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Optimization of process parameters of TIG welding of duplex stainless steel without filler rod by grey-Taguchi method

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Input parameters of welding have played an important role in producing the quality of welding joint. Welding quality has been improved using proper process parameters with sound knowledge base. Current, welding speed and the shielding gas flow rate have been used as the most important influencing parameters of Tungsten Inert Gas (TIG) welding on Duplex Stainless Steel (DSS). In the present work, multi-objective optimization of TIG welding process parameters of Duplex Stainless Steel - ASTM/UNS 2205 has been determined. These welding process parameters have been optimized to achieve the required quality of DSS welding joints. The quality of the TIG welding on DSS has been evaluated in term of tensile test. The grey-based Taguchi technique has been used to solve this multi- optimization problem. Analysis of Variance (ANOVA) has been applied to evaluate the significance of the individual factors on desired results which are ultimate tensile strength, yield strength and percentage of elongation. Additional confirmatory experiment has been done to verify the optimal results. The application possibilities of the grey-based Taguchi method for incessant development of welding quality of DSS in many fields, like chemical industries, oil refineries, gas manufacturing industries etc. have been shown by this work.

Keywords: Anova, Duplex stainless steel, Optimization, Signal to noise ratio, Taguchi design, Tungsten inert gas welding

1 Introduction

Duplex stainless steel has many useful applications in fabrication work, often as a substitute of austenitic stainless steel and also in other areas of fabrication and manufacturing industries. The exceptional blend of double phase configuration of ferrite with austenite has been seen in DSS. Strength and corrosion resistance have been provided by Austenite structure and ferrite phase structure respectively.

Previous researchers have been performed extensive investigations on welding joints of different stainless steel materials using different welding processes with deferent welding parameters. Palani and Murugan[1] investigated the cladding effect on weld bead geometry using different factors, like current, welding speed, nozzle-to-plate distance at the time of welding. The material considered was stainless steel 317L, but not DSS. Del Coz Diaz et al.[2] used finite element technique with birth and death procedure to identify the significant role of material characteristics of dissimilar stainless steels. Zou *et al.*[3] investigated the effect of oxygen on crystallographic orientation in DSS weld. They showed that the duplex steels had characterized by high strength. Lakshmi narayanan *et al.*[4] investigated the mechanical and microstructural properties of AISI 409M ferritic stainless joints. Juang and Tarng[5] determined the best TIG weld bead structure. They used Taguchi technique to analysis the weld pool structure using different welding process factors like gas flow rate, arc gap, speed and welding current on stainless steel material. Tarng and Yang[6] optimized the weld bead geometry of GTAW process on stainless steel by Taguchi method. Tarng *et al.*[7] investigated on the optimal weld bead structure of TIG welded stainless steel to determine the process parameters by using modified Taguchi method. Tarng et al.[8] researched related to grey-based Taguchi technique to decide optimal process factors of submerged arc welding in hard facing. The Taguchi technique had been used by some researchers[9,10] to solve the optimization difficulties within the area of manufacturing technology. The process used a sensible investigational design said orthogonal array design with signal to noise ratio (S/N ratio). This obliged the objective functions to optimize within investigational domain. However, the multi-objective optimization

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problem cannot be evaluated by traditional Taguchi technique. To conquer this problem, Taguchi technique by grey relational analysis had an extensive use in TIG welding as well as in manufacturing and production engineering problems[11]. This hybrid grey-Taguchi analysis is able to execute multi response optimization problem successfully. Adenan *et al.*[12] observed the formation of thick hybrid layer on the surface of 2205 DSS in thermo chemical heat treatment of this material. Both carbon and nitrogen diffusions formed expanded austenite (γ N/C) and expanded ferrite (α C). However, the precipitation of nitride (Cr_2N) occurred at the layer, suggesting the possibility of deterioration of the corrosion resistance of 2205 DSS. Sotomayor *et al.*[13] determined the adhesive property of duplex stainless steel on a thermoplastic. They also examined the rupture failures of that material. Several conditions like humidity had significant role to evaluate the effectiveness of surface treatment.

