Gas supply and wire feeder:

The smith's gas unit used in the study is a pressure flow device capable of proportionately mixing Argon and CO_2ininfinitely varying proportions. The gas flow rate and gas mixing ratio were set using separate knobs provided in the front panel. In this study the gas flow rate was kept at 20 lit/min. The mixing accuracy as reported by the manufacturer is about + or – 2% of the full scale.

Figure 3. Gas flow meter

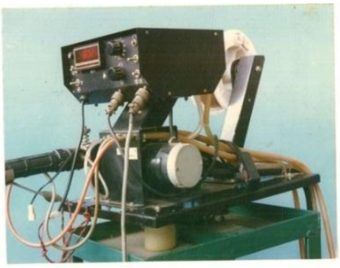

Figure 4. Wire feeder

Figure 5. Experimental setup

The wire feeder unit employed is a millermatic four roll drive feed unit .It provides a continuously variable wire feed speed from about 1.0 m/mm to 18 m/min.

CONDUCTION OF EXPERIMENT AS PER DESIGN MATRIX

Sixteen experimental runs were conducted as per the 2^{5-1} fractional factorial design matrix at random to avoid any systematic error creeping into the system. The surface plates were cross-sectioned at their midpoints to obtain test specimens. The values of the response are given in Table 4.

Table 4. Design matrix with responses

Std Order	Run Order	Center Pt	Blocks	A	B	C	D	E	Penetration 'mm'	Weld bead width in 'mm'	Dilution in %
32	1	1	1	1	1	1	1	1	0.75	11.9	43.9
19	2	1	1	-1	1	-1	-1	-1	0.87	8.6	47.9
15	3	1	1	-1	1	1	1	-1	1.09	10	55.53
23	4	1	1	-1	1	1	-1	1	0.88	6.8	45.12
27	5	1	1	-1	1	-1	1	1	0.56	7.5	73.68
9	6	1	1	-1	-1	-1	1	-1	0.81	10	35.11
4	7	1	1	1	1	-1	-1	1	0.83	7.2	45.56
3	8	1	1	-1	1	-1	-1	-1	0.51	8.0	48.0
31	9	1	1	-1	1	1	1	-1	1.13	9.2	56.9
11	10	1	1	-1	1	-1	1	1	0.54	7.0	56.7
14	11	1	1	1	-1	1	1	-1	0.64	6.8	73.4
25	12	1	1	-1	-1	-1	1	-1	0.87	11.0	34.71
1	13	1	1	-1	-1	-1	-1	1	0.64	6.8	65.16
10	14	1	1	1	-1	-1	1	1	0.59	10.3	40.0
7	15	1	1	-1	1	1	-1	1	0.84	6.0	43.85

Std Order	Run Order	Center Pt	Blocks	A	B	C	D	E	Penetration 'mm'	Weld bead width in 'mm'	Dilution in %
26	16	1	1	1	-1	-1	1	1	0.67	11.3	38.9
12	17	1	1	1	1	-1	1	-1	0.79	11.5	44.47
24	18	1	1	1	1	1	-1	-1	0.84	6.8	76.56
8	19	1	1	1	1	1	-1	-1	0.88	6.6	76.6
16	20	1	1	1	1	1	1	1	0.79	11.2	45.02
17	21	1	1	-1	-1	-1	-1	1	0.72	6.0	65.0
30	22	1	1	1	-1	1	1	-1	1.02	6.0	73.68
21	23	1	1	-1	-1	1	-1	-1	0.54	9.5	81.58
2	24	1	1	1	-1	-1	-1	-1	0.69	10.0	40.0
13	25	1	1	-1	-1	1	1	1	0.91	11.2	50.0
6	26	1	1	1	-1	1	-1	1	0.73	11.2	39.1
22	27	1	1	1	-1	1	-1	1	0.75	12	41.68
18	28	1	1	1	-1	-1	-1	-1	0.71	10.6	40.1
20	29	1	1	1	1	-1	-1	1	0.85	8.0	47.6
29	30	1	1	-1	-1	1	1	1	0.87	11.9	52.28
28	31	1	1	1	1	-1	1	-1	0.75	11.0	44.8
5	32	1	1	-1	-1	1	-1	-1	0.84	8.9	80.0

MATHEMATICAL MODEL

The study attempts relate the important welding process parameters to process output characteristics, through developing empirical regression models for various target parameters. Linear Regression function is fitted to the data and the coefficient values are found using regression analysis with the help of MINITAB statistical software. The developed mathematical models are accurately representing the actual pulsed MIG welding process.

