Estimation of Angular Distortion of FCAW welded SS 202 plates by Mathematical Modeling

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Abstract - *Flux cored arc welding (FCAW) is a semi-automatic or automatic arc welding process which uses a tubular electrode filled with flux. In the present work flux cored stainless steel -308L wire is used. The base metal used in the present work is austenitic stainless-steel grade 202. This material provides good corrosion resistance, toughness and strength at a reasonable price as compared to other stainless-steel grades such as grade 302. In the present work the effects on the angular distortion of the plate, is observed by changing the input parameters which are wire feed rate, welding speed, voltage, nozzle to plate distance and torch angle. An attempt is made to relate input parameters to angular distortion through a Mathematical model for optimum results. This has been done by utilization of the statistical technique of central composite face centered design whose adequacy is then tested using the ANOVA analysis. Further, the results hence obtained were analyzed with the help of response surface methodology (RSM).*

Key Words: FCAW, Stainless steel, angular distortion, mathematical model, ANOVA, RSM

1. INTRODUCTION

Flux cored arc welding (FCAW) is a fusion welding process performed by an electric arc produced between a continuous filler metal electrode and the weld pool [1]. FCAW is gaining popularity because of its ability to provide good quality consistent welds to metals like structural steel, iron alloys, nickel-based alloys which are commonly used in industries and its self-shielding ability that makes the FCAW setup portable because of elimination of gas cylinders from the setup, hence this promotes its use on construction sites. The welds produced by FCAW exhibit better notch strength. Increasing demand of FCAW establishes a need to investigate the effects of various controllable parameters on the quality of weld achieved from FCAW for efficient welding. In the present work the effects on response parameter, which is angular distortion of the weld, is investigated by changing the controllable parameters which are wire feed rate, welding speed, voltage, nozzle to plate distance and torch angle respectively. In arc welding processes the workpiece undergoes uneven expansion and contraction due to rapid cooling and heating which leads to distortion in different direction of workpiece. Angular distortion or out-of-plane distortion is one such defect that makes the workpiece distort in angular directions around the weld interface [2]. It is very important to keep these distortions as minimum as possible within the workpiece so as to maintain the aesthetics of the joint and eliminate the possibility of dimensional deviations causing misfits and hence forming strong base for the study [3]. The material selected for the present work is stainless steel of grade 202 which is a manganese alloyed austenitic stainless steel which is designed as a cost-effective solution to 302-grade with similar corrosion and mechanical properties [4]. It has excellent weldability and formability because of its austenitic microstructure [5]. Literature survey has revealed that not much work has been reported on these issues relating to stainless steel 202 welds, thereby making a reasonable ground for carrying out the present study. Table-1 and Table-2 shows the chemical composition and mechanical properties of SS 202. Flux cored wire used for the present study is of grade 308L which is a flux cored wire for single or multi-pass welds on stainless steels which is noted for its low spatter generation, excellent bead shape and appearance and ease of slag removal. It has very good deposit efficiency when used for flat and fillet welds of medium and heavy thickness plates and has been designed for various combination of gases. 308L filler provides weld deposits with low susceptibility to cracking [7]. Table-3 shows the chemical composition of flux cored wire 308L. Though different combination of gases can be used, industrial grade CO_2 has been selected for the present work. In the present work CO_2 has been selected over the other options available as it provided more welding heat and better weld penetration.

Table - 1: Chemical composition of SS 202 [5]

UNS		%C	%Mn	%S	%P	%Si	%Ni	%Cr	%N
S202	Min	-	7.5	-	-	-	4.0	17.0	-
	Max	0.15	10.0	0.03	0.060	1.0	6.0	19.0	0.25

Table - 2: Mechanical properties of SS 202 [5]

Mechanical Properties	UTM (MPa)	YS (MPa)	%EL	Hardness (BHN)
SS 202	≥ 620	≥ 260	≥ 40	≤ 241

Table – 3: Chemical composition of filler wire [8]

Chemical composition	%C	%Si	%Mn	%Cr	%Ni
308L	0.03	0.62	1.56	19.5	10.5

2. Experimental Setup

The experiments were conducted on a set-up consisting of a welding power source of rating 400A with 100% duty cycle, and having a flat V-I characteristics usually required for semi and fully automatic welding operations. To achieve a constant weld bead on the plate a mechanized welding carriage was used where the welding torch is fixed on a radially rotating arm that has an arrangement that allows it to move up and down along the column and a tilting arrangement to change the torch angle. Plates to be welded were placed on the moving carriage which is driven by a motor and gear box arrangement whose speed varies from 0 cm/min to 50 cm/min in a stepless manner. Industrial grade CO2 was used for shielding and flow rate of the gas was set to 15litre/min.

