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Research Article

Parametric Optimization of TIG Welding Process in Butt Joining of Mild Steel and Stainless Steel

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Abstract

Tungsten inert gas (TIG) welding is widely used technique for dissimilar welding of metals. In the present work, TIG welding operation has been studied for favorable welding condition for maximizing the ultimate load and breaking load of weld specimen. Current, gas flow rate and filler rod diameter are considered as input parameters. Experimentation has been done as erL$_{16}$ *orthogonal array of Taguchi method. Grey relational analysis has been utilized for converting multi-responses into single response i.e. grey relational grade. Then the analysis of signal to noise ratio has been applied to determine significance of input parameters. Optimal condition has been obtained by Taguchi method. Confirmation test have also been conducted to verify the optimum condition.*

Keywords: *TIG welding, Dissimilar welding, Ultimate load, Breaking load, Taguchi method, Grey relational analysis.*

1. Introduction

Dissimilar metal joints are used in various engineering applications such as nuclear power plant, coal fired boilers and automobile manufacturing. For joining of dissimilar metals, pressure welding is preferred due to high temperature involved during operation. In welding of dissimilar welding, there are significant differences in material properties such as coefficient of thermal expansion, modulus of elasticity, Poisson's ratio combined with the configuration of the joint leads high stresses around the joining interface (Rakesh *et al*., 2014). Joining dissimilar materials are generally more challenging than that of similar metals because of difference in physical, mechanical and metallurgical properties of the parent metals to be joined.

TIG welding is very useful for dissimilar welding of metals compared to laser welding because of high welding quality, high stability in welding of variety of industrial applications. TIG welding commonly used method for welding of materials such as stainless steel, mild steel, aluminum, titanium etc. In TIG welding, selection of correct welding process parameters is very important to decide the quality of the weld specimen. Because of different properties of materials, welding of the dissimilar materials like stainless steel with mild steel (Mishra *et al*., 2014), stainless steel with aluminum (Borrisutthekul *et al*., 2010) etc., are important areas of research.

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Stainless steel materials are very popular for structural applications due to their excellent physical properties. These materials have high demand in engineering applications like civil construction, nucler reactors, thermal power plants, vessels and heat exchangers etc. (Sun and Karppi, 1996), (Joseph *et al*., 2005), (Jang *et al*., 2008). Mild steel is undoubtedly the cheapest and most commonly used construction material. It is extensively used for water pipes, boats, docks, tanks, vessels, ocean facilities like off-shore platforms, harbor structure and sheet piling (Wang *et al*., 2010) marine environments Melvhers and Jeffrey, 2008) etc., because of its low nobility and structural defects (Elkais *et al*., 2013).

From the literature survey, it can be noted that joining of the stainless steel and mild steel have industrial importance for many applications. But joining of dissimilar materials in TIG welding becomes complex problem due to different properties of material and varies process parameters in it. The literature suggests that an systematic optimization approach is required to analyze the TIG welding for joining dissimilar materials. Taguchi method is a statistical design and analysis approach, used for optimizing welding processes. Grey relational analysis is very useful for optimizing multiple performance characteristics simultaneously. Grey relational analysis combined with Taguchi method is very efficient optimization methodology to analyze and optimize multi responses combinedly. Some of the researchers had done investigation on TIG welding operation for obtaining desired responses with use of above said technique (Raghuvir *et al*., 2013), (Cheng *et al*., 2011), (Singh and Singh, 2013), (Ugur *et al*, 2009), (Singh *et al*., 2013), (Saurav *et al*., 2008), (Hsiao *et al*., 2008), (Aydin *et al*., 2010) those are given below.

Raghuvir *et al*., (2013) investigated the effect of welding parameters: welding speed, current and flux on depth of penetration and width in TIG welding of 304L stainless steel. Response methodology utilized for analyzing and optimizing the welding operation to maximize penetration and minimize bead width combined. Cheng *et al*. ,(2011) made an analysis to investigate the effects of oxide fluxes on weld surface, weld morphology, angular distortion and weld defect in TIG welding of dissimilar materials mild steel and stainless steel. Singh and Singh , (2013) analyzed the TIG welding process to identify the desired welding condition to optimize metal deposition rate and hardness of the wed bead of stainless steel materials using Taguchi method. They considered current, gas flow rate and no of passes as input parameters. Significant process parameters were identified through analysis of variance.