NORMAL PROBABILITY PLOT FOR PENETRATION, WELD BEAD WIDTH AND DILUTION

Validating ANOVA Assumptions It is necessary to check the assumptions of ANOVA before draw conclusions. There are three assumptions in ANOVA analysis: normality, constant variance, and independence. Normality assumptions have been checked.

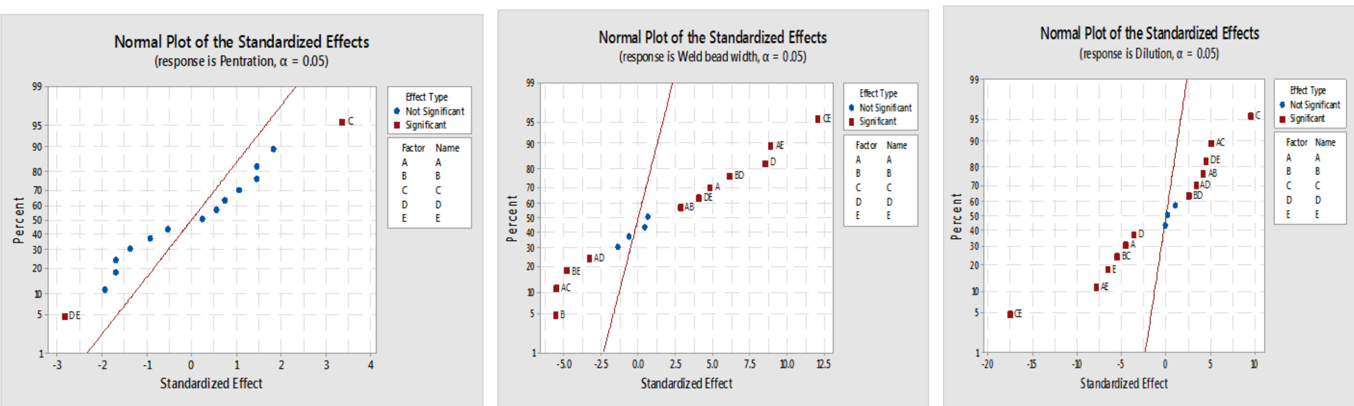

Figure 6. Normality plot for Penetration, weld bead width and Dilution

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The normality plot of the residuals above shows that the residuals follow a normal distribution in all the three cases. It indicates significant and insignificant factors and residuals follow a straight line. According to the above normal plots C and DE are significant for penetration, C, E, BC, CD, are insignificant for weld bead width and B, BE, CD are insignificant for Dilution case.

PARETO PLOT FOR PENETRATION, WELD BEAD WIDTH AND DILUTION MODEL

Pareto chart shows the same results. Since some of the terms are insignificant, we can drop these terms in the model.

