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Research Article

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Multi-response Optimization of Process Parameters of TIG Welding of Beta Titanium alloy without use of filler rod by Grey-Taguchi method

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Abstract: Welding process input parameters have significant impact on quality of weld joint. Quality of weld can be improved by selection of proper input process parameters and with suitable welding technique/process. During the welding of autogenous welding of challenging Beta titanium alloy current, nozzle to plate distance and shielding gas flow rate have been used as an important input parameters. In this paper, multi-objective optimization of TIG welding technique input parameters have been optimized to achieve the best quality of beta titanium joint. The quality of TIG welded joint without use of filler rod has been assessed in terms of tensile test and impact toughness test. To solve the multi-objective optimization problem, a grey-Taguchi method has been used. To evaluate the effect of individual factor on desired output results i.e. ultimate strength, percentage elongation, and toughness an Analysis of Variance (ANOVA) has been used. An additional confirmatory experiment was carried out to model. An improvement of 9% in grey relational grade was found at optimized parameters.

Keywords: Beta titanium alloy, ANOVA, Signal to Noise ratio, Taguchi Design and Grey Relational Grade and Toughness

1Introduction

Titanium and its alloys possess a unique combination of properties – high specific strength, low density, excellent resistance to elevated temperatures and superior corrosion resistance – that make them irreplaceable in demanding sectors such as the aerospace, automotive engineering, biomedical implants and chemical processing plant [1]. However, joining these materials reliably remains a persistent engineering challenge.
Titanium alloys have been joined by a number of processes including tungsten inert gas (TIG) welding, electron beam welding, laser beam welding, friction stir welding and more recently, hybrid laser-MIG techniques. A TIG weld can be autogenous or it can be with filler wire. This is largely a matter of the thickness of the work piece. The high chemical reactivity of titanium, especially the strong tendency to combine with atmospheric oxygen and nitrogen, remains a major difficulty in welding, since such contamination embrittles the joint microstructure and compromises weld integrity.
A large volume of research has been carried out on the effect of welding process parameters and the welding process itself on the quality of the weld produced in titanium alloys. Akhonin et al. [2] investigated the influence of TIG welding parameters on the microstructure and mechanical behavior of pseudo-β alloy VT19 joints by varying the travel speed and filler wire feed rate with and without a flux layer, and established the relationship between tensile strength and β-phase content in the weld.
Reda et al. [3] studied the thermal, metallurgical and mechanical behavior of