In the present work, duplex stainless steel plates are joined by TIG welding. Nine butt-welding joints have been made by TIG welding under varying input parameters. The Taguchi's L9 orthogonal array design has been used to design the experiments, with three controllable factors, viz. current, welding speed and shielding gas flow rate. Factor levels have been chosen on the basis of trial runs and the knowledge of text book. Welding excellence has been evaluated by X-ray radiography test and tensile test of the weldment. Therefore, it is intended to determine the optimal process conditions of TIG welding of DSS to achieve desired weld qualities, like yield strength, ultimate tensile strength, and percentage of elongation. Grey–based Taguchi methodology for process optimization has been carried out to solve this multi–response optimization problem. After that, ANOVA test has been carried out to identify the significance of the individual factor on the desired responses, like ultimate tensile strength, yield strength and percentage elongation. Interaction effects of process parameters, like current, gas flow rate and speed of welding on ultimate tensile strength, yield strength and percentage of elongation have also been studied. Additional confirmatory experiment has been carried out to check the optimal result.

2 Materials and Methods

2.1 Taguchi method

Dr. Genichi Taguchi introduced a technique related to orthogonal array design of experiments with the concept of Signal to Noise (S/N) ratio. It creates optimum process control parameters, excellence of product and economy of the cost of the product. This technique is utilized for design of high quality manufacturing process in efficient and systematic way at reduced cost. It prepares less discrepancy for tests to get result by setting optimal process control factors. Thus, the preferred results are obtained by the addition of design of experiments with parametric optimization method in Taguchi technique. Orthogonal array gives the desired investigation with least number of investigational trials. Taguchi technique provides the numerical evaluation of signal to noise ratio. It is basically a logarithmic function in order to provide preferred result, in the form of objective functions of optimization. This relation takes together, the mean and changeability. Actually S/N ratio is the combined relation between mean of Signal and standard deviation of Noise. This technique helps to perform the analysis of testing results, to identify the optimal condition for desirable outcome. The S/N ratios are usually employed by three ways. They are: Lower the better (LB), Nominal the best (NB) and Higher the better (HB). The optimum arrangement is the factor combination which indicates the maximum S/N ratio.

2.2 Grey relational analysis combined with Taguchi method

Experimental results are the calculated quality uniqueness of products which were initially normalized, ranging from zero to one. This procedure is called grey relational creation. After that, grey relation co-efficients were evaluated to represent the co-relation between preferred and investigational data. Calculation was done on the basis of normalized investigational data. Next step was carried out by averaging the grey relational co-efficients to decide the overall grey relational grade. This evaluated grey relational grade was reliable for the uniqueness of multi response method. This technique changed the multi response optimization problem into the single response optimization condition. Here, the objective function was overall gray relational grade. The best factor setting was then subsequently determined to provide outcome of maximum grey relational grade. However, in grey based Taguchi method, the optimum condition was arrived at, by applying S/N ratio concept on the overall grey relation grades.

In case of lower the better principle of any organized data, as required, lower the better principle was employed and normalization of data i.e. grey relational generation was obtained by the following equation:

$$x_i(k) = \frac{\max\ y_i(k) - y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \quad ...(1)$$

The organized data of yield strength, ultimate tensile strength and percentage of elongation, as per the requirement for the larger value, normalized data was calculated by:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max\ y_i(k) - \min\ y_i(k)} \quad ...(2)$$

where, x_i (k) was calculated subsequent to grey relational creation, minimum $y_i(k)$ was the least measurement of $y_i(k)$ on behalf of k^{th} reply. Also maximum $y_i(k)$ was the biggest measurement of $y_i(k)$ on behalf of k^{th} reply.

The grey relational coefficient $\xi_i(k)$ was calculated by:

$$\xi_i(k) = \frac{\Delta_{min} + \psi\Delta_{max}}{\Delta_{0i}\ (k) + \psi\Delta_{max}} \quad ...(3)$$

where, $\Delta_{0i} = || x_0(k) - x_i(k) ||$ = difference between absolute measurement of x_0 (k) and x_i (k) ..(3a)

ψ is the differentiate coefficient $0 \leq \psi \leq 1$, $\Delta_{min} = \forall j^{min} \in i \forall k^{min} || x_0\ (k) - xj\ (k) ||$ = the least measurement of Δ_{oi}, also $\Delta_{max} = \forall j^{max} \in i\ \forall k^{max} || x_o\ (k) - xj\ (k) ||$ = biggest measurement of Δ_{oi}. The perfect series is x_0 (k) (k=1, 2, 3 ……), called as reference order or reference sequence, used for reply. Meaning of grey relation grade within the route of grey relational investigation was to reveal the level of correlation among the orders (number of orders is 9, if the number of trials or experiments is 9) [x_0 (k) along with x_i (k), i = 1, 2, 3…….. ,] The grey relational grade γ_i was expressed after calculating the average value of grey relational coefficients as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} \xi_i(k) \quad ...(4)$$

here, n = number of procedure responses. The bigger result of grey relational grade correlates with relational level between the reference order x_0 (k) and the set order x_i (k).