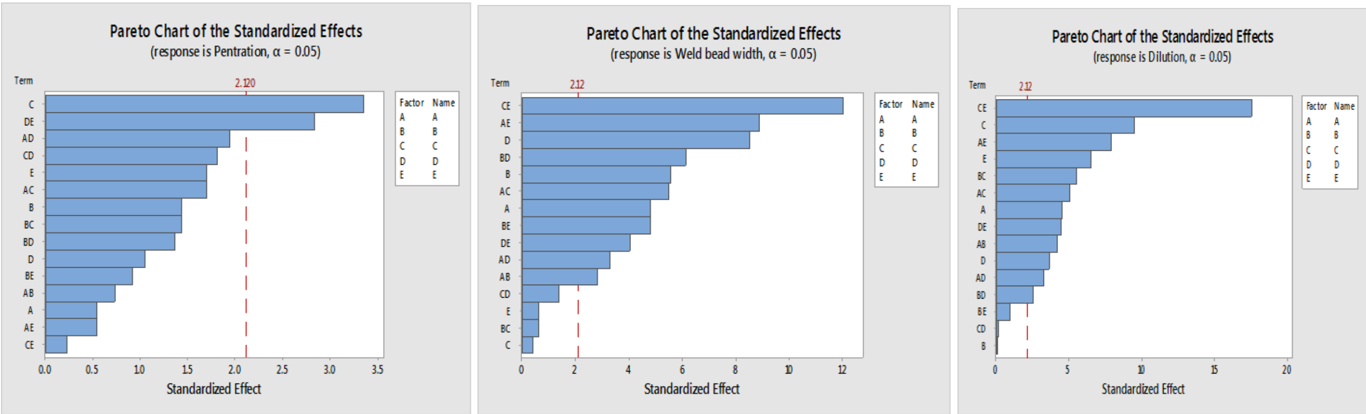

Figure 7. Pareto chart for Penetration, weld bead width and Dilution

Table 5. ANOVA for penetration

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	0.506487	0.033766	2.76	0.026
Linear	5	0.215462	0.043092	3.52	0.025
A	1	0.003613	0.003613	0.30	0.594
B	1	0.025312	0.025312	2.07	0.170
C	**1**	**0.137812**	**0.137812**	**11.26**	**0.004**
D	1	0.013613	0.013613	1.11	0.307
E	1	0.035113	0.035113	2.87	0.110
2-Way Interactions	10	0.291025	0.029102	2.38	0.059
A*B	1	0.006613	0.006613	0.54	0.473
A*C	1	0.035113	0.035113	2.87	0.110
A*D	1	0.046513	0.046513	3.80	0.069
A*E	1	0.003612	0.003612	0.30	0.594
B*C	1	0.025313	0.025313	2.07	0.170
B*D	1	0.023113	0.023113	1.89	0.188
B*E	1	0.010512	0.010512	0.86	0.368
C*D	1	0.040612	0.040612	3.32	0.087
C*E	1	0.000613	0.000613	0.05	0.826
D*E	**1**	**0.099012**	**0.099012**	**8.09**	**0.012**
Error	16	0.195800	0.012238		
Total	31	0.702287			

Table 6. Regression coefficients with P-values

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		0.7781	0.0196	39.79	0.000	
A	-0.0213	-0.0106	0.0196	-0.54	0.594	1.00
B	0.0563	0.0281	0.0196	1.44	0.170	1.00
C	**0.1312**	**0.0656**	**0.0196**	**3.36**	**0.004**	1.00
D	0.0413	0.0206	0.0196	1.05	0.307	1.00
E	-0.0662	-0.0331	0.0196	-1.69	0.110	1.00
A*B	0.0288	0.0144	0.0196	0.74	0.473	1.00
A*C	-0.0662	-0.0331	0.0196	-1.69	0.110	1.00
A*D	-0.0762	-0.0381	0.0196	-1.95	0.069	1.00
A*E	0.0212	0.0106	0.0196	0.54	0.594	1.00
B*C	0.0562	0.0281	0.0196	1.44	0.170	1.00
B*D	-0.0537	-0.0269	0.0196	-1.37	0.188	1.00
B*E	-0.0362	-0.0181	0.0196	-0.93	0.368	1.00
C*D	0.0713	0.0356	0.0196	1.82	0.087	1.00
C*E	0.0088	0.0044	0.0196	0.22	0.826	1.00
D*E	**-0.1112**	**-0.0556**	**0.0196**	**-2.84**	**0.012**	1.00

Table 7. Model summary –Penetration

S	R-sq	R-sq(adj)	R-sq(pred)
0.110623	72.12%	45.98%	0.00%

Discussion: Table 6 shows the estimation coefficient (Coef.) of each variable term in a regression model for penetration along with the corresponding standard deviation (SD coef), t-statistics (t-Stat) and probability (P) values determined at 5% significance level. Variable terms with P < 0.05, are C, and DE which are considered statistically significant for penetration of weld bead geometry. Therefore, a second-order model was built to describe the behavior of each response, followed by the optimization stage to find the best setting for each factor. The second-order models for penetration of weld bead geometry in terms of coded variables with all significant terms are given in Equation (1).The value of R^2 was 72.12%. This means that regression model provided an explanation of the relationship between independent factors and the response. The associated *p*-value for the model was lower than 0.05 (i.e. α = 0.05, or 95% confidence) which indicated that the model was considered to be moderately statistically significant.

