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ORIGINAL ARTICLE

Optimization of MAG welding process parameters using Taguchi design method on dead mild steel used in automotive industry

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Abstract Welding is a basic manufacturing process for making components or assemblies. Recent welding economics research has focused on developing a reliable machinery database to ensure optimum production. Research on welding of materials like steel is still critical and ongoing. Welding input parameters play a very significant role in determining the quality of a weld joint. The metal active gas (MAG) welding parameters are the most important factors affecting the quality, productivity, and cost of welding in many industrial operations. The aim of this study is to investigate the optimization of process parameters for metal active gas welding for 60 mm × 60 mm × 5 mm dead mild steel plate work piece using the Taguchi method to formulate the statistical experimental design using a semi-automatic welding machine. An experimental study was conducted in the automotive industry, Bishoftu, Ethiopia. This study presents the influence of four welding parameters (control factors) like welding voltage (volt), welding current (ampere), wire-speed (m/min.), and gas (CO_2) flow rate (Lt./min.) with three different levels for variability in the welding hardness. The objective functions have been chosen in relation to parameters of MAG welding i.e., welding hardness in final products. Nine experimental runs based on an L_9 orthogonal array (OA) Taguchi method was performed. An OA, signal-to-noise (S/N) ratio and analysis of variance (ANOVA) are employed to investigate the welding characteristics of dead mild steel plate and used in order to obtain optimum levels for every input parameter at 95% confidence level. The optimal parameters setting was found is welding voltage at 22 V, welding current at 125 amperes, wire speed at 2.15 m/min, and gas flow rate at 19 Lt./min. by using the Taguchi experimental design method within the constraints of the production process. Finally six conformations welding have been carried out to compare the existing values; predicted values with the experimental values confirm its effectiveness in the analysis of welding hardness (quality) in final products. It is found that welding current has a major influence on the quality of welded joints. Experimental results for optimum setting gave better hardness of welding condition than initial setting. This study is valuable for different material and thickness variation of welding plate for Ethiopian industries.

Keywords Weld quality · Metal active gas welding · Dead mild steel plate · Orthogonal array · Analysis of variance · Taguchi method

1 Introduction

Generally the quality of a weld joint is directly influenced by the welding input parameters during the welding process; therefore, welding can be considered as a multi—input multi -output process. Unfortunately, a common problem that has faced the manufacturer is the control of the process input parameters to obtain a good welded joint with the required bead geometry and weld quality with minimal detrimental residual stresses and distortion.

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Traditionally, it has been necessary to determine the weld input parameters for every new welded product to obtain a welded joint with the required specifications. To do so, requires a time-consuming trial and error development effort, with weld input parameters chosen by the skill of the engineer or machine operator. Then welds are examined to determine whether they meet the specification or not. Finally the weld parameters can be chosen to produce a welded joint that closely meets the joint requirements. Also, what is not achieved or often considered is an optimized welding parameters combination, since welds can often be produced with very different parameters. In other words, there is often a more ideal welding parameters combination, which can be used if it can only be determined.

In order to overcome this problem, various optimization methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. In the last two decades, Taguchi techniques have been used to carry out such optimization.

In this economic globalization and continuous appearing of new technologies an industry faces problems to achieve the maximum degree of competitiveness in the market. The case automotive industry (Bishoftu, Ethiopia) manufactures parts/assembling of different vehicles. During assembling of vehicles, the type of joining of metal that the industry used is MAG welding process. But the industry loss the customers due to welding defects, in addition to this the industry lost unwanted expense for repairing of welding defects. In order to solve this problem, Taguchi experiment was conducted in automotive industry especially in Body and Frame Production Factory.

The main objective of the research paper is to establish an optimum parameter setting for a MAG welding process using Taguchi Design method for maximizing welding hardness in order to achieve high quality products. Specific objectives are to study about the influence of MAG welding parameters on dead mild steel, to design a series of experiments with the help of Taguchi Design method in order to study about MAG welding, to study about best combination of solution for maximizing weld hardness, to set up welding process parameters of MAG welding machine for specific material, and to perform validation experiment using the optimal parameters combination.

Ghazvinloo et al. (2010) studied the effect of arc voltage, welding current, welding speed on fatigue life, impact energy, and bead penetration of AA6061 joints produced by robotic MIG welding. Aghakhani et al. (2011) studied parametric optimization of gas metal arc welding process by Taguchi method on weld dilution.

Singh and Vijayakumar (2012) investigated on the optimization and effect of welding parameters on indentation of resistance spot welded austenitic stainless steel AISI 301L. Abbasi et al. (2012) studied the effect of metal arc welding parameters on the weld bead and shape factor characteristic. In this study the specimen used for welding were mild steel.