Ugur *et al*, (2009) had done investigation on tungsten inert gas welding (TIG) to predict optimal parametric setting to optimize multi-responses using the grey relational analysis and Taguchi method. Sixteen experimental runs based on L_{16}orthogonal array of Taguchi method were conducted. Multi-responses: bead geometry; bead width, bead height, penetration, area of penetration as well as width of heat affected zone and tensile load had been converted to single objective optimization problem i.e. grey relational grade that is representing all the responses. Then the analysis of signal-to-noise ratio had applied on grey relational grade to check the significance of welding parameters. Optimal welding setting had also been obtained by Taguchi method. From the confirmatory results of their study, stated that grey relation analysis in combination with Taguchi technique was feasible to continuous improvement in product quality in manufacturing industry.

Singh *et al*. (2013) studied the TIG welding operation to improve quality characteristics tensile load, area of penetration, bead width, bead height and penetration. They used grey based Taguchi method to conduct experiments, analyze and optimize multi-responses simultaneously. Saurav *et al*. (2008) used Taguchi method followed by grey relational analysis to solve multi response characteristics in submerged arc on plate welding using welding parameters voltage, traverse sped, stick out, wire feed rate and creed feed and output responses were weld penetration, weld width, weld reinforcement and depth of heat effected zone. Hsiao *et al*., (2008) identified the optimal parametric setting of plasma arc welding by the Taguchi method with grey relational analysis. Torch stand-off, welding current, welding speed and plasma gas flow rate were selected as welding parameters and welding groove root penetration, welding groove width, front side undercut were chosen as output responses. Aydin *et al*. (2010) also optimized friction stir welding process to yield desired tensile strength and elongation.

Present study is planned to study the TIG welding while welding of dissimilar materials mild steel and stainless steel with use of integrated grey Taguchi method. Effects of welding parameters are investigated through analysis of signal-to-noise ratio. The optimal conditions have also been predicted to optimize ultimate load and breaking load combinely.

2.1 Taguchi method and Grey Relational Analysis

Taguchi method is an efficient and robust technique for optimizing the process variables to enhance the system performance. The main aim of analysis is to investigate how different process parameters affect process performance characteristics. The experimental design proposed by Taguchi, uses the orthogonal array to plan the experiments. In Taguchi method, only limited parametric combinations considered instead to check all possible combinations like factorial design. This method allows us to determination of factors which most affect product quality with a minimum number of experiments, thus saving time and resources (Fratila and Caizar, 2011).

Taguchi method uses a procedure that applies orthogonal arrays of statistical designed experiments to obtain the best results. It uses the analysis of signal-to-noise ratio (S/N) to measure the performance characteristics of the system or process. S/N ratios can categorize to three types: larger-the-better (Eq. 1), smaller-the-better (Eq. 2) and nominal-the-better (Eq. 3). The parametric setting that maximizes the S/N ratio is the optimal parametric combination.

$$\text{Larger-the-Better:} \frac{S}{N} ratio = -10log10\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

$$\text{Smaller-the-Better:} \frac{S}{N} ratio = 10log10\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right)$$

$$\text{Nominal-the-Bes} \frac{S}{N} ratio = -10log_{10}\left(\frac{\mu^2}{d^2}\right)$$

where, n = number of parameters; y = output response; μ= mean; d= standard deviation.

In 1989, Deng was first proposed grey system theory, which is an effective mathematical tool to deal with system / process analysis characterized by inexact and incomplete information. The grey theory is based on known information. If the system or process information is known, system is called as white system; if information is unknown, it is called as black system; and if a system / process information is partially known then it is called as grey system (Das and Sahoo, 2011). Grey relational analysis (GRA) had also proposed by Deng in his grey theory to solve multiple attribute decision making or multiple performance characteristic problem. It is proved to be an accurate method to solve those types of problems (Singh *et al*., 2013), (Saurav *et al*., 2008), (Hsiao *et al*., 2008), Aydin *et al*., 2010). The grey relational analysis is based on the minimization or reduction of difference between the ideal referential alternative to real referential alternative. The main objective of the GRA is to analyze the input or process variables; those are expected to influence the outcome which comes from the system / process. The grey relational grade can be used for finding relationship between the input (i.e. independent) and dependent (i.e. dependent). GRA provides the following steps to analyze the system or process.