Table 8. ANOVA for weld bead width

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	126.735	8.4490	32.03	0.000
Linear	5	33.692	6.7385	25.55	0.000
A	1	6.125	6.1250	23.22	0.000
B	1	8.201	8.2013	31.09	0.000
C	1	0.045	0.0450	0.17	0.685
D	1	19.220	19.2200	72.87	0.000
E	1	0.101	0.1013	0.38	0.544
2-Way Interactions	10	93.042	9.3042	35.28	0.000
A*B	1	2.101	2.1012	7.97	0.012
A*C	1	8.000	8.0000	30.33	0.000
A*D	1	2.880	2.8800	10.92	0.004
A*E	1	20.801	20.8013	78.87	0.000
B*C	1	0.101	0.1013	0.38	0.544
B*D	1	9.901	9.9012	37.54	0.000
B*E	1	6.125	6.1250	23.22	0.000
C*D	1	0.500	0.5000	1.90	0.188
C*E	1	38.281	38.2812	145.14	0.000
D*E	1	4.351	4.3513	16.50	0.001
Error	16	4.220	0.2638		
Total	31	130.955			

Table 9. Regression coefficients with P-values (Weld bead width)

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		9.0875	0.0908	100.10	0.000	
A	**0.8750**	**0.4375**	**0.0908**	**4.82**	**0.000**	1.00
B	**-1.0125**	**-0.5063**	**0.0908**	**-5.58**	**0.000**	1.00
C	0.0750	0.0375	0.0908	0.41	0.685	1.00
D	**1.5500**	**0.7750**	**0.0908**	**8.54**	**0.000**	1.00
E	0.1125	0.0563	0.0908	0.62	0.544	1.00
A*B	**0.5125**	**0.2563**	**0.0908**	**2.82**	**0.012**	1.00
A*C	**-1.0000**	**-0.5000**	**0.0908**	**-5.51**	**0.000**	1.00
A*D	**-0.6000**	**-0.3000**	**0.0908**	**-3.30**	**0.004**	1.00
A*E	**1.6125**	**0.8063**	**0.0908**	**8.88**	**0.000**	1.00
B*C	-0.1125	-0.0563	0.0908	-0.62	0.544	1.00
B*D	**1.1125**	**0.5562**	**0.0908**	**6.13**	**0.000**	1.00
B*E	**-0.8750**	**-0.4375**	**0.0908**	**-4.82**	**0.000**	1.00
C*D	-0.2500	-0.1250	0.0908	-1.38	0.188	1.00
C*E	**2.1875**	**1.0937**	**0.0908**	**12.05**	**0.000**	1.00
D*E	**0.7375**	**0.3688**	**0.0908**	**4.06**	**0.001**	1.00

Table 10. Model summary – weld bead width

S	R-sq	R-sq(adj)	R-sq (pred)
0.513566	96.78%	93.76%	87.11%

Discussion: Table 9 shows the estimation coefficient (Coef) of each variable term in a regression model for weld bead width along with the corresponding standard deviation (SD coef), t-statistics (t-Stat) and probability (P) values determined at 5% significance level. Variable terms with P < 0.05, A, B, D, AB, AC, AD, AE, BD, BE, CE, DE are considered statistically significant for weld bead width of weld bead geometry. The second-order models for weld bead width of weld bead geometry in terms of coded variables with all significant terms are given in Equation (2).The value of R^2 was 93.76%. This means that regression model provided an explanation of the relationship between independent factors and the response. The associated *p*-value for the model was lower than 0.05 (i.e. α = 0.05, or 95% confidence) which indicated that the model was considered to be statistically significant.