Sapakal and Telsang (2012) investigated that the influence of welding parameters like welding current, welding voltage, welding speed on penetration depth of MS C20 material during MIG welding process. Anoop and Kumar (2013) investigated Taguchi method to design process parameters that optimize mechanical properties of weld specimen Aluminum alloy 7039 used in aircraft, automobiles, and infantry combat vehicles and high speed trains.

Kumar et al. (2013) describe the use of Taguchi's parameter design methodology for parametric study of gas metal arc welding of stainless steel and low carbon steel. Arya et al. (2013) investigated the optimization of process parameters for MIG welding. The objective function have been chosen in relation to parameters of MIG welding bead geometry tensile strength, bead width, bead height, penetration and heat affected zone for quality target.

Patil and Waghmare (2013) studied the influence of welding parameters like welding current, welding voltage, welding speed on ultimate tensile strength of AISI 1030 mild steel material during welding. In this study, the mild steel welding failure problems encountered by loads were successfully addressed by applying the Taguchi method.

In Singh (2013) research work, experiments were carried in order to investigate gas metal arc welding (GMAW) optimum parameters of mild steel AISI 1016 using Taguchi's design method.

Therefore, this research proposes an effective process parameter (*i.e.,* welding voltage, welding current, wire speed and gas flow rate) optimization approach to help the industry for MAG welding process improvement.

2 Taguchi method for the optimization of process parameters

Optimization of process parameters is the key step in the Taguchi method (Juang and Tarng 2002) for achieving high quality without increasing cost. This is because optimization of process parameters can improve quality characteristics and the optimal process parameters obtained from the Taguchi method are insensitive to the variation of environmental conditions and other noise factors.

Basically, classical process parameter design is complex and not easy to use. A large number of experiments have to be carried out when the number of process parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire process parameter space with a small number of experiments only. A loss function is then defined 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 loss function is further transformed into S/N ratio.

Usually, there are three categories of the quality characteristic in the analysis of the S/N ratio, *i.e.,* nominal—the—best, smaller—the—best, and larger—the—better (Ross 1996).

Nominal is the best characteristic:

$$\mathrm{S/N} = 10\log\left(\frac{\overline{\mathrm{Y}}^2}{\mathrm{S}^2}\right) \tag{1}$$

Smaller is the best characteristic: Is employed when an objective is close to the target.

$$\mathrm{S/N} = -10\log\left[\left(\frac{1}{n}\right)\left(\sum_{i=1}^{n}\mathrm{Y}_i^2\right)\right] \tag{2}$$

When the objective is to make the response is as small as possible. Its target value becomes zero.

Larger is the best characteristic:

$$\mathrm{S/N} = -10\log\left[\left(\frac{1}{n}\right)\left(\sum_{i=1}^{n}\frac{1}{\mathrm{Y}_i^2}\right)\right] \tag{3}$$

where, Y is value of response variables, $\overline{\mathrm{Y}}$ is the mean of the given data, *n* is the number of observations in the experiments, and S is the mean square. For this study larger—the—better is selected because the objective function is attaining the best welding strength.

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 (Tarng et al. 1999; Juang and Tarng 2002; Kumar and Sundarrajan 2005; Nataraj and Arunachalam 2005), a larger S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with the higher S/N ratio.

Furthermore, a statistical ANOVA is performed to see which process parameters are statistically significant. The optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design.

3 Experimental setup

3.1 Methodology

The steps applied for Taguchi optimizations in this study are follows.

- Identify the noise factors,
- Define the process objective,
- Determine the design parameters affecting the process,
- Create OA for the parameters design indicating the number of experiments,
- Conduct the experiments,
- Analyze the data and determine optimum levels for control factors,
- Perform the verification experiment.

Figure 1 shows that parameter diagram of the MAG welding process, including noise factor, inputs for the welding machine, and control factors for this study.

3.2 Welding machine and work material specifications

In the MIG welding process, a 1 mm diameter consumable welding wire (AWS ER70S—6) is used to strike an electric arc with the base metal. The heat generated by the electric arc is used to melt and join the base metal. In this study a Kaireda (KE—350) MAG welding machine is used to weld the similar plates of dead mild steel (C: 0.05–0.15%, 31.17 HRA). Two plates of size 60 mm × 60 mm × 5 mm are tacked together to form a weld pad. Welding is carried out in the down hand position and beads are laid along the weld pad centerline to form a butt joint. The plates are allowed to cool at room temperature, after the completion of welding.

Table 1 shows chemical composition of dead mild steel sample (actual specimen) that is used to perform the experiments and its composition was tested using spectrometer.