TIG welded Ti–6Al–4V plates (12 mm thick) with the objective to identify an optimum welding current. The results indicated a maximum tensile strength and hardness at a current of 130 A.
Omoniyi et al. [4] studied the TIG-welding of Ti6Al4V sheet (2–3 mm) at various current and argon shielding gas flow rates and correlated the parameters to mechanical and microstructural results.
Prilutsky et al. [5] reviewed metallurgical and process fundamentals of arc welding of titanium and titanium-based alloys discussing strategies of the improvement of both weld efficiency and quality, with particular emphasis on factors governing the penetration depth.
A more complete review of titanium weldability was provided by Ranatowski [6]. He included new alloy classes, principles of welding metallurgy and the various joining processes which can be used for this family of alloys.
Lisiecki et al. [7] compared the various laser welding technologies for butt-joining Ti6Al4V sheets (1.5–2 mm thickness) and found that the melting behavior during the HPDL laser welding process was significantly different from that of the disk laser welding process, with the HPDL process creating high-quality welds.
Yulian et al. [8] compared electron beam welding (EBW-HV) with CO2 laser welding and TIG welding for joining 0.5 mm commercially pure titanium sheet and found that EBW was best suited to this thickness producing defect free seams.
Gao et al. [9] compared pulsed Nd:YAG laser welding and conventional TIG fusion welding of 0.8 mm Ti6Al4V sheet in terms of residual distortion, weld geometry, microstructure and mechanical properties. Laser-welded joints showed less overall distortion than TIG welds, a finer microstructure, a narrower heat-affected zone and higher hardness [9].
Schwab et al . [10] demonstrated that titanium alloy sections of up to 16 mm thickness can be welded in a single pass by TIG welding using titanium-based filler wires. This dramatically increases productivity and the weld metal deposited exhibits superior properties than the base material.
Pushpa et al. [11] extensively reviewed titanium alloys classification and applications, emphasizing the necessity of further research to enhance service temperature limits and wear resistance.
Bendikiene [12] carried out an experiment at an industrial scale, where three TIG welding modes for commercially pure titanium were compared; pulsed welding with controlled short interruptions and standard continuous TIG welding were tested by means of standard destructive and non-destructive testing methods; the results showed the need for proper shielding gas coverage for pure titanium.
Feng et al. [13] used a post-weld treatment of warm laser shock peening (WLSP) and obtained a 42.3% increase in the high-cycle fatigue limit (from 399 ± 5 MPa to 568 ± 19 MPa). The improvement was attributed to the high magnitude and thermal stability of the induced compressive residual stress and the surface nanostructuring.
Ren et al. [14] investigated the fracture behavior of TIG-welded TA15 titanium alloy under tensile and fatigue loading. They concluded that the tensile failure was primarily dominated by weld geometry and the plastic deformation ability of the weldment.
Fu et al. [15] characterized microstructure, texture and mechanical properties of multipass TIG-welded near-α Ti–4Al–2V joints and showed that compared to the base metal, a more complex mixture of α′ martensite, acicular α and Widmanstätten α+β lath structures was present in the heat affected zone and fusion zone.
Sagar et al. [16] modelled the temperature field in Ti-6Al-4V (Grade 5) TIG welds using a moving heat source and element birth and death technique in ANSYS. They validated the model against experimental welds and confirmed the inverse relationship between welding speed and peak temperature.

The wider importance of titanium welding to industrial application was reviewed by Ahmed et al. [17] who pointed out that the choice of process is highly dependent on the application and concluded that the generally preferred route for titanium and its alloys is gas tungsten arc welding (GTAW).

Despite this large body of work, relatively little research has been done specifically on the welding behavior of beta titanium alloys. The present study fills this gap by joining beta titanium alloy plates by GTAW process without adding filler wire. A total of 27 weld joints were made (an L9 orthogonal array with three replicates each condition). The three controlling input factors selected were current, nozzle-to-plate distance, and shielding gas flow rate . Each of the three factors was experimented at three levels, which were decided based on preliminary trial runs. In order to determine the optimum process window for welding beta titanium alloy, the weld quality was assessed by tensile and impact toughness tests. Multi-response optimization problem was solved by grey relational analysis with the Taguchi method and the relative contribution of each input parameter to tensile strength, impact toughness and percentage elongation was ascertained by using analysis of variance. Finally, a confirmatory experiment was conducted to validate the optimized model.

2 Materials and Methods

2.1 Material

Beta titanium alloy (BT-20) was taken as base metal for this study. The chemical composition of BT-20 alloy is shown in Table 1. Thickness of welded plates are 2.5mm and no filler rod is used.

Table 1- Chemical composition(%) of BT-20

Fe	C	Si	Mo	V	N
0.08	0.01	0.01	1.63	2.20	0.001
Ti	Al	Zr	O	H	
86.86	6.69	2.22	0.086	0.002	

2.2 Experimental Work.

TIG welding was carried out on beta titanium alloy plates. The dimension of each welding plate was taken as 130mmx55mmx2.5mm. Butt joint was prepared by welding two plates together i.e. weld sample size become 130mmx110mmx2.5mm. Welding was done without use of filler rod. Argon gas was used as shielding gas from both top and bottom side by using specially designed test set up. Tungsten electrode of 2.0mm diameter was used. The plates prepared for welding are shown in Fig.1. Welding set up is shown in Fig. 2.



