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PARAMETERS OPTIMIZATION OF GAS METAL ARC WELDING PROCESS (GMAW) BY USING DESIGN OF EXPERIMENTS

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Abstract: The weld quality at the joint is directly influenced by the input welding parameters. A common problem faced by manufacturer is to control process input parameter to obtain the good welded joint with required bead geometry, good mechanical properties, weld quality with minimal detrimental residual stresses and distortion. In this study an attempt is made to investigate the effects and optimization of welding process parameters on the tensile strength in the Gas metal arc welding (GMAW) process. The experimental studies were conducted under various input parameters as welding direction, wire speed, travel speed, arc voltage, contact tip to work distance, torch angle and gas flow rate. Taguchi experimental design method was used to determine the settings of welding parameters. The level of importance and percentage contribution of each parameter on the tensile strength was determined by using analysis of variance (ANOVA). The optimum welding process parameter combination was obtained by using the analysis of signal-to-noise (S/N) ratio.

Key words: **Gas metal arc welding (GMAW), Ultimate tensile strength, Taguchi method, Optimization, Deign of experiments (DOE**).

I. INTRODUCTION

Welding is a process of joining materials and is more economical and is a much faster process compared to both casting and riveting. GAS-METAL ARC WELDING (GMAW) is an arc welding process that joins metals together by heating them with an electric arc that is established between a consumable electrode (wire) and the work piece. An externally supplied gas or gas mixture acts to shield the arc and molten weld pool. Although the basic GMAW concept was introduced in the 1920s, it was not commercially available until 1948. At first, it was considered to be fundamentally a high-current-density, small-diameter, bare-metal electrode process using an inert gas for arc shielding. Its primary application was aluminum welding. As a result, it became known as metal-inert gas (MIG) welding, which is still common nomenclature. Subsequent process developments included operation at low current densities and pulsed direct current, application to a broader range of materials, and the use of reactive gases (particularly carbon dioxide) and gas mixtures. The latter development, in which both inert and reactive gases are used, led to the formal acceptance of the term gas-metal arc welding. The GMAW process can be operated in semi-automatic and automatic modes. All commercially important metals, such as carbon steel, high-strength low-alloy steel, stainless steel, aluminum, copper, and nickel alloys can be welded in all positions by this process if appropriate shielding gases, electrodes, and welding parameters are chosen [1].

Literature reports that work has been done on various aspects of modeling, simulation, and process optimization in the Gas metal arc welding (GMAW) process. Detailed analysis has been made to establish relationships between welding parameters weld strength, weld quality, and productivity to select welding parameters leading to an optimal process.

Farhad k.et al [2] established input-output relationships for metal active gas (MAG) welding for gas pipe lines. Ganjigatti J. P. et al[3]has made an attempt to determine the input output relationships of the MIG welding of mild steel plates by using regression analysis based on the data collected as per full factorial design of experiments.Kishore k. et al[4] has made an attempt to analyze the effect of process parameters in qualitative manner on defects of welded joints like , lack of penetration, blow holes and Cracks for welding of AIS11040 steel using process of shielded metal gas welding(metal inert gas and tungsten inert gas welding**).** Mustafa k. k. et al [5] has studied the tensile, fatigue, hardness, impact properties of welded joints of EN AW- 6061-T6 aluminium alloy obtained with friction stir welding (FSW) and conventional metal inert gas welding (MIG). Lakshminarayanan A. K. et al [6] studied the effect of welding processes such as GTAW, GMAW and FSW on mechanical properties of AA6061 aluminium alloy. Jayaraman et al [7] discusses the use of TAGUCHI experimental design technique for maximizing the tensile strength of friction stir welded cast aluminium alloy A319. Kumanan et al [8] detailed the application of TAGUCHI technique and regression analysis to determine the optimal process parameters for weld bead geometry (weld bead width, weld bead hardness, depth of penetration) in submerged arc welding of mild steel plates. Tewari, et al[9] studied the effect of various welding parameters on the weld ability (depth of penetration) of Mild Steel specimens welded by using metal arc welding.

