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Microstructure analyses and comparison of optimization results for GTAW process parameters through different advanced statistical tools

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Abstract: Gas Tungsten Arc welding (GTAW) widely uses for many welding applications, especially for good quality welds in fabrication, manufacturing, and construction industries. Perfection level exhibits by the weld are associated with the entire volume of the weld, its profile, surface appearance, and microstructure and show the quality of that weld. Several controllable process parameters may affect the quality of weld in terms of weld shape, bead, imperfections, and desire mechanical/chemical properties. Therefore effect of some important parameters like current, travel speed, and gas flow rate on the final weld structure and its quality for SS TP304L material are studied through different experiments and analyses by using a design of experiment-based advanced statistical tools. Joints weld by using several levels of these parameters and then weld quality of these joints analyze in terms of ultimate tensile strength, and hardness. The optimization results of different statistical techniques compare to find the accuracy of this study. Moreover, the microstructure of final weldment welded based on optimal results is also analyzed. Therefore this study finds out the best welding conditions for the quality weld after optimizing these process parameters.

Keywords: Design of experiment, microstructure, optimizing, statistical, tensile strength, weld quality

1. Introduction

Gas Tungsten Arc welding (GTAW) is also known as Helium Arc or tungsten inert gas welding. This process was initially developed in the 1930s BY Russel Meredith [1] to weld magnesium by using inert gas of helium and tungsten as an electrode. This process replaced riveting and helped to joined aircraft components of Al & Mg by welding through this process. Previously there are many refinements, and changes apply to this process. But the HeliArc welding process that was demonstrated by Meredith and developed in the aircraft industry has continued to this day with no change in its fundamentals. Direct current electrode negative with the Tungsten electrode initiate stable arc and can produce an excellent weld. Since from invention number of improvements was made in this process, including a constant current power source, water or gas-cooled torches were developed, and the tungsten electrode was alloyed with some active elements to improve and made stable emissivity [1,2]. Gases and their blends were also introduced to improve the performance of this process [3].

In this process, the non-consumable electrode of tungsten is used to initiate an arc and to melt the metals. The electrode always held in a torch, which is connected to a gas source to provide gas for shielding. The contact tube is a watered cool copper tube and is used to connect an electrode with the power source. The contact tube also provides cooling to prevent over-heating, whereas the workpiece attaches to a power source with another cable. Shielding gas moves through Torch in a nozzle and directs towards the weld pool area. This kind of shielding is more useful as compared to the shielding in the SMAW process because of two reasons. One is the use of argon or helium (as inert gases), and the second is that gas nozzle directed towards the weld area. Sometimes non-inert gas also used in small quantities, so GTAW looks more appropriate name for this process. For thicker sections, when the filler rod uses, then it can be added manually or automatically into the arc [4].

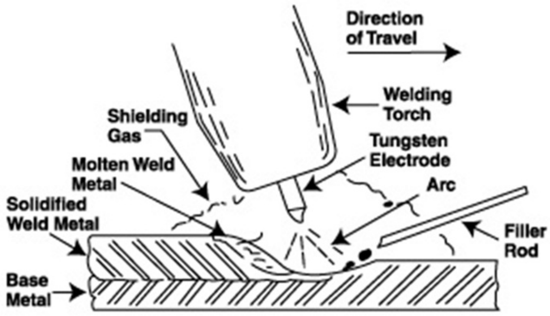


Figure 1. Gas Tungsten Arc Welding process [5]

2. Design methodology

For this work, the orthogonal array method of the Taguchi technique [6] selected with three levels of three welding variables (Current, gas flow rate, and travel speed) and two responses (Ultimate tensile strength and hardness). Then the S/N ratio has computed for each process level analysis. Here a higher S/N ratio of any process parameter level corresponds to the optimum level. In S/N ratio analyses for UTS "larger the better" and for hardness "smaller the better" was selected as a target for calculations. By design of experiment using central composite design (CCD) of response surface analyses used for optimization [7] along with desirability function [8]. ANOVA for variance analyses [9] also performed. Finally, confirmation weld welded to ascertain the optimization results.