The reference order x_0 (k) presents most excellent procedure order; so, highest relation grade means that the resulting factor arrangement was closer to the optimum. The grand mean and the main effect of grey relational grade were evaluated from the mean response. They were extremely significant to evaluate the optimum process parameters. The Taguchi method was combined with grey relational grade. The concept of S/N ratio was used to determine the optimum parametric value.

2.3 Experimental works

In this experiment, TIG welding was performed on duplex stainless steel plates. The dimension of each welding pate was taken as 75 mm × 50 mm × 3 mm. Butt welding joint was completed. Filler rod was not utilized at the time of welding process. Argon gas was used as the shielding gas. The diameter of Tungsten electrode was 2.4mm. TIG welding on DSS was completed with the help of IGBT digital welding inverter (400A, III phase) of electra engineering (India) Pvt. limited. Materials were welded with suitable welding parameters like current, gas flow rate, welding speed. The photographic view of the arrangement of TIG welding equipment is shown in Fig. 1. Photographic view of welding sample no. 2 is shown in Fig. 2. The trial runs of welding joints and final welding joints were completed successfully with the help of these welding equipments.

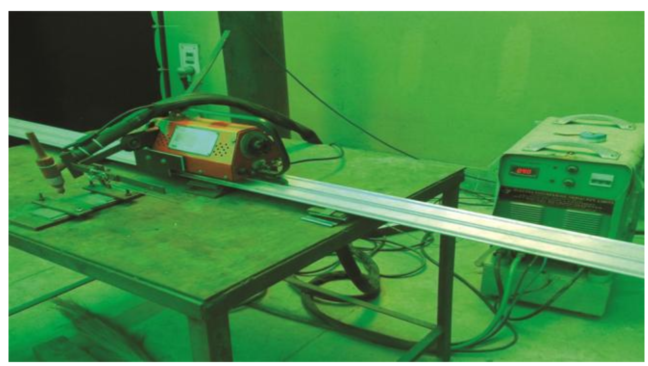

Fig. 1 — TIG welding setup.

Fig. 2 — Welding sample no. 2.

Table 1 — Composition of DSS

Composition of elements in %	C	Si	Mn	P	S	Cr	Mo	Ni	Al
	0.0210	0.2800	1.7200	0.0220	0.0140	22.6500	3.1800	4.7300	0.0100
	Co	Cu	Nb	Ti	V	Pb	Fe	N	
	0.0780	0.0090	0.0400	0.0080	0.0110	0.0030	67.123	0.1010	

Table 2 — Welding process factors with their levels

Factors	Units	Notations	Levels		
			1	2	3
Welding Current	A	C	80	85	90
Gas Flow Rate	l/min	F	7	7.5	8
Welding speed	mm/s	S	2.3	2.8	3.5

Table 3 — Orthogonal array design of 3rd levels with using values

Run	Welding current (C) in A	Shielding gas flow rate (F) in l/min	Welding speed (S) in mm/s
1	80	7	2.3
2	80	7.5	2.8
3	80	8	3.5
4	85	7	2.8
5	85	7.5	3.5
6	85	8	2.3
7	90	7	3.5
8	90	7.5	2.3
9	90	8	2.8

Base metal

In this study the base metal was a duplex stainless steel (ASTM/UNS: 2205). The chemical composition of this DSS material is shown in Table 1. The microstructural feature of the base metal exhibits a duplex structure with embedded grains of austenite and ferrite.

Process parameters and their levels

The process factors were decided based on several experimental trials. Here, 3 levels of current, 3 levels of gas flow rate and 3 levels of welding speed were taken to complete the joining process. Welding process factors with their levels are listed in Table 2.

Experimental plan

In present work, Taguchi's orthogonal array design of experiment, L9 was used in sequence to recognize the optimal factor arrangement for preferable welding excellence. Nine butt joint TIG welded samples were created to determine the results of ultimate tensile strength, yield strength and percentage of elongation. Taguchi's orthogonal array (3^{rd} level designs) is shown by Table 3 below.

