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Effects of Process Parameters on Angular Distortion of Gas Metal Arc Welded Structural Steel Plates

Mathematical models were developed to study the effects of process variables on the angular distortion of multipass GMA welded structural steel plates

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ABSTRACT. Angular distortion is a major problem and most pronounced among different types of distortion in the butt welded plates. This angular distortion is mainly due to nonuniform transverse shrinkage along the depth of the plates welded. Restriction of this distortion by restraint may lead to higher residual stresses. However, these can be reduced by providing initial angular distortion in the negative direction if the magnitude of angular distortion is predictable. It is difficult to obtain a complete analytical solution to predict angular distortion that may be reliable over a wide range of processes, materials, and process control parameters. In this study, the statistical method of three-factors, five-levels factorial central composite rotatable design has been used to develop mathematical models to correlate angular distortion with multipass GMAW process parameters. Direct and interaction effects of the process parameters were analyzed and presented in the graphical form. Further, these mathematical models help to optimize the GMAW process and to make it a cost-effective one by eliminating the weld defects due to angular distortion.

Introduction

Gas metal arc welding (GMAW) is a widely used fabrication process in industry due to its inherent advantages such as deep penetration, smooth bead, low spatter, and high welding speed. In arc welding processes, due to rapid heating and cooling, the workpiece undergoes an uneven expansion and contrast in all the directions. This leads to distortion in different directions of the workpiece. Angular distortion or out-of-plane distortion is one such defect that makes the workpiece distort in angular directions around the weld interface. Postweld treatment is required to eliminate the distortion so that the workpiece is defect free and accepted.

The extent of angular distortion depends on 1) the width and depth of the fusion zone relative to plate thickness, 2) the type of joint, 3) the weld pass sequence, 4) the thermomechanical material properties, and 5) the welding process control parameters (Ref. 1).

One of the methods to remove the angular distortion during the fabrication process is to provide an initial angular distortion in the negative direction. If an exact magnitude of angular distortion is predicted, then a weld with no angular distortion would be the result.

It is difficult to obtain analytical solution to predict angular distortion. Hence, various investigations were made to study the effects of various parameters on angular distortion using statistical methods.

KEYWORDS

Mathematical Models
Process Parameters
Multipass Welding
Angular Distortion
Central Composite
Rotatable Design

Kihara and Masubuchi (Ref. 2) have made an experimental investigation of how various welding process parameters, including the shape of the groove and the degree of restraint, affect the angular distortion in butt joint welds. Hirai and Nakamura (Ref. 3) conducted an investigation to determine the values of angular changes and coefficient of rigidity for angular changes as a function of plate thickness and weight of the electrode consumed per unit length of weld. Kumose et al. (Ref. 4) studied how effectively elastic prestraining could reduce the angular distortion of fillet welds in low-carbon steel.

Watanabe and Satoh (Ref. 5) used a combination of empirical and analytical methods to study the effects of welding conditions on the distortion in welded structures. Mandal and Parmar (Ref. 6) used a statistical method of two-level full-factorial techniques to develop mathematical models, and reported that welding speed had a positive effect on angular distortion for single-pass or multipass welding. In multipass welding, the magnitude and effect of angular distortion is more dominant than in single-pass welding.

In this experimental work, mathematical models were developed to establish a relationship between important process variables, namely, time between successive passes (t), number of passes (N), and wire feed rate (F), and angular distortion in structural steel plates joined with the multipass GMAW process.

With a view to achieve the above-mentioned aim and to obtain the required information about the main and interactive effects of process variables on angular distortion, statistical experiments based on central composite rotatable design were conducted (Refs. 7, 8).

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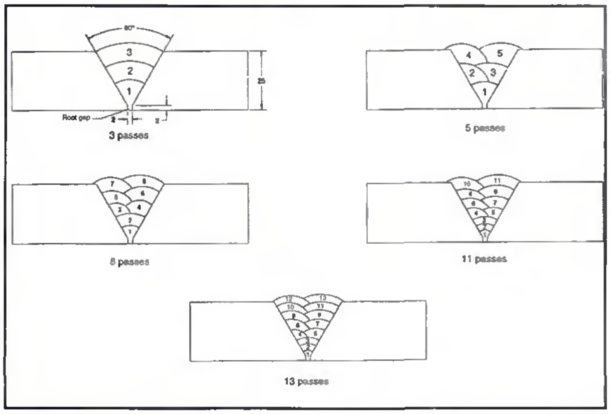

Fig. 1 — Cross section of the weldment for different number of passes.

