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Process Parameter Optimization of Bead geometry for AISI 446 in GMAW Process Using Grey-based Taguchi Method

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Abstract : *Gas metal arc welding is process is becoming widespread in the welding industries as it can easily be applied to variety of metals. Quality of weldment depends upon welding input parameters. This experimental study aims at developing a multi-objective optimization problem to achieve desired weld bead geometry of GMAW. Objective functions optimized by Taguchi's L9 orthogonal array design and S/N ratio. Welding voltage, welding speed, wire feed rate and gas flow rate have been selected as the input process parameters. Quality targets are bead width, bead height and depth of penetration for AISI 446. The Grey relational analysis in combination with Taguchi approach is used to solve this multi-objective optimization problem. Additionally the most significant factor identified by using ANOVA.*

Keywords -*Bead Geometry, Gas Metal Arc Welding, Grey Relational Analysis,Taguchi Orthogonal Array*

I. Introduction

The Gas metal arc welding processes are quickly replacing the shield arc stick electrode process because the GMAW process can easily be applied to both ferrous and nonferrous metals. GMAW processes are also popular as they can deposit a large quantity of weld metal in a relatively short period of time. GMAW plays a significant role in many industries. Welding is mainly important in heavy fabrication industry, which includes machinery, farming equipment, process tools for manufacturing and mining, and infrastructure for petroleum refining and distribution. During the welding process, input parameters influenced the weldment quality. Therefore, welding becomes as a multi-input multi-output process. To catch the preferred weld quality in GMAW process it is necessary to study input and output process parameters interrelationships. The optimization and prediction of process parameters is a significant aspect in welding process. This experimental study aims at developing a multi-objective optimization problem to achieve preferred weld bead geometry for AISI 446 grade of steel of 8 mm thickness in GMAW process by using grey-based Taguchi method. It is necessary to control shape of weld bead geometry in determining mechanical properties as it is affected by weld bead geometry shape. Therefore, proper selection of process parameter is necessary. It is not easy task to developed mathematical models which gives relationship between input and output process parameters of GMAW process because there were some unknown nonlinear process parameters [1]. Therefore, it is better to solve this problem by experimental models. Multiple regression technique was used to found the empirical models for various welding processes [2, 3]. Datta et at [4] planned multiple regression model and predicted the bead geometry volume of SAW process. Gunaraj et al [5-6] used five-level factorial techniques to developed mathematical models for prediction and optimization of weld bead for the SAW process. Kim et al [7] used multiple regression and neural network to develop an intelligent system for GMAW process. Li et al [8] used Self-Adaptive Offset Network to know the non-linear relationship between the geometry variables and process parameters of SAW process. Tang et al [9] examined the correlation between process parameters and bead geometry for TIG welding process using a back propagation neural network. Thao et al [10] using SPSS window software developed correlation between process parameters and bead geometry parameters for GTAW process.

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II. Grey-Based Taguchi Method

For the design of high quality manufacturing system Taguchi's philosophy is an effective method. Dr. Genichi Taguchi has investigated a method based on orthogonal array experiments, which offers much-reduced variance for the experiment with optimum setting of process control parameters. The combination of design of experiments with parametric optimization of process to obtain the desired target is achieved in the Taguchi method. Orthogonal array (OA) offers a set of balanced experimentations and signal-to-noise ratios, which are the logarithmic functions of desired output serves as objective functions for optimization. This technique aids in data analysis and prediction of optimum results. Taguchi method uses a statistical measure of performance called signal-to-noise ratio to evaluate optimal parameters settings. The S/N ratio takes both the mean and the variability into account which is the ratio of the mean to the standard deviation. The quality characteristic of the process to be optimized defines the ratio. The standard S/N ratio has three criteria's, Lower the best (LB), Nominal is best (NB) and higher the better ((HB). The parameter combination, which has the highest S/N ratio, gives the optimal setting.

In Grey relational analysis, Grey relational generation is the process which normalizes the experimental data range from zero to one and it transferring the original data into comparability Sequences. Next, Grey relational coefficient is calculated based on normalized experimental data to represent the relationship between the actual and desired experimental data. Overall Grey relational grade be an average of the Grey relational coefficient of selected responses. Grey relational grade gives the overall performance characteristics of the multiple response process. This method converts a multiple objective problem into single objective with the objective function as overall Grey relational grade.