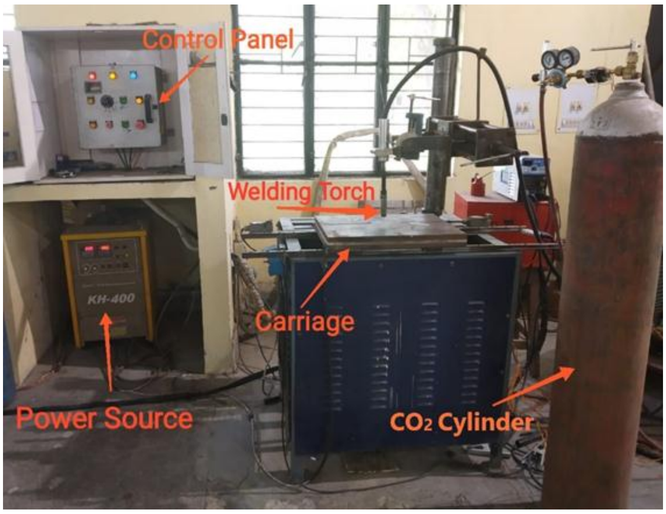

Fig – 1: The Experimental Setup

3. Plan of Research

The research work carried out so far was as per the plan given below;

1) Identification of the process parameters
2) Estimation of their working limits
3) Developing the design matrix
4) Conducting the experiments as per the design matrix
5) Measurement of the angular distortion
6) Developing the mathematical model
7) Testing the adequacy of the developed model
8) Analysis of the results
9) Conclusions

3.1 Identification of the process parameters

Process parameters were decided by conducting trial runs, referring to previously done researches on angular distortion and literature survey which revealed that angular distortion primarily depends on five controllable welding parameters which are wire feed rate, welding speed, voltage, nozzle to plate distance, torch angle.

3.2 Estimation of their working limits

Multiple trial runs were conducted to establish the working limits for all the input parameters in which one parameter was varied while the other parameters were set to a base level and it was observed whether the setting provides a bead of consistent quality without any visual defects. Table-4 shows the working limits for the various input parameters. Input parameters are varied between 5 levels [6].

Table – 4: Working limits of process parameters.

	Input Parameter	Unit	(-2)	(-1)	(0)	(+1)	(+2)
1.	Wire Feed Rate	m/min	0.5	0.7	1.0	1.3	1.5
2.	Welding Speed	cm/min	30	35	40	45	50
3.	Welding Voltage	Volts	20	22	24	26	28
4.	Nozzle to Plate Distance (NPD)	Mm	10	12.5	15	17.5	20
5.	Torch Angle	Degrees	70	80	90	100	110

3.3 Developing the design matrix

Design expert software was utilized to make the design matrix used in the experimentation. Matrix was based on the central composite face centered technique. Number of input parameters and number of levels of each parameter was provided to design expert, on the basis of which a matrix of 32 runs was designed out of which 24=16 points come from fractional factorial design 2*5=10 are the star points and 6 points are the center points. Replications are done at center so that experimental data becomes more reliable. Table-5 shows the generated design matrix.

3.4 Conducting the experiment as per the design matrix

The design matrix consisted of 32 runs which were conducted as per the design matrix in random manner so as to eliminate the systematic error from being introduced into the experiment. The plates were placed on the carriage table in proper orientation and were displaced forward or backward relative to the torch with the help of carriage table. The torch was attached to a radial arm of the unit which has an arrangement that allow the arm to move up and down along the column and a tilting arrangement, which provides the torch with sufficient degrees of freedom to obtain the weld according to the parameters set in various runs of design matrix.