In this paper, the use of the Taguchi method to determine the welding process parameters with the optimal tensile strength is reported. This is because the Taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality at the design stage. In recent years, the Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost.

II DESIGN OF EXPERIMENTS FOR OPTIMIZATION OF PROCESS PARAMETER (TAGUCHI METHOD)

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Dr. Genichi Taguchi of Japan who maintained that variation. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. The Taguchi method is best used when there is an intermediate number of a variable (3 to 50), few interactions between variables, and when only a few variables contribute significantly.
A loss function is defined by Taguchi is used to calculate the deviation between the experimental value and the desired value. Taguchi recommends the use of the loss function to measure the deviation of the quality characteristic from the desired value. The value of the overall loss function is further transformed into a signal- to-noise (S/N) ratio. Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio, *i.e* .the lower-the-better, the larger-the-better, and the more-nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a larger S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio.
Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. The optimal combination of the process parameters can then be predicted

2.1 Degree of Freedom (DOF) Rules

1. The overall mean always uses 1 degree of freedom.
2. For each factor, A, B, if the number of levels are n_A, n_B, for each factor, the degree of freedom = number of levels - 1; for example, the degree of freedom for factor A=n_A-1.
3. For any two-factor interaction, for example,
AB interaction, the degree of freedom = (n_A-1) x (n_B-1).

2.2 Experimental Design

Taguchi experimental design follows a three-step procedure

Step 1 : Find the total degree of freedom (DOF)
Step 2 : Select a standard orthogonal array using the following two rules
Rule 1 : The number of runs in the orthogonal array ≥ total DOF.
Rule 2 : The selected orthogonal array should be able to accommodate the factor level combinations in the experiment.
Step 3 : Assign factors to appropriate columns using the following rules
Rule 1 : Assign interactions according to the linear graph and interaction table.
Rule 2 : Use special techniques, such as dummy level and column merging, when the original orthogonal array is not able to accommodate the factor levels in the experiment.
Rule3 : Keep some columns empty if not all columns can be assigned.

III. EXPERIMENTATION

The base material, filler wire mechanical properties, welding process parameters, their levels, and an experimental detail has been presented in the following sub headings.

3.1 Material and Properties

Indian Standard (IS) 2062 Mild steel is the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. So IS 2062 mild steel was selected for our study. The properties of base metal and filler wire are shown in the following table 1(a) and 1(b) respectively.

Table 1(a)-Chemical and mechanical properties of work piece material (IS 2062)

	C	Mn	Si	P	S
Percentage Composition	0.201	0.563	0.197	0.019	0.039

	Yield strength (Mpa)	Ultimate tensile (Mpa)	% elongation
Mechanical Properties	240	460	23

Table 1(b)-Chemical analysis of filler material (AWS ER70S-6)

	C	Mn	Si	P	S
Percentage Composition	0.100	1.500	0.900	0.025	0.025

3.2 Welding Parameters and their Levels

Based on the literature study the process parameters affecting the weld quality is welding direction, wire speed, travel speed, arc voltage, contact to work distance, torch angle and gas flow rate. Total seven parameters were selected. Out of seven parameters, welding direction was taken two levels and remaining six parameters was taken as three levels for our study. The input values for the parameters were taken from the Lincoln electric company, GMAW welding process manual book. The details of the welding parameters, levels are shown in table 2.

Table 2- Welding parameters and their levels

Notation	Welding parameter	Level 1	Level 2	Level 3
W	Welding direction	Pulling	Pushing	-
F	Wire speed (mm/min)	4500	5000	5500
S	Travel speed (mm/min)	260	330	400
V	Voltage (volts)	20	21	22
D	Contact tip to work (mm)	12	15	18
A	Torch angle (degrees)	70	75	80
G	Gas flow rate (l/min)	15	20	25

3.3 Selecting the Orthogonal Array

Based on the number of parameters and the no of levels, total degree of freedom has been calculated. The total degrees of freedom are 14.based on the Taguchi rules for selecting the orthogonal array, $L_{36}$was selected. The L_{36} orthogonal arrays with the selected values are presented in the table 3.