Fig 1 Pile of plate prepared for welding(54Nos)

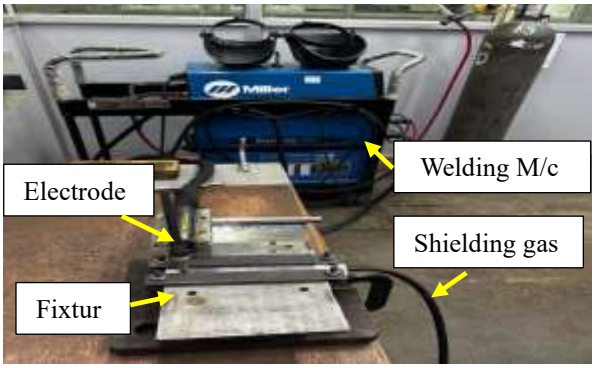


Fig 2 TiG Welding Set up

2.3 Process Parameters and Levels

Experimental trials have been carried out to decide the range of process parameters. Based on experimental trials, three level of each parameter viz current, nozzle to plate distance and shielding gas flow rate were choosen to carry out this work. Input process parameters with their level are listed in Table 2 below.

Table 2- Process Parameters and Level

Factors	Units	Notations	Levels		
			1	2	3
Current	A	I	85	90	95
NTPD	mm	D	2	3	4
Gas Flow rate	l/min	Q	9	10	11

2.4 Taguchi Method. Taguchi orthogonal array has been used to design the experimental trial. Experiment was performed with three factor each at three levels. Therefore, degree of freedom for design is six. The orthogonal array L9 satisfies the requirement and same has been choosen for carrying out the experiment.

2.5 Grey relational analysis method for optimization.

The grey relational approach provides an efficient management on uncertainty, multi-input and discrete da(ta. It also reveals the necessary information on the interaction of input parameters [18]. Steps for carrying out the same is described below.

*Step 1 C*alculate Signal to Nose ratio for all the responses by use of applicable formula as mentioned below.

i. Larger the Better

$$\frac{S}{N}\ ratio(r) = -10log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{a_{ij}^2} \qquad (1)$$

Where n= number of replications,
a_{ij}*= response value where i= 1,2,3 .. n; j= 1,2….k.*

It is used where maximization of response is desired.

ii Smaller the Better

$$\frac{S}{N}\ ratio(r) = -10log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}a_{ij}^2 \qquad (2)$$

It is used where maximization of response is desired.

iii Nominal the best

$$\frac{S}{N}\ ratio(r) = -10log_{10}\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{\mu^2}{\sigma^2} \qquad (3)$$

Where $\mu = \frac{a1+a2+a3+\cdots\ldots\ldots an}{n}$

$$\Sigma^2 = \frac{\sum(ai-a^-)^2}{(n-1)}$$

This is known as nominal the best type of problem. Object is to minimize the mean squared error around the target value.

Step 2 *a_{ij} is normalized as $y_{ij\ (0\leq y_{ij}\leq 1)}$ using the formula given below to reduce the variability.*

$$y_{ij} = \frac{aij-\min(aij,i=1,2.3\ldots n)}{\max(aij,i=1,2,..n)-\min(aij,i=1,2..n)} \quad -(4)$$

(Equation-4 is used for S/N ratio with larger the better case)

$$yij = \frac{aij - \text{miax}(aij, i = 1,2.3\ldots n)}{\max(aij, i = 1,2,..n) - \min(aij, i = 1,2..n)}$$

--(5)

(equation-5 is used for S/N ratio with smaller the better case).

Step 3 Calculate grey relational coefficient for the normalized S/N ratio values

$$\rho\big(y0(k), yi(k)\big) = \frac{\Delta\min + \epsilon\Delta max}{\Delta oi(k) + \epsilon\Delta max} \qquad (6)$$

Where

i) i = 1,2….n, k =1,2 ..m, n is the number of experimental data and m is the number of response.

ii) y0(k) is known as reference sequence and it is equal to 1.

iii) $\Delta oi = \|y0(k) - yi(k)\|$

iv) $\Delta min = Minimum\ value\ of \Delta oi$

v) $\Delta max = Maximum\ Value\ of \Delta oi$

vi) ϵ is the distinguishing coefficient, such that $0 \leq \epsilon \leq 1$.