Table -5: Design matrix

Std	Run	Factor 1 A:wire feed rate m/min	Factor 2 B:welding speed cm/min	Factor 3 C:voltage V	Factor 4 D:NPD mm	Factor 5 E:torch angle degrees	Response 1 Angular Distorti... Degrees
10	1	1	-1	-1	1	1	5.05
3	2	-1	1	-1	-1	-1	3.98
9	3	-1	-1	-1	1	-1	4.06
5	4	-1	-1	1	-1	-1	3.8
30	5	0	0	0	0	0	4.72
12	6	1	1	-1	1	-1	4.47
29	7	0	0	0	0	0	4.91
1	8	-1	-1	-1	-1	1	4.72
4	9	1	1	-1	-1	1	4.11
28	10	0	0	0	0	0	4.31
16	11	1	1	1	1	1	4.72
17	12	-2	0	0	0	0	4.1
22	13	0	0	2	0	0	4.98
18	14	2	0	0	0	0	4.72
20	15	0	2	0	0	0	3.74
27	16	0	0	0	0	0	4.05
11	17	-1	1	-1	1	1	4.93
15	18	-1	1	1	1	-1	4.54
19	19	0	-2	0	0	0	4
24	20	0	0	0	2	0	5.27
7	21	-1	1	1	-1	1	4.14
23	22	0	0	0	-2	0	4.49
32	23	0	0	0	0	0	4.9
26	24	0	0	0	0	2	5.43
13	25	-1	-1	1	1	1	3.93
31	26	0	0	0	0	0	4.75
6	27	1	-1	1	-1	1	4.55
14	28	1	-1	1	1	-1	5.17
21	29	0	0	-2	0	0	4.35
2	30	1	-1	-1	-1	-1	4.02
8	31	1	1	1	-1	-1	4.45
25	32	0	0	0	0	-2	4.28

3.5 Measurement of the angular distortion

Angular distortion in the plates was analyzed using an application called Image-Meter. Measurement of angular distortion is conducted by first placing the plate on a flat surface, in present work surface plate was used as the reference surface. Photo of the front view of the plate was clicked, which was then analyzed in the application to find out the angular distortion in degrees. Two measurements for angular distortion was taken for a plate, one on each side and average of the two values was taken as the value of angular distortion for the given plate. Table-5 shows the angular distortion for various runs.

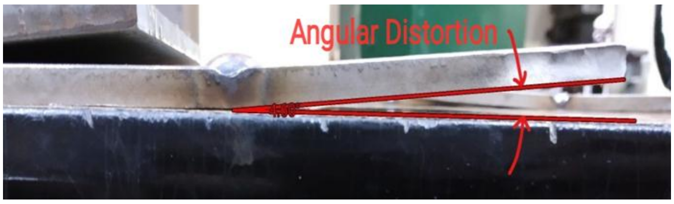

Fig - 2 : Angular distortion measurement in Image-Meter.

3.6 Developing the mathematical model

General function that relates the response parameter and the input parameters can be shown as

$$Y = f(A, B, C, D, E)$$

Where, Y is angular distortion and input parameters A, B, C, D and E are wire feed rate, welding speed, voltage, nozzle to plate distance and torch angle respectively. Actual mathematical equation that relates response to the input parameters is shown below, which was generated when the angular distortion values recorded for the number runs with varying input parameters were provided to the design expert software.

$$\text{Angular distortion} = 4.62 + 0.15A - 0.02B + 0.05C + 0.19D + 0.16E - 0.13AB + 0.15AC + 0.09AD - 0.06AE + 0.04BC + 0.05BD - 0.04BE - 0.01CD - 0.18CE - 0.05DE - 0.06A^2 - 0.20B^2 - 0.004C^2 + 0.04D^2 + 0.04E^2$$

3.7 Testing the adequacy of developed model

The adequacy of the developed model was checked using the ANOVA technique. The detailed ANOVA table is shown below, which clearly shows that the developed model is significant, while the lack of fit is not significant and is possibly due to random errors and not due to any assignable cause.

