International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 06 Issue: 04 | Apr 2019 www.irjet.net p-ISSN: 2395-0072

Prediction of Angular distortion in TIG Welded Stainless Steel 202 Sheets by using Mathematical Modeling

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Abstract - *Gas Tungsten Arc Welding (GTAW) has been used extensively for industrial applications requiring excellent quality joints owing to the versatility of this process and capability to weld almost all the metals and in all welding positions. The process also lends itself to automation. The process is especially popular in welding relatively thin gauge metal sheets required in aircraft, food processing, automobile and coach building industries. The present investigative work aims to study the effect of different individually controllable input parameters like welding current, welding speed and torch angle on the resulting angular distortion of the weldment made out of butt-welded thin sheets of stainless Steel 202. An attempt has been made to develop a mathematical model that relates these input parameters to the response parameter. Such models help establishing relationship between the input and output parameters in such a way that within the operating range of the input parameters, the value of response parameter can be predicted with fair accuracy at any combination of input parameters. The developed model can then be used in the form of a program to attain minimum value of distortion in case of robotic/automated welding. Statistical technique of central composite face centered design has been used to develop the model and ANOVA is used to check the adequacy of the same.*

***Key Words*: GTAW, Stainless steel, angular distortion, mathematical modeling, ANOVA**

1. INTRODUCTION

The TIG welding process is an extensively used arc welding process characterized by the use of a non-consumable tungsten electrode. The process in its basic form is used in autogenous mode but the use of filler metal is also not uncommon. The setup of this process is portable, increasing its utility in the in-situ welding operations. The process gives best quality welds in almost all materials and can be fully automated to meet the demands of the industry. Stainless steel grade 202 has wide applications in making seamless stainless steel tube for boilers, heat exchangers tubes, super heater tubes, cook wares and extensively used in food processing, air craft, coach building and chemical industry. [1]

The optimization of TIG welding process parameters play important role for the final product quality in terms of weld distortions, joint efficiency and mechanical properties. As the fusion welding processes involve non-uniform heating and cooling of the metals, the distortions are unavoidable because of unequal expansions and contractions experienced by different layers across the thickness of the material being welded. Angular distortions are influenced by three main variables - thermal stresses, constructional rigidity and metallurgical properties of the material [2]. 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 weldments, but may also result in lack of fits, which might disrupt the final assemblies [3]. Hence optimization of the process parameters is necessary to minimize the distortions. Post weld treatment is required to eliminate the distortion so that the work piece is defect free and accepted. [4]

The material selected for present investigative study is Stainless Steel 202. It is manganese alloyed austenitic stainless steel, which is designed as a cost-effective alternative to 302 grades with similar corrosion and mechanical properties at lower temperatures and less harsh corrosive environments [5]. Being austenitic, it has excellent weldability and formability.

SS 202 is a widely used versatile grade of steel but it has been found that there is relatively less research reported on welding of AISI 202 SS grade [6]. This makes a strong base for choosing this material for the present study. The chemical properties and distinctive mechanical and physical properties of the material are given below.

Fig. 1 Angular Distortion

TABLE 1 Mechanical Properties of Stainless Steel 202 [5]

Mechanical Properties	SS202
Ultimate Tensile Strength (MPa)	≥620

Yield Strength (MPa)	≥260
% Elongation	≥40
Hardness (BHN)	≤241

TABLE 2 Chemical Composition of Stainless Steel 202 [5]

Material %	**SS202**	
	MIN	**MAX**
C	-	0.15
Mn	7.50	10.00
S	-	0.030
P	-	0.060
Si	-	1.00
Ni	4.0	6.0
Cr	17.0	19.0
N	-	0.25

Elaborated experimental work was carried to investigate the effect of input parameters on angular distortion. The adequacy of the mathematical model developed was tested using ANOVA technique, mathematical equation was generated using regression analysis and the 3D surface plots were obtained from design expert software.

2. EXPERIMENTAL SETUP

A welding power source of current rating 200A was used for the welding. The power source was invariably of drooping V-I characteristic. A constant arc length of 15mm was maintained throughout the experiments. The shielding gas used was industrially pure argon at a flow rate of 15 lpm. The consistency in the results was achieved by using an automated welding carriage unit wherein the torch was attached to a radial rotating arm capable of moving up down and across the table. To have a step less control of carriage speed ranging from 0 cm/min to 50 cm/min, a driving motor and a gearbox arrangement with a variable frequency drive was used to move the base table of the apparatus. The setup is shown in the figure 2 below.

