



International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS)

www.iasir.net

Parameter Optimization and Prediction of Bead Geometry of SAW Using Response Surface Methodology

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Abstract: Submerged arc welding also known as sub arc welding has become a chief welding process because of its ability to deposit large amounts of metal with high penetration. The quality of weld depends on bead geometry of the weld which in turn depends on the process variables. This paper deals with the application of factorial design approach for optimising four submerged arc welding parameters viz. Arc voltage, welding speed, weld feed speed and nozzle to plate distance. Governing mathematical models were developed for the submerged arc welding of 6mm-thick MS plates using 3.15-mm diameter MS electrodes. The main and interaction effects of the process control variables on important bead geometry parameters were determined quantitatively and their influence is presented. Design Expert 8 software has been used to develop a set solutions with their desirability values, these solutions can be used to get the optimised results.

Keywords: submerged arc welding; response surface method; mathematical model, process variables; design expert

I. Introduction

Submerged arc welding or sub arc welding is one of the most widely used welding technique in shipbuilding, windmill construction, in pressure vessel construction etc. Sub arc welding is quite prominent because of its inherent advantages of deep penetration, smooth bead and superior quality [1]. The most common problem which an engineer faces is the, optimization of the parameters, which affect the weld quality. The optimum solution to get the desired weld quality is always a compromise as welding is always a multi objective function. An extensive study on the application of Taguchi technique and regression analysis to determine the optimal process parameters for submerged arc welding (SAW) had made by S Kumanan [2]. A software system computing the bead geometry of submerged arc welds was developed by Chandel [3] had presented theoretical predictions of various input parameters on the melting rate and bead geometry in SAW. Murugan [4] gave an apparent design of relationship between the input process parameters and the weld bead geometry in GMAW by developing a four factor five level mathematical model for predicting weld bead geometry within the optimal region of control parameters for stainless steel surfacing. In order to optimize the direct affects and interaction effects of process parameters should be found for decreasing the trial runs of SAW, reducing trial runs is essential to reduce to cost of welding procedure also [5,6]. For automatic and semi-automatic SAW, the process parameters should be fed to the system based on some mathematical model [7-9]. Therefore development of mathematical models through effective and strategic planning, design and execution of experiments is quite essential. These models facilitate optimization of the process. Development of mathematical models also helps to improve the understanding of the effect of process parameters on bead quality and heat input and to optimize the same, to obtain a high-quality welded joint at a relatively low cost with high productivity.

Factorial design planning is simply applied to determine and represent the cause and effect relationship between true mean responses and input control variables influencing the responses. Three kinds of design of experiments [10-11] are possible between output and input variables. Screening designs are used in beginning of process where more than five factors are involved, to recognize the most critical factors. Characterization designs narrow the numbers of factors to only a few and permit for some quantitative understanding of the interactions among factors. Optimization designs focus on only one or two factors, but in much more depth to gain a precise understanding of relationships between factors. A full factorial design combines the levels for each factor with all the levels of every factor. It covers all combinations and provides best data. However it consumes more time and resources. While a fractional Factorial design, uses too many of resources, or if a slightly non orthogonal array is accepted a fractional design is used.

II. Experimental Method

The experiments were conducted as per the design matrix randomly to avoid errors due to noise factors. The mild steel work piece ($120 \times 50 \times 6$ mm – 2 pieces) is cut and V groove of angle 45° as per the standards is prepared. The experiments were conducted with rectifier type semi-automatic SAW equipment with AC power source. Copper coated electrodes AWS ER70S-6, 3.15 mm diameter, of coil form (ESAB brand) and basic-fluoride-type (equivalent to DIN 8557) granular flux was used. The job was firmly fixed to a base plate by means of tack welding and then the submerged arc welding was finally carried out. The welding parameters were recorded during actual welding to determine their fluctuations, if any. The slag was removed and the job was allowed to cool down. Welding is carried out for the square butt joint configuration. The job is cut at three sections for similar welding conditions.

IIA. Determination of different levels

Different levels of each parameter are determined by carrying out trial runs for quality weld by visual inspection of the weld. The table 1 shows the list of parameters chosen with their limits.

IIB. Design Matrix

As mentioned earlier factorial design technique has been adopted in order to get substantial results. The factorials are also known as 2^k factorials, where 2 is the number of levels and k is no of important process variables [12].