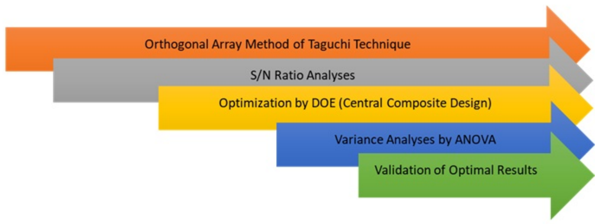


Figure 2. Design methodology for GTAW optimization

3. Experiment set up and plan

The material used in the welding shop for each run of welding was a 6mm thickness stainless steel plate of material ASTM A240 TP 304L with a single bevel angle. This material is selected because this is a common stainless steel material that uses for the fabrication of pressure vessels, heat exchangers, and tanks in the oil and gas field. Chemical composition of this material is given below [10]:

Specification	Type	Carob, C	Manganese, Mn	Phosphorous, P	Sulfur, S	Silicon, Si	Chromium, Cr	Nickel, Ni	Nitrogen, N
A 240	Austenitic (Chromium-Nickel) (Chromium-Manganese-Nickel)								
	304L	0.03	2	0.045	0.03	0.75	17.5-19.5	8.0-12.0	0.1

Where response values are measured in actual, whereas mechanical tests performed in Mechanical testing Lab against each run of the experiment. Specimens for tensile testing prepared from weld pieces in a transverse direction to the welds in transverse and then GALDABINI SUN60-V630 machine (where UTS=Max. Load/Original cross-section area) used for tensile testing. Then hardness of weld and HAZ area were measured by using Wilson Hardness 432SVD machine. Average of hardness readings for each piece was used to present hardness value for weld metal. Weld Joints design, geometry, and typical layout for hardness testing locations given below in Figure 3 and GTAW welding equipment and machines used for testing in experimental work shown in Figure 4.

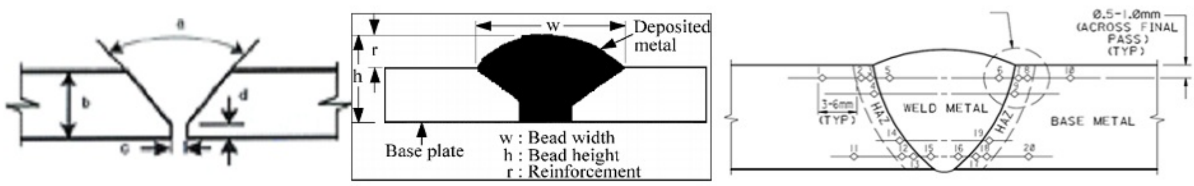


Figure 3. Weld Joint Design/geometry and hardness test location [WPS used for welding given in Annexure-4]

Figure 4. GTAW welding equipment, UTS and hardness machines used for experiment work

The experimental layout of this study was consist of an L9 orthogonal array. Three important variables with three levels each selected as factors are (A: Current, B: Gas flow Rate and C: Travel speed), and two responses are (Y1: UTS, Y2: hardness), as shown in Tables 1 & 2. Factors are continuous where continuous means those factors which can be assigned some numerical values. The level of process variables and relevant response values shown in Table 3. For analyses, each level of process variable S/N ratio computed where a higher S/N ratio meant better quality characteristics. Therefore the highest S/N ratio corresponds to an optimal value. S/N ratio for UTS and hardness and then based on the different ranking of variables calculated shown in Tables 4 & 5. Formulas used here for calculating responses as larger the better (UTS) and smaller the better (hardness) given in below Eqs. (1) & (2). Here n is no. of variables and Y response values.