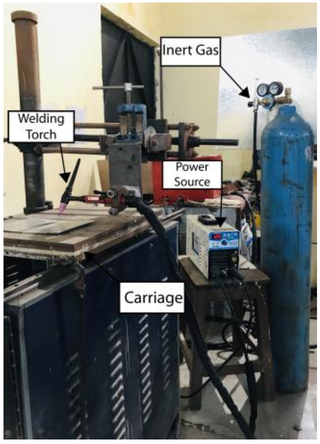

Fig. 2 Experimental setup

3. PLAN OF RESEARCH

The research work was carried out in the following steps:

1. Identification of the independently controllable input parameters.
2. Estimating the working limits for the parameters selected.
3. Developing the design matrix experimentation.
4. Conducting the experiments as per the design matrix and recording the response.
5. Developing the mathematical model.
6. Checking the adequacy of the developed model.
7. Results and their discussions.

3.1 Identification of the independently controllable input parameters

On the basis of past experience, literature survey and some elementary experiments, three independently controllable input parameters were identified which were found to have significant effect on the angular distortion resulting from the welding process. These parameters were welding current, welding speed and torch angle.

3.2 Estimating the working limits for the parameters selected

Multiple trial runs were conducted to ascertain the working limits of the input parameters. This was done by varying one parameter while keeping the others at some basic level. It was seen that a uniform weld bead was attained without any visual defect when working under the estimated working limits as given in table 3. The parameters were varied at three levels coded as (+1) for highest, (0) for middle and (-1) for lowest limit.

Table 3 Working Limits of welding parameters

S No.	Input Parameter	Unit	(-1)	(0)	(+1)
1.	Welding Current	Amperes	120	140	160
2.	Welding Speed	Cm/min	30	35	40
3.	Torch Angle	Degrees	45	67.5	90

3.3 Developing the design matrix experimentation

The design matrix for the study was formulated in the design expert software using the central face centered technique and 20 experimental runs were obtained. These 20 experiments consist of $2^3=8$ (full factorial points) plus 2x3=6 (center points) plus 6 star points. The design matrix developed is shown in table 4 below

Table 4 Design Matrix

Run	Welding Current (Ampere)	Welding Speed (cm/min)	Torch Angle (Degree)	Distortion Angle (Degree)
1	120	35	22.5	11.42
2	120	40	45	14.9
3	140	35	22.5	9.26
4	160	40	0	14.39
5	140	35	22.5	9.88
6	160	35	22.5	11.2
7	120	40	0	16.74
8	140	35	0	12.23
9	160	40	45	10.31
10	160	30	45	8.69
11	140	35	45	10.07
12	140	35	22.5	7.22
13	140	40	22.5	12.89
14	120	30	0	9.075
15	140	35	22.5	7.68
16	140	30	22.5	9.19
17	140	35	22.5	9.12
18	160	30	0	15.76
19	140	35	22.5	7.16
20	120	30	45	9.98

3.4 Conducting the experiments as per the design matrix and recording the response

The 20 practical runs were carried out as per the design matrix. These runs were conducted in a random order to remove systematic error, if any. The amount of angular distortion was measured by using a surface plate and a height gauge as shown in figure 3. The weldment was placed on the surface plate with one of the plates pressed against surface plate with help of weights such that the edge of the other plate is raised by an amount equal to the angular distortion. The measuring tip of the height gauge was set to zero by touching it to the surface plate. The tip was then raised to the level of the elevated edge of the raised plate and the reading is taken (H). The angular distortion in degrees can be straightaway calculated by Sinθ=H/p where p is the width of the plate. The same procedure was applied on the other plate of the weldment and their average is presented in the table 4.

Fig. 3 Angular Distortion Measurement

3.5 Developing the mathematical model

The relationship between angular distortion and the input parameters can be expressed as follows:

Y = f (A, B, C)

Where, Y represents the response and A, B and C are welding current, welding speed and torch angle respectively.

The mathematical relation between the response and the input parameters can be given by a general regression equation as given below

Angular Distortion = $b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+b_{13}x_1x_3+b_{23}x_2x_3+b_{11}x_{11}^2+b_{22}x_2^2+b_{33}x_3^2$

Where b_0 is the model coefficient b_1, b_2, b_3 are the regression coefficients for linear effects, b_{12}, b_{23} and b_{23} are the regression coefficient for the interaction effects and b_{11} b_{22} b_{33} are regression coefficients for the quadratic effects.

The actual mathematical equation expressing relationship between response and input parameters as developed by design expert software is given below after dropping insignificant terms.