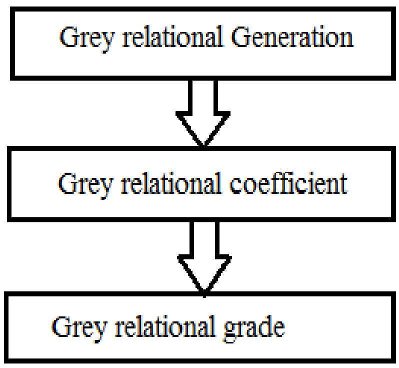

Fig.1Procedure ofgreyrelational analysis.

Grey relational grade is the result of the evaluation of the optimal parametric combination. Taguchi method gives the optimal factor setting for maximizing overall Grey relational grade. [11]
In Grey relational generation, the normalized bead width, bead height, following to lower-the-better (LB) criterion can be stated as:

$$x_i(k) = \frac{\max\ yi(k) - yi(k)}{\max\ yi(k) - \min\ y(i)} \qquad (1)$$

Bead penetration should follow larger-the-better criterion, which can be stated as:

$$X_i(k) = \frac{yi(k) - \min yi(k)}{\max yi(k) - \min\ yi(k)} \qquad (2)$$

Where, $x_i(k)$ = the value after the Grey relational generation, min $y_i(k)$ = the smallest value of $y_i(k)$ for the kth response, and max $y_i(k)$ = the largest value of $y_i(k)$ for the kth response. The normalized data after Grey relational generation are tabularized in table 5. An ideal sequence is $x_0(k)$ (k=1, 2, 3......,25) for the responses. Grey relational grade is to reveal the degree of relation between the 9 sequences [$x_0(k)$ and $x_i(k)$, i=1, 2, 3........9] (Table 3).
We can calculate the Grey relational coefficient ξi(k) as:

$$\xi_i\ (k) = \frac{\Delta\min + \Psi\Delta\max}{\Delta oi\ (K) + \Psi\Delta\max} \qquad (3)$$

where, $\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|$ = difference of the absolute value $x_0(k)$ and $xi(k)$,
ψ is the distinguishing coefficient $0 \leq \psi \leq 1$
$\Delta_{\min} = \forall j^{\min} \in i \forall k^{min} \left\| x_0(k) - x_j(k) \right\|$ = the smallest value of Δ_{0i}, and
$\Delta_{max} = \forall j^{\min} \in i \forall k^{max} \left\| x_0(k) - x_j(k) \right\|$ = largest value of Δ_{0i}.

The Grey relational grade γ_i can be computed after be an average of the Grey relational coefficients as:

$$\gamma_i = \frac{1}{n} \sum_{k-1}^{n} \xi i\ (k) \qquad (4)$$

where *n* = number of process responses. The greater value of Grey relational grade relates to extreme relational degree between the reference sequence $x_0(k)$ and the known sequence $x_i(k)$. The reference sequence $x_0(k)$ represents the best process sequence; therefore, higher Grey relational grade means that the corresponding parameter combination is nearer to the optimal. The mean response of the Grey relational grade, its grand mean and the main effect plot are very significant as optimal process condition may well be evaluated from this plot.

III. Research Methodology

Systematic approach required to develop the mathematical models that predict and control the bead geometry parameters for GMAW process includes the next steps [12].

3.1 Identification of process parameters plus their limits.
3.2 Development of design matrix
3.3 Conducting the experiments as per design matrix.
3.4 Preparation of specimen
3.5 Measurements of the responses.
3.6 Analysis of experimental data by Grey-based Taguchi method. Following steps are included in analysis.

- Determination of Grey relational Generation
- Determination of Grey relational coefficient
- Determination of Grey relational grade
- Determination of response table for Grey relational grade

3.7 S/N ratio plot for overall Grey relational grade
3.8 Confirmation Experiment
3.9 Evaluation of the significance of the factor by analysis of variance (ANOVA)

3.1 Identification of process parameters and their levels in GMAW

The process parameters play very important role to determine the good weld bead. The rough trials are necessary for a smooth appearance of weld bead and the working ranges of the parameters are found out. If the functioning ranges are smaller or larger the limits, then proper weld bead will not appear. Therefore, proper setting with selection of the process parameters is required for good appearance of bead. The four welding input parameters selected are the welding voltage (V), welding speed (S), wire feed rate (F) and gas flow rate (G) and the output parameters are bead penetration (BP), bead height (BH) and bead width (BW) as shown in Fig. 2. The weld bead geometry will influence the mechanical properties of the weldment. These are key controllable process parameters and it is desirable to have minimum three levels of process parameters to reveal the true performance of response parameters. The lower and upper limits of parameters are coded as 1 and 3 respectively. Intermediate ranges coded value can be calculated as:

$$x_i = 2(2x-(x_{max}+ x_{min})) / (x_{max}- x_{min}) \quad (5)$$

where, x_i = The required coded value of a parameter x; x is any parameter value from x_{max} to x_{min};
x_{min} = The lower level of the parameter;
x_{max} = The upper level of the parameter.