$$S/N(\text{Largest the best}) = -10 * log(\sum(1/Y2)/n), \tag{1}$$

$$S/N(\text{Smallest the best}) = -10 * log(\sum(Y2)/n). \tag{2}$$

Table 1. Factors for the experiment

Name	Units	Type	Role	Level 1	Level 2	Level 3
A:Current	Amp	Continuous	Controllable	80	115	150
B:Gas Flow rate	L/Min	Continuous	Controllable	8	10	12
C:Travel Speed	mm/Min	Continuous	Controllable	80	95	110

Table 2. Responses Selected for the experiment

Name	Units	Analyze	Goal
Y1: Ultimate Tensile Strength (UTS)	MPA	Mean	Maximize
Y2: Hardness	HRB	Mean	Minimize

Table 3. GTAW L9 orthogonal arrays data for the experiment

	Factors					Responses		
Experiment No.	Levels			Current (A)	Gas Flow Rate (B)	Travel Speed (C))	UTS (Y1)	Hardness (Y2)
				(Amp)	(L/Min)	(mm/Min)	(MPa)	(HRB)
1	1	1	1	80	8	80	496	87.96
2	1	2	2	80	10	95	507	84.68
3	1	3	3	80	12	110	555	91.42
4	2	1	2	115	8	95	526	85.26
5	2	2	3	115	10	110	544	77.39
6	2	3	1	115	12	80	511	79.88
7	3	1	3	150	8	110	571	81.44
8	3	2	1	150	10	80	533	75.11
9	3	3	2	150	12	95	564	72.66

4. S/N ratio analyses

Each factor effect on responses and then their ranking based on the S/N ratio given in Table 4 & 5. For factors ranking (a), the gas flow rate has a major effect along with traveling speed, whereas current has the least impact on Hardness. Because a low gas flow rate causes porosity, and a very high gas flow rate causes to increase brittleness. Then very high/low traveling speed causes a sudden increase and decrease in weld joint temperature, and in HAZ, this causes high hardness, which is not desirable.

Similarly, from Rank (b), we can see current and gas flow rates have a major impact, whereas travel speed has the least. Because current along with proper gas flow rate controls metal transfer rate, penetration, spatters, post-weld cleaning and therefore affects the quality of the weld by influencing metallurgical and mechanical properties. From these analyses, a high value of UTS i-e 564 MPa observed when a current was 150 A and gas flow rate value 12L/min. Similarly, the lower value of hardness 72.66 found when the Gas Flow rate was 12l/min with a travel speed of 95 mm/min.

Table 4. S/N Ratio for responses SN-L for UTS and SN-S for hardness

UTS Y1	Hardness Y2	Y1∧2	y2∧2	SN-S	1/y1′2	1/y2′2	sum	SN-L
496	87.96	246016	7736.962	-51.0338112	4.0648E-06	0.00012925	0.00013331	19.3756134
507	84.68	257049	7170.702	-51.209352	3.8903E-06	0.00013946	0.00014335	19.2180621
555	91.42	308025	8357.616	-51.9918262	3.2465E-06	0.00011965	0.0001229	19.5522789
526	85.26	276676	7269.268	-51.5220464	3.6143E-06	0.00013757	0.00014118	19.2511376
544	77.39	295936	5989.212	-51.7886938	3.3791E-06	0.00016697	0.00017035	18.8433406
511	79.88	261121	5279.476	-51.2670512	3.8296E-06	0.00018941	0.0001546	19.0539111
563	81.44	316969	6632.474	-52.0716088	3.1549E-06	0.00015077	0.00019257	18.5770835
533	75.11	284089	5641.512	-51.6096424	3.52E-06	0.00017726	0.00018078	18.7142785
571	72.66	326041	6380.814	-52.2065952	3.0671E-06	0.00015672	0.00015979	18.9822941

Table 5. S/N Ratio and ranking for factors

Factors	Current, A	Gas Flow Rate, B	Travel Speed, C	Factors	Current, A	Gas Flow Rate, B	Travel Speed, C
low	-51.4117	-51.5875	-51.3035	low	19.38198	19.20301	19.04793
High	-51.7443	-51.6564	-51.7984	high	18.90367	18.99316	19.0707
Delta (Difference)	0.33261	0.068878	0.494852	Delta	0.478311	0.209856	0.022765
Rank (a)	1	3	2	Rank (b)	3	2	1

5. Design of experiment by central composite design

Central Composite Design [11] is a response surface methodology used to design this experiment. This methodology not only fits the quadratic model with sequential experiments but also a useful and accurate model for confounded factor interactions with quadratic effects up to 4th order [9].