Table 1: Welding process variables and their limits

s.no	Parameters	Units	Level 1	Level 2
1	voltage	volts	31.5	37
2	feed	m/min	0.375	0.625
3	speed	m/min	1.75	2.25
4	Nozzle to plate distance	mm	28	34

Table 2: Design matrix

S.no	V	F	S	N
1	-1	-1	-1	-1
2	1	-1	-1	-1
3	-1	1	-1	-1
4	1	1	-1	-1
5	-1	-1	1	-1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	-1
9	-1	-1	-1	1
10	1	-1	-1	1
11	-1	1	-1	1
12	1	1	-1	1
13	-1	-1	1	1
14	1	-1	1	1
15	-1	1	1	1
16	1	1	1	1

For full factorial approach number of runs are equals to 2^k whereas for half factorial or fractional factorial number of runs are equal to 2^{k-1} . If full factorial approach had been practiced then number of possible runs will be 2^4 i.e., 16. If half factorial approach had been applied according to which the number of treatment combinations becomes 2^{k-1} (8). The factorial design matrix is as shown in the table 2.

III. Results and Disucssions

Experiments are conducted as per the plan and The samples are prepared by a standard metallographic process and the average values of the penetration, reinforcement height, and width are measured using digital venire calliper of least count 0.02 mm

IIIA. Mathematical modelling

Response function represents any output parameter as a function of input parameters; $y = f(V, F, S, N)$. The function selected is a second degree equation with the square terms of input parameters being neglected. The resulting function is as follows.

$$Y = b_0 + b_1V + b_2F + b_3S + b_4N + b_{12}(VF) + b_{13}(VS) + b_{14}(VN) + b_{23}(FS) + b_{24}(FN) + b_{34}(SN) \dots \dots \dots (1)$$

Where $b_0, b_1, b_2, b_3 \dots$ are coefficients of the equation 1. These coefficients are found using design expert 8 software. The coefficients are tabulated in the table 4.

Table 3: Outputs from the experiments

S.no	V	F	S	N	P	B	HI
1	31.5	0.375	1.75	28	3.7	12.2	4.5
2	37	0.375	1.75	28	3.3	14.7	5.92
3	31.5	0.625	1.75	28	4.7	13.5	2.8
4	37	0.625	1.75	28	4.1	18.9	3.78
5	31.5	0.375	2.25	28	2.95	9.9	5.04
6	37	0.375	2.25	28	2.7	12.6	6.34
7	31.5	0.625	2.25	28	3.8	11.1	3.5
8	37	0.625	2.25	28	3.6	11.5	4.6
9	31.5	0.375	1.75	34	4	12.7	4.23
10	37	0.375	1.75	34	3.74	15.78	5.71
11	31.5	0.625	1.75	34	4.1	15.83	2.52
12	37	0.625	1.75	34	3.8	19.22	3.62
13	31.5	0.375	2.25	34	2.7	10.32	4.59
14	37	0.375	2.25	34	2.5	11.5	5.92
15	31.5	0.625	2.25	34	4.1	11	3.22
16	37	0.625	2.25	34	3.88	12.1	4.11

Table 4: List of coefficients

Coefficients	penetration	bead width	HI
b0	18.9837	-101.49	-7.8346
b1	-0.272	2.54	0.4172
b2	-2.5756	32.69	-3.4122
b3	-6.7701	41.87	2.8323
b4	-0.1201	1.22	0.0582
b12	-0.0382	0.15	-0.2647
b13	0.0627	-0.82	-0.0318
b14	0.0036	-0.02	-0.0001
b23	5.14	-21.38	2.3625
b24	-0.1017	0.37	0.0228
b34	0.0242	-0.37	-0.06

IIIB. ANOVA for Penetration

The table 5 shows the penetration values for 3 samples each. The results observed for the penetration were analysed using MINITAB15 software. The principle of F test is that, the F value should be large compared to e-pooled. Larger the F value more is the significance of factor. Table 6 shows the results of ANOVA by which it can be observed that the feed and speed contribute majority to the penetration while voltage and nozzle to plate distance do not contribute much and the same is depicted in the Figure 1. Figure 2 shows the mean effect plot, i.e., how the penetration value changes from its mean with a change in the level of input parameter.

