PREDICTION OF ANGULAR DISTORTION IN GTA WELDED STAINLESS STEEL 304 PLATES BY MATHEMATICAL MODELLING

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ABSTRACT- *Tungsten Inert Gas (TIG) welding is a fusion welding process where arc is established between a non-consumable tungsten electrode and the workpiece. The process can weld any material with an excellent weld quality. Being primarily an autogenous process, it suffers with limitations like slow speeds, and less deposition rates, but with the introduction of external filler metal these deficiencies can be overcome. The process is extensively used in food processing, aviation, chemical and other light fabrication industries. As the process involves high heat input, there are chances of thermally generated stresses in the material due to uneven rates of heating and cooling experienced by the different sections of weldment. Theses stresses, if not taken care of, may result in distortion of the final weld. The amount of distortion depends upon many factors like the input weld parameters. These distortions may cause rejection of the product hence are totally undesirable. The present work is focussed on the study of angular distortion in stainless steel 304 which is austenite grade and is used widely in chemical and food industry owing to its excellent corrosion resistance. An attempt is made to develop a mathematical expression that can be used to predict the amount of angular distortion at different values of the input parameters. The adequacy of the developed model will be checked by ANOVA and the results shall be analysed graphically by response surface methodology.*

Keywords: *Stainless steel 304, angular distortion, input parameters, mathematical model, ANOVA, graphical analysis.*

1.0 INTRODUCTION

Angular distortion, as shown in figure 1, is a welding defect which occurs because of the generation of stresses during rapid heating and cooling cycles experienced during arc welding processes with TIG no exception. This defect once produced is very difficult to treat as it requires elaborated post weld heat treatment which generally is not economical and sometimes is not practically possible owing to the shape and size of the weldment. Through the literature survey and past experience it is known that the angular distortion is influenced by the welding parameters. It is therefore pertinent to ensure that the welding parameters are so selected that the resulting angular distortion is minimal. A number of elaborated studies have been carried out for minimizing the distortion. The problem of distortion becomes significant in case of thin gauge materials owing to their less resistance to thermally generated deformations. These distortions not only spoil the aesthetics of the weldment, but may also result in lack of fits, which might disrupt the final assemblies [1]. The higher pulse frequency, smaller pulse spacing, greater amplitude ratio, and greater duration ratio can reduce the angular distortion and of pulsed TIG weldment [2]. Grove angle has a positive effect on angular distortion [3]. Hence optimization of the process parameters is necessary to minimize the distortions. Post weld treatment if applied should eliminate the distortion so that the work piece is defect free and accepted [4].

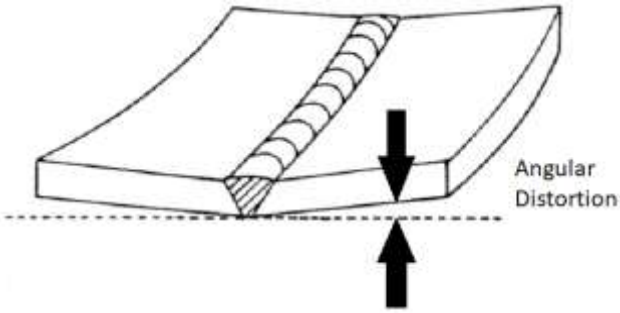

Figure 1: Angular Distortion in butt welded joint

The material selected for the present investigation is stainless steel 304 which offers good workability, excellent corrosion resistance and fairly good weldability as advantages for being used as a preferred material in fabrication industry. One of the major concerns for the designers in fabrication industry while working with this material is to have correct fitment of the assemblies. This requirement severely gets affected if there is angular distortion in the weldment. The present work has been taken up to address this issue in a quantitative and structured manner. For this, first of all the input factors which could affect the resulting angular distortion were identified. Out of many such factors, three were found to be relevant for the present study viz. welding current, welding speed and the torch angle respectively. To conduct the experiments required for the purpose in a logical way so that the proper effects of these parameters are taken care of, some statistical technique was required and design of experiments was found to be relevant because of its many advantages like ease of handling the data, ease of use, effective tools of analysis etc. Central composite face centred technique was adopted for the development of mathematical model in the present case [5]. The adequacy of the model was tested by ANOVA technique and the response surface methodology was used to analyse the graphical results.

2.0 EXPERIMENTAL SETUP

The experiments were conducted on a constant voltage power source of with rated capacity of 200 amps and open circuit voltage of 35 volts. It has drooping V-I characteristics required for manual and semi-automatic TIG welding processes. All the welds were made on a mechanised carriage unit which was motor driven with chain and sprocket arrangement, a gear box of 60:1 ratio was used to transfer the drive to the precision linear slides of the carriage as shown in figure-2. The speed control was affected through a variable frequency drive, enabling the attainment of speeds form 0-50 cm/min. this unit resulted in maintaining a consistent weld quality throughout and ensure reproducible welds at desired and pre-set speeds. Industrial pure grade argon gas was used for shielding purpose at a flow rate of 15litres/min to ensure reasonable shielding of the arc.