The quantitative relation between responses and factors in term of response surface methodology expressed as follow:

$$Y = f(Current,\ Gas\ flow\ rate,\ Travel\ speed),$$

whereas Y is the responses that are to be optimized, and the other is a function of the controllable factors.

The system behavior obtained through the quadric model, which was developed through the least square method by considering the interaction of factors to maximize or minimize the response variables.

Eq. 3 that derived by Douglas C. Montgomery in statistical quality control and used for the development of a quadratic model.

$$\begin{aligned} Y =& \beta_0 + \beta_1(\text{Current}) + \beta_2(\text{Gas flow rate}) + \beta_3(\text{travel speed}) \\ &+ \beta_{11}(Current^2) + \beta_{22}(\text{gas flow rate}^2) + \beta_{33}(\text{travel speed}^2) + \beta_{12}(\text{current*gas flow rate}) \\ &+ \beta_{13}(\text{current*travel speed}) + \beta_{23}(\text{gas flow rate*travel speed}). \end{aligned} \quad (3)$$

Here betas are linear, quadratic, and interaction coefficients of input factors. The β_0 is the intercept term, whereas $\beta_1/\beta_2/\beta_3$ and $\beta_{11}/\beta_{22}/\beta_{33}$ are the linear terms and interaction between variables terms, respectively. To give flexibility in additional design levels can also be defined by introducing star/axial and center points.

Formula for calculating no of experiments is, N = 2^n + 2*n + n_c

Here N represents total experiments, n No. of factors and n_c No. of star points as shown in Figure 5.

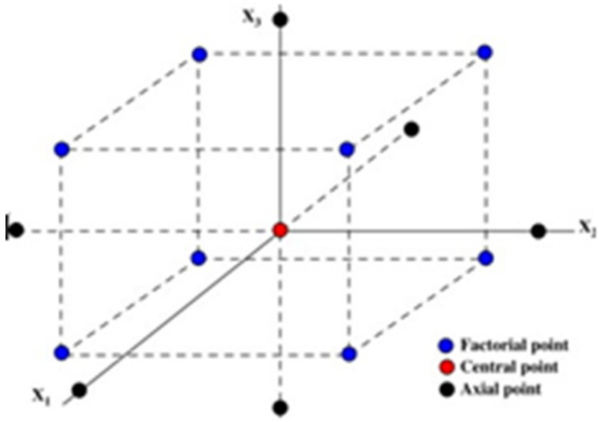


Figure 5. Selection of factors level in Central composite design

It is a rotatable composite design because it provides a constant prediction for all points which are midway between the design center placed in last. The star points in the rotatable center composite design are the distance of each axial point. With three factors and n_c =4 star points, 18 experiment runs calculated by using the above formula, and with one replica total of 36 experiment runs are obtained. The DOE summarizes in Table 6, and the detail of the experiment data is given in Table 7 [12].

Table 6. Design of Experiment

Type of Factors	Design Type	CenterPoint Per Block	CenterPoint Placement	Replica yes	Design is Randomized	Total Runs
Process	Central composite design: 2∧3 + star	12	Last		Yes	36

6. Variance analyses by anova

Analyses of variance (ANOVA) also performed to investigate the influence of controllable factors on measured responses through p-value by using Stat Graphics software [13]. In Hypothesis testing, when the null hypothesis is true P-Value shows probability for a given statistical model to find the significance of results. Before experimenting, first choose a model and threshold value of p, which is called "significance level," normally 5% or 1%, and denoted as α (here 5% has selected). Normally 5% or 1% and denoted as α (here 5% has selected). Very small p-value i-e less than 0.05 shows strong indication against the null hypothesis, whereas a large p-value greater than 0.05 shows weak indication against the null hypothesis. But when P values are close to the cutoff i-e 0.05, then it could be marginal going either way. Degree of freedom tells about independent no of information that went into the calculation of estimate & depends upon the exact design of your test. If Df is one, then it all about means.