1. Normalization of set of experimental results between 0 &1
2. Calculation of grey relational coefficient from the normalized data
3. Calculation of grey relational grade by averaging the grey relational coefficients. The grey relational grade is treated as overall response of the process instead of multiple attributes or response(s) i.e. ultimate load and breaking load in the present work
4. Analyze the experimental results using the grey relational grade, statistical analysis of variance and signal noise ratio
5. Selection of optimal levels of process parameters
6. Verification of the optimal parametric condition by conducting confirmation experiments.

3 Experimental Set Up And Procedure

The plan has been made and work-piece materials (i.e. mild steel and stainless steel) have been cut into desired dimensions. The selected process parameters and its levels are given in Table 1. The setup has been made ready and prepared for doing TIG welding. Basic diagram for TIG welding is shown in Fig. 1. Butt joints are made under varied conditions of welding as given L_{16} orthogonal array of Taguchi method (Table 2). 16 welded samples are thus made by through TIG welding process. Photographic view of the experimental set up is shown in Fig. 2.

Table 1 Input parameters and their levels

Welding parameters	Units	Levels			
		1	2	3	4
Current (A)	A	90	100	110	120
Glass flow rate (B)	l/min	12	14	16	18
Filler road (C)	mm	1.6	2	2.5	3

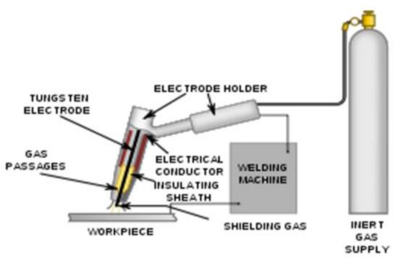

Fig. 1 Schematic diagram of TIG welding operation

Table 2 L_{16} orthogonal array of Taguchi method

S. No.	Current (A)	Gas flow rate (l/min)	Filler rod diameter (mm)
1	90	12	1.6
2	90	14	2.0
3	90	16	2.5
4	90	18	3.0
5	100	12	2.0
6	100	14	1.6
7	100	16	3.0
8	100	18	2.5
9	110	12	2.5
10	110	14	3.0
11	110	16	1.6
12	110	18	2.0
13	120	12	3.0
14	120	14	2.5
15	120	16	2.0
16	120	18	1.6

Fig. 2 Experimental setup

4 Results and Discussion

Welding experiments are done as per L_{16} orthogonal array of Taguchi methodology and corresponding results i.e. ultimate load and breaking load are shown in Table 3. Grey relational technique is proposed to convert multi-objective problem of TIG welding of mild and stainless steel into single-objective optimization problem. Then Taguchi analysis has also been done to study the effects of welding parameters on output responses and optimize them.

4.1 Grey relational generation

In grey relational analysis, the experimental results are first normalized in the range between zero and unity. This process of normalization is called the grey relational generation. The next step is to calculate the grey relational coefficients from the normalized experimental data to express the relationship between the desired and actual experimental data. Then the overall grey relational grade is calculated by averaging the grey relational coefficient corresponding to each selected response. The overall evolution of the multiple responses is based on the grey relational grade. Grey relational analysis converts a multi objective problem into a single objective problem with the objective function of overall grey relational grade. The corresponding level of parametric combination with highest grey relational grade is considered as the optimum parametric combination (Lin and Lin, 2002).

In grey relational analysis, the normalized data corresponding larger-the-better criterion can be expressed as follows:

$$x_{ij} = \frac{y_{ij}-min_j y_{ij}}{max_j y_{ij}-min_j y_{ij}} \quad (4)$$

where xi (k) is the value after grey relational generation while min yi(k) and max yi(k) are respectively the smallest and largest values of yi(k) for the k^{th} response. Obtained data after grey relational generation are given in Table 4.