Table -6: ANOVA table

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5.30	20	0.2652	2.93	0.0355	significant
A-wire feed rate	0.5643	1	0.5643	6.23	0.0298	
B-welding speed	0.0096	1	0.0096	0.1059	0.7509	
C-voltage	0.0620	1	0.0620	0.6843	0.4257	
D-NPD	0.9048	1	0.9048	9.98	0.0091	
E-torch angle	0.6534	1	0.6534	7.21	0.0212	
AB	0.2809	1	0.2809	3.10	0.1061	
AC	0.3969	1	0.3969	4.38	0.0604	
AD	0.1332	1	0.1332	1.47	0.2507	
AE	0.0650	1	0.0650	0.7175	0.4150	
BC	0.0361	1	0.0361	0.3983	0.5408	
BD	0.0462	1	0.0462	0.5101	0.4900	
BE	0.0342	1	0.0342	0.3777	0.5514	
CD	0.0042	1	0.0042	0.0466	0.8330	
CE	0.5256	1	0.5256	5.80	0.0347	
DE	0.0484	1	0.0484	0.5341	0.4802	
A^2	0.1355	1	0.1355	1.49	0.2470	
B^2	1.21	1	1.21	13.33	0.0038	
C^2	0.0005	1	0.0005	0.0057	0.9411	
D^2	0.0720	1	0.0720	0.7945	0.3918	
E^2	0.0550	1	0.0550	0.6067	0.4525	
Residual	0.9969	11	0.0906			
Lack of Fit	0.3875	6	0.0646	0.5300	0.7691	not significant
Pure Error	0.6093	5	0.1219			
Cor Total	6.30	31				

The adequacy of the model is again proved by the scatter plot between the predicted and actual values, as the scattered points in the diagram lies close to the center line.

Table-7 shows that the R2 value is 0.8418 which further proves the adequacy of the developed model.

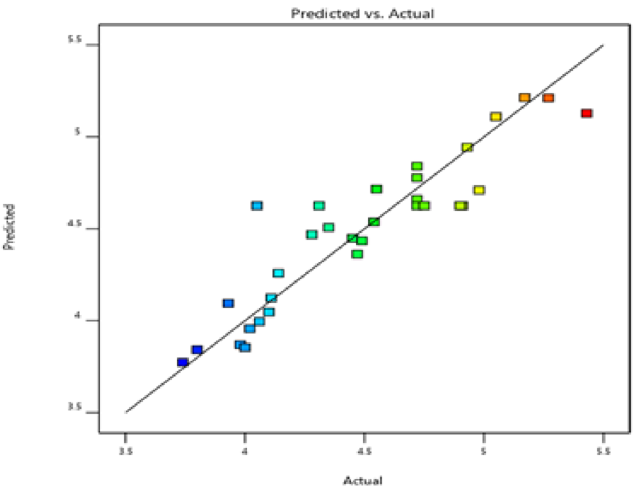

Fig-3: Scatter plot diagram for Angular Distortion

Table -7: Fit statistics of the model

Std. Dev.	0.3010	**R^2**	0.8418
Mean	4.49	**Adjusted R^2**	0.5541
C.V. %	6.71	**Predicted R^2**	-0.7573
		Adeq Precision	5.9063

3.8 Analysis of the results

3.8.1 Effect of Wire feed rate on angular distortion

Fig-4 shows that with the increase in wire feed rate, angular distortion is increased. This can be attributed to the fact that as wire feed rate increases, the current input increases which causes the heat input to the workpiece to increase hence causing more melting of the base metal and with the increased wire feed rate, more filler metal goes into the weld pool which causes the weld pool size to increase even more. As the weld pool size increases the angular distortion on the contraction of the molten base metal also increases.