Table 4 — Outcomes of X-ray radiography examination

Sample no.	Observation	Remarks
1	Little undercut	Acceptable
2	No significant defects	Acceptable
3	No significant defects	Acceptable
4	No significant defects	Acceptable
5	Capping undercut	Acceptable
6	No significant defects	Acceptable
7	No significant defects	Acceptable
8	No significant defects	Acceptable
9	No significant defects	Acceptable

X-ray radiography examination

X-ray and gamma ray were utilized to identify disruption and inclusion inside the opaque material. X-ray picture of inner portion of weld was seen on a fluorescence screen and also on developed film. The X-ray radiography investigation of DSS welding samples (each sample size is 3″x6″, butt joint) was performed at Inspection survey & surveillance (India) Pvt. ltd. The outcomes of x-ray radiography test are shown in Table 4. Figure 3 shows the X-ray radiographic images of sample no. 4 & 9 out of nine samples.

3 Results and Discussion

3.1 Tensile test and results

Completing X-ray radiography investigation, tensile testing samples were created from the TIG welding plates, by Electronica sprintcut-734 wire electrical discharge machining (WEDM) (input power supply 3 Phase, AC 415 V, 50 Hz, linked load 15 KVA). Photographic view of tensile specimen preparation by WEDM is shown in Fig. 4(a) Photographic view of tensile test specimens as per ASTM E8 is shown in Fig. 4(b) and tensile sample after test is shown by Fig. 4(c).

The tensile testing samples were investigated with the help of tensile testing machine Instron by Blue star engineering & electronics Ltd, Model no. : BSUT-60-JD-SERVO, serial no. : 2016/048, maximum capacity: 600 KN. Data related to tensile strength are listed in Table 5. These results were used for analysis and evaluate the optimal factor arrangement which was very much necessary to

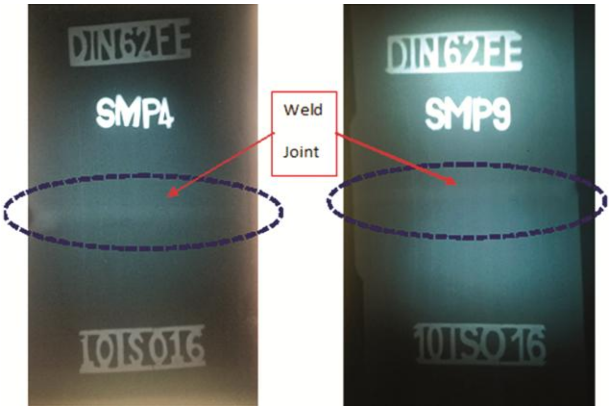

Fig. 3 — X-ray radiography film of sample no. 4 & 9.