Table 3- Experimental layout using L_{36} orthogonal array

RUN	W	F (mm/min)	S (mm/min)	V (volts)	D (mm)	A (degrees)	G (l/min)
1	Pulling	4500	260	20	12	70	15
2	Pulling	5000	330	21	15	75	20
3	Pulling	5500	400	22	18	80	25
4	Pulling	4500	260	20	12	75	20
5	Pulling	5000	330	21	15	80	25

6	Pulling	5500	400	22	18	70	15
7	Pulling	4500	260	21	18	70	20
8	Pulling	5000	330	22	12	75	25
9	Pulling	5500	400	20	15	80	15
10	Pulling	4500	260	22	15	70	25
11	Pulling	5000	330	20	18	75	15
12	Pulling	5500	400	21	12	80	20
13	Pulling	4500	330	22	12	80	20
14	Pulling	5000	400	20	15	70	25
15	Pulling	5500	260	21	18	75	15
16	Pulling	4500	330	22	15	70	15
17	Pulling	5000	400	20	18	75	20
18	Pulling	5500	260	21	12	80	25
19	Pushing	4500	330	20	18	80	25
20	Pushing	5000	400	21	12	70	15
21	Pushing	5500	260	22	15	75	20
22	Pushing	4500	330	21	18	80	15
23	Pushing	5000	400	22	12	70	20
24	Pushing	5500	260	20	15	75	25
25	Pushing	4500	400	21	12	75	25
26	Pushing	5000	260	22	15	80	15
27	Pushing	5500	330	20	18	70	20
28	Pushing	4500	400	21	15	75	15
29	Pushing	5000	260	22	18	80	20
30	Pushing	5500	330	20	12	70	25
31	Pushing	4500	400	22	18	75	25
32	Pushing	5000	260	20	12	80	15
33	Pushing	5500	330	21	15	70	20
34	Pushing	4500	400	20	15	80	20
35	Pushing	5000	260	21	18	70	25
36	Pushing	5500	330	22	12	75	15

3.4 Material Configuration and Edge Preparation

The rolled plates of IS 2062 low carbon alloys were sheared to the required dimensions (200 mm×100 mm). Single 'V' butt joint configuration, as shown in figure 1 was prepared to fabricate GMAW welded joints.

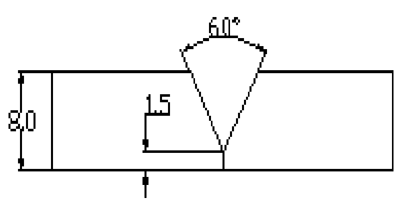

Figure 1-Edge preparation

3.5 Experimental Design and Setup

The experiment was conducted at THE GLOBE RADIO COMPANY, pettai, Tirunelveli, India, with the following setup.KEMPACT2530 semiautomatic MIG welding machine was used to join the IS 2062 mild steel plates of size 200 mm (length) x 100 mm (width) x 8 mm (Thickness). Copper coated wire AWS- ER70S-6, of diameter 1.2 was used as a consumable. Commercial carbon dioxide (CO_2) was used as the shielding gas for all the experiments. The initial joint configuration was obtained by securing the plates in position using tack welding GMAW welds. All necessary care was taken to avoid joint distortion, and the joints were made with suitable clamps. Double pass welding was used to fabricate the joints. The experimental setup and clamping arrangement was shown in figure 2 and 3 respectively.

Figure 2-Experimental set up

Figure 3-Clamping arrangement

3.6 Tensile Test Specimen Preparation

Welded joints are sliced as shown in figure 4 in traverse direction using a power hack saw and horizontal milling machine, tensile specimens were prepared to required dimensions as per ASTM E8M-04 as shown figure 5. Two tensile specimens were prepared from each joint to evaluate transverse ultimate tensile strength. Sample of tested specimens are shown in the following figure no. 6.