Table 5: Values of penetration for 3 samples each

V	F	S	N	Penetration		
				sample 1	sample 2	sample 3
-1	-1	-1	-1	3.7	3.68	3.73
-1	-1	1	1	2.64	2.7	2.7
-1	1	-1	1	3.9	4.2	4.1
1	-1	-1	1	3.8	3.8	3.6
1	-1	1	-1	3.74	3.6	3.7
1	1	-1	-1	2.7	2.7	2.6
1	1	1	1	4.1	4.2	4.1

Table 6: ANOVA table for penetration

S.NO	Factor	DOF	SSQ	Variance	F- Ratio	Pure Sum	P
1	V	1	0.01	0.01	0.012	0	0
2	F	1	7.68	7.688	8.929	6.827	42
3	S	1	5.63	5.636	6.545	4.775	29
4	N	1	0.01	0.016	0.018	0	0
5	Other	3	2.58	0.86			27

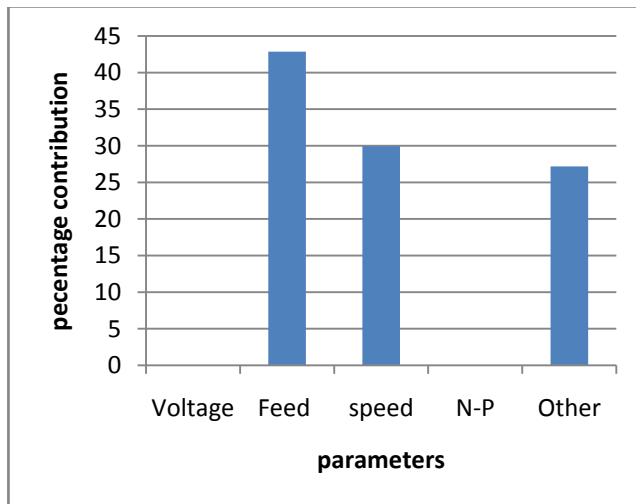


Fig. 1: Contribution of each parameter on penetration

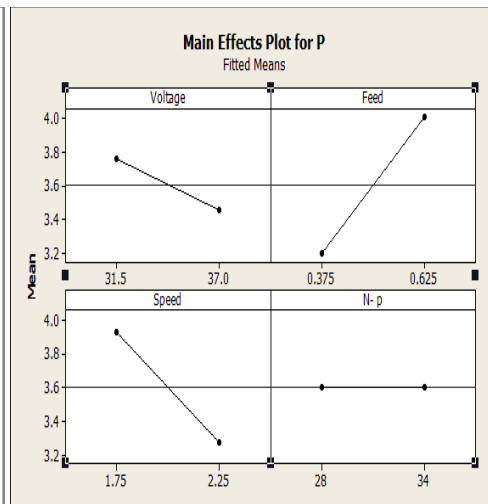


Fig. 2: Main effect plot for penetration

IIIC: ANOVA for Bead Width

The table 7 shows the bead width values for 3 samples each. The results observed for the bead width were analysed using MINITAB 15 software. The table 8 shows the results of ANOVA by which it can be observed that Voltage and Speed are the most influencing parameters. Figure 3 shows the contribution for each parameter and figure 4 shows the main effect for bead width.

Table 7: Values of bead width for 3 samples each

V	F	S	N	Bead Width		
				sample 1	sample 2	sample 3
-1	-1	-1	-1	12.2	12.3	12.1
-1	-1	1	1	9.2	9.2	9.3
-1	1	-1	1	12.2	12	12.2
-1	1	1	-1	11.1	11	11.2
1	-1	-1	1	14.3	14.2	14.3
1	-1	1	-1	12.6	12.7	12.6
1	1	-1	-1	18.9	18.7	18.8
1	1	1	1	12.1	12.1	12

Table 8: ANOVA table for bead width

S.No	factor	DOF	SSQ	Variance	F	Pure Sum	P
1	V	1	8.20	8.203	44.17	9.08	41.15
2	F	1	1.57	1.574	8.48	1.38	6.294
3	S	1	9.26	9.268	44.17	8.01	36.32
4	N	1	2.46	2.466	13.28	2.28	10.33
	Other	3	0.55	0.185			5.892