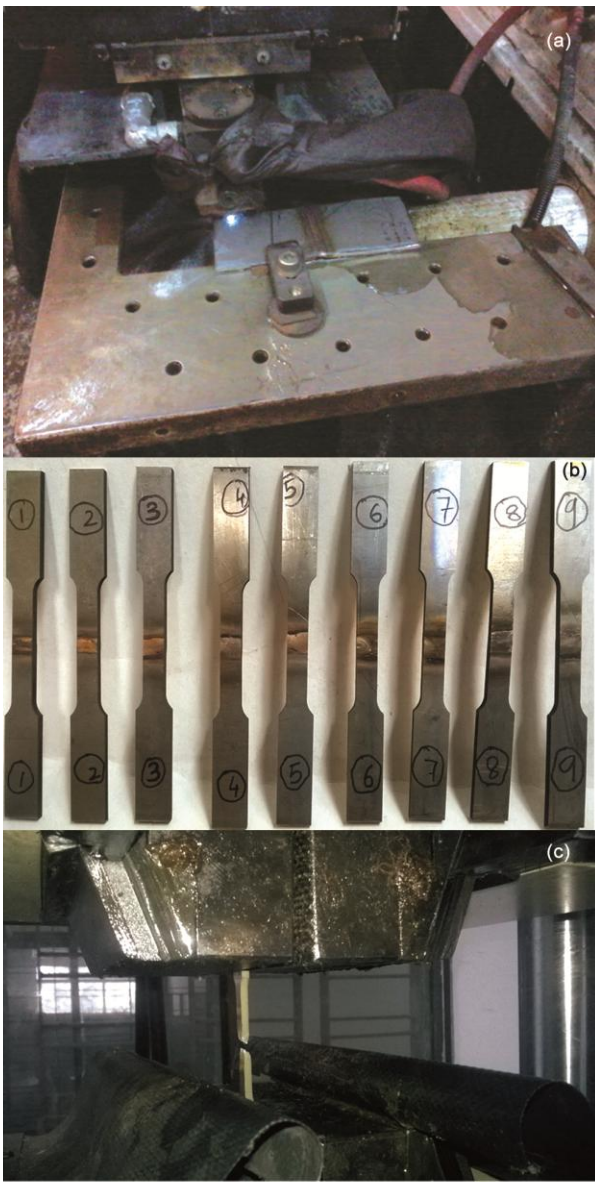

Fig. 4 — (a) Tensile specimen, (b) tensile test specimens, and (c) tensile sample after test.

Table 5 — Tensile test results

Sample no.	Yield strength (MPa)	Ultimate tensile strength (MPa)	Percentage of elongation (%)
1	183.3	460	10.4530
2	236.7	595	11.6650
3	253.3	635	17.7770
4	243.3	610	14.9470
5	260	645	14.9070
6	253.3	630	11.9810
7	256.7	640	14.0340
8	243.3	610	10.9380
9	260	650	14.4790

Table 6 — Results preprocessing of every performance quality (grey relational generation)

Experiment no.	Yield strength	Ultimate tensile Strength	Percentage of elongation
Ideal sequence	1	1	1
1	0	0	0
2	0.696219	0.710526	0.165483
3	0.913838	0.921053	1
4	0.782269	0.789474	0.613599
5	1	0.973684	0.608138
6	0.913838	0.894737	0.208629
7	0.956975	0.947368	0.48894
8	0.782269	0.789474	0.066221
9	1	1	0.5497

realize the desire excellence of TIG weld within the experimental domain.

3.2 Parametric optimization

In this present study, TIG welding process parameters were optimized using grey-Taguchi method. Normalized investigational results were transferred into grey relational co-efficient of every quality characteristics. Then, grey relational co-efficient for every response was collected to calculate grey relational grade. Larger result of grey relational grade with equivalent to factor arrangement was understood to be nearer of the optimal.

3.3 The procedure and results in each step

Firstly investigational results were created into normalized data (Grey relation generation). Higher-the-better condition was chosen for percentage of elongation, yield strength and ultimate strength (Eq. 2 is used). These normalized results for every factor of yield strength, ultimate strength and percentage of elongation have been tabulated in Table 6.

To calculate grey relational coefficient the value of Δoi for each of the responses was required, which is shown in Table 7. The grey relational co-efficient of every performance quality was evaluated with the help of Eq. 3, tabulated in Table 8. After that, this grey

Table 7 — Calculation of Δoi for each of the responses

Experiment no.	Yield strength	Ultimate tensile strength	Percentage of elongation
Ideal sequence	1	1	1
1	1	1	1
2	0.303781	0.289474	0.834517
3	0.086162	0.078947	0
4	0.217731	0.210526	0.386401
5	0	0.026316	0.391862
6	0.086162	0.105263	0.791371
7	0.043025	0.052632	0.51106
8	0.217731	0.210526	0.933779
9	0	0	0.4503

Table 8 — Grey relation co-efficient of each performance characteristics (withψ=0.5)

Experiment no.	Yield strength	Ultimate tensile strength	Percentage of elongation
Ideal sequence	1	1	1
1	0.333333	0.333333	0.333333
2	0.62206	0.633333	0.374667
3	0.853007	0.863637	1
4	0.69664	0.703704	0.564079
5	1	0.95	0.560625
6	0.853007	0.826087	0.387185
7	0.920768	0.904761	0.49453
8	0.69664	0.703704	0.348729
9	1	1	0.52615

Table 9 — Grey relational grades

Experiment no.	Grey relational grade
1	0.333333
2	0.543353
3	0.905548
4	0.654808
5	0.836875
6	0.68876
7	0.773353
8	0.583024
9	0.84205

relational co-efficient of every response was collected to calculate grey relational grade with the help of Eq. 4. This was overall feature of every characteristics in weld quality. This overall grey relational grade has been tabulated in Table 9. Therefore, the single objective optimization problem was prepared from multi-criteria optimization problem by grouping the Taguchi technique and grey relational analysis. Grey relational grade's larger result is indicating the optimal result of related factor combination. Response for S/N Ratios tabular form of overall grey relational grade has been shown in Table 10. The Main effect plot for S/N ratios and the Main effect plot for means are shown in Figs 5 & 6 respectively. The S/N ratio for overall grey relational grade was evaluated with the help of larger-the-better principle by Eq. 5.