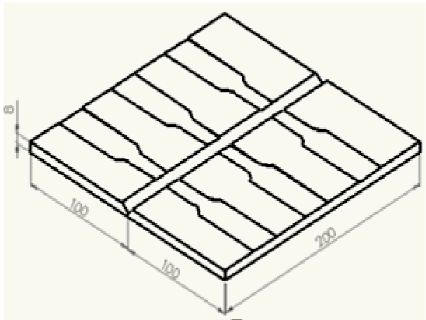

Figure 4-Butt welding position

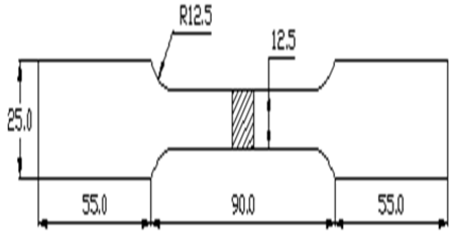

Figure 5-dimentions of tensile test specimen

Figure 6-Sample of tested specimens

3.7 Overall Loss Function and its S/N Ratio

Tensile strength of the welded structures belongs to the larger-the-better quality characteristics. The loss function of the larger-the-better quality characteristics can be expressed as

$$L_j = (\frac{1}{n} \sum_{k}^{n} = 1 \frac{1}{yi^2} \dots \dots \dots (1)$$

$$H_j = -10 \log L_j \dots \dots \dots (2)$$

Where n is the number of tests, and y_i is the experimental value of the i^{th} quality characteristic, L_j overall loss function, and H_j is the S/N ratio. By applying Equations (1) and (2), the H_j corresponding to the overall loss function for each experiment of L36 was calculated and given in Table 4.

Table 4-Means and S/N ratios of Taguchi's design of experiment

Run	Ultimate tensile strength		Signal to Noise ratio (DB)	Mean (N/mm^2)
	#1	#2		
1	408	416	52.3	412
2	180	182	45.15	181
3	362	364	51.2	363
4	424	408	52.38	416
5	366	354	51.12	360
6	352	414	51.58	383
7	436	416	52.58	426
8	316	310	49.91	313
9	120	120	41.58	120
10	418	412	52.36	415
11	150	145	43.37	147.5
12	398	406	52.08	402
13	426	438	52.71	432
14	232	225	47.17	228.5
15	416	428	52.5	422
16	356	352	50.98	354
17	120	120	41.58	120
18	350	340	50.75	345
19	210	200	46.23	205
20	278	270	48.75	274
21	170	170	44.61	170
22	408	403	52.16	405.5
23	424	419	52.5	421.5
24	120	120	41.58	120

25	418	411	52.35	414.5
26	124	118	41.65	121
27	120	120	41.58	120
28	382	389	51.72	385.5
29	326	332	50.34	329
30	120	120	41.58	120
31	292	294	49.34	293
32	425	372	51.95	398.5
33	350	345	50.82	347.5
34	224	220	46.93	222
35	120	120	41.58	120
36	304	312	49.77	308

IV. RESULTS AND DISCUSSIONS

In order to find out influence of each level of parameter, analyses of mean is used with S/N ratio and mean ultimate tensile strength. Means of S/N ratio and ultimate tensile strength for welding direction at level 1 and level 2 can be computed by averaging the S/N ratios and ultimate tensile strengths for experiments 1-18 and 19-36 respectively. Similar way for the remaining factors can be calculated by averaging the S/N ratios and ultimate tensile strengths corresponding to their levels. Parameter with large difference means high influence to weldabilty as its level is changed.

4.1 Means for S/N Ratio and Ultimate Tensile Strength

Based on the experimental results obtained by the tensile test, means for S/N ratio and ultimate tensile strength was calculated and presented in table 5 and 6 respectively.