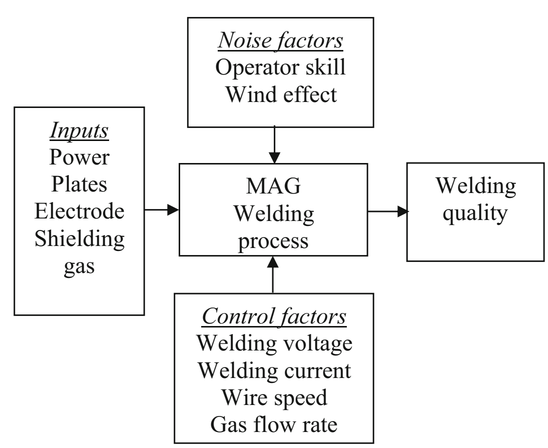

Fig. 1 Parameter diagram of MAG welding process

Table 1 Chemical composition of dead mild steel work piece

Element	Content (%)	Element	Content (%)	Element	Content (%)
C	0.063	Cu	0.036	Ce	< 0.003
Si	< − 0.0009	Nb	< 0.010	B	< 0.0001
Mn	0.38	Ti	< 0.003	Zn	0.014
P	0.003	V	< 0.0003	La	0.011
S	0.011	W	0.10	Zr	< 0.000
Cr	0.012	Pd	< − 0.005	As	< 0.005
Mo	< -0.007	Sn	0.005	Fe	99.2
Ni	0.0005	Co	0.002		
Al	0.022	Ca	0.0006		

3.3 Welding parameters and their levels

Taguchi's L_9 orthogonal design have been implemented with four control parameters/factors *i.e.,* welding voltage, welding current, wire speed, and gas flow rate and three levels to carry out the experiments as it allows nine numbers of experiments which reflects the whole process quite satisfactorily while being practical, economic, and as well as time saving (see Table 2).

3.4 L_9 3 level Taguchi orthogonal array

Nine experiments are conducted depending upon the number of mentioned factors (see Table 3) by using the standard Taguchi OA table. Table 3 show Taguchi standard OA table for selected four parameters with three levels which are used for running the experiments.

3.5 Analysis of S/N ratio

In Taguchi's parameter design, the basic objective is to identify the conditions which optimize process/product performance. In arriving at this optimal set of conditions, Taguchi advocates the use of S/N ratio, the need is to maximize the quality of weld or product by minimizing the effect of noise while maximizing the quality of welding. The S/N ratio is treated as a response (output) of the experiment, which is a measure of variation when uncontrolled noise factors are present in the MAG welding process.

For the present study, as the objective was to establish an optimum parameter setting maximize quality of weld. So it is decided to select the S/N ratio related to larger—the—better quality characteristics. Once the experimental design has been determined and the trials have been carried out, the measured performance characteristic from each trial can be used to analyze the relative effect of the four parameters.

To demonstrate the data analysis procedure, the L_9 OA will be used, but the principles can be transferred to any type of array. Performing ANOVA, one can decide which independent factor dominates over other and the percentage contribution of that particular independent variable also determined.

To determine the effect of each variable on the output, S/N ratio, needs to be calculated for each conducted experiments. The calculation of the S/N for the experiment in the array is shown for the case of a specific target value of the performance characteristic is calculated by using Eq. (3) and summary is shown in Table 4.

For experiment one:

$$\eta_1 = -10\log\left[\left(\frac{1}{1}\right)\left(\frac{1}{46.65^2}\right)\right] = 33.38 \text{ bB}$$

Overall S/N ratio mean (m):

$$\begin{aligned} m &= \frac{1}{\text{No.of experiment}}(\eta_1 + \eta_2 + \ldots + \eta_8 + \eta_9) \\ &= \frac{1}{9}(33.38 + 33.02 + 333.34 + 33.26 + 32.51 \\ &\quad + 33.41 + 33.00 + 33.06 + 33.16) = 33.13 \text{ dB} \end{aligned} \tag{4}$$

After calculating the S/N ratio for each experiment, the average S/N value is calculated for each factor and level, and summary of it is shown in Table 5.

Table 2 Welding parameters and their levels

Parameters	Code	Level 1	Level 2	Level 3
Welding voltage (volts)	A	22	26	30
Welding current (ampere)	B	117	121	125
Welding wire speed (m/min.) (Actual measured length)	C	2.15	2.26	2.28
Gas flow rate (Lt./min.)	D	11	15	19

Table 3 L_9 Orthogonal array

Experiment No	A (Welding voltage)	B (Welding current)	C (Wire speed)	D (Gas flow rate)	Designation			
					A	B	C	D
1	22	117	2.15	11	1	1	1	1
2	22	121	2.26	15	1	2	2	2
3	22	125	2.28	19	1	3	3	3
4	26	117	2.26	19	2	1	2	3
5	26	121	2.28	11	2	2	3	1
6	26	125	2.15	15	2	3	1	2
7	30	117	2.28	15	3	1	3	2
8	30	121	2.15	19	3	2	1	3
9	30	125	2.26	11	3	3	2	1