The individual process parameters levels are tabulated in Table 1.

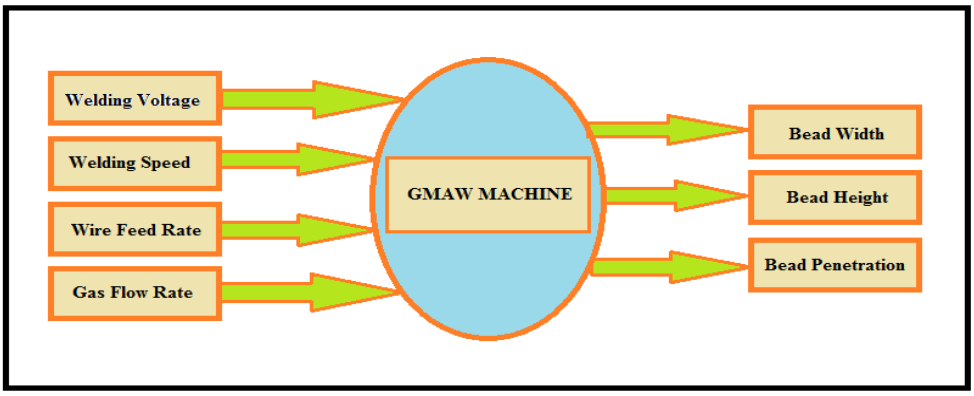

Fig. 2 Input and output process parameters of GMAW

Table 1 Process parameters and their limits

Process Parameters	Notation	Unit	Levels of Factors		
			1	2	3
Open Circuit Voltage	V	Volts	26	27	28
Gas Flow Rate	G	lit/min	16	17	18
Wire Feed Rate	F	cm/min	1.75	2.0	2.25
Welding Speed	S	cm/min	20	22	24

3.2 Development of design matrix

To facilitate the objective of determining the optimal level of each design parameter, Taguchi popularized the use of orthogonal arrays as an easy way to design fractional factorial experiments. Taguchi began by selecting several "good" basic fractional factorial designs and, for each, setting up table, which he calls an orthogonal array. These tables may be used in very simple ways to design an experiment. For three level designs, he provides an orthogonal array $L_{9,}$ for up to four factors. Finally, there are methods to use the three levels tables for 9 runs. The experimental design proceeds are simply the assignment of effects of columns after the selection of orthogonal array. Table 2 shows the nine experimental runs as per the Taguchi's L9 orthogonal array design matrix. Therefore with four controllable parameters, at three different levels the experimentation has been carried out.

Table 2 Taguchi L9 Orthogonal array design

Sr. No.	Voltage (V)	Wire Feed Rate (cm/min)	Welding Speed (cm/min)	Gas Flow Rate (lit/min)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.3 Conducting the experiments as per design matrix.

In this work, GMAW machine manufactured by ATE, Pune, INDIA is used. It is a 3-phase, 50Hz frequency, 300A, forced air cooling semi-automatic machine. The torch is fixed to the frame at 90^0 to the work specimen can be kept on trolley which will move at perfect path. Gas flow rate can be vary and measured by flow meter. The mixture of argon (98%) and oxygen gas (2%) is used as a shielding gas. The wire feed and welding voltage regulators are provided in the machine to changes the values of same. Variation of welding voltage automatically changes the current. Therefore, four process parameters welding voltage, wire feed rate, welding speed and gas flow rate can be varied in this machine. Based on design matrix, the experimentations are done by varying input parameters.

In this present work, AISI 446 grade stainless steel is used as work-piece material. The stainless steel filler rod of AISI 309L is recommended by American welding Society (AWS) used for conducting the experiments. The chemical composition of work-piece and filler rod material is shown in Table 3.