4.2 Grey relational coefficient

The grey relational co-efficient can be calculated as

$$\xi i(k) = \frac{\Delta \min + \Delta \max}{\Delta 0i(k) + r\Delta \max} \quad (5)$$

Table 3 L_{16} orthogonal array and output responses

S.no	Input parameters			Output responses	
	Current, A (A)	Gas flow rate, B (l/min	Filler rod diameter, C (mm)	Ultimat. load	Breakn. load
1	90	12	1.6	12.0	11.7
2	90	14	2.0	12.7	11.2
3	90	16	2.5	12.2	14.0
4	90	18	3.0	12.5	12.8
5	100	12	2.0	13.9	10.0
6	100	14	1.6	16.7	9.8
7	100	16	3.0	14.0	12.3
8	100	18	2.5	14.5	11.5
9	110	12	2.5	12.8	10.5
10	110	14	3.0	14.1	9.6
11	110	16	1.6	13.9	12.0
12	110	18	2.0	15.2	10.1
13	120	12	3.0	13.7	10.3
14	120	14	2.5	15.8	10.9
15	120	16	2.0	13.8	11.9
16	120	18	1.6	16.9	10.4

4.3 Grey relational grade

After obtaining the grey relational coefficient, grey relational grade is determined by taking the average of the grey relational coefficients. The grey relational grade can be expressed as follows:

$$\alpha i = \sum_{k=1}^{n} \xi i(k) / n \quad (6)$$

Where n is the number of performance characteristics. where Δ0i = ||x0(k) _ xi(k)|| = difference of the absolute value between x0(k) and xi(k); Δmin = smallest value of $\Delta 0i$; Δmax = largest value of $\Delta 0i$; and here 'r' is distinguish co- efficient which is used to adjust the difference of the relational coefficient, usually r is within the set {0, 1}, generally 'r' value is taken as 0.5. ξ_i(k) is Grey relation co-efficient. The grey relational coefficient values are also given in Table 5.

The grey relational grade is obtained by averaging the grey relational coefficient values of ultimate load and breaking load and shown in Table 6.

4.4 Grey relational ordering

In relational analysis, the practical meaning of the numerical values of grey relational grades between elements is not absolutely important, while the grey relational ordering between them yields more subtle information. The combination yielding the highest grey relational grade is assigned an order of 1 while the combination yielding the minimum grade is assigned the lowest order (Das and Sahoo, 2011). The ordering of the present grey grades is shown in the last column of Table 6.

Table 4 Normalized data for ultimate load and breaking load

S. No.	Normalized data	
	Ultimate load	Breaking load
1	0	0.477273
2	0.142857143	0.363636
3	0.040816327	1
4	0.102040816	0.727273
5	0.387755102	0.090909
6	0.959183673	0.045455
7	0.408163265	0.613636
8	0.510204082	0.431818
9	0.163265306	0.204545
10	0.428571429	0
11	0.387755102	0.545455
12	0.653061224	0.113636
13	0.346938776	0.159091
14	0.775510204	0.295455
15	0.367346939	0.522727
16	1	0.181818

Table 5 Grey relational coefficients

S. No.	Values of Δoi		Grey relational coefficient	
	Ultimate load	Breaking load	Ultimate load	Breaking load
1	1	0.522727	0.333333	0.488889
2	0.857143	0.636364	0.368421	0.44
3	0.959184	0	0.342657	1
4	0.897959	0.272727	0.357664	0.647059
5	0.612245	0.909091	0.449541	0.629032
6	0.040816	0.954545	0.924528	0.34375
7	0.591837	0.386364	0.457944	0.564103
8	0.489796	0.568182	0.505155	0.468085
9	0.836735	0.795455	0.374046	0.385965
10	0.571429	1	0.466667	0.333333
11	0.612245	0.454545	0.449541	0.52381
12	0.346939	0.886364	0.590361	0.360656
13	0.653061	0.840909	0.433628	0.372881
14	0.22449	0.704545	0.690141	0.415094
15	0.632653	0.477273	0.441441	0.511628
16	0	0.818182	1	0.37931

4.5 Analysis of signal to noise ratio

The statistical technique analysis of signal-to-noise ratio has been applied on grey relational grade to identify the significant input parameters. Result of analysis of variance (ANOVA) is shown in Table 7. In the ANOVA test, F-tests value of the parameters are comparing with the standard F table value ($F_{0.05}$) at 5% significance level (95% confidence level). If P-values in the table are less than 0.05 then the corresponding variables considered as statistically significant (Choudhary *et al*., 2014). From the ANOVA (Table 7), it is found that the input parameters current (A) gas flow rate (B) and filler rod diameter (C) do not have significant effect, as its P values are greater than 0.05.