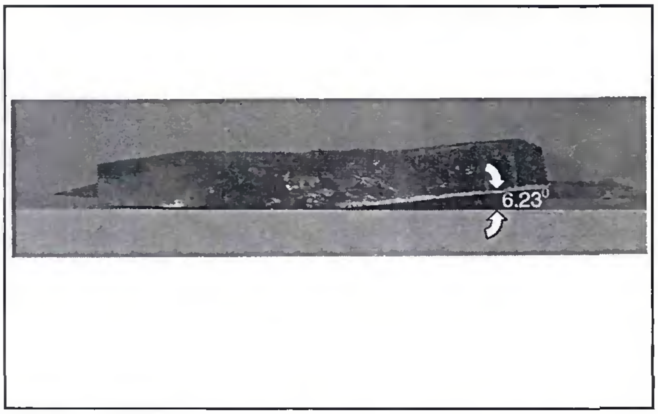

Fig. 2 — Photograph showing angular distortion during experiment (Specimen 2).

These developed models are very useful to determine quantitatively the angular distortion in the negative direction, so that after welding, angular distortion will not be there in the fabricated component. They are also useful for selecting optimum process variables for minimizing distortion in welded structures.

Table 1 — Process Control Parameters and Their Limits

Process Parameters	Units	Notations	Limits				
			–1.682	–1	0	1	1.682
Time gap between successive passes	min	t	6.6	10	15	20	23.4
Number of passes	—	N	3	5	8	11	13
Wire feed rate	M min^{-1}	F	4.2	4.5	5	5.5	5.8

Experimental Procedure

The experiments were designed based on five-level factorial central composite rotatable designs with full replications (Ref. 9).

These experiments were conducted as per the design matrix using semiautomatic thyrister-controlled GMAW equipment. A servomotor-driven manipulator was used to maintain uniform welding speed. Copper-coated steel wire AWS ER70S-6 (BW-2), 1.2 mm diameter, in the form of coil was used, with CO_2 as the shielding gas. Structural steel plate (IS: 2062) specimens 300 × 150 × 25 mm were welded together. Before the start of actual welding, the plates were tack welded at the ends. The tack welded plates were supported freely on a weld pad during welding. The edge preparation and welding sequence for different number of passes is shown in Fig. 1.

Plan of Investigation

The plan was to carry out the research in the following steps (Ref. 8):

1. Identify the important process parameters.
2. Find the upper and lower limits of the process parameters.
3. Develop the design matrix.
4. Conduct the experiments as per the design matrix.
5. Record the responses, viz. angular distortion (α).
6. Develop the mathematical model.
7. Test the significance of the coefficients, recalculating the value of the significant coefficients and arriving at the final mathematical model.
8. Test the adequacy of the mathematical model.
9. Validate the mathematical model.
10. Compile results and discussion.

Identification of the Process Parameters

The following independently controllable process parameters were identified to carry out the experiments: time between successive passes (t), number of passes (N), and wire feed rate (F). The other important process parameter, welding speed, was also considered. But when N and F are considered as independent parameters, the welding speed has to be adjusted to fill the same volume of V-groove during welding. Hence, even though welding speed is an important independent process parameter, it was not selected in this research.

Finding the Limits of the Process Parameters

Trial runs were carried out by varying one of the process parameters while keeping the rest of them at constant values (Ref. 7). The working range was decided upon by inspecting the bead for smooth appearance and the absence of any visible defects. The upper limit of the factor was coded as +1.682 and the lower limit as –1.682. The coded values for intermediate values were calculated from the following relationship:

$$X_i = 1.682\left[\frac{2X - (X_{max} + X_{min})}{X_{max} - X_{min}}\right] \quad (1)$$

Where X_i is the required coded value of a variable X; and X is any value of the variable from X_{min} to X_{max}. The selected process parameters with their limits, units, and notations are given in Table 1.