Step 4 Calculation of the Grey Relational Grade(GRG).

$$\rho_j = \frac{1}{m}\sum_{i=1}^{m}\{y0(k), yi(k)\} \qquad (7)$$

Where **ρ**j is the grey relational grade of j[th] experiment.

Step 5 Determine Optimal factor and their levels

The higher GRG means better product quality. On basis of higher GRG, the factor effect can be estimated and optimal level for each factor may be calculated. For example to evaluate the effect of particular factor , calculate the average of grey relational grade value (AGV) for each level. Max of AGV among all levels of that particular factor is the best level of that factor.

Step 6 Analysis of Variance(ANOVA) for significant factor.

The object of ANOVA is to identify the effect of individual factor on the process result. The sum of squared deviation due to each parameter and sum of the squared error is calculated. Percentage contribution of each parameter in the total sum of the squared deviations is used to analyse the Importance of process parameter change on the performance. When F value is large the process parameter has significant effect on output.

Step 7 Predicted optimum condition

After selection of optimal design parameters, the next step is to predict and verify the quality characteristics using the optimal level of each parameter. The factor level obtained in step 5 are used. The estimated grey relational grade using optimal level of design parameter grey relation grade can be obtained as follows

$$\bar{\cap} = \cap_m + \sum_{i=1}^{\beta} (\cap_i - \cap_m)$$

Where

$\cap_m$ = Overall mean of average grey grade

$\cap_i$ = average grey grade corresponding to i^{th} significant factor on j^{th} level.

β= Number of significant factors

2.6 Plan of Experimentation

Taguchi L9 orthogonal array DOE was used to gather as much as possible data with minimum number of experiments. In addition, each trial is repeated three times and average of three values is taken in analysis. Therefore, total twenty-seven butt joint GTAW welded samples were prepared to determine ultimate tensile strength(U), percentage elongation(e) and impact toughness (T). Taguchi's orthogonal array(3^{rd} Level) along with response parameters is shown in Table 3 below.

Principle of randomization was used . Welded plates with level of experimental parameters i.e. current, nozzle to plate distance and gas flow rate are shown in Fig 3 .



Fig. 3 welded plates with levels(27Nos)

From welded sample tensile test pieces were prepared as per ASTM E8 (subsize) and for Charpy Impact Toughness test, test piece was prepared as per E23-07(subsize) as per ASTM-239. Tensile Test samples were cut from welded plate by wire EDM and shown in Fig. 4.



Fig. 4 Tensile Test Specimens(27Nos)

Charpy tensile test piece are also cut through wire EDM from welded plates and notch was prepared through a single point cutting tool. Prepared specimen are shown in Fig. 5 .



Fig. 5 Specimens(27Nos) of Charpy Test

Broken Specimen after tensile and charpy test are shown in Fig. 6 and Fig. 7 respectively.



Fig.6 Broken specimen after Tensile test specimen

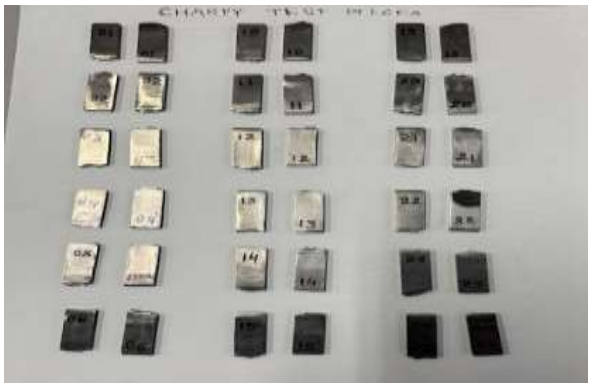


Fig. 7 Broken Specimen after charpy Test

Table 3 L_9 Orthogonal Array with factors and responses

Exp. No.	Factors			Responses		
	I	D	Q	Elongation(e) in %	UTS (U)in MPa	Toughness (T)in KJ/m2
1	1	1	1	7.05	1048.2	291.67
2	1	2	2	5.93	1048.2	283.33
3	1	3	3	5.31	1004.7	275.00
4	2	1	2	5.83	1017.2	225.00
5	2	2	3	8.21	1040.4	266.67
6	2	3	1	4.47	1022.8	250.00
7	3	1	3	7.26	1027.5	333.33
8	3	2	1	5.33	1027.9	250.00
9	3	3	2	5.21	1034.5	275.00