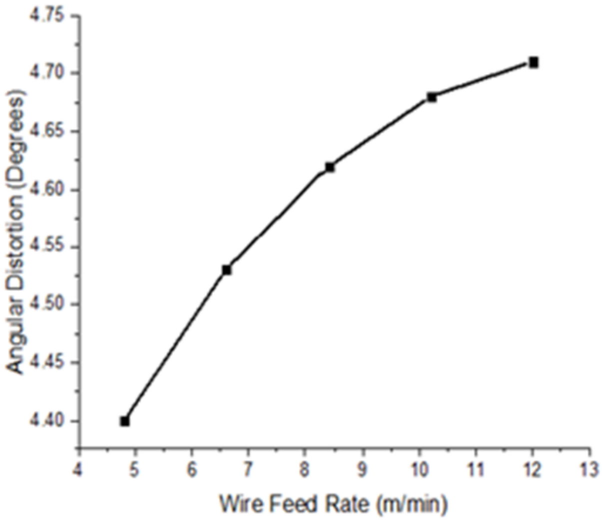

Fig - 4: Plot of Wire feed rate vs Angular distortion

3.8.2 Effect of Welding speed on angular distortion

Fig-5 shows that the angular distortion increases as the welding speed increases from 30cm/min to 40 cm/min, this is because after being melted, weld pool cools down more rapidly with increased welding speed, causing more angular distortion. After a 40 cm/min welding speed the angular distortion starts to decrease with increase in welding speed because the heat transmitted by the arc to the plate decrease which causes the weld bead size to decrease, hence as the contracting metal decreases, angular distortion also decreases. Secondly, there can be interactive effects of other input factors that could have contributed to the sudden decrease in the angular distortion.

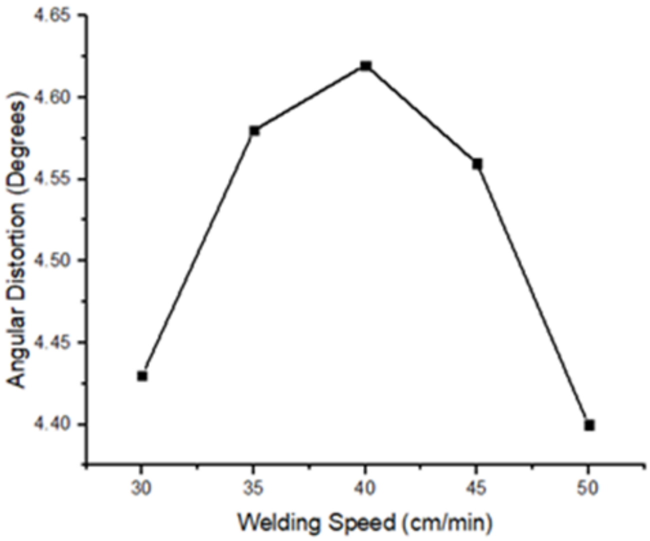

Fig - 5: Plot of Welding speed vs Angular Distortion

3.8.3 Effect of Voltage on angular distortion

Fig-6 shows that as voltage increases, angular distortion also increases. With the increase in voltage the input current and the span of arc increases due to which the heat input to the base metal increases and the weld pool size increases. Angular distortion increases when weld bead size increases because the contracting metal increases.

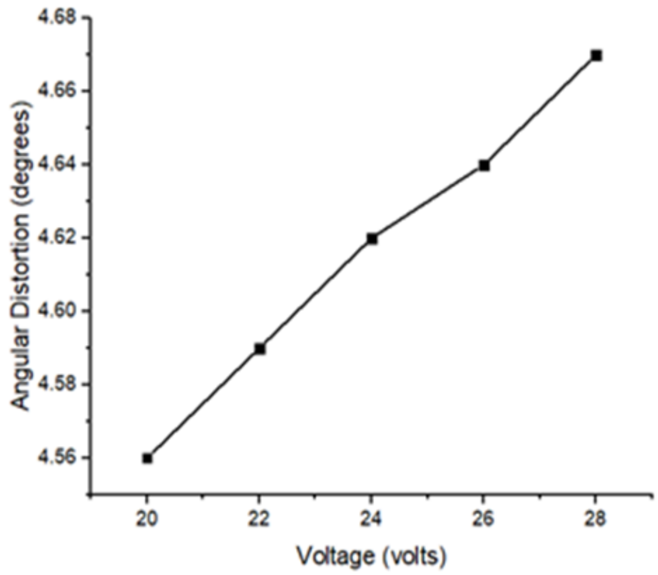

Fig - 6: Plot of Voltage vs Angular Distortion

3.8.4 Effect of NPD on angular distortion

Fig-7 shows that with the increase in the NPD, angular distortion also increases. As NPD increases the, the length of the wire coming out of the nozzle also increases which causes the current to flow through larger distance, which leads to the generation of heat that increases with increase in NPD. More heat generation leads to more heat input to the base metal thereby increasing the weld pool size. As the contracting metal increases, the angular distortion caused by the contraction also increases [7].