Table 11. ANOVA for Dilution

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	6354.93	423.66	43.29	0.000
Linear	5	1627.60	325.52	33.26	0.000
A	1	200.75	200.75	20.51	0.000
B	1	0.07	0.07	0.01	0.934
C	1	876.86	876.86	89.60	0.000
D	1	130.94	130.94	13.38	0.002
E	1	418.98	418.98	42.81	0.000
2-Way Interactions	10	4727.33	472.73	48.30	0.000
A*B	1	170.25	170.25	17.40	0.001
A*C	1	250.38	250.38	25.58	0.000
A*D	1	107.57	107.57	10.99	0.004
A*E	1	611.71	611.71	62.50	0.000
B*C	1	299.94	299.94	30.65	0.000
B*D	1	61.47	61.47	6.28	0.023
B*E	1	9.17	9.17	0.94	0.347
C*D	1	0.25	0.25	0.03	0.875
C*E	1	3018.84	3018.84	308.46	0.000
D*E	1	197.76	197.76	20.21	0.000
Error	16	156.59	9.79		
Total	31	6511.52			

Table 12. Regression coefficients with P-values (Dilution)

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		9.0875	0.0908	100.10	0.000	
A	0.8750	0.4375	0.0908	4.82	0.000	1.00
B	-1.0125	-0.5063	0.0908	-5.58	0.000	1.00
C	0.0750	0.0375	0.0908	0.41	0.685	1.00
D	1.5500	0.7750	0.0908	8.54	0.000	1.00
E	0.1125	0.0563	0.0908	0.62	0.544	1.00
A*B	0.5125	0.2563	0.0908	2.82	0.012	1.00
A*C	-1.0000	-0.5000	0.0908	-5.51	0.000	1.00
A*D	-0.6000	-0.3000	0.0908	-3.30	0.004	1.00
A*E	1.6125	0.8063	0.0908	8.88	0.000	1.00
B*C	-0.1125	-0.0563	0.0908	-0.62	0.544	1.00
B*D	1.1125	0.5562	0.0908	6.13	0.000	1.00
B*E	-0.8750	-0.4375	0.0908	-4.82	0.000	1.00
C*D	-0.2500	-0.1250	0.0908	-1.38	0.188	1.00
C*E	2.1875	1.0937	0.0908	12.05	0.000	1.00
D*E	0.7375	0.3688	0.0908	4.06	0.001	1.00

Table 13. Model summary – Dilution

S	R-sq	R-sq(adj)	R-sq(pred)
0.513566	96.78%	93.76%	87.11%

Discussion :Table 12 shows the estimation coefficient (Coef) of each variable term in are regression model for weld bead width along with the corresponding standard deviation (SD coef), t-statistics (t-Stat) and probability (P) values determined at 5% significance level. Variable terms with P < 0.05, A, C,D, E,AB, AC, AD, AE, BC,BD,CE, DE are considered statistically significant for dilution for weld bead geometry. The second-order models for weld bead width of weld bead geometry in terms of coded variables with all significant terms are given in Equation (3).The value of R^2 was 96.78%. This means that regression model provided an explanation of the relationship between independent factors and the response. The associated *p*-value for the model was lower than 0.05 (i.e. α = 0.05, or 95% confidence) which indicated that the model was considered to be statistically significant.

EFFECTS AND INTERACTION OF PROCESS VARIABLES:

MAIN EFFECTS AND INTERACTION OF PROCESS VARIABLES ON DEPTH OF PENETRATION :