3 Results and Discussion:

Implementation of solution methodology and results are summarised below**.**

Step 1 Calculate the S/N ratios for obtained response and predicted S/N ratios of the starting conditions using applicable equation (1),(2) and (3) depending upon the nature of quality characteristics. The computed S/N ratios for each quality characteristics are shown in Table 4.

Table 4 S/N ratios value of responses

Exp. No.	S/N ratios		
	e	U	E
1	16.96	60.41	49.30
2	15.46	60.41	49.05
3	14.51	60.04	48.79
4	15.32	60.15	47.04
5	18.29	60.24	48.52
6	13.01	60.20	47.96
7	17.22	60.24	50.46
8	14.53	60.24	47.96
9	14.34	60.29	48.79

Step 2 Normalize the S/N ratio values by equation (4), (5) and (6) . The results are given in Table 5.

Table 5 Normalized S/N ratios value of responses

Exp. No.	Normalized Value of S/N ratio y_{ij}		
	e	U	T
1	0.75	1.00	0.66
2	0.46	1.00	0.59
3	0.28	0.00	0.51
4	0.44	0.29	0.00
5	1.00	0.82	0.43
6	0.00	0.42	0.27
7	0.80	0.53	1.00
8	0.29	0.54	0.27
9	0.25	0.69	0.51

Step3 Perform the grey relational analysis. Calculate the grey relational coefficient for the normalized S/N ratios value listed in table 5 by using equation (6). The value of ϵ is taken as 0.5. Equal weightage to all the process parameters are given.

Table 6 Grey relational Coefficient and Grey grade value

Exp.No.	Grey relational coefficient			Grey grade
	e	U	T	
1	0.67	1.00	0.60	0.753
2	0.48	1.00	0.55	0.677
3	0.41	0.33	0.51	0.417
4	0.47	0.41	0.33	0.406
5	1.00	0.74	0.47	0.736
6	0.33	0.46	0.41	0.401
7	0.71	0.51	1.00	0.742
8	0.41	0.52	0.41	0.446
9	0.40	0.62	0.51	0.508

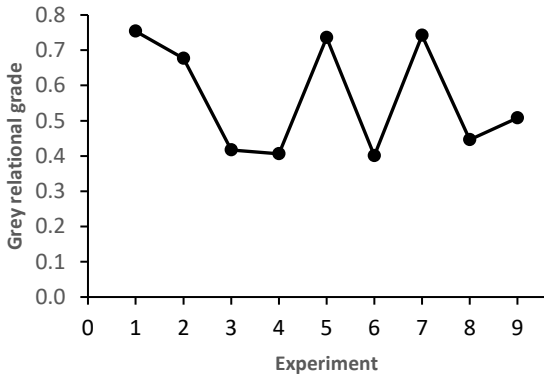


Fig.8 Experiment No Vs GRG value

Step 4 Grey relational grade are computed by equation(7). Finally, the grades are considered for optimizing the multi response parameters design problem. The results are summarized in table 6.

Step 5 From the value of grey relational grade obtained in table 6, the main effects of parameter are tabulated in table 6.

Table 6 Main effects on grey grade

Factors		1	2	3
I	Current	**0.615**	0.514	0.565
D	Distance	**0.634**	0.620	0.442
Q	Flow rate	0.533	0.530	**0.632**

Step 6 Based on maximization of grade value as mentioned in Table 6, we obtain optimal parameters combination are $I_1D_1Q_3$.