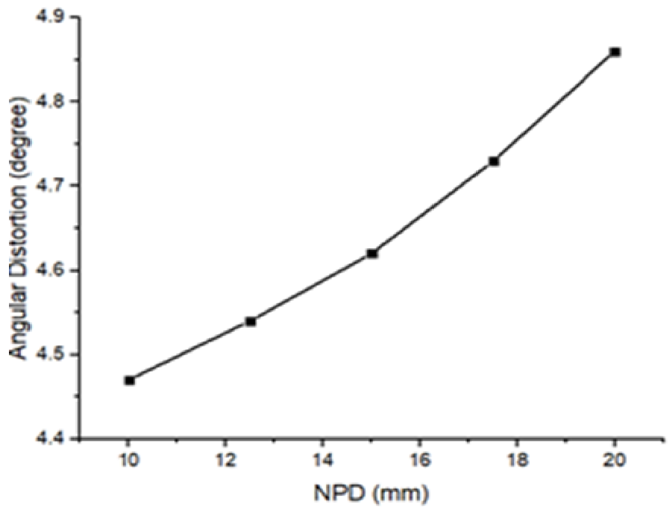

Fig - 7: Plot of NPD vs Angular Distortion

3.8.5 Effect of Torch angle on angular distortion

Fig-8 shows that as torch angle increases, angular distortion also increasing which is due to the fact that with increase in the torch angle the span of the arc increases which causes the heat input to be distributed to a wider area, hence widening the weld bead and decreasing the penetration. As the weld width increases the top the bead experiences more contraction which leads to increased angular distortion [8].

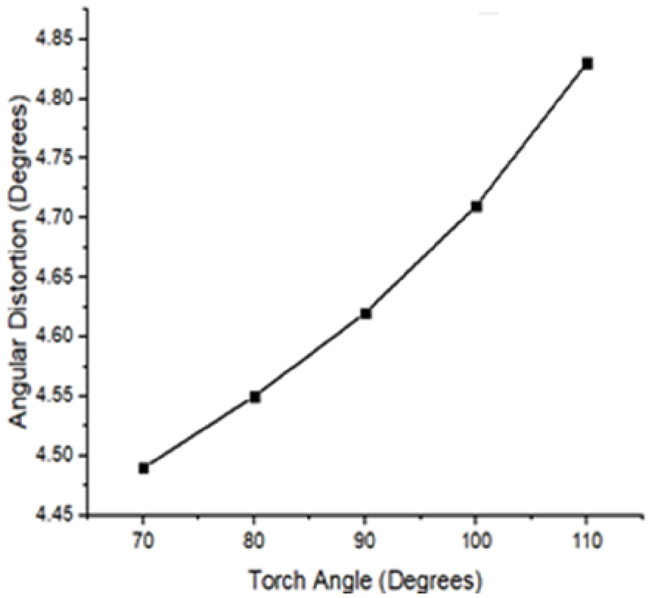

Fig - 8: Plot of Torch angle vs Angular Distortion

3.8.6 Interaction effect of Welding speed and WFR on Angular Distortion

Fig-9 shows that the welding speed has positive effect on the angular distortion from 30cm/min to 45cm/min welding speed for the reason already explained in section 3.8.1, after which a reverse trend is observed, which is probably because of dominating effect of welding speed at higher values.