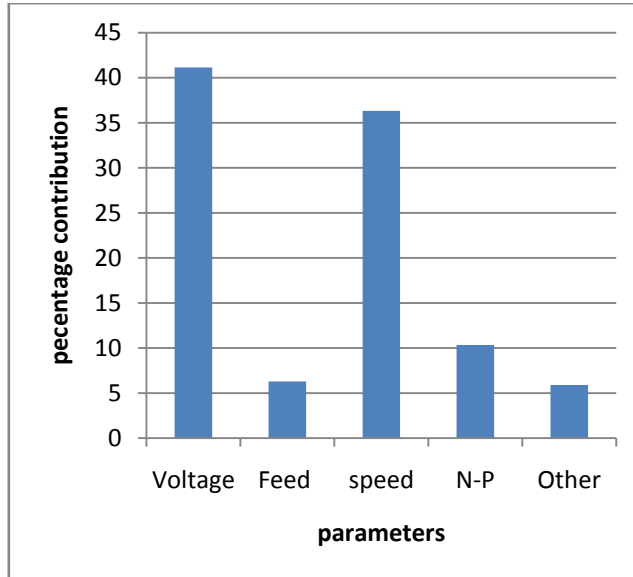


Fig. 3: Contribution of each parameter on penetration

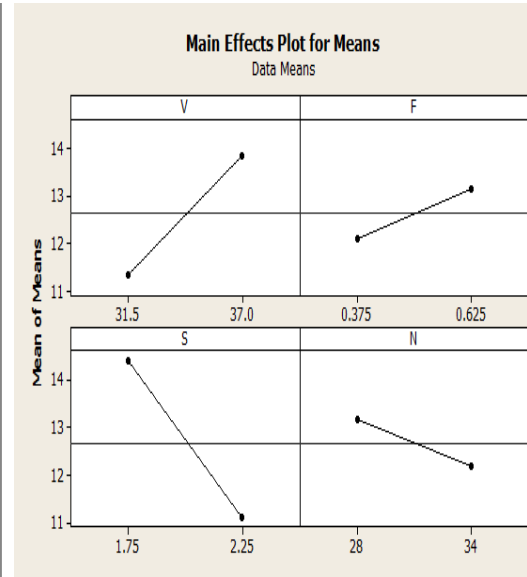


Fig. 4: Main effect plot for penetration

IIID. Direct of parameters

Figure 5 shows the penetration reduces slightly but the bead width and heat input increase steadily with the increase in welding voltage. Figure 6 shows all the important bead parameters P, W, HI will increase with the increase in F. this is because at higher feed rates more amount of material gets deposited into the weld bead therefore it has a positive effect. Weld speed has a negative impact on all bead width parameters. From fig 7 it can be observed that as the speed increases welding occur at higher speed therefore metal deposition rate decreases as result of which penetration, bead width and heat input all decreases. From figure 8 it can be observed that as nozzle to plate distance increases the arc length increases. This increase in the arc length spreads the arc cone at its base. Therefore, the value of W increases as N increases. P is not significantly affected by N.

IIIE. Interaction Effects of Process Variables

From Fig 9, it can be observed that W increases as V increases for all values of S. But this increasing trend of W with the increase in V decreases gradually as S increases. These effects occur because V has a positive effect but S has negative effect on W, These effects are explained in Fig 10, which shows the contour plot of W for the interaction effect of V and S when F and N are at their midpoints (0). Any combination of points on a line of contour plot can be chosen to get the desired bead width value.[7]. Figure 11 shows the interaction effect of F and S on P. It was found F has a positive effect but S has a negative effect on W. Because of these effects, the value of P increases with the increase in F for all values of S. But, because of the negative effect of S on P, the rate of increase P with the increase in F gradually decreases as S increases from its lower limit to upper limit. Figure12 shows the contour plot for penetration against feed and speed. From the figure it can be inferred that any combination of points of feed and speed lying on the lines drawn on contour plot can be chosen to get the desired value of penetration.