Table 5-Analysis of mean table for S/N ratio

Welding parameter	Level 1	Level 2	Level 3	Max-Min
Welding direction	49.52	47.52		2
Wire speed (mm/min)	51	47.09	47.47	3.91
Travel speed (mm/min)	48.72	47.95	48.9	0.95
Voltage (volts)	45.69	50.13	49.75	4.44
CTWD (mm)	50.59	47.13	47.84	3.45
Torch angle (degrees)	48.65	47.86	49.06	1.2
Gas flow rate (l/min)	49.03	48.605	47.93	1.1

Table 6-Analysis of mean table for ultimate tensile strength

Welding parameter	Level 1	Level 2	Level 3	Max-Min
Welding direction	324.44	265.28		59.16
Wire speed (mm/min)	365.04	251.17	268.38	113.87
Travel speed (mm/min)	307.88	274.46	302.25	33.42

Voltage (volts)	219.13	340.25	325.21	121.12
CTWD (mm)	354.71	252.04	277.83	102.66
Torch angle (degrees)	301.79	274.21	308.58	34.37
Gas flow rate (l/min)	310.92	298.9167	274.75	36.17

From the analysis of means table for S/N ratios and ultimate tensile strengths, voltage has the largest difference followed by wire speed, contact tip to work distance, welding direction, gas flow rate, torch angle and travel speed.

4.2 Main Effects Plots for Means and S/N Ratio

The data from the mean table 5 and 6 was plotted to know the best level of the parameter from the experiment using statistical software Minitab 15 English and the graphs are shown in figure 7 and 8 respectively.

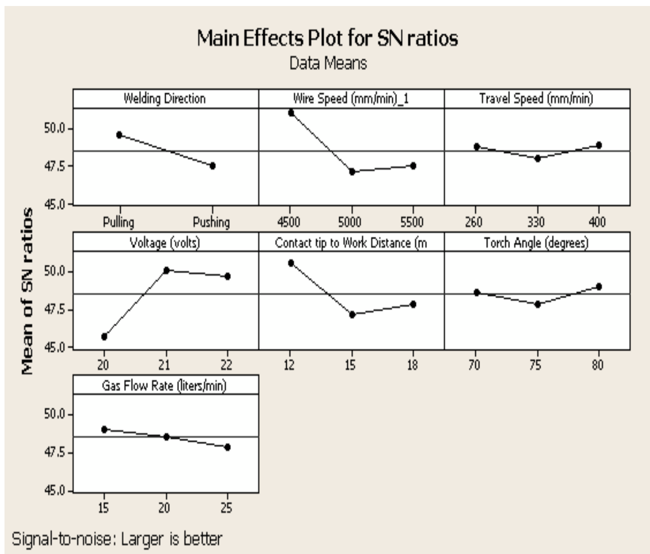

Figure 7-Main effect plots S/N ratios

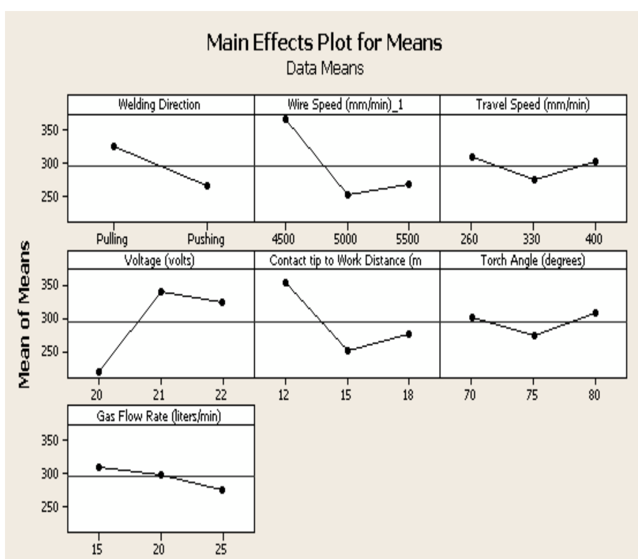

Figure 8-Main effect plots for means

From the means and S/N plots, welding direction level 1, wire speed level 1, travel speed level 1, voltage level 2, CTWD level 1, torch angle level 3, and gas flow rate level 1, has the optimum parameter.