Table 4 Experimental results for Rockwell hardness and S/N ratio

Experiment No	A 1	B 2	C 3	D 4	Trial-Rockwell hardness (HRA)			Average hardness (HRA)	S/N value
1	22	117	2.15	11	46	46.9	45.6	46.65	33.38
2	22	121	2.26	15	42.5	44.2	44.9	46.65	33.38
3	22	125	2.28	19	50.5	43.8	41.8	49.7	33.34
4	26	117	2.26	19	45.1	48.3	44.6	46.1	33.26
5	26	121	2.28	11	43.3	41.7	40.3	43.5	32.51
6	26	125	2.15	15	50.3	46.2	44.9	45.8	33.41
7	30	117	2.28	15	47.7	42.7	44.5	43.7	33.00
8	30	121	2.15	19	43.7	46.5	46.7	42.9	33.06
9	30	125	2.26	11	42.6	41.8	47.7	49.9	33.16

Table 5 Response table for S/N ratios (dB)

Level	A (Welding voltage)	B (Welding current)	C (Wire speed)	D (Gas flow rate)
1	33.25	33.21	33.28	33.02
2	33.06	32.86	33.15	33.14
3	33.07	33.30	32.95	33.22
Delta	0.19	0.44	0.33	0.20
Rank	4	1	2	3

$$m_{A_1} = \frac{1}{3}(\eta_1 + \eta_2 + \eta_3) = \frac{1}{3}(33.38 + 33.02 + 33.34) = 33.25 \text{ dB}$$

$$m_{B_1} = \frac{1}{3}(\eta_1 + \eta_4 + \eta_7) = \frac{1}{3}(33.38 + 33.26 + 33.00) = 33.21 \text{ dB}$$

$$m_{C_1} = \frac{1}{3}(\eta_1 + \eta_6 + \eta_1) = \frac{1}{3}(33.38 + 33.41 + 33.06) = 33.28 \text{ dB}$$

$$m_{D_1} = \frac{1}{3}(\eta_1 + \eta_5 + \eta_9) = \frac{1}{3}(33.38 + 32.51 + 33.16) = 33.02 \text{ dB}$$

The range (delta) R (Delta = High S/N—Low S/N) of the S/N for each parameter is calculated. The larger the delta value for a parameter, the larger the effect of variable has on the process and its value is indicated in Table 5. This is because the same change in signal causes a larger effect on the output variable being measured.

Table 5 reveals that welding current is first, second is wire speed, and gas flow rate is third are the significant parameters for maximum strength. Table 5 show the optimal parameter combination (larger—the—better) is $A_1B_3C_1D_3$.

Since the initial parameter combination for the industry is found to be $A_2B_2C_2D_2$, the initial overall mean is calculated as follows.

Initial S/N ratios mean (m_i):

$$m_i = m + (m_{A_2} - m) + (m_{B_2} - m) + (m_{C_2} - m) + (m_{D_2} - m) = 33.13 + (33.06 - 33.13) + (32.86 - 33.13) + (33.15 - 33.13) + (33.14 - 33.13) = 32.82\ dB$$

3.6 Analysis of variance

The F-ratio is traditionally used to determine the significance of a factor. In this study, a statistical technique that identifies factors significantly affecting the MAG welding results. It is consists of:

- Sum of squares for distributions of all characteristic values (experimental data),
- Decomposing this total sum into the sum of squares for all factors used in the experiment,
- Calculating variances through the sum of squares for all factors over their degree of freedom (DoF),
- Calculating the variance ratio F0 by dividing each variance by the error variance and,
- Searching which factors significantly affect experimental results by analyzing the error variance.

The purpose of ANOVA is to investigate which welding process parameters significantly affect the quality characteristics. This is accomplished by separating the total variability of the S/N ratios, which is measured by the sum of squared deviations from the total mean of the S/N ratio, into contributions by each welding process parameter and the error. The percentage contribution by each of the welding process parameters in the total sum of the squared deviations can be used to evaluate the importance of the process parameter change on the quality characteristics. ANOVA is calculated as (Ross 1996).