Table 3 Chemical Composition of Materials

Material (%)	C	Si	Mn	S	P	Cr	Ni	Mo	Ti	V	Cu	Nu	Fe
AISI 446	0.08	0.35	0.85	0.003	0.030	23.45	0.40	….	…	…	…	…	74.84
AISI 309L	0.02	0.42	1.80	0.01	0.02	24.80	12.92	0.01	0.124	0.049	0.03	0.025	59.772

3.4 Preparation of Specimens

To evaluate the bead geometry of the stainless steel weldment, specimens having dimension of 150mm x 100mm x 8mm with a single V shaped groove of 30^0 were used for each piece as per the design data on the 100 mm side of the plate using vertical milling machine. Fig 3 shows a schematic diagram of work piece prepared. The land and root gap of 2mm is provided between the two work pieces. The experiments are conducted using GMAW machine based on Taguchi's orthogonal array design matrix which consist of nine trails.

Fig. 3 Work piece prepared

3.5 Measurements of the response parameters

The experiments are conducted by single pass. The samples are cut into three parts for the measurement of bead geometry parameters using water jet cutting machine.A schematic diagram of welded plates is shown in Fig. 4.The samples are prepared as per American Society of Testing Materials (ASTM) standards. The metallurgical polishing process revealed the bead geometry for measuring the BH, BW and BP. The silicon carbide of 220, 320 and 500 emery papers and etchant like oxalic acid is used. The bead geometry parameters are measured at three places and the average values are measured and tabulated in Table 4.

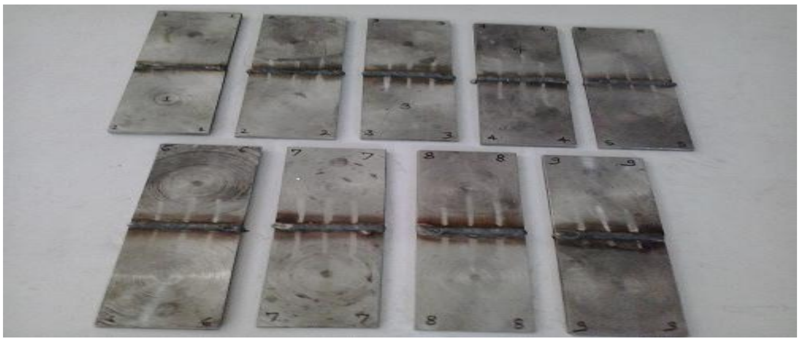

Fig. 4 Welded Samples

Table 4Experimental Data

Sample No.	Bead Width (mm)	Bead Height (mm)	Bead Penetration (mm)
1	8.14	1.44	6.92
2	8.56	2.29	7.66
3	10.69	3.39	6.42
4	10.26	3.58	5.94
5	8.46	2.53	6.27
6	8.29	3.22	7.06
7	8.58	2.68	6.48
8	10.91	2.88	6.42
9	10.17	3.63	7.43

3.6 Analysis of experimental data by Grey-based Taguchi method.

The result obtained for bead width, bead height and bead penetration after experimentation have been first normalized. The bead height and bead width should be minimum and the bead penetration should be maximum. Therefore lower-the-better (LB) criteria for bead height, bead width using equation 1 and larger-the-better (LB) criterion for bead penetration using equation 2 has been selected. The normalized data for each of this parameter are given in Table 5.

Table 5 Data preprocessing of all performance characteristic (Grey relational generation)

Experiment No.	Bead Width (mm)	Bead Height (mm)	Penetration (mm)
Ideal Sequence	1	1	1
1	0.8394	0.9087	0.5000
2	0.7121	0.5560	0.8776
3	0.0667	0.0996	0.2449
4	0.1970	0.0207	0.0000
5	0.7424	0.4564	0.1684
6	0.7939	0.1701	0.5714
7	0.7061	0.3942	0.2755
8	0.0000	0.3112	0.2449
9	0.2242	0.0000	0.7602

The Δ_{0i} for each of the responses have been calculated and tabulated in Table 6. These evaluations of Δ_{0i} for each response have been collected to evaluate Grey relational coefficient.

Table 6Evaluation of Δ_{0i} for each of the responses

Experiment No.	Bead Width (mm)	Bead Height (mm)	Penetration (mm)
Ideal Sequence	1	1	1
1	0.1606	0.0913	0.5000
2	0.2879	0.4440	0.1224
3	0.9333	0.9004	0.7551
4	0.8030	0.9793	1.0000
5	0.2576	0.5436	0.8316
6	0.2061	0.8299	0.4286
7	0.2939	0.6058	0.7245
8	1.0000	0.6888	0.7551
9	0.7758	1.0000	0.2398

In Table 6, reference sequence is ideal sequence. After calculating Δmax, Δmin and Δ0i, altogether grey relational coefficients may be evaluated by (3). These Grey relational coefficients for each response have been collected to calculate Grey relational grade and are exposed in Table 7.