Angular distortion=+9.0 - 0.17*A + 1.65*B - 1.42*C - 1.54*AB - 1.28*AC + 0.03BC + 1.38A^2 + 1.11B^2 + 1.22C^2

3.6 Checking the adequacy of the developed model

The adequacy of the developed model can be checked by using ANOVA technique. The ANOVA analysis carried on design expert software has generated the result shown in table 5.

Table 5 ANOVA Analysis

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	130.50	9	14.50	7.52	0.0020	significant
A-Current	0.3115	1	0.3115	0.1616	0.6962	
B-Speed	27.34	1	27.34	14.18	0.0037	
C-Torch Angle	20.29	1	20.29	10.53	0.0088	
AB	19.02	1	19.02	9.87	0.0105	
AC	13.04	1	13.04	6.77	0.0264	
BC	0.0075	1	0.0075	0.0039	0.9515	
A^2	5.23	1	5.23	2.71	0.1305	
B^2	3.38	1	3.38	1.76	0.2147	
C^2	4.09	1	4.09	2.12	0.1760	
Residual	19.28	10	1.93			
Lack of Fit	12.38	5	2.48	1.80	0.2681	not significant
Pure Error	6.90	5	1.38			
Cor Total	149.78	19				

The above table clearly shows that the model is significant and the lack of fit is insignificant. The high value of R^2 is given by table 6 also confirms this claim.

Table 6 Fit Statistics

Std. Dev.	1.39	**R^2**	0.8713
Mean	10.86	**Adjusted R^2**	0.7554
C.V. %	12.79	**Predicted R^2**	0.0588
		Adeq Precision	7.8845

The scatter plot generated by the software indicating the relationship between predicted vs. actual values further substantiates the adequacy of developed model.

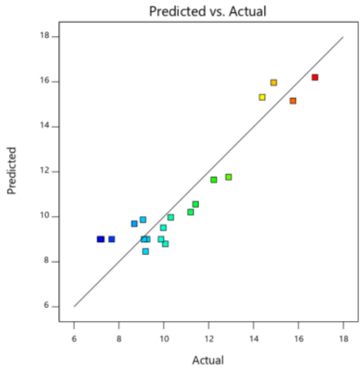

Fig. 4 Predicted v/s Actual Scatter Plot

3.7 Results and their discussions

The results obtained after conducting the investigative work explained till now are given in the graphical form and explained below.

3.7.1 Current vs. Angular Distortion

From figure 5, it is seen that initially, as the current was increased, there was a steady decrease in the angular distortion. This could be due to the fact that when the current was low, heat input was less. As a result, there was rapid cooling due to which distortion was more. When the current was increased, heat input was more due to which the different layers in the weldment underwent cooling at a slower rate. Hence the thermal stresses generated were more uniform. This resulted in a decrease in the angular distortion. But after a point (140 Amperes), a gradual increase in the angular distortion was observed. This might be due to the fact that after this point, the heat input was too much which resulted in a deeper penetration; resulting in the gradual increase in the angular distortion.

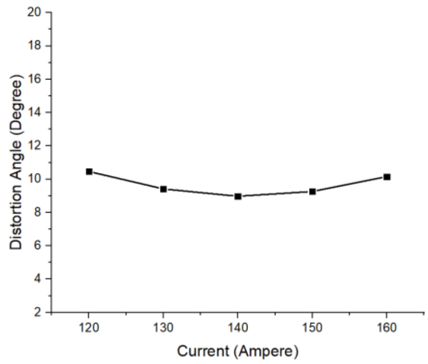

Fig. 5 Effect of Welding current on Distortion Angle

3.7.2 Welding Speed vs. Angular distortion

It can be seen in figure 6 that as the welding speed increases, there is a minor increase in the distortion angle of the produced weldment. This increase could be attributed to the fact that as the welding speed increases, the amount of heat going into the weld reduces, resulting in a rapid cooling of the joint. More rapid the cooling is, more is the non-uniformity in the thermal stresses generated. This causes a slight increase in the angular distortion, within the selected range of speed.

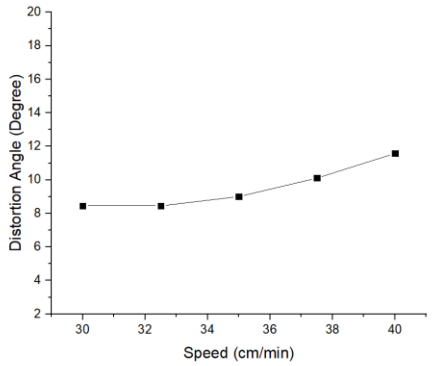

Fig. 6 Effect of Welding speed on Distortion Angle

3.7.3 Torch angle vs. Angular Distortion

From figure 7, it can be seen that an increase in the torch angle results in a steady increase in the angular distortion of the weldment produced. This could be attributed to the fact that as the torch angle increases, the arc spread increases. An increase in the arc spread means there is a greater heat input. This increase in the heat input results in the increase in the resulting angular distortion.