Developing the Design Matrix

A five-level, three-factors, central composite rotatable factorial design (Ref. 10) consisting of 20 sets of coded conditions is shown in Table 2. The design matrix comprises a full replication factorial design 2^3 [= 8] plus six star points and six center points. All welding parameters at the intermediate level (0) constitute center points and combinations at either its lowest (–1.682) or highest (+1.682) level with the other two parameters at the intermediate level constituting the star points. Thus the 20 experimental runs allowed the estimation of the linear, qua-

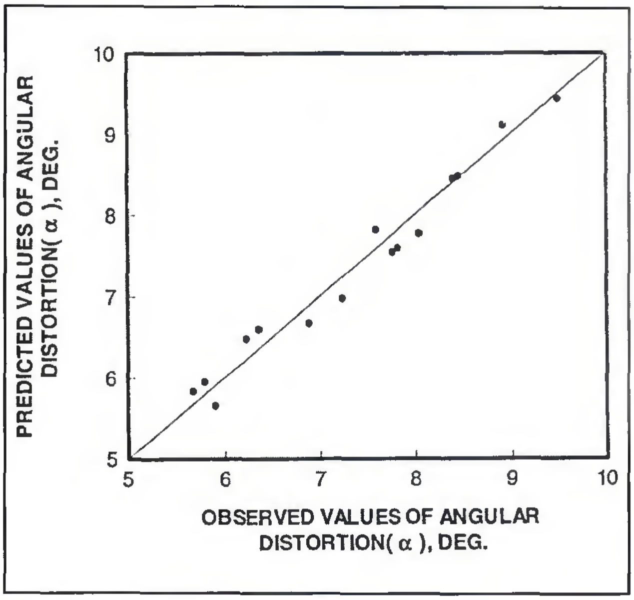

Fig. 3 — *Scatter diagram for angular distortion.*

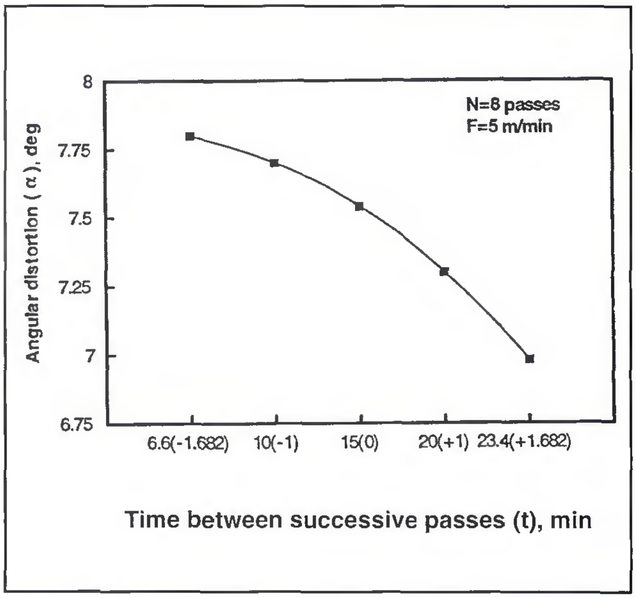

Fig. 4 — Direct effect of time gap between successive passes on angular distortion.

dratic, and two-way interactive effects of the process parameters on the angular distortion.

Conducting the Experiment as per the Design Matrix

The experiments were conducted as per the design matrix at random, to avoid the possibility of systematic errors infiltrating the system.

Recording the Responses

The angular distortion (α) was measured using sine bar principle with the help of a vernier height gauge. A plate with distortion is shown in Fig. 2. The measured values of α are given in Table 2. In this table, for experimental runs 15 to 20, even though the experimental setup and all welding conditions remain the same, the responses vary slightly. This is due to the effect of unknown and unpredictable variables called noise factors, which crept into the experiments. To account for the impact of these unknown factors on the response, replicated runs (15–20) were included in the design matrix.