Figure 2: Experimental setup

3.0 PLAN OF INVESTIGATION

The investigation was carried out by following the steps given below:

1. Identification of process parameters and their working ranges
2. Development of the design matrix
3. Conducting the experiments as per the design matrix
4. Measuring the angular distortion
5. Development of mathematical model
6. Testing the significance of the model
7. Results and their analysis
8. Conclusions

3.1 Identification of process parameters and their working ranges

There are several input parameters which can affect the welding output like – voltage, current, speed, gas flow rate, torch angle, pulse frequency, etc. in the present work however, three were selected viz. welding current (A), welding speed (B) and torch angle (C). The working ranges of these parameters were ascertained by performing a number of trial runs and upper and lower limits of these ranges were fixed by inspecting the visible quality of the welds. The upper limit is represented by (1) whereas the lower limit by (-1) as shown in the table-1, below

Table-1: Selected parameters and their working ranges

Process Parameters	**(-1)**	**(0)**	**(1)**
Current (ampere)	130	145	160
Speed (cm/min)	30	35	40
Torch Angle (degree)	0	22.5	25

3.2 Development of the design matrix

The experiments for the present work required to be conducted in a proper manner so as to yield meaningful results. This could be done by designing the experimental runs in such a way that effect of all the parameters are taken into account. To achieve this, a statistical technique of design of experiments was applied with specific use of central composite face centred approach. The design matrix was developed by using design expert software and is given in table-2.

Table-2: Design matrix and response

Std	Run	Factor 1 A:Current ampere	Factor 2 B:Speed cm/min	Factor 3 C:Angle degree	Response 1 Angular distortion degree
15	1	145	35	22.5	11.1
8	2	160	40	45	3.75
5	3	130	30	45	0.73
2	4	160	30	0	10.05
12	5	145	40	22.5	12.22
20	6	145	35	22.5	11.45
13	7	145	35	0	-8.85
10	8	160	35	22.5	11.06
17	9	145	35	22.5	1.6
1	10	130	30	0	7.3
4	11	160	40	0	-7.4
3	12	130	40	0	2.3
9	13	130	35	22.5	13.62
7	14	130	40	45	19.31
11	15	145	30	22.5	12.64
19	16	145	35	22.5	10.49
6	17	160	30	45	-12.36
16	18	145	35	22.5	11.05
18	19	145	35	22.5	11.45
14	20	145	35	45	14.9

3.3 Conducting the experiments as per the design matrix

The series of experiments were conducted as per the design matrix. A total of 20 test welds were performed with their run order staggered to avoid experimental error if any. Tack welds were made before carrying out the welding. A root gap of about 1mm was maintained. The final weld runs were made by setting the work pieces on the welding carriage table and traversing it at the desired speed. The welding torch was clamped on the radial arm of the carriage for easy manipulation. The welds were visually inspected for any anomaly and were found satisfactory.

3.4 Measuring the angular distortion

For measuring the distortions after welding, the weldments were placed one by one on the surface plate and a height gauge was used. The measuring tip of the height gauge was first set to zero on the surface plate. On a single plate, two readings were taken, first by putting weight on one side and the height was measured of the other side and doing the same

for other side. After placing the weight, the measuring tip was raised to the plate and the height was recorded. The average of the two was taken as a single observation. Following this procedure, all the readings were taken.

3.5 Development of mathematical model

The input variables can be considered to be related to the angular distortion by the following general equation, which depicts that the response parameter is a function of parameters viz. welding current, welding speed and torch angle respectively.

Angular Distortion = f (A, B, C)

The second degree polynomial equation which can express the mathematical relation between response and the inputs can be expressed as;

$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{23} BC + \beta_{31} CA + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2$

Where, β_0 = Model coefficient,

β_1, β_2 and β_3 = Coefficients of the linear terms

β_{12}, β_{23} and β_{31} = Coefficients of the interaction terms and

β_{11}, β_{22} and β_{33} = Coefficients of the square terms

Angular Distortion = +10.37 -3.82*A +1.18*B +2.29*C -1.87*AB -2.71*AC +7.14*BC +0.71 A^2 +0.80 B^2 -8.60 C^2

The presence of square terms shall justify the curvature in the surface plots explained later.

3.6 Testing the significance of the model

The significance of the model was tested using ANOVA analysis as shown in table-3 below.