Table 6 Grey relational grade and ordering

S. No.	Grey relational grade	Ordering
1	0.4111110	12
2	0.404211	13
3	0.671329	2
4	0.502362	7
5	0.539287	5
6	0.634139	3
7	0.511023	6
8	0.486620	9
9	0.380005	16
10	0.400000	15
11	0.486675	8
12	0.475509	11
13	0.403255	14
14	0.552618	4
15	0.476535	10
16	0.689655	1

Table 7 Analysis of signal-to-noise ratio

Source	DF	Seq SS	Adj SS	Adj MS	F
A	3	8.496	8.496	2.832	1.11
B	3	9.235	9.235	3.078	1.21
C	3	6.317	6.317	2.106	0.83
Residual Error	6	15.272	15.272	2.545	
Total	15	39.320			

4.6 Effects of welding parameters

S/N ratio of grey relational grade of ultimate load and breaking load is calculated for each parametric combination. While calculating S/N ratios values, larger-the-better criteria have been applied, because grey relational grade needs to maximize. So Eq. (1) is used for determining the S/N ratios, shown in Table 8. On examination of the Delta values, welding current (A) is found to be most significant factor, next is gas flow rate (B). Filler rod diameter (C) has lesser effect on both the responses. By using these S/N ratio values given in Table 8, the main effect plots have been made using MINITAB 16 software and shown in Fig. 3. Optimum parametric setting can be found from the main effect plots at highest S/N ratio values of grey relational grade corresponding to each factor. From Figure 3, it is observed that the optimum condition is A2 B4C1 (i.e. current = 100 A, glass flow rate = 18 l/min and filler rod = 1.6 mm).

Table 8 Response table for signal to noise ratios

Level	A	B	C
1	-6.257	-7.344	-5.290
2	-5.352	-6.234	-6.532
3	-7.269	-5.496	-5.818
4	-5.676	-5.480	-6.915
Delta	1.917	1.864	1.625
Rank	1	2	3

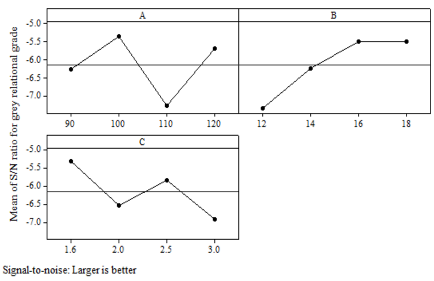

Fig. 3 Main effect plots for grade relational grade

4.7 Validation test

Confirmatory test is conducted at the optimal condition to verify improvement of output responses. Test result reveal that grey Taguchi method is effective to optimize TIG welding of mild and stainless steel materials.

Conclusions

In the present investigation, welding parameters are analyzed and optimized in TIG welding of dissimilar materials (mild steel and stainless steel) to maximize the ultimate load and breaking load simultaneously by using grey relational analysis combined with Taguchi method. The following important points are drawn from this study:

1. From analysis of variance (ANOVA), it is noted that welding parameters current, gas flow rate and filler diameter are not significant on both the responses.
2. Response table for signal to noise ratio reveals that current is the most significant factor, next is gas flow rate followed by filler rod diameter.
3. Optimum parametric condition: current = 100 A, gas flow rate = 18 l/min and filler rod diameter = 1.6 mm, is obtained by Taguchi method.
4. Confirmatory test result shows the validity of the optimum condition.
5. Hybrid technique: grey relational analysis. Taguchi method is very efficient for process optimization (Ugur *et al*, 2009), (Singh *et al*., 2013), (Saurav *et al*., 2008),

(Hsiao *et al*., 2008), Aydin *et al*., 2010), (Nikhil *et al*., 2014), that is proved in the present work as well.

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