Table 2 — Design Matrix and Observed Values of Angular Distortion

S. No.	Design Matrix t	N	F	α (degree)
1	−1	−1	−1	6.37
2	+1	−1	−1	6.23
3	−1	+1	−1	8.92
4	+1	+1	−1	8.45
5	−1	−1	+1	5.80
6	+1	−1	+1	5.68
7	−1	+1	+1	8.40
8	+1	+1	+1	7.59
9	−1.682	0	0	7.82
10	+1.682	0	0	7.24
11	0	−1.682	0	5.91
12	0	+1.682	0	9.50
13	0	0	−1.682	8.05
14	0	0	+1.682	6.89
15	0	0	0	7.76
16	0	0	0	7.70
17	0	0	0	7.59
18	0	0	0	7.53
19	0	0	0	7.70
20	0	0	0	7.12

Developing the Mathematical Model

The response function representing angular distortion can be expressed as α = f (t, N, F), and the relationship selected being a second-order response surface. The function is as follows (Ref. 9):

$$\alpha = b_0 + b_1 t + b_2 N + b_3 F + b_{11} t^2 + b_{22} N^2 + b_{33} F^2 + b_{12} tN + b_{13} tF + b_{23} NF \quad (2)$$

Where coefficients b_1, b_2, and b_3 are linear terms, coefficients b_{11}, b_{22}, and b_{33} are second-order terms, and coefficients b_{12}, b_{13}, and b_{23} are interaction terms.

Quality America — DOE PC IV, software package (Ref. 11) was used to calculate these coefficients. The mathematical model thus developed follows:

$$\alpha = 7.579 - 0.184\, t + 1.122\, N - 0.326\, F - 0.95\, t^2 - 0.033\, N^2 - 0.116\, F^2 - 0.127\, tN - 0.040\, tF - 0.032\, NF \quad (3)$$

Testing the Significance of the Coefficients

The values of the coefficients give an idea to what extent the process parameters affect the responses quantitatively. Insignificant coefficients were dropped along with the parameters with which they are associated, without affecting the accu-

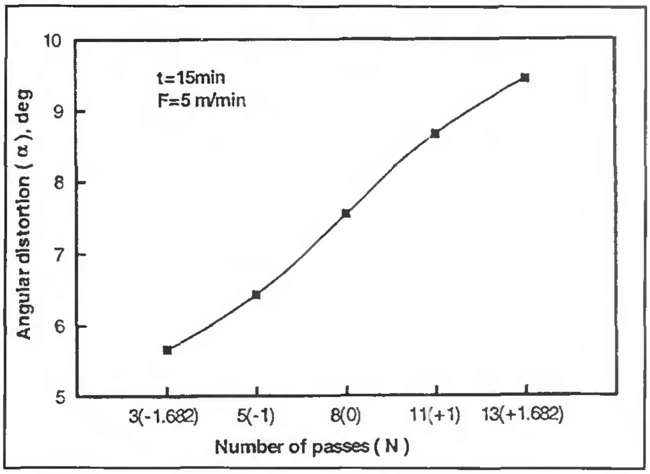

Fig. 5 — Direct effect of number of passes on angular distortion.

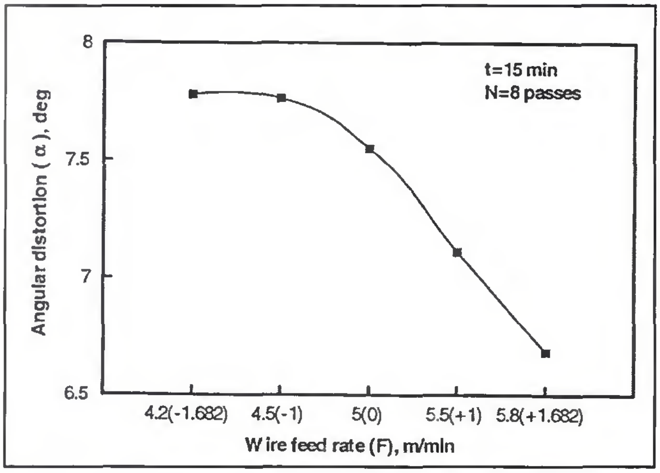

Fig. 6 — Direct effect of wire feed rate on angular distortion.