Sum of squares (SS) due to mean:

$$SS_m = \text{No. of Exp.} \times \text{Overall S/N ratio mean sqaure} \tag{5}$$

$$SS_m = 9 \times m^2 = 9 \times 33.13^2 = 987837 dB^2$$

$$\begin{aligned} \text{Total sum of squares (SS)} &: \\ &= \sum_{i=1}^{n} (\eta_i - m)^2 \\ &= (\eta_1 - m)^2 + (\eta_2 - m)^2 + (\eta_3 - m)^2 + (\eta_4 - m)^2 + (\eta_5 - m)^2 + (\eta_6 - m)^2 + (\eta_7 - m)^2 + (\eta_8 - m)^2 + (\eta_9 - m)^2 \\ &= (33.38 - 3313)^2 + (33.02 - 33.13)^2 + (33.34 - 33.13)^2 + (33.26 - 33.13)^2 + (32.51 - 33.13)^2 \\ &\quad + (33.41 - 33.13)^2 + (33.00 - 33.13)^2 + (33.06 - 33.13)^2 + (33.16 - 33.13)^2 \\ &= 0.6211\ dB^2 \end{aligned} \tag{6}$$

SS due to each parameter also calculated as follows.

$$\begin{aligned} \text{SS due to factor A} &= \left[(\text{No. of experiments at level } A_1) \times (m_{A1} - m)^2\right] \\ &+ \left[(\text{No. of experiments at level } A_2) \times (m_{A2} - m)^2\right] \\ &+ \left[(\text{No. of experiments at level } A_3) \times (m_{A3} - m)^2\right] \end{aligned} \tag{7}$$

SS due to factor A: $SS_A = 3(m_{A_1} - m)^2 + 3(m_{A_2} - m)^2 + 3(m_{A_3} - m)^2 = 3(33.25 - 33.13)^2 + (33.06 - 33.13)^2 + 3(33.07 - 33.13)^2 = 0.0687 dB^2$.

SS due to factor B: $SS_B = 3(m_{B_1} - m)^2 + 3(m_{B_2} - m)^2 + 3(m_{B_3} - m)^2$

$$= 3(33.21 - 33.13)^2 + 3(32.86 - 33.13)^2 + 3(33.30 - 33.13)^2 = 0.3246\ dB^2$$

SS due to factor C: $SS_C = 3(m_{C_1} - m)^2 + 3(m_{C_2} - m)^2 + 3(m_{C_3} - m)^2$

$$= 3(33.28 - 33.13)^2 + 3(33.13 - 33.13)^2 + 3(32.95 - 33.13)^2 = 0.1659 dB^2$$

SS due to factor D: $SS_D = 3(m_{D_1} - m)^2 + 3(m_{D_2} - m)^2 + 3(m_{D_3} - m)^2$

$$= 3(33.02 - 33.13)^2 + 3(33.14 - 33.13)^2 + 3(33.22 - 33.13)^2 = 0.0609 dB^2$$

$$\text{Mean square is given by, } MS = \frac{SS}{DoF} \tag{8}$$

Mean square A: $MS_A = \frac{SS_A}{DoF_A} = \frac{0.0687}{2} = 0.0344\ dB^2$.

Mean square B: $MS_B = \frac{SS_B}{DoF_B} = \frac{0.3246}{2} = 0.1623\ dB^2$.

Mean square C: $MS_C = \frac{SS_C}{DoF_C} = \frac{0.1659}{2} = 0.0830\ dB^2$.

Mean square D: $MS_D = \frac{SS_D}{DoF_D} = \frac{0.0609}{2} = 0.0305\ dB^2$.

Percentage contribution (P) of each factor is calculated as the ratio of SS of each factor to total SS as follows.

$$P_A = \frac{SS_A}{SS_T} \times 100\% = \frac{0.0687}{0.6211} \times 100\% = 11.06\%$$

$$P_B = \frac{SS_B}{SS_T} \times 100\% = \frac{0.3246}{0.6211} \times 100\% = 52.27\%$$

$$P_C = \frac{SS_C}{SS_T} \times 100\% = \frac{0.1659}{0.6211} \times 100\% = 26.81\%$$

$$P_D = \frac{SS_D}{SS_T} \times 100\% = \frac{0.0609}{0.6211} \times 100\% = 9.86\%$$

3.7 Degrees of freedom

DoF provides an indication of the amount of information contained in a data set. DoF is applied to characterize four separate items as follows.

$$\text{DoF of a factor} = \text{No. of levels of the factor} - 1 \quad (9)$$

$DoF_A = 3 - 1 = 2$; $DoF_B = 3 - 1 = 2$; $DoF_C = 3 - 1 = 2$; $DoF_D = 3 - 1 = 2$

$$\text{DoF of an experiment} = \text{Total no. experiments} - 1 \quad (10)$$

DoF of an experiment $= 9 - 1 = 8$.

From the above calculations, F ratio is indeterminate because the DoF_E is zero and its value is tabulated in Table 6.

The DoF for the error will be equal to the actual degrees of freedom for the study minus the sum of the degrees of freedom for the various factors. In the present case—study, the DoF for the error will be zero.

$$\text{DoF} = \text{Total DoF} - \text{Sum of each parameter} \quad (11)$$

$$DoF_E = 8 - 2(4) = 0$$

$$F - \text{ratio}: F_A = \frac{MS_A}{MSE} \quad (12)$$

F_A-ratio is indeterminate because MSE = 0. Similarly F_B, F_C and F_D are indeterminate as shown in the Table 6. Hence in order to attain the best information from an experiment, all of the columns should be used to study process parameters. However, no error DoF to estimate MSE.