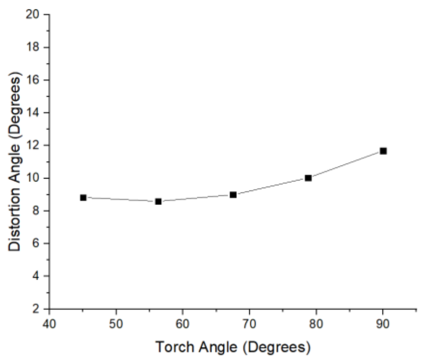

Fig. 7 Effect of torch angle on Distortion Angle

3.7.4 Interaction effect of welding current and welding speed

As shown in Figure 8, there is a steady increase in the angular distortion when the welding speed was increased for all values of current. On the other hand, on increasing the current, initially there was a decrease in the angular distortion up to a point (140A). But after this point, a gradual increase in the angular distortion was seen for the reason already explained in section 3.7.1.

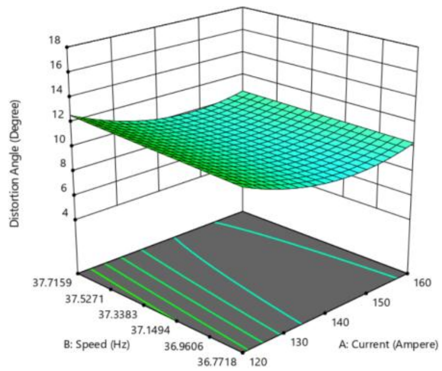

Fig. 8 Interaction effects of Welding speed and Welding current

3.7.5 Interaction effect of welding speed and torch angle

As seen in figure 9, there is a steady increase in the angular distortion when the torch angle was increased for all values of welding speed. It is also seen that the angular distortion increases on increasing the welding speed for all the values of the torch angle for the reasons already explained in article 3.7.2 and 3.7.3.

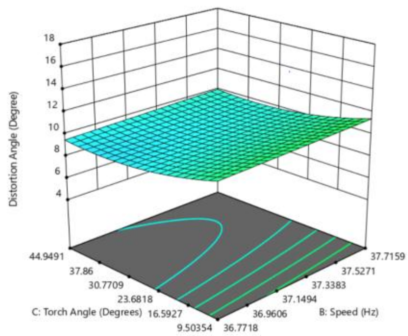

Fig. 9 Interaction effects of Torch angle and Welding speed

3.7.6 Interaction effect of welding current and torch angle

It can be seen from figure 10 that at lower values of welding current, the angular distortion increased on increasing the torch angle. Clearly, increasing the torch angle results in a higher arc spread which means increasing heat spread. This leads to a wider heat zone, which resulted in an increased angular distortion. But for the higher values of current, a decrease in the angular distortion can be seen. This could be due to the dominating effect of welding current on the angular distortion at higher values of current; which has been explained in article 3.7.1

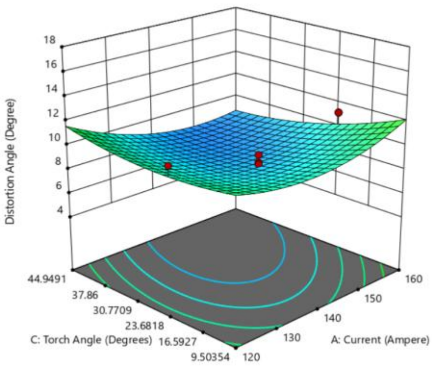

Fig. 10 Interaction effects of Torch angle and Welding current

3. CONCLUSIONS

The following conclusions can be arrived at after analyzing the results discussed above:

1. Centre composite face centred technique was found to be satisfactory for the development of mathematical model in the present case.
2. Torch angle was found to have positive effect on angular distortion.
3. There was a slight increase observed with the increase in welding speed.
4. Welding current was found to have a slight decrease initially but later on had an increasing effect on angular distortion.
5. There were no visual defects whatsoever that were observed on the weldments within the working ranges of the input parameters.

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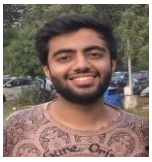

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