Table 10 — Response Table for S/N Ratios Larger is better

Level	C	F	S
1	-5.234	-5.151	-5.822
2	-2.821	-3.844	-3.490
3	-2.804	-1.865	-1.547
Delta	2.430	3.286	4.275
Rank	3	2	1

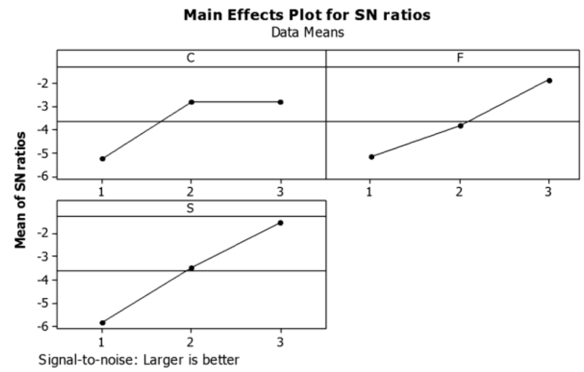

Fig. 5 — Main effect plot for SN ratios.

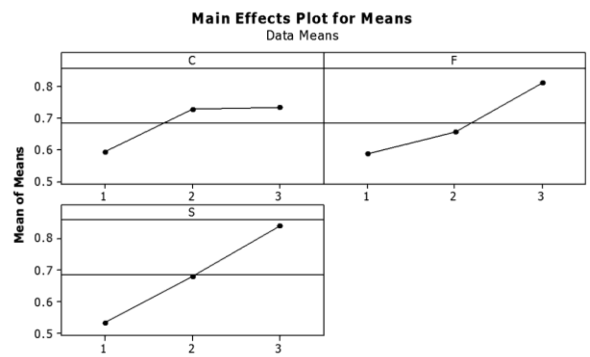

Fig. 6 — Main effect plot for means.

$$\text{SN (Larger-the-better)} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad ...(5)$$

where, n indicates no. of measurements, y_i indicates measurement of quality significance.

The responses of every welding factor were evaluated by orthogonal investigational design at every level. As per example, at first calculate the average of grey relational grades which are called mean grey relational grades. These mean grey relational grades were evaluated for current level 1, 2, 3. The mean grey relational grade proportion for every stage of other factors was calculated in same way (Table 11). Total mean grey relational grade was also evaluated through averaging the total entries.

Table 11 — Response table of overall mean grey relational grade

Level	C	F	S
1	0.5941	0.5872	0.5350
2	0.7268	0.6544	0.6801
3	0.7328	0.8121	0.8386
Delta	0.1387	0.2250	0.3036
Rank	3	2	1
Total mean Grey relational grade=0.684567			

The results in this table are not the final one because here the method was combined Grey-Taguchi. Taguchi's S/N ratio concept was applied next.

The Main effect plot for S/N ratios and the Main effect plot for means of overall grey relational grade are shown in Figs 5 & 6 respectively. Total mean grey relational grade is also given in the Table 11.

Using Figs 5 & 6, optimal parameter arrangement was evaluated by considering higher the better principle.

From the main effect plot for S/N ratios and main effect plot for means, it is clear that the optimal parameter setting evaluates C3, F3 and S3 which means current is 90 A, gas flow rate is 8 l/ min and speed of welding is 3.5 mm/s.

3.4 Confirmatory experiment

After evaluating the optimal factor setting, it was necessary to confirm the development of quality uniqueness with the help of optimal parametric arrangement. The expected grey relational grade was evaluated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{0}(\overline{\gamma_i} - \gamma_m) \quad ...(6)$$

where, γ_m indicates overall mean grey relational grade, $\overline{\gamma_i}$ indicates mean grey relational grade at optimum stage. Also, o denotes the quantity of most important design parameters which influence excellence performances. Expected grey relational grade is equal to the mean grey relational grade plus summation of differentiation between mean grey relational grade and overall mean grey relational grade at optimal level of every factor. Table 12 shows contrast of predicted strength parameters along with the percentage of elongation with the actual results by utilizing the optimal TIG welding parameters. Here, excellent agreement was seen between these. It gave the evidence of the usefulness of this proposed work related to product/ process optimization. Here, more than single objective was satisfied at the same time. Basically, in grey based Taguchi technique, the purpose is to find out a factor arrangement which accomplished the maximum overall grey relational grade. Here, characteristic aspect was only the overall grey relational grade. All individual performance characteristics were represented by grey relational grade. Objective functions were chosen related to parameters. And every response was specified with equivalent influence. The Taguchi optimization method and the best parametric arrangement calculation were dependent on the response variables chosen and also their own influences.