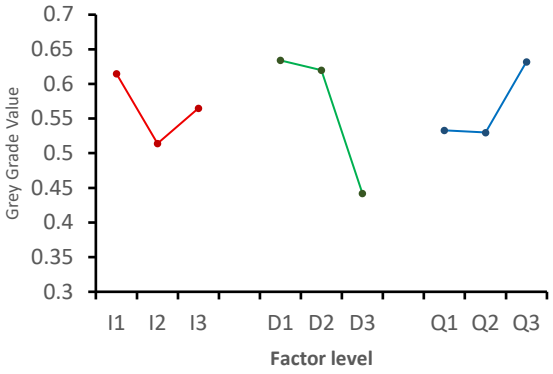


Fig. 9 Factors effect on grade values

Step 7 Using the grey grade value, ANOVA is formulated for identifying significant factors. The results of ANOVA are shown in Table 7. From ANOVA it is clear that Nozzle to plate distance (34.11%) influence more on welding of Titanium alloy

Table7 Results of ANOVA on grey grade

Factors	Dof	Sum of Square	Mean Square	F-Test	% Contribution
I	2	0.02	0.010	0.222	10.00
D	2	0.07	0.035	0.777	35.00
Q	2	0.019	0.010	0.222	9.500
Error	2	0.09	0.045	--	45.01
Total	8	0.20	0.025	--	100.00

followed by current(10.64%) and gas flow rate (9.94%).

Step 8 Predicted optimum condition

To predict the optimum condition, the following equation is used to calculate the expected mean ($\overline{\cap}$) at the optimal setting.

$$\overline{\cap} = I_1 + D_1 + Q_3 - 2 * T_{gg}$$

Where I_1= Max of average GRG Value of factor I (i.e at optimal level)

D_1= Max of average GRG Value of factor D (i.e at optimal level)

Q_3 = Max of average GRG Value of factor Q (i.e at optimal level)

T_{gg}= Average of GRG value of all experiments

$\overline{\cap}$ = 0.615+0.634+0.632-2*0.565

The expected mean(μ) at the optimal setting is found to be 0.751.

3.1 Confirmation Experiment

To verify the mechanical properties of beta titanium alloy BT-20 welded plates by TiG welding process, the confirmatory experiment at the optimum setting of the parameters was carried out. The response values of experimental trial at optimum conditions are elongation=6.98%, UTS(U)= 1043MPa and Impact toughness =275Kj/m2. The grey relational grade values as per above experimental trial results found to be 0.821. The GRG value is improved by 9%.

1. Conclusion

Welding experiments were conducted on a TIG welding set up having shielding Argan gas flow from top and bottom side of the test pieces with 2.0mm Dia of tungsten electrode and 2.5mm thick plate of Beta titanium alloy as work material**.** The percentage elongation, ultimate tensile strength and impact toughness were recorded under different welding condition for various combination of welding parameters as per Taguchi orthogonal array. The following conclusion were drawn.

- It is revealed that nozzle to plate distance, gas flow rate and current level are prominent factors which affect the welding of beta titanium alloy. Nozzle to plate distance influence (P= 35.00%) more, followed by current (P= 10.00%) and Shielding gas flow rate (P=9.50%).
- The best mechanical properties were obtained with 2.0mm tungsten electrode diameter at Nozzle to plate distance of 2mm, current at 85A and g shielding gas flow rate is 11.0 litre per minute.
- Confirmation test results showed that determined optimum welding process parameters satisfy the real requirement of welding operation of Beta titanium alloy.

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Data availability : The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Clinical Trial Statement

This study did not involve any clinical trial, human participants, or animal subjects. Therefore, clinical trial registration is not applicable.

Declaration of Ethical Approval: This study did not involve human participants, animals, or any clinical investigations. Therefore, ethical approval was not required. All experimental work was conducted in accordance with relevant institutional guidelines and standard laboratory practices.

Declaration of Competing Interest: Authors have no conflicting interest to declare which is relevant to this article.

Consent to Participate : not applicable

Consent to Publish Declaration : All authors have reviewed and approved the manuscript and give their consent for its publication upon acceptance by the journal.

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