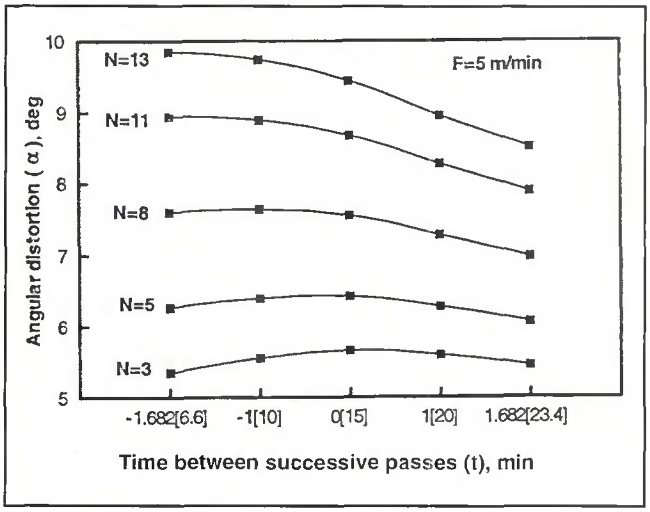

Fig. 7 — Interaction effect of time between successive passes and number of passes on angular distortion.

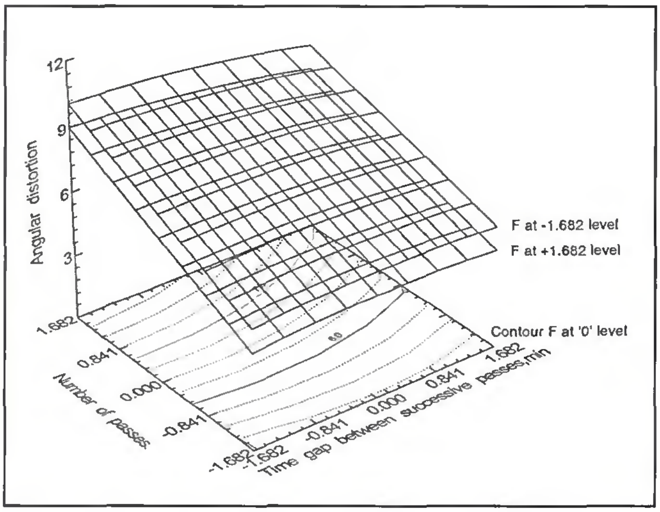

Fig. 8 — Response surface for interaction effect of time between successive passes and number of passes on angular distortion.

racy of the model very much. This was carried out by conducting backward elimination analysis with t — probability criterion kept at 0.75 (Ref. 11). The significant coefficients were recalculated and the final mathematical model was developed using only these significant coefficients. The final mathematical model as determined by the above analysis is represented in the following:

$$\alpha = 7.552 - 0.184\,t + 1.122\,N - 0.326\,F - 0.95\,t^2 - 0.113\,F^2 - 0.127\,tN \qquad (4)$$

Checking the Adequacy of the Model Developed

The adequacy of the model was tested using the analysis of variance techniques (ANOVA). As per this technique (Ref. 8), 1) the calculated value of the F–ratio of the model developed should not exceed the standard tabulated value of F–ratio for a desired level of confidence (say 95%), and 2) if the calculated value of the R–ratio of the model developed exceeds the standard tabulated value of the R–ratio for a desired level of confidence (say 95%), then the model may be considered adequate within the confidence limit. From Table 3, it is found that the model is adequate.

Validation of Mathematical Model

Validity of the developed models was tested by drawing scatter diagrams that show the observed and predicted values of angular distortion. A representative scatter diagram is shown in Fig. 3. To determine accuracy of the model conformity, test runs were conducted. For these runs, process parameters were assigned some intermediate values within their limits. A comparison was made between actual and predicted values. The result shows that the model accuracy is above 95%.

Results and Discussions

The mathematical model given above can be used to predict the angular distortion by substituting the values of the respective process parameters. Also, the values of the process parameters can be obtained by substituting the value of allowable angular distortion values. The angular distortions calculated from the final model for each set of coded values of welding parameters are represented graphically in Figs. 4–12. These graphs show generally convincing trends between cause and effect. The direct effects and interaction effects are discussed below.