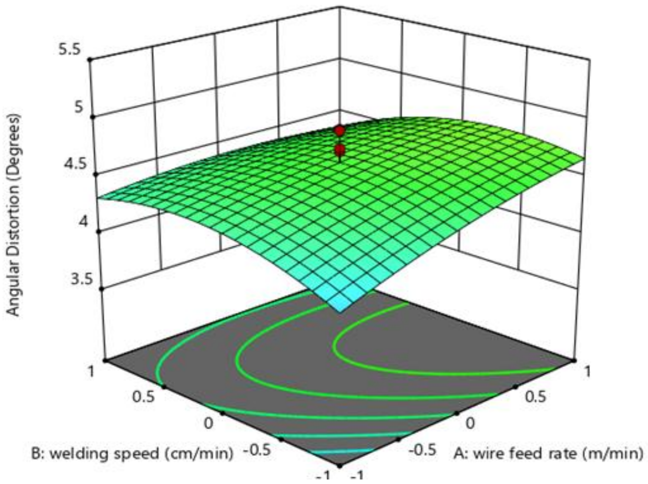

Fig - 9: Interaction effect of Welding speed and WFR on Angular Distortion

3.8.7 Interaction effect of Voltage and WFR on Angular Distortion

Fig-10 shows that the interaction of voltage and WFR has a positive effect on the angular distortion after the lower limit of both the factors, as the values of voltage and WFR increases the angular distortion also increases, reason of which has been discussed in 3.8.1 and 3.8.3.

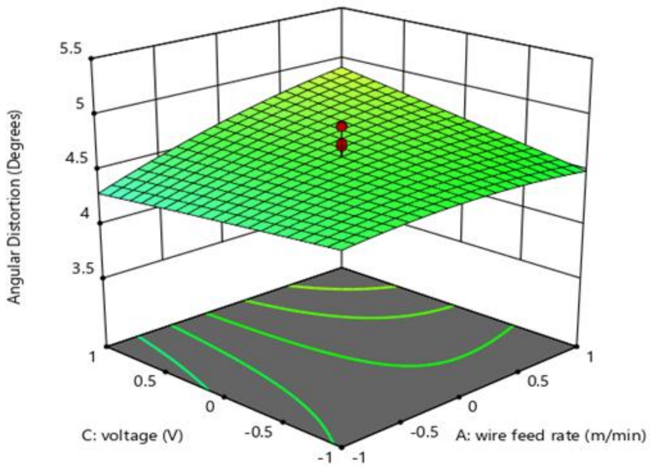

Fig - 10: Interaction effect of Voltage and WFR on Angular Distortion

3.8.8 Interaction effect of NPD and WFR on Angular Distortion

Fig-11 shows that the interaction effect of NPD and WFR has positive effect on the angular distortion after their lower limits, with the increase in NPD and WFR the angular distortion also increases as explained in section 3.8.1 and 3.8.4, and reaches its maximum value at upper limits of the two factors.

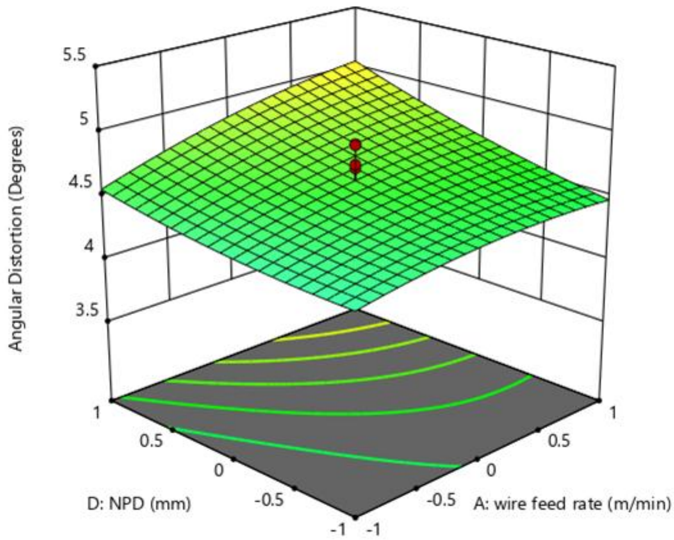

Fig - 11: Interaction effect of NPD and WFR on Angular Distortion

3.8.9 Interaction effect of Torch angle and WFR on Angular Distortion

Fig-12 shows that the interaction effect of torch angle and WFR has positive effect on the angular distortion after their lower limits, with the increase in torch angle and WFR angular distortion increases due to the reasons as explained in section 3.8.1 and 3.8.5.