Table-3: ANOVA table

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1008.09	9	112.01	3.17	0.0434	significant
A-Current	145.62	1	145.62	4.12	0.0698	
B-Speed	13.97	1	13.97	0.3952	0.5436	
C-Angle	52.58	1	52.58	1.49	0.2506	
AB	27.83	1	27.83	0.7872	0.3958	
AC	58.86	1	58.86	1.67	0.2259	
BC	408.12	1	408.12	11.55	0.0068	
A^2	1.39	1	1.39	0.0394	0.8466	
B^2	1.77	1	1.77	0.0500	0.8275	
C^2	203.54	1	203.54	5.76	0.0373	
Residual	353.48	10	35.35			
Lack of Fit	277.53	5	55.51	3.65	0.0907	not significant
Pure Error	75.95	5	15.19			
Cor Total	1361.58	19				

The ANOVA table clearly proves the adequacy of the developed model as the model is significant and the lack of fit is not significant. Further the value of R^2 of 74.04 as shown in table-4, for the model proves its significance.

Table-3 Fit Statistics table

Std. Dev.	5.95		**R^2**	0.7404
Mean	6.82		**Adjusted R^2**	0.5067
C.V. %	87.17		**Predicted R^2**	-0.7582
			Adeq Precision	7.1914

The scatter diagram generated by the software also indicates towards the adequacy of the developed model as the points are scattered close to the centre line as shown in figure-3.

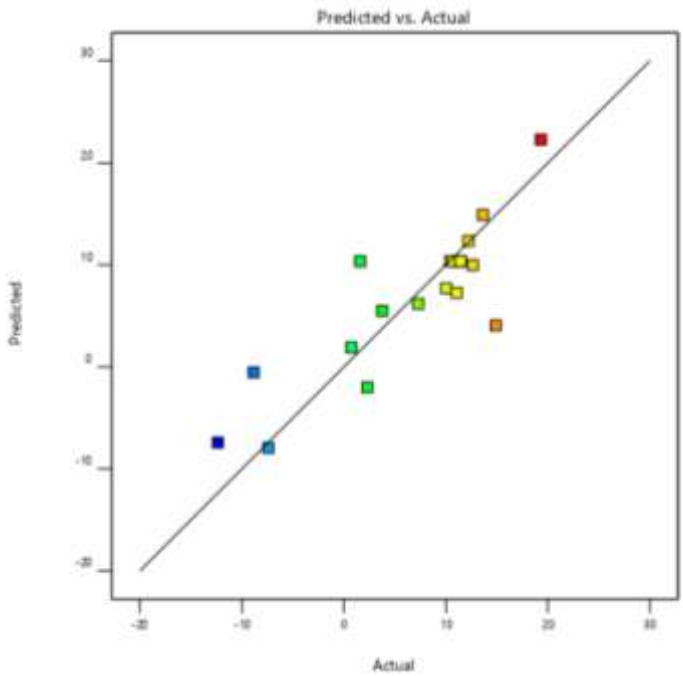

Figure 3: Scatter diagram of predicted Vs actual values

3.7 Results and their analysis

The results of the present work are indicated in the graphical form in figures 4-6.

3.7.1 Interaction effect of current and speed on angular distortion

As shown in figure 4, the angular distortion is found to increase with the welding speed and shows an opposite trend with welding current. The probable reason could be that with the increase in speed, the heat input per unit length of the weld is less resulting in rapid cooling of the joint thereby resulting in generation of thermal stresses causing distortion. Whereas with the increase in current the heat input is more resulting in relatively more uniform cooling with lesser stresses and hence generation of lesser distortion.

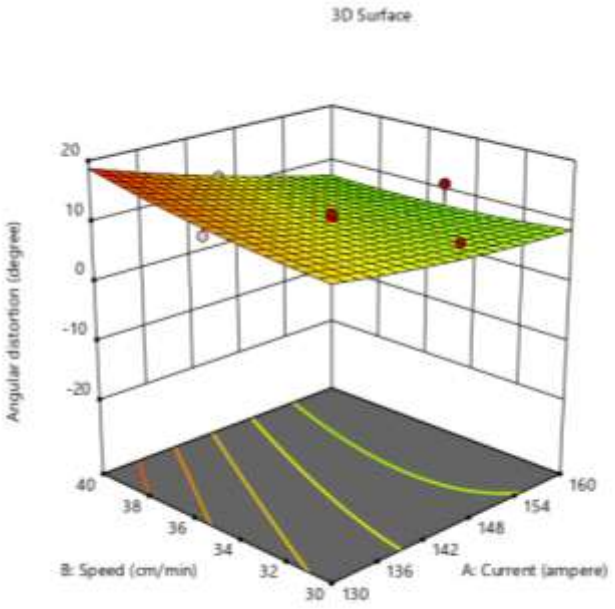

Figure- 4: Interaction effects of welding current and welding speed on angular distortion

As we can see in figure 5, the angular distortion decreased initially with the increase in welding speed at lower values of torch angle. The probable reason could be that as the speed increased, the heat input to the weld decreased thereby reducing the angular distortion. But the trend reversed at higher torch angles. The probable explanation for this could be that at higher torch angles the effect of torch angle dominated over the effect of welding speed. As with increase in torch angle, the angular distortion increases because of the widening of the arc and spread of heat over a larger area.