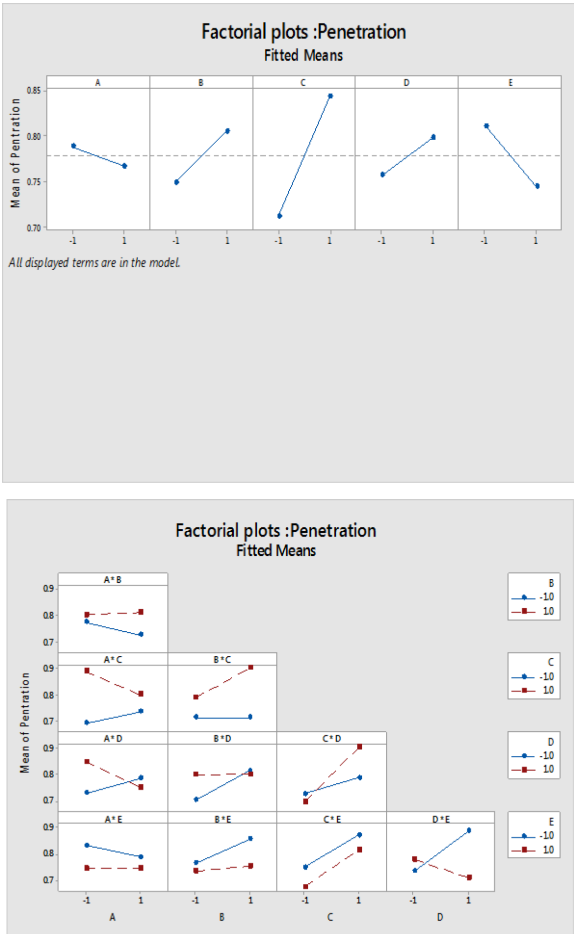

Figure 8. Illustration of main and interaction effect on Penetration

MAIN EFFECTS AND INTERACTION OF PROCESS VARIABLES ON PENETRATION

From Figure 8, it is evident that Penetration (P) increases with an increase in pulse time (C) and as the Back ground current (D) increases, penetration (P) decreases considerably. Factors A, B and C will not enhance the penetration much as they are insignificant. There is an interaction effect between background current (D) and background current time period (E), as the background current (D) increases ,penetration (P) decreases.

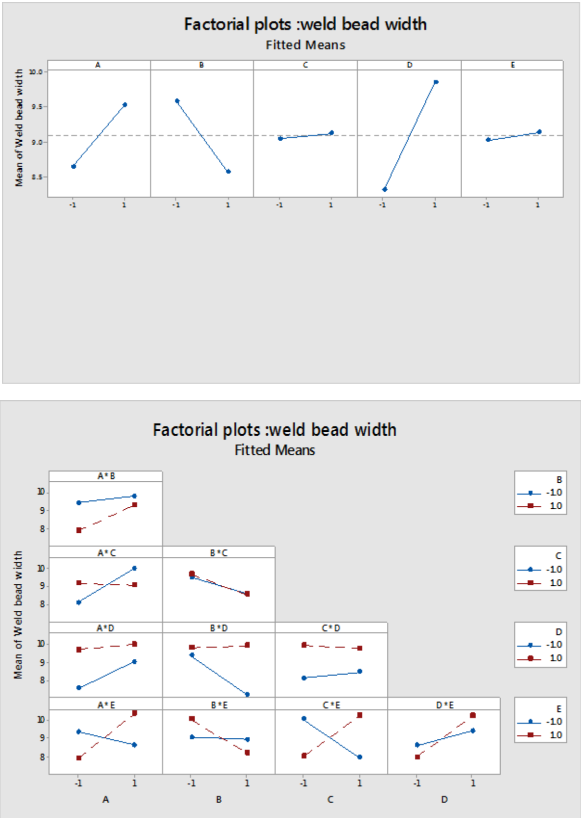

Figure 9. Illustration of main and interaction effect on weld bead width

MAIN EFFECTS AND INTERACTION OF PROCESS VARIABLES ON WELD BEAD WIDTH (W)

From Figure 9, it is evident that weld bead width (W) increases with an increase in pulse current (A) and back ground current (D) and as the Welding speed (B) increases, weld bead width (W) decreases considerably. Increase the Factors Pulse time (C)and background current (D) will not enhance the weld bead width at all. There is an interaction effect between factors Pulse current and pulse time (AC), Pulse current and background current time period (AE), Welding speed and background current period (BE), Pulse time and background current period (CE),background current and background current period(DE).