From the means and S/N plots, welding direction level 1, wire speed level 1, travel speed level 1, voltage level 2, CTWD level 1, torch angle level 3, and gas flow rate level 1, has the optimum parameter.

4.3 Confirmation Run

The fundamental part of Taguchi approach is the confirmation run. For this experiment the factors and their levels are W_1, F_1, S_1, V_2, D_1, A_3, and G_1 respectively. The outcome result of the confirmation run is calculated using the following equation.

$\mu = W_1 + F_1 + V_2 + D_1 - (N-1)\,T$………… (3)

Where μ = estimate of the response for ultimate tensile strength

T=overall average of the response data

μ=49.52+51+50.13+50.59-(4-1) 48.52 =55.68 DB

The Experiment number one had good results at
52.3 DB using the most of the same factors and their levels, which is very close to the predicted value with
6.07- % error. Thus the experiment is a success.

4.4 Analysis of Variance (ANOVA)

Process parameters, which significantly affect welding performance, are obtained through ANOVA. Research of ANOVA is acquired through separating total variability of S/N ratios into contributions by each of welding process parameter and error. Total variability of S/N ratio is computed by the sum of squared deviations (SS_T) from total mean of S/N ratios as

$$SS_T = \sum_{i=1}^{n} = (\beta i - \beta m) \dots\dots\dots\dots (4)$$

$$SS_m = \frac{(\Sigma\, \beta i)^2}{\beta m} \dots\dots\dots\dots (5)$$

$$SS_p = \frac{(\Sigma\, \beta^2\, pi)}{N} - SS_m \dots\dots\dots\dots (6)$$

$$SS_E = SS_T - \sum SS_p \dots\dots\dots\dots (7)$$

$$F = \frac{SS_p / f_p}{SS_E} \dots\dots\dots\dots (8)$$

Where βi, grade value of each experiment (i=36); βm, average of sum of S/N ratio; n is the number of experiments in orthogonal array; βpi, sum of i^{th} level of parameter p (i=3).total sum of squared deviations SS_T is separated into two types, which are the sum of squared deviations of welding process parameters (SS_P) and sum of squared error (SS_E).fp is degree of freedom, which is the number of comparisons between parameters. F statically provides a decision at some confidence level as to whether these parameters have important effect on performance characteristic. Large F-value indicates that the change of welding parameter has made a significant effect on performance characteristic. Contribution (%) for each welding parameter in total sum of squared deviations is used to evaluate the important process parameter.
Based on the formulas presented in 4-5-6-7-8 equations analysis of variance table was calculated for S/N ratio and ultimate tensile strength ratio and the values are shown in table 7 and 8 respectively and also percentage contribution of parameters are shown in the following figures 9 and 10 respectively.

Table 7- Analysis of variance (ANOVA) table for S/N ratio

Welding parameter	DOF	Sum of Squares	MS	F- Ratio	Expected Sum of squares	% Contribution
Welding direction	1	35.72	35.72	9.58	31.99	8.09
Wire speed (mm/min)	2	111.82	55.91	14.99	104.36	26.4
Travel speed (mm/min)	2	6.08				
Voltage (volts)	2	145.52	72.76	19.51	138.06	34.94
CTWD (mm)	2	79.69	39.84	10.68	72.23	18.28
Torch angle (degrees)	2	8.97				
Gas flow rate (l/min)	2	7.32				
Pooled error	6	22.37	3.72		48.46	12.26
	13	395.12			395.12	100