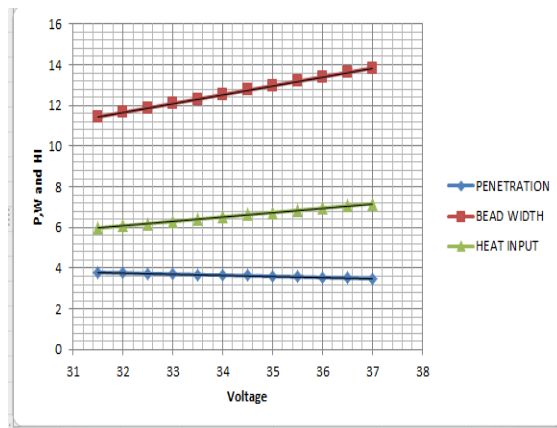


Figure 5: Effect of voltage

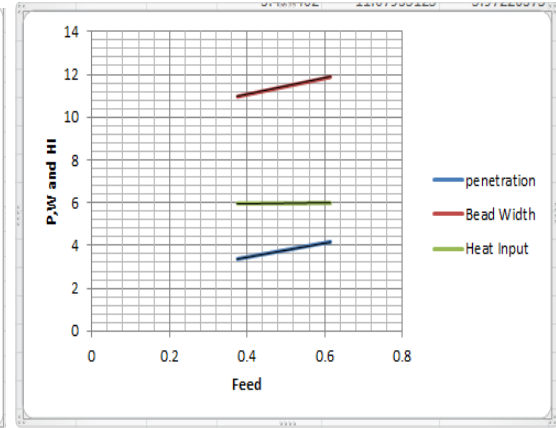


Fig. 6: Effect of feed

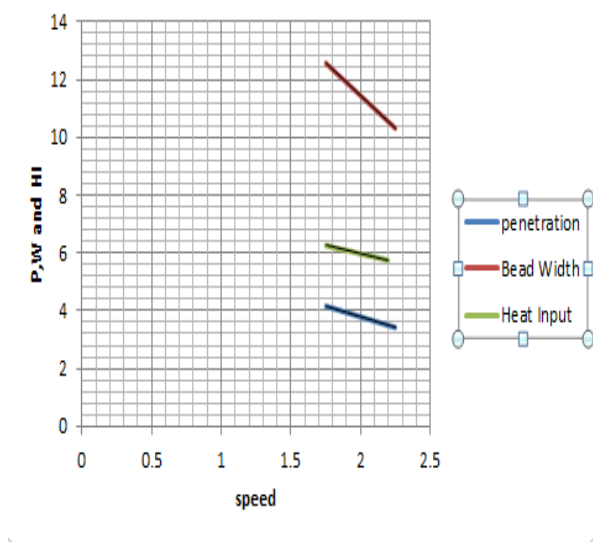


Fig. 7: Effect of speed

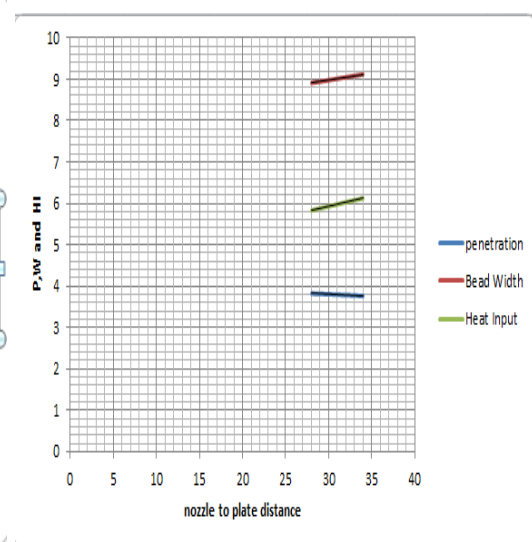


Fig. 8: Effect of nozzle to plate distance

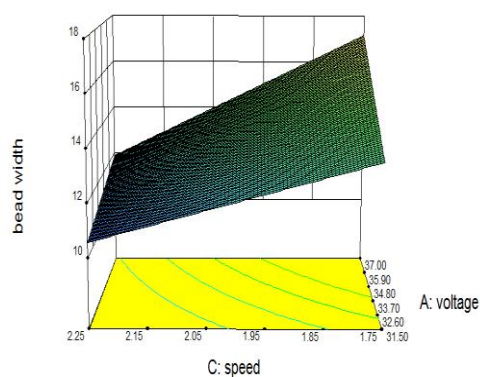


Fig. 9: Interaction effect of speed and voltage on bead width

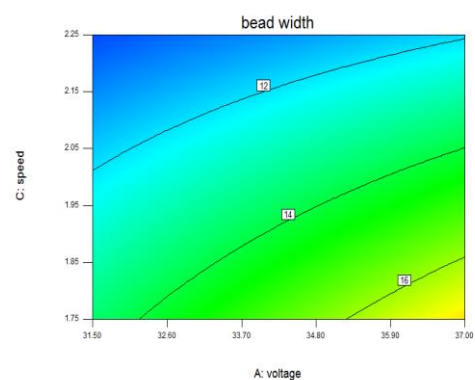


Fig. 10: Contour plot for bead width

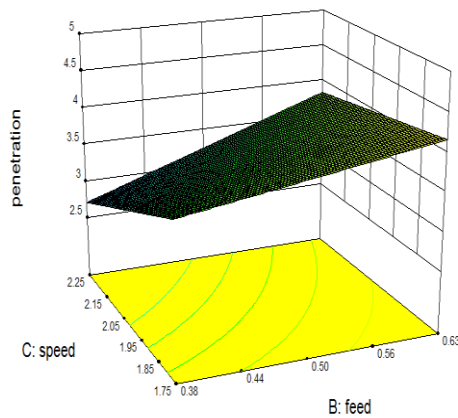


Fig. 11: Interaction effect of speed and feed on penetration

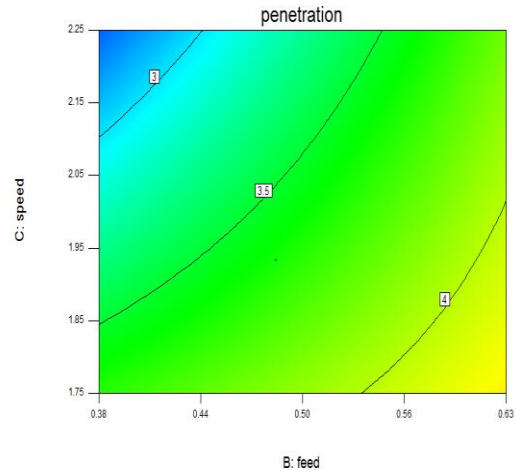


Fig. 12: Contour plot for penetration

IIIF. Desirability

We know that a small layer of fused zone is sufficient to get the required strength to the weld bead. Higher penetration is always desirable while the increase in bead width and heat input is not desirable as these will increase the power required for welding. Therefore a importance level for optimisation is given to the penetration, Bead width and heat input as given below a desirability function is developed. This values range from 0-1. 0 value for desirability indicates that this combination of output parameters is least desirable and 1 value for desirability indicates that combination of output parameters is highly desirable. The desired importance level of each parameter is shown in the table 9.

Table 9: Goal for each input and output parameter with importance level

Name	Goal	Lower Limit	Upper Limit	Importance
A:voltage	is in range	31.5	37	3
B:feed	is in range	0.375	0.625	3
C:speed	is in range	1.75	2.25	3
D:N	is in range	28	34	3
penetration	maximize	2.5	4.7	5
bead width	minimize	9.9	19.22	4
HI	minimize	2.52	6.34	3