Table 7Grey relational coefficient of each performance characteristics (with $\Psi = 0.5$)

Experiment No.	Bead Width (mm)	Bead Height (mm)	Penetration (mm)
Ideal Sequence	1	1	1
1	0.7569	0.8456	0.5000
2	0.6346	0.5297	0.8033
3	0.3488	0.3570	0.3984
4	0.3837	0.3380	0.3333
5	0.6600	0.4791	0.3755
6	0.7082	0.3760	0.5385
7	0.6298	0.4522	0.4083
8	0.3333	0.4206	0.3984
9	0.3919	0.3333	0.6759

Grey relational grade is the total characteristic of all the features of weld quality. The overall Grey relational grade has been determined by (4) and is tabulated in Table 8.

Table 8 Grey relational grade

Experiment No.	Grey relational grade
1	0.8458
2	0.7768
3	0.3737
4	0.3557
5	0.5652
6	0.6241
7	0.5498
8	0.3916
9	0.5093

Thus, the multi-objective optimization problem can be transformed into a single comparable objective function optimization problem by the combination of Taguchi approach and Grey relational analysis. Maximum grey relational grade equivalents factor combination to the closer optimal parametric setting.
The mean response for the overall Grey relational grade is shown in Table 9.

Table 9Response table (mean) for Overall Grey relational grade

Factors	Grey relational grade					
	Level 1	Level 2	Level 3	MAX	MIN	Delta
V	0.6687	0.5300	0.4905	0.6687	0.4905	**0.1782**
F	0.5825	0.5941	0.5125	0.5941	0.5125	**0.0816**
S	0.6196	0.5602	0.5094	0.6196	0.5094	**0.1102**
G	0.6363	0.6763	0.3766	0.6763	0.3766	**0.2997**
Total mean gray relational grade is **0.5631**						
Delta = range (maximum-minimum)						

Total mean Grey relational grade is the average of all entries in Table 8.
3.7 Calculation of S/N ratio
Fig. 5 represents the S/N ratio for overall Grey relational grade, calculated using LB (larger-the-better) criterion as:

$$\text{SN (Larger-the-better)} = -10 \log\left[\frac{1}{n}\sum_{i-1}^{n}\frac{1}{yi^2}\right] \quad (6)$$

Where n = the number of measurements, and y_i = the measured characteristic value
The mean response for S/N ratio is tabulated in Table 10.

Table 10Response table for S/N ratio

Factor	Level 1	Level 2	Level 3	MEAN
V	-3.4953	-5.5146	-6.1872	-5.0657
F	-4.6935	-4.5223	-5.8056	-5.0071
S	-4.1581	-5.0324	-5.8591	-5.0166
G	-3.9264	-3.3974	-8.4824	-5.2688