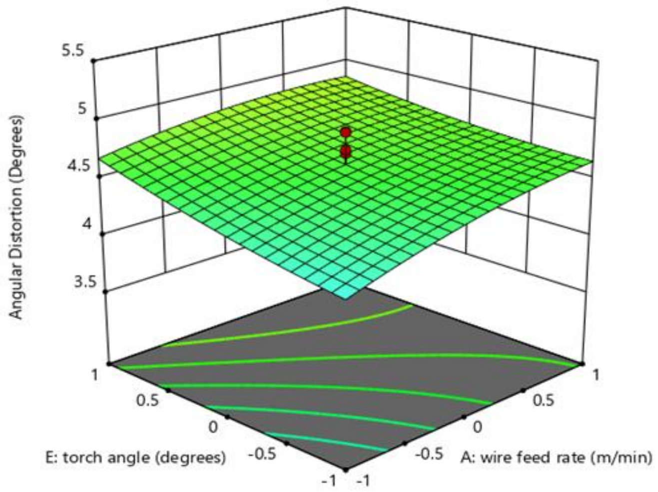

Fig - 12: Interaction effect of Torch angle and WFR on Angular Distortion

3.8.10 Interaction effect of Torch angle and NPD on Angular Distortion

Fig-13 shows that both NPD and torch angle have positive effect on the angular distortion after the lower limit of both the factor, as the factors are increased angular distortion also increases and assumes maximum value at the upper limit of the two factors, reason for which is explained in section 3.8.4 and 3.8.5.

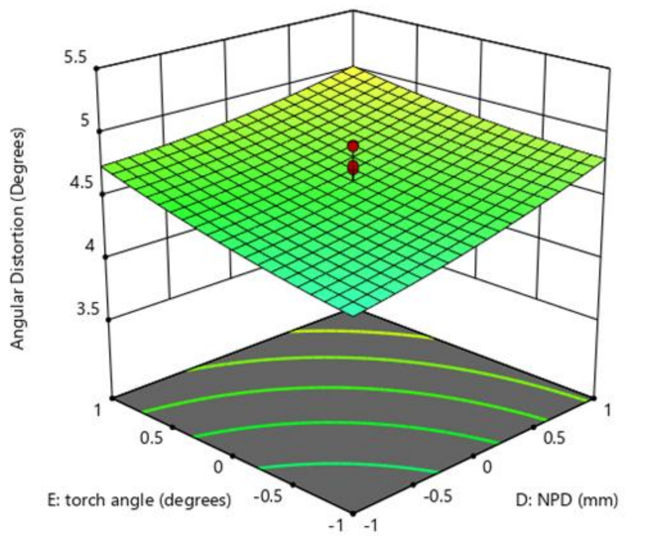

Fig - 13: Interaction effect of Torch angle and NPD on Angular Distortion

4. CONCLUSIONS

Following conclusions can be established after analyzing the results obtained above:

1. Central composite face centered design has proved to be beneficial in investigating the effect of input parameters angular distortion.
2. Angular distortion experiences a continuous increase with the increase in WFR.
3. Welding speed has shown an overall decrease in angular distortion when varied from lower limit to upper limit though it value increased at intermediate levels due to interactive effects.
4. Angular distortion experiences a continuous increase with increase in voltage.
5. Angular distortion experiences a continuous increase with increase in NPD.
6. Angular distortion experiences a continuous increase with increase in torch angle.
7. The minimum angular distortion was found at minimum welding speed and minimum WFR, while maximum angular distortion was found at maximum welding speed and maximum WFR.
8. The minimum angular distortion was found at maximum voltage and minimum WFR while maximum Angular distortion was found at maximum voltage and maximum WFR.
9. The minimum angular distortion was found at minimum NPD and minimum WFR while maximum angular distortion was found at maximum NPD and maximum WFR.
10. The minimum angular distortion was found at minimum torch angle and minimum WFR while maximum angular distortion was found at maximum torch angle and maximum WFR.
11. The minimum angular distortion was found at minimum torch angle and minimum NPD while maximum angular distortion was found at maximum torch angle and maximum NPD.

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