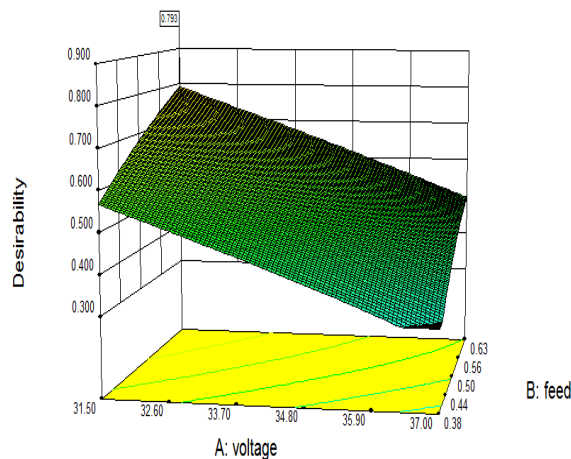


Fig. 13: Interaction effect of feed on desirability

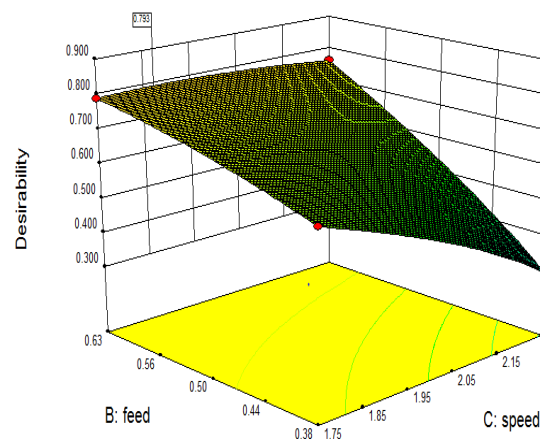


Fig. 14: Interaction effect of speed on desirability

Table 10: List of solutions with their desirability level

s.no	V	F	S	N	D
1	31.5	0.62	2.03	28	0.78
2	31.5	0.62	2.03	28	0.78
3	31.5	0.62	2.07	28.01	0.78
4	31.5	0.62	2	28.01	0.78
5	31.5	0.62	2.1	28	0.78
6	31.53	0.62	2.1	28	0.78
7	31.5	0.62	1.94	28	0.78
8	31.5	0.62	1.92	28	0.78
9	31.5	0.62	1.98	28	0.78
10	31.5	0.62	1.89	28.01	0.78
11	31.52	0.62	2.18	28	0.78
12	31.5	0.62	1.89	28	0.78
13	31.58	0.62	1.92	28	0.78
14	31.5	0.62	2.17	29.05	0.78
15	31.5	0.62	1.86	28	0.78
16	31.5	0.62	2.19	28.98	0.78
17	31.5	0.62	2.25	28	0.78
18	31.5	0.62	1.83	28	0.77
19	31.5	0.62	2.25	28	0.77
20	31.5	0.62	2.19	30.9	0.77
21	31.5	0.62	2.25	31.19	0.77
22	31.5	0.62	2.25	31.19	0.77
23	31.5	0.62	2.25	31.45	0.77
24	31.5	0.62	2.25	31.9	0.77
25	31.5	0.62	1.76	28	0.77
26	31.5	0.62	2.25	32.64	0.77
27	31.5	0.62	2.25	33.62	0.76
28	31.5	0.62	2.25	33.91	0.76
29	31.54	0.62	1.75	28	0.76
30	31.57	0.62	2.25	34	0.76
31	31.5	0.62	2.22	34	0.76
32	31.5	0.6	1.78	28	0.76
33	31.7	0.62	1.78	28	0.76
34	31.5	0.58	1.75	28	0.75
35	31.69	0.61	1.75	28	0.75
36	31.5	0.57	1.75	28.12	0.75
37	32.57	0.62	2.25	28.01	0.74
38	32.21	0.62	2.19	34	0.74
39	32.69	0.62	2.25	28	0.74
40	31.5	0.59	2.24	28	0.73
41	31.5	0.59	2.24	34	0.72
42	33.49	0.62	2.25	33.99	0.71
43	34.03	0.62	2.25	34	0.70
44	34.58	0.62	2.25	34	0.69

Figures 13 and 14 show the interaction effect for desirability by varying the voltage and feed and speed and feed respectively. From the discussion we can come to a conclusion that there can be any number of solutions for a particular value of desirability few of such combinations of parameters with their desirability levels are listed in the table 10.

IV. Conclusions

The feed and speed contribute most to the penetration of the weld bead whereas voltage and speed contribute most to the bead width. All weld bead parameters increase with an increase in wire feed rate and decrease with increase in weld speed. Penetration reduces as voltage increases, but bead width increases considerably with the increase in voltage. As the nozzle-to-plate distance increases all bead parameters decrease except bead width. Interaction effects show that the effect of speed on bead width is low at lower voltages and high at higher voltages. Interaction effects show that the rate of increase of P with the increase in F gradually decreases as S increases.

from its lower limit to upper limit. The equations developed for Penetration, Bead Width and Heat input can be used to predict these output parameters when all input parameters lie within limits. The parameters with required desirability can be used for the purpose of welding.

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