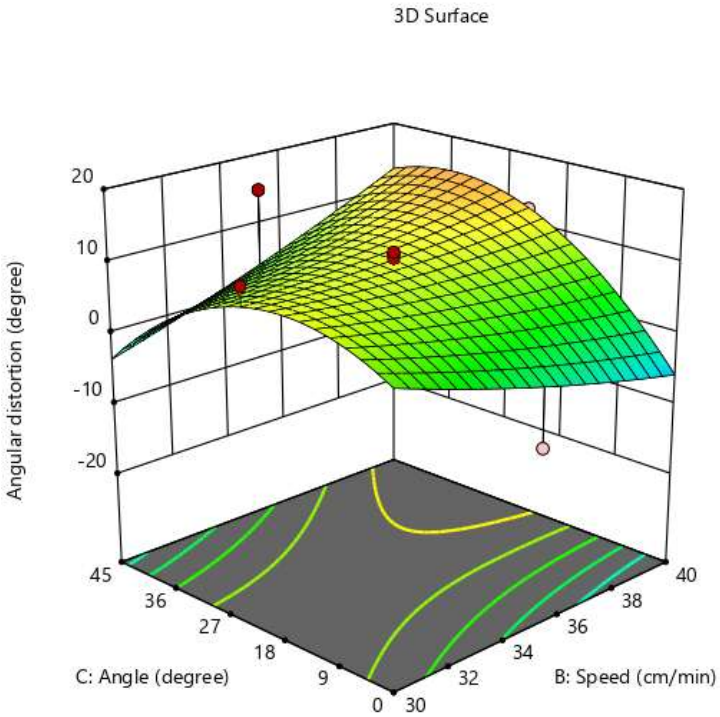

Figure- 5: Interaction effects of welding speed and torch angle on angular distortion

As shown in figure 6, the angular distortion decreased very slightly with an increase in welding current whereas it first increased at lower torch angles and then decreased at higher torch angles. It is maybe because as we increase the torch angle, the arc widens and heat is spread over a larger area. Here, torch angle is the dominating factor which almost nullifies the effects of welding current on distortions.

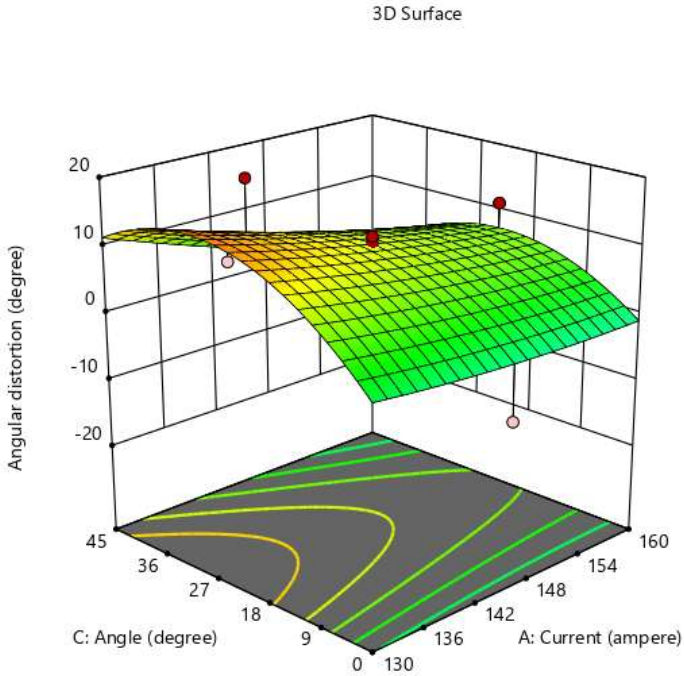

Figure- 6: Interaction effects of welding current and torch angle on angular distortion

3.8 Conclusions

- The statistical technique of central composite face centred approach is successfully used.
- The mathematical model is developed for the angular distortion.
- Welding speed has a negative effect, welding current has negligible and torch angle has positive effect on the angular distortion within the limits of the parameters selected
- The maximum angular distortion was found at welding speed of 40 cm/min and at welding current- 130 amperes.
- The maximum angular distortion was found at about 30^0 torch angle and at welding current- 130 amperes.
- The maximum angular distortion was found at welding speed of 40 cm/min and at torch angle of about 36^0.
- The minimum angular distortion was found at welding speed of 30 cm/min and at welding current- 160 amperes.
- The minimum angular distortion was found at torch angle of 0^0 and at welding current- 160 amperes.
- The minimum angular distortion was found at welding speed of 30 cm/min and at torch angle of 45^0.

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