Direct Effect of Time between Successive Passes on Angular Distortion

Figure 4 represents the direct effect of time between successive passes (t) on angular distortion (α). From the figure, it is clear that α decreases with the increase in

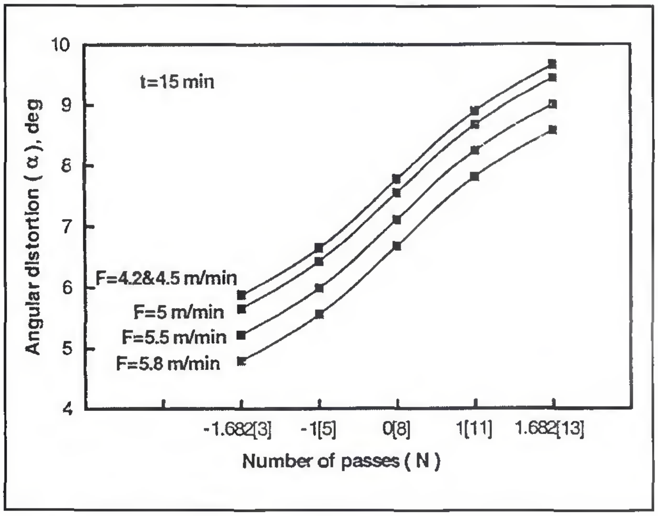

Fig. 9 — Interaction effect of number of passes and wire feed rate on angular distortion.

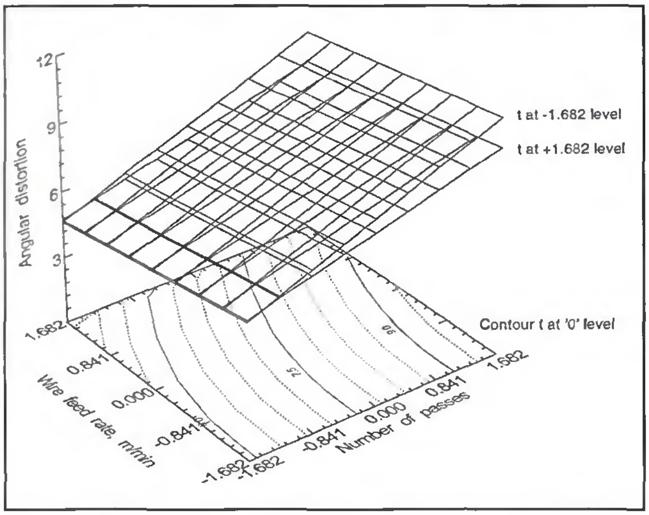

Fig. 10 — Response surface for interaction effect of number of passes and wire feed rate on angular distortion.

Table 3 — Calculation of Variance for Testing the Adequacy of the Model

Parameter	1st-Order Terms (SS)	df	2nd-Order Terms (SS)	df	Lack of Fit (SS)	df	Error Terms (SS)	df	F Ratio	R Ratio	Whether the Model is Adequate
Angular distortion	19.094	3	0.45	6	0.532	5	0.274	5	1.938	39.57	Adequate

F – Ratio = MS – Lack of fit/MS – Pure error.
R – Ratio = MS – factors/MS – Pure error.
Where, MS – Mean square = SS/df: SS – sum of squares; df – degrees of freedom.
F – Ratio$_{(5,5,0.05)}$ = 5.05 and R – ratio$_{(9,5,0.05)}$ = 3.48

t. When t is longer, more heat is lost by the plate and the plate temperature is lower as compared to that when t is less. So, some of the heat applied to the plate during the next pass will be utilized in preheating the plate. Hence, the net heat added to the plate is less compared to when the plate temperature is high. As the width of bead increases with the increase in heat input (Ref. 8), the angular distortion is more when t is shorter, because more bead width provides more contraction in the top of the bead.

Further, it is reported that the angular distortion is given by the following empirical relation (Ref. 12):

$$\alpha = 2\beta \, T \tan\left(\frac{\theta}{2}\right) \tag{5}$$

where β = thermal expansion coefficient, T = temperature of the material softening, and θ = groove angle.

