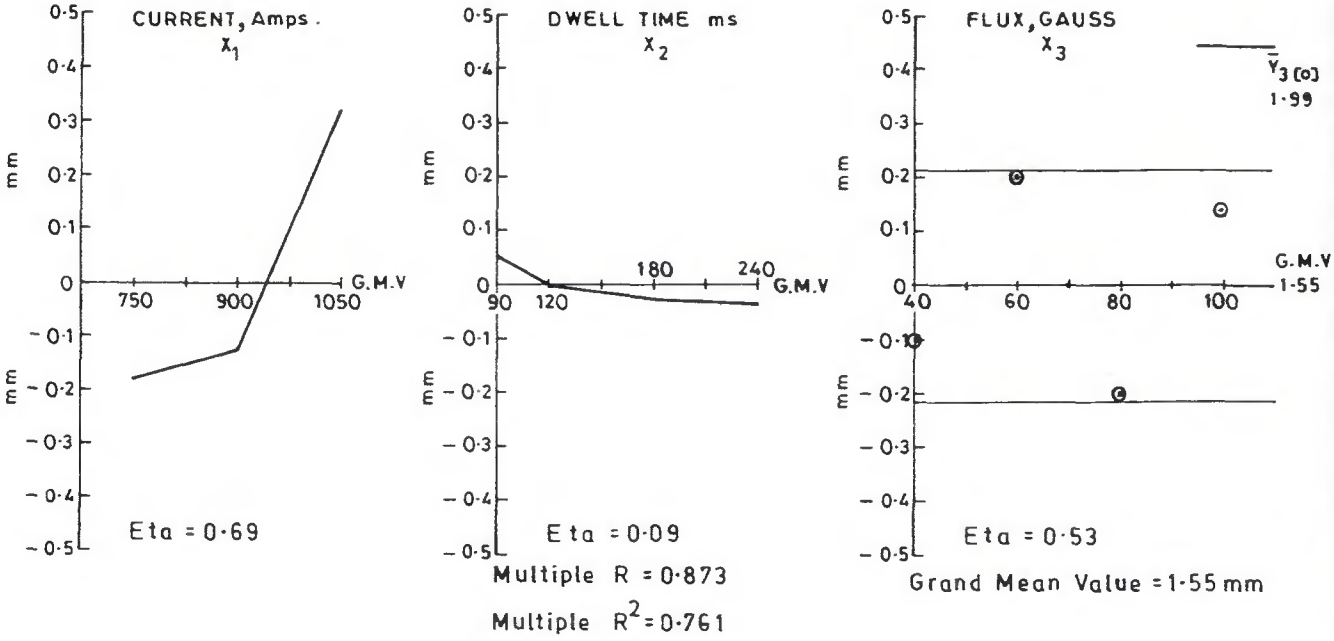

Fig. 5 — Deviations of category mean values from grand mean value of penetration, mm (Y_2), 60-mm strip.

characteristics was observed by increasing peak magnetic flux beyond 40 gauss.

A current of 900 A appears to be optimum for 60-mm strip. It gives the least dilution under magnetically steered conditions.

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