However, an approximate estimate of the MSE can be obtained by pooling the factors having the smallest sum of squares. Since factor A and D have the smallest sum of square, then the new MSE can be calculated to produce meaningful results.

$$MSE = \frac{SS_A}{DoF_A} + \frac{SS_D}{DoF_D} = \frac{0.0687}{2} + \frac{0.0609}{2} = 0.0648\ dB^2$$

Pooled error DoF is calculated as:

$$DoF_{PE} = DoF_A + DoF_D = 2 + 2 = 4$$

Pooling is the process of disregarding an individual factors contribution and then subsequently adjusting the contribution of the other factors. Generally, factors that are believed to be insignificance are pooled. In the present study, the factors A and D are used to estimate the error sum of squares. Together they account for four degrees of freedom and their SS is 0.1248.

F ratio is calculated as the ratio of factor mean square to the MSE.

$$F_B = \frac{\text{Mean square of B}}{\text{Mean square of error}} = \frac{0.1623}{0.0648} = 2.51$$

$$F_C = \frac{\text{Mean square of C}}{\text{Mean square of error}} = \frac{0.0830}{0.0648} = 1.28$$

Table 7 reveals that factor B contributes the most *i.e.,* 48.45% and also the contribution of C is 30.79%. But the contribution of factors A and D is not relatively significance.

4 Results and discussion

4.1 Determining the optimum condition

Both the response and S/N ratio can be used to derive the optimum condition, which is basically the optimum

Table 6 Results of analysis of variance for hardness

Parameters	DoF	Sum of squares	Mean square	F ratio	Percent contribution
A	2	0.0687	0.0344	–	11.06
B	2	0.3246	0.1623	–	52.27
C	2	0.1659	0.0830	–	26.81
D	2	0.0609	0.0305	–	9.86
Error	0	0	0		0
Total	8	0.6211			100

Table 7 Results of analysis of variance after pooled error

Parameters	DoF	Sum of squares	Mean square	F ratio	Percent contribution
A	Pooled				
B	2	0.3246	0.1457	2.51	52.27
C	2	0.1659	0.0926	1.28	26.81
D	Pooled				
Error	4	0.1296	0.0648		20.92
Total	8	0.6211			100

combination of treatment levels for the given response and noise conditions. Since the quality characteristics, is a larger—the—better characteristic, the larger response is the ideal level for a welding process parameter. The S/N ratio, however, will always be highest at the optimum condition, since not all treatment combinations have been run in the experiment; this requires a separate analysis which considers all possible treatment combinations.

In this study the effect of main input welding parameters on the weld quality in MAG welding process were investigated. Results shown that among main input welding parameters the effect of the welding current is more significant, welding wire speed has the next significant effect on welding strength. Increasing the wire feed rate and the current increases the welding quality. The gas flow rate and voltage have relatively low effect on the welding quality.

4.2 Confirmation experiment

The confirmation experiment is the final step in the design of experiment process. It is performed by conducting a test using a combination of the factors and levels evaluated. The sample size of confirmation experiment is larger than the sample size of trial in the previous experiment. After determining the optimum conditions, a new experiment was designed and conducted with the optimum levels of the welding parameters. Therefore six experiments were performed by using the optimal parameter combination $A_1B_3C_1D_3$. The final step is to predict and verify the improvement of the performance characteristic.

The predicted S/N ratio using the optimal levels of the welding parameters can be calculated as follows.

$$\begin{aligned}\eta_{opt} &= m + (m_{A_1} - m) + (m_{B_3} - m) + (m_{C_1} - m) \\ &\quad + (m_{D_3} - m) \\ &= 33.13 + (33.25 - 33.13) + (33.30 - 33.13) \\ &\quad + (33.28 - 33.13) + (33.22) = 33.66 \text{ dB}\end{aligned}$$

After identifying the most influential parameters, the final phase is to verify the hardness of the material by conducting the confirmation experiments. The $A_1B_3C_1D_3$ is an optimal parameter combination for dead mild steel of the MAG welding process. Therefore, the condition $A_1B_3C_1D_3$ of the optimal parameter combination of the MAG welding process was treated as a confirmation test. If the optimal setting for dead mild steel with a wire diameter 1 mm, welding current 125 A, welding voltage 22 V, welding wire speed 2.15 m/min, and gas flow rate 19 Lt./min was used.

For the confirmation test total six experiments were performed with the optimal parameter combination of welding current, welding voltage, welding wire speed and gas flow rate. The results as a function of welding parameters and their response have been summarized in the following Table 8.