When t is longer, a larger amount of heat is lost by the plate and the temperature is lower compared to when t is shorter. So, the heat applied to the plate during the next pass will result in a marginal rise in temperature of the plate, and hence, α is less.

Direct Effect of Number of Passes on Angular Distortion

Figure 5 represents the direct effect of number of passes (N) on angular distortion (α). From this, it is clear that the α increases with the increase in N. Generally, in an unrestrained joint, the degree of angular distortion is approximately proportional to the number of passes (Ref. 13). The same trend is experienced here also. However, the slope of the curve decreases with the increase in N. In multipass welds, previously deposited weld metal provides restraint, so the angular distortion per pass decreases as the weld is built up.

Direct Effect of Wire Feed Rate on Angular Distortion

Figure 6 depicts the direct effect of wire feed rate (F) on angular distortion (α). From this, it is clear that α decreases with the increase in F. For the same number of passes (N = 8), if F increases automatically, the welding speed also has to be increased in order to maintain the total volume of metal deposited in the V-groove to be same.

Artem Pilipenko (Ref. 12) reported a relationship for angular distortion.

$$\alpha = 0.13\frac{IU}{vh^2} \tag{6}$$

where I = current, U = voltage, v = welding speed, and h = plate thickness.

Watanabe and Satoh (Ref. 5) reported another relationship for angular distortion.

$$\alpha = C_1\left(\frac{I}{h\sqrt{vh}}\right)^{m+1} \exp\left\{-C_2\left(\frac{I}{h\sqrt{vh}}\right)\right\} \tag{7}$$

where C_1, C_2, and m = constants.

From these two equations, it is clear that the increase in welding speed results in a decrease in the angular distortion.

Interaction Effect of Time between Successive Passes and Number of Passes on Angular Distortion

Figure 7 represents the interaction effect of time between successive passes (t) and number of passes (N) on the angular distortion (α). From the figure, it is clear that α remains constant when N = 3 passes and decreases for other values of N with the increase in t. The rate of decrease

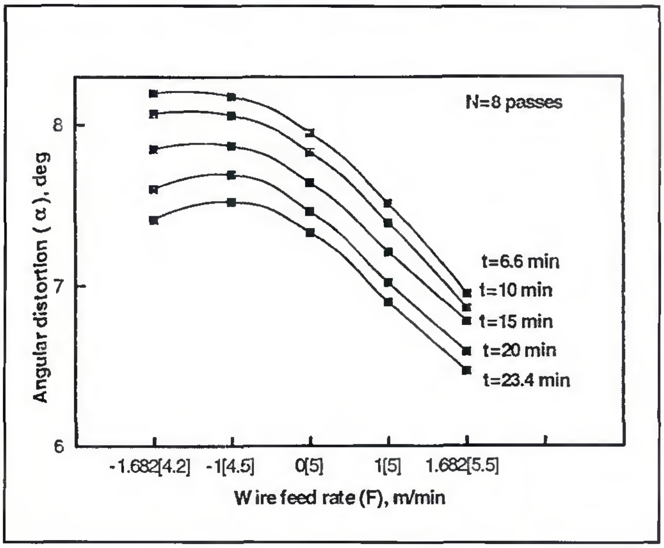

Fig. 11 — Interaction effect of wire feed rate and time between successive passes on angular distortion.

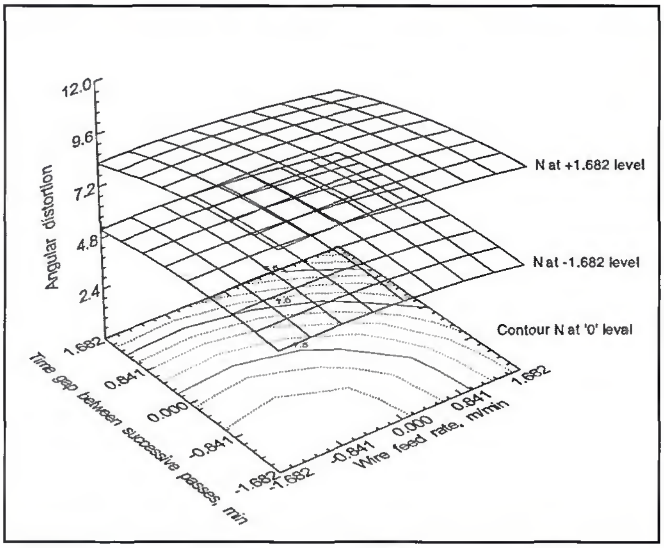

Fig. 12 — Response surface for interaction effect of wire feed rate and time between successive passes on angular distortion.