Table 12 — Result of confirmatory experiment

	Factor setting	Experimental factor setting by optimal process condition	
		Prediction	Experiment
Level of factors	C3F1S3	C3F3S3	C3F3S3
Yield strength	256.9	262	270
Ultimate tensile strength	642	654	665
Percentage of elongation	14.253	16.207	17.061
S/N ratio of Overall Grey relational grade	-2.0947	-0.9154	-0.48691
Overall Grey relational grade	0.785715	0.899974	0.945485
Improvement of Grey relational grade =0.15977			

3.5 Analysis of variance (ANOVA)

ANOVA is a statistical analysis method. It provided some significant conclusions through the analysis of investigational results. This technique was extremely constructive to expose the importance level of effects of factor(s). It segregated the whole response changeability (sum of squared deviations regarding grand mean) into contributions rendered by every parameter and mistake. Therefore,

$$SS_T = SS_F + SS_E \quad ...(7)$$

$$SS_T = \sum_{j=1}^{p}(\gamma_j - \gamma_m)^2 \quad ...(8)$$

where, SS_T – Total sum of squared deviations concerning the mean,

γ_m – Grand mean of the response, γ_j – Mean response for j th testing,

P – Number of the experiments within orthogonal array; , SS_E is the sum of square deviation by fault; , SS_F is the sum of square deviations by every factor.

The mean square deviation was calculated with the help of ANOVA table is defined as:

Table 13 — Analysis of Variance utilizing Adjusted SS for experiments

Source	DF	Seq SS	Adj SS	Adj MS	F	P
C	2	0.036901	0.036901	0.018450	9.16	0.098
F	2	0.079997	0.079997	0.039999	19.86	0.048
S	2	0.138308	0.138308	0.069154	34.33	0.028
Error	2	0.004029	0.004029	0.002014		
Total	8	0.259235				

S = 0.0448819 R-Sq = 98.45% R-Sq(adj) = 93.78%

$$MS = \frac{\text{SS (Sum of squared deviation)}}{\text{DF (Degr ee of freedom)}}$$

F value of Fisher's F ratio (Variance ratio) is defined as:

$$F = \frac{MS\ for\ a\ term}{MS\ for\ the\ error\ term}$$

P value (probability of significance) was next evaluated with the help of F value.

ANOVA analysis of overall grey relational grade is shown by Table 13. Here, MINITAB release16.2.1 (user manual) was used.

Here, the P value of welding speed (S) became 0.028 which is less than 0.03 (97.2% confidence level). Hence, it suggests that welding speed is major important factor. The P value of gas flow rate (F) became 0.048 which is less than 0.05 (95.2% confidence level). The least significant factor was current (C) whose P value is highest, 0.098 (90.9% confidence level).

The value of R-sq implies that at least 98.45 % of variability in data for the responses was explained by the experimental model.

The significance of the factors revealed by ANOVA is consistent with the calculations listed in table 10 .Current is shown with rank 3 in table 10, welding speed with rank 1 .The same is observed in Table 11 as well.

4 Conclusion

Based on the results of present investigation and analysis of the experimental data, the following conclusions have been drawn in respect of TIG welding of Duplex Stainless Steel ASTM/UNS: 2205.

a) Combined methodology of Taguchi optimization procedure and grey relational analysis has been successfully utilized to determine the optimum result of multi objective optimization of yield strength, tensile strength and percentage of elongation of TIG welding of duplex stainless steel.

b) The optimal parametric combination has become C3, F3, S3 i.e. welding current is 90 A, Gas flow rate is 8 l//min and welding speed is 3.5 mm/s.

c) ANOVA has shown that the most significant factor is welding speed, whereas welding current contributes the least, in so far as multi-objective criterion has been concerned.

d) The confirmative test has validated the result obtained from grey-based Taguchi method.

e) Present optimized values with the corresponding levels of the input parameters, have led to sound butt joint, and it has been tested in the present study.

f) The present study has established the application feasibility of grey–based Taguchi method for solving multi-objective optimization problem in the area of TIG welding of duplex stainless steel.

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