Significance at 95% confidence, F (0.05; 1, 6) =5.99

Significance at 95% confidence, F (0.05; 2, 6) =5.14

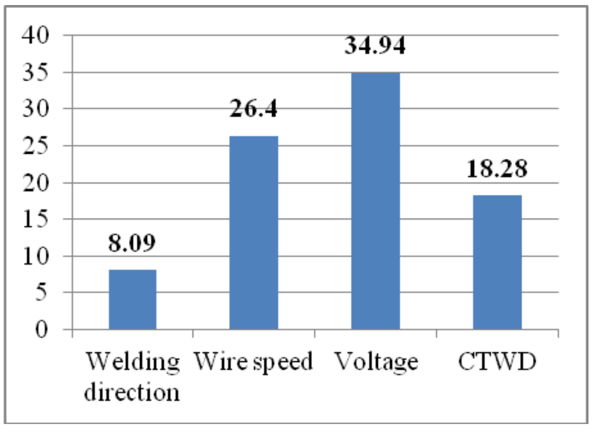

Figure 9: Percentage contribution for S/N ratio

Based on the signal to noise ratio, from the analysis of variance table it concluded that welding parameter, voltage 34.94%, Wire speed 26.4%, CTWD18.28- %, and welding direction 8.09% affecting the ultimate tensile strength of the welded joint.

Table 8-Analysis of variance table for ultimate tensile strength

Welding parameter	DOF	Sum of Squares	MS	F- Ratio	Expected Sum of squares	% Contribution
Welding direction	1	31506	31506	7.94	27542.69	8.63
Wire speed (mm/min)	2	90432	45216	11.47	82505.21	25.88

Travel speed (mm/min)	2	7682				
Voltage (volts)	2	104604	52302	13.19	96677.63	30.32
CTWD (mm)	2	68461	34230	8.63	60534.54	18.98
Torch angle (degrees)	2	7954				
Gas flow rate (l/min)	2	8144				
Pooled error	6	23781	3963		51526.41	16.16
	13	318786			318786.4	100

Significance at 95% confidence, F (0.05; 1, 6) =5.99

Significance at 95% confidence, F (0.05; 2, 6) =5.14

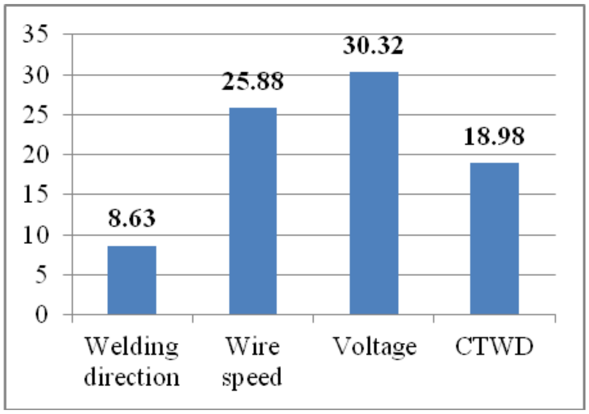

Figure 10: percentage contribution for ultimate tensile strength

Based on the mean ultimate tensile strength, from the analysis of variance table it concluded that welding parameter, voltage 30.32%, Wire speed 25.88%, CTWD 18.98 %, welding direction 8.63% affecting the ultimate tensile strength. From an F table, the critical values for (1, 2) and (2, 6) degrees of freedom are 5.99 and 5.14 respectively, which is less than the calculated value from the analysis of variance table, so factors W, F, V, D are significant .

V. CONCLUSIONS

This paper describes the use of design of experiments (DOE) for conducting experiments. Thirty six experiments are conducted for predicting the ultimate tensile strength of gas metal arc welded IS 2062 mild steel alloy using Taguchi method. From the investigation the following important conclusions are derived.

From the analysis of variance(ANOVA) it is concluded that welding parameters, voltage 34.94%, Wire speed 26.4%, CTWD 18.28 %, welding direction 8.09% affecting the ultimate tensile strength. Voltage is the factor that has the greatest influence on ultimate tensile strength of welded joint, followed by wire speed, contact tip to work distance, and welding direction. A maximum ultimate tensile strength of 432 Mpa is exhibited by the gas metal arc welded joints fabricated with the optimized parameters of pulling direction, 4500 mm/min wire speed, 260 mm/min travel speed,. 21 volts voltage, 12 mm contact tip to work distance, 80 degrees Torch angle, 15 liters /min gas flow rate. The Experiment number one had good results at 52.3 DB using the most of the same factors and their levels, which is very close to the calculated value 55.68 DB with 6.07 % error. Thus the experiment is a success.

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