Since the six hardness experimental value of the Table 8 are the outcomes of a single parameter combination, the final confirmation of Rockwell hardness test results are shown in Table 9.

S/N ratio (η) calculation of Rockwell hardness test for confirmation experiment is calculated using Eq. (3) as follows.

$$\eta = -\log\left[\frac{1}{1}\left(\frac{1}{47.95^2}\right)\right] \quad = 33.62 \text{ dB}$$

Table 10 is used to compare the initial value, prediction and confirmation experiment result. From this, the hardness value is increased after the confirmation experiment.

Table 5 reveals that the welding current S/N ratio has maximum and minimum value of 33.30 dB and 32.86 dB respectively, welding voltage S/N ratio having the maximum and minimum value of 33.25 dB and 33.06 dB respectively, wire speed of maximum and minimum value of S/N ratio 33.28 dB and 32.95 dB and finally the gas flow rate of maximum and minimum value of 33.22 dB and 33.02 dB.

From Fig. 2a the value of S/N ratio decreases as the voltage increases at the same time hardness also decrease. Figure 2b the S/N ratio has two phase the first phase as the current increases until it attain 121 A, it decreases starting from 121 to 125 A S/N ratio increases. Figure 2c shows that the S/N ratio decreases as the welding wire speed increases from 2.15 m/min. up to 2.28 m/min. similarly hardness also decrease as the wire speed increases. Figure 2d the S/N ratio increases as the value of the gas flow rate increase from 11 Lt./min. up to the third level of this

Table 8 Confirmation results of Rockwell hardness test

Trial No	A	B	C	D	Trial-Rockwell hardness test (HRA)			Average hardness value (HRA)
					1	2	3	
1	22	125	2.15	19	48.9	49.4	56.9	51.73
2	22	125	2.15	19	51.0	64.4	43.2	52.87
3	22	125	2.15	19	44.9	55.5	46.5	48.97
4	22	125	2.15	19	41.7	44.2	49.2	45.03
5	22	125	2.15	19	48.0	43.8	43.0	44.93
6	22	125	2.15	19	42.6	47.4	42.5	44.17

Table 9 Confirmation Rockwell hardness test result

A_1	B_3	C_1	D_3	Confirmation-Average hardness value (HRA)					
				Trials					
				1	2	3	4	5	6
22	125	2.15	19	51.73	52.87	48.97	45.03	44.93	44.17
				Average hardness value (HRA) = 47.95					

experiment which is 19 Lt./min. similarly the hardness value also increases.

4.3 Calculating the confidence interval

$$\text{C.I.} = \sqrt{\frac{\left[F_{(1,n_2)} V_e\right]}{N_{\text{eff.}}}} \quad (13)$$

where n_2 = degree of freedom for error, V_e = error variance (error mean square), $N_{\text{eff.}}$ = effective number of replications, $F_{0.05,1,4}$ = 7.71 from the standard F distribution table.

Error variance V_e = 0.0312

$$N_{\text{eff.}} = \frac{\text{Total number of results}}{\text{DOF mean } (= 1 + \text{DOF of all factors included in the estimate of mean})} \quad (14)$$

$$N_{\text{eff.}} = \frac{9}{1+4} = 1.8$$

$$\text{C.I.} = \sqrt{\frac{7.71 \times 0.0312}{1.8}} = \pm 0.366$$

This is the variation of the estimated result at the optimum, which is the optimal result lies between

$$\left(\eta_{\text{opt.}} + \text{C.I.}\right) \text{ and } \left(\eta_{\text{opt.}} - \text{C.I.}\right) \text{ at } 95\%$$

confidence level.

C.I. of $A_1B_3C_1D_3 = 33.66 \pm 0.366$

$33.234 < \eta_{\text{opt.}} < 34.026$

5 Conclusion

From the analysis of the results using the S/N ratio approach, analysis of variance and Taguchi's optimization method, the following can be concluded:

- It is found that the parameter design of Taguchi method provides a simple, systematic and efficient methodology for the optimization of the process parameters.