is less (about 0.2 deg) when N is 5. This value increases steadily with the increase in N and maximum when N = 13 (about 1.34 deg). This is because N has a positive effect on α, but t has negative effect on α, as discussed previously. The value of α is maximum (about 9.85 deg) when t and N are respectively at their lower (–1.682) and higher (+1.682) limits. The value of α is minimum (about 5.35 deg) when t and N are respectively at their higher and lower limits. The increase in the rate of decrease indicates that at lower values of N, the net effect on α is the combined negative effect of t and positive effect of N. But at higher values of N, the negative effect of t in decreasing α is predominant over the positive effect of N on α.

These effects are further explained with the help of a response surface plot, as shown in Fig. 8. From the contour surface, it is noted that α is maximum (about 9.9 deg) when t and N are respectively at their lower (–1.682) and higher (+1.682) limits, and is minimum (about 5.2 deg) when t and N are respectively at their higher and lower limits.

Interaction Effect of Number of Passes and Wire Feed Rate on Angular Distortion

Figure 9 shows the interaction effects of number of passes (N) and wire feed rate (F) on angular distortion (α). From the figure, it is clear that α increases with the increase in N for all values of F. Also, the increasing pattern is almost similar (about 3.78 deg) when F is at lower limits (–1.682) and (about 3.87 deg) when F is at higher limits (+1.682). This is because the positive effect on α when N is at lower limits (–1.682) is higher and at higher limits (+1.682) is lower. But the negative effect on α when F is at lower limits is lower, and at higher limits, it is higher. These combined effects make the net interaction effects a similar one for all values of F.

These effects are further explained with the help of a response surface plot, as shown in Fig. 10. It is evident from the contour surface that α is maximum (about 9.67 deg) when N and F are respectively at their higher (+1.682) and lower (–1.682) limits and is minimum (about 4.8 deg) when N and F are respectively at their lower and higher limits.

Interaction Effect of Wire Feed Rate and Time Gap between Successive Passes on Angular Distortion

Figure 11 shows the interaction effects of wire feed rate (F) and time between successive passes (t) on angular distortion (α). From the figure, it is clear that for all values of t the value of α increases in the initial stages of F, and then decreases steadily with the increase in F. This is because of the combined effects of increasing trend of α with the increase in t at lower limits (from –1.682 to –1) and almost a constant trend of α with the increase in F at lower limits (from –1.682 to –1). However, the decrease in α for all values of t is high (about 0.79 deg) when F is at lower limits (–1.682) and is low (about 0.56 deg) when F is at higher limits (+1.682).

These effects are further explained with the help of a response surface plot, as shown in Fig. 12. It is evident from the contour surface that α is maximum (about 8.18 deg) when t and F are respectively at their lower (–1.682 and –1) limits and is minimum (about 6.47 deg) when t and F are at their higher limits. Further, from the plot it is evident that parameter N has a greater effect on α compared to parameters t and F.

Conclusions

The conclusions below were arrived at from this investigation.

1) The second-order quadratic mathematical models are useful in predicting angular distortion of multipass welds.

2) Out of the three process variables selected for investigation, the number of passes (N) had a strong effect on angular distortion (α). The value of α is about 4.5 deg when other parameters are at lower limits, and it is about 3.1 deg when other parameters are at higher levels.

3) The increasing trend of the angular distortion with the increase in number of passes has to be considered carefully in practice to control angular distortion.

4) The process parameters, namely, time between successive passes and wire feed rate, have a negative effect on angular distortion.

Acknowledgment

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2) **Introduction.** A short statement giving relevant background, purpose, and scope to help orient the reader. Do not duplicate the abstract.

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