MAIN EFFECTS AND INTERACTION OF PROCESS VARIABLES ON DILUTION

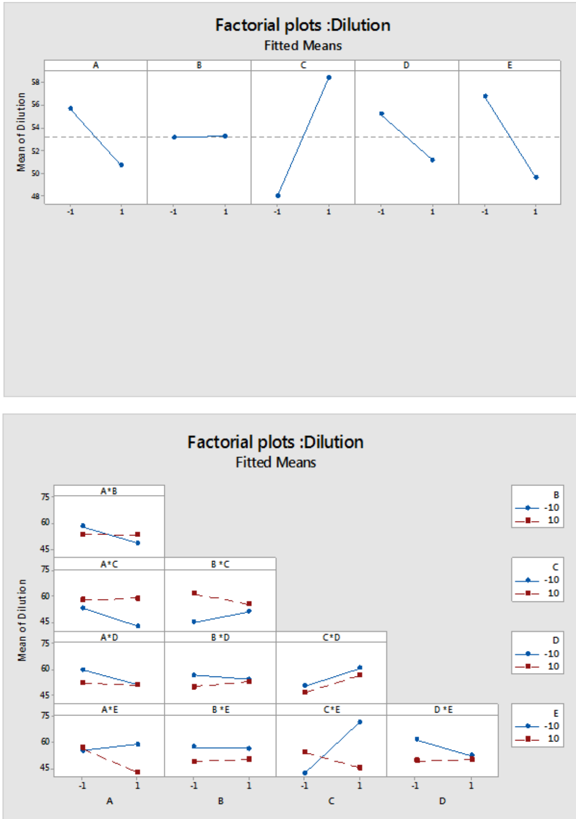

Figure 10. Illustration of main and interaction effect on Dilution

From Figure 10, it is evident that Dilution (D) increases with an increase in pulse time (C).As Pulse time (A),background current (D) background current time period (E) increases, the dilution decreases. There is no effect of welding speed (B) on Dilution when welding speed varies from lower level to higher level. There is an interaction effect between factors Pulse current and background current time period (AE), Pulse time and background current period (CE).

MATHEMATICAL MODELS IN CODED FORM

After testing adequacy and significance of each coefficient of the regression equations we obtained the linear mathematical models for penetration, weld bead width and dilution in the coaded form as follows.

$$\text{Penetration} = 0.7781 - 0.0106\,A + 0.0281\,B + 0.0656\,C + 0.0206\,D - 0.0331\,E + 0.0144\,A*B - 0.0331\,A*C - 0.0381\,A*D + 0.0106\,A*E + 0.0281\,B*C - 0.0269\,B*D - 0.0181\,B*E + 0.0356\,C*D + 0.0044\,C*E - 0.0556\,D*E \quad (1)$$

$$\text{Weld bead width} = 9.0875 + 0.4375\,A - 0.5063\,B + 0.0375\,C + 0.7750\,D + 0.0563\,E + 0.2563\,A*B - 0.5000\,A*C - 0.3000\,A*D + 0.8063\,A*E - 0.0563\,B*C + 0.5562\,B*D - 0.4375\,B*E - 0.1250\,C*D + 1.0937\,C*E + 0.3688\,D*E \quad (2)$$

$$\text{Dilution} = 53.215 - 2.505\,A + 0.047\,B + 5.235\,C - 2.023\,D - 3.618\,E + 2.307\,A*B + 2.797\,A*C + 1.833\,A*D - 4.372\,A*E - 3.062\,B*C + 1.386\,B*D + 0.535\,B*E - 0.088\,C*D - 9.713\,C*E + 2.486\,D*E \quad (3)$$

In calculating the predicted value of the optimization parameters, the coaded values of the factors are inserted in to the mathematical model.

Rule 1.If an interaction effect has a positive sign, then for increasing the optimization parameter, what is required is a simultaneous increase or decrease of the value of the factors, for example the combination X_1= +1 and X_2 = +1 or X_1= -1 and X_2 = -1.

Rule 2.If the interaction effect has a negative sign, then to increase the optimization parameter the factors should simultaneously change in different directions for example the combination X_1= +1 and X_2 = -1 or X_1= -1 and X_2 = +1.

Table 14. Prediction of weld bead geometry for a treatment using the above model

Sl. no.	A	B	C	D	E	Dilution in %	Weld bead width in 'mm'	Penetration in' mm'
1	-1	-1	1	1	-1	65.15	9.25	1.04

CONCLUSION

Fractional factorial technique can be effectively utilized to design the experiments for pulsed MIG welding. Mathematical models based on regression and analysis of variance technique can be an effective tool for prediction of weld bead geometry and shape relations. The developed models can also be utilized for predicting the values of controlled variables for achieving desired weld bead profile. These equations can be usefully employed for control of weld bead contours in mechanized and robotic welding system. The models can provide a picture of interaction between control factors and response factors. The suitable ranges of pulse current, pulse time, welding speed ,background current and back ground current time period used for the experiment provide a useful data ,which can be utilized for making bead in V- groove plate of medium thickness(10-15 mm).The established welding parameters for 12 mm thick plate with 6 mm depth V- groove (90 ^{0} included angle) can be employed to get good quality of weld bead.

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