Table 10 Results of the confirmation experiment

	Initial process parameters	Optimal parameter combination		Improvement in S/N ratio
		Prediction	Experiment	
	$A_2B_2C_2D_2$	$A_1B_3C_1D_3$	$A_1B_3C_1D_3$	
S/N ratio	32.82	33.66	33.62	0.80
Hardness value (HRA)	46.75	47.95		

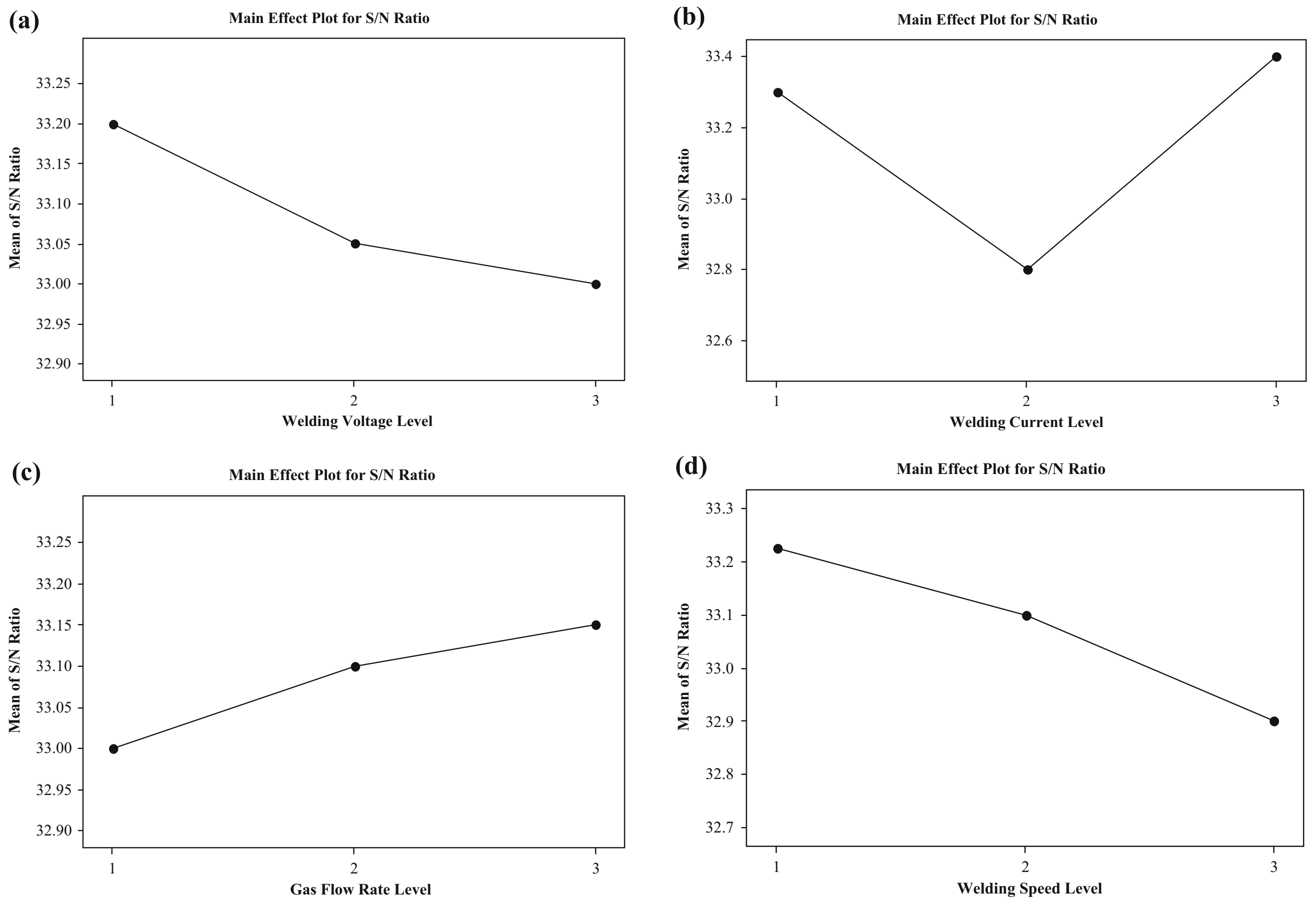

Fig. 2 **a** Mean S/N ratios vs. welding voltage **b** Mean S/N ratios vs. welding current **c** Mean S/N ratios vs. gas flow rate **d** Mean S/N ratios vs. welding (wire) speed

- When the welding current increases, the hardness of the welded part shows experimentally two phases: first when the value of the current increasing from 117 to 121 A the hardness was decreasing but when the value of the current was increasing from 121 to 125 A the hardness shows experimentally increasing and attain an optimal point at 125 A.
- When the welding wire speed is taken into consideration, the hardness decreases with increase in welding wire speed. The optimal value is found in the first level at 2.15 m/min.
- When the gas flow rate is taken into consideration, the hardness increases with increase in gas flow rate, at level three (19 Lt./min.) the optimal point was attaining.
- When the welding voltage is taken into consideration, the hardness decreases with increase in welding voltage, the optimal point was attaining at level one (22 V).
- The welding current has the most significant effect on the welding hardness so its contribution is 52.27%.
- The gas flow rate and the voltage have relatively small significant effect on welding hardness.

Declarations

Conflict of interest This research has no any declarations of interest to be disclosed.

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