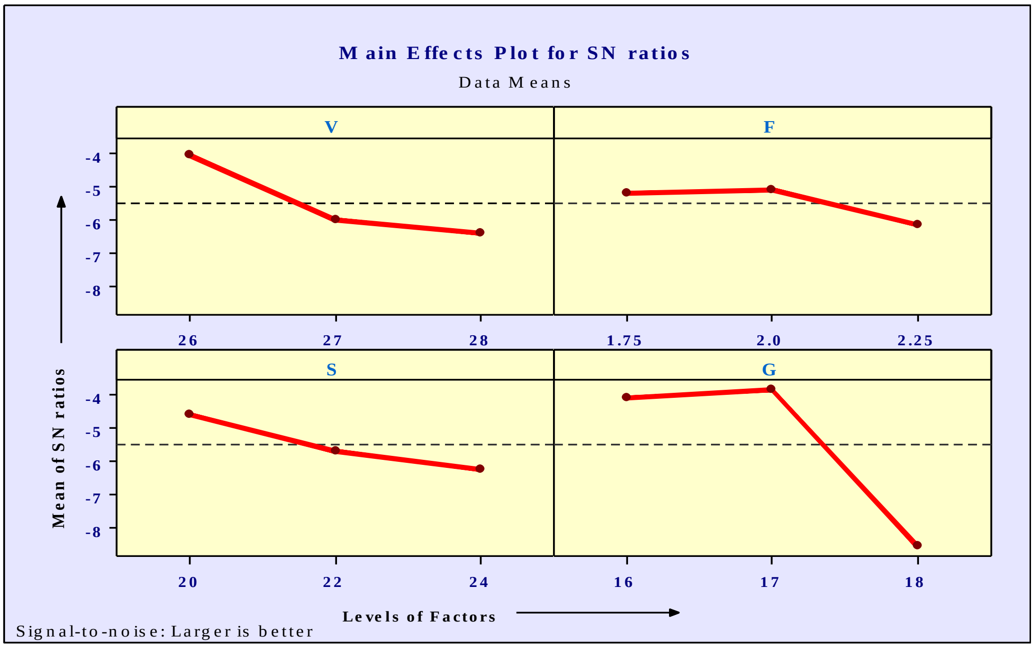

Fig. 5S/N ratio plot for overall Grey relational grade

3.8 Confirmation experiment

After assessing the optimal parameter settings, the next steps are prediction and verify the improvement of quality targets using the optimal parametric combination. The predictable Grey relational grade $\hat{\gamma}$ using the optimal level of the design parameters can be determined by table 8 and (7):

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{0} (\gamma_i - \gamma_m) \qquad (7)$$

That means the predicted Grey relational grade is equivalent to the mean Grey relational grade plus the summation of the difference between overall mean Grey relational grade and mean Grey relational grade for each of the factors at optimal level.

S/N ratio for predictable grey relational grade have been calculated using (6)

S/N ratio for predictable grey relational grade = -1.3313

The Grey relational grade and S/N ratio for Initial factor settings V1 F1 S1 G1, predicted optimal parametric process setting V1 F1 S1 G2 and experimental optimal parametric process setting V1 F1 S1 G2 are shown in column no. 2, 3 and 4 respectively in Table 11.

Table 11 signifies the comparison of the predicted bead geometry parameters with that of actual by using the optimal welding conditions; improvement in overall Grey relational grade has been observed. This confirms the usefulness of the proposed approach in relation to process optimization, where more than one objective has to be fulfilled concurrently.The overall Grey relational grade is main performance feature in Grey-based Taguchi method; The Grey relational grade is the demonstrative of all individual performance characteristics. In the current study, objective functions selected are relative to parameters of bead geometry; and all the responses give equal weight age. It may be noted that results of a confirmatory experiment shows that using optimal parameter setting the weldment undertakes lower value of depth of penetration. The Taguchi optimization technique and the optimal parametric combination thus calculated depend on the selected response variables and their individual weight ages.

Table 11 Results of confirmatory experiment

	Initial factor setting	Optimal process condition	
		Prediction	Experiment
Levels of factors	$V_1 F_1 S_1$ G1	$V_1 F_1 S_1 G_2$	$V_1 F_1 S_1 G_2$
Bead Width	8.14		9.26
Bead Height	1.44		1.2
Penetration	6.92		7.99
S/N ratio of overall Grey relational grade	-1.7460	-1.3313	-1.5798
Overall Grey relational grade	0.8179	0.8579	0.8337
Improvement in grey relational grade = 0.0158			

3.9 Analysis of variance (ANOVA)

ANOVA is a statistical technique, which can infer some important conclusions based on analysis of the experimental data. If the P-value for a term appears less than 0.05 then it may be concluded that, the effect of the factor is significant on the selected response. Using MINITAB release 15, ANOVA for overall Grey relational grade has been exposed in Table 12. It is saw that P-value for Gas flow rate is 0.040 (less than 0.05). So it is obvious that gas flow rate is the most significant factor. The effects of other factors on Grey relational grade look insignificant. Gas flow rate G (P-value highest) come to be the most insignificant factor.

Table 12 Analysis of variance using adjusted SS for tests

Source	DF	SS	MS	F	P
V	2	0.0526	0.0263	0.84	0.479
F	2	0.0117	0.0058	0.15	0.862
S	2	0.0182	0.0091	0.25	0.790
G	2	0.1589	0.0794	5.78	0.040
Error	6	0.1888	0.315		
Total	14	0.2414			

IV. Conclusion

The following conclusions are from the experimentation:

1. Grey based Taguchi method was successfully applied for process parameter optimization of bead geometry for AISI 446 in GMAW process.
2. In order to achieve the best bead geometry viz. maximum bead penetration and minimum bead width as well as bead height following optimal settings were determined: Welding Voltage – 26 V, wire feed rate- 1.75 cm/min, welding speed- 20 cm/min and gas flow rate- lit/min.
3. Gas flow rate was identified as the most significant factor for bead geometry using ANOVA.

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