Table 7. Experiment data of CCD analyses

Run	A- Current	B-Gas Flow Rate	C-Travel Speed	Y1-UTS	Y2-Hardness	Desirability
Unit	(Amp)	(L/Min)	(mm/Min)	(MPa)	(HRB)	dy1/dy2
1	150	12	80	562	75.25	0.904/0.846
2	80	8	110	496	84.68	0/0.352
3	80	12	110	555	74.92	0.808/0.863
4	150	10	110	548	75.26	0.712/0.846
5	80	12	80	516	73.53	0.273/0.936
6	150	12	110	543	72.32	0.643/1
7	80	8	80	496	87.03	0/0.229
8	150	8	110	533	78.91	0.506/0.654
9	80	8	95	529	77.66	0.452/0.720
10	115	8	80	510	79.96	0.191/6
11	115	8	95	519	75.87	0.315/0.814
12	150	10	80	534	76.03	0.520/0.805
13	150	12	95	563	72.66	0.917/0.982
14	115	8	110	522	81.49	0.356/0.519
15	80	8	80	504	85.96	0.109/0.285
16	80	10	95	507	84.68	0.150/0.352
17	150	8	95	506	78.69	0.136/0.667
18	150	8	80	511	79.48	0.205/0.625
19	115	10	110	531	76.23	0.479/0.795
20	115	12	80	511	78.51	0.205/0.676
21	80	10	80	519	77.66	0.315/0.720
22	80	10	95	516	76.41	0.273/0.786
23	150	12	95	565	72.46	0.945/0.992
24	115	12	95	556	74.61	0.821/0.880
25	115	12	110	534	73.09	0.520/0.959
26	150	10	80	543	75.11	0.643/0.854
27	150	10	95	535	78.76	0.534/0.662
28	80	10	110	513	77.89	0.233/0.708
29	80	12	95	527	73.68	0.424/0.928
30	115	10	80	523	75.21	0.369/0.848
31	115	10	95	544	77.54	0.657/0.726
32	80	12	110	555	91.42	0.808/0
33	115	8	95	526	85.26	0.410/0.322
34	115	10	110	544	77.39	0.658/0.734
35	115	12	80	513	78.58	0.233/0.672
36	150	8	110	569	80.15	1/0.590

Variance analyses for weld hardness and ultimate tensile strength are calculated and given in Tables 8 and 9. For Standard Pareto charts, see Figure 6.

Table 8. Variance Analyses for hardness

Hardness	Sum of Squares	Df	Mean Square=Sum of Square/Df	F-Ratio=Mean Square/Error	P-Value
A:Current	55.6206	1	55.6206	2.10	0.4984
B:Gas Flow rate	13.9458	1	13.9458	0.53	0.0401
C:Travel Speed	89.5540	1	89.5540	3.38	0.0487
AB	42.0986	1	42.0986	1.59	0.2480
AC	70.1808	1	70.1808	2.65	0.1478
BC	4.04630	1	4.04630	0.15	0.7077
R-sq. = 77.9316 %, R-sq. (adjusted for d.f.) = 46.4052 %, Std. The error of Est. = 5.14914, Mean absolute error = 2.75586					

ANOVA Table 8 [13] shows hardness variability for each factor separately and their interactions as well. A P-Value, less than 0.05 for any factor and their interaction, shows significance in these analyses. Therefore based on P values from this table, we can say gas flow rate and traveling speed have a direct momentous effect on hardness. Although P values for the interaction of travel speed and current (AC) are more than 0.05 difference is very less. R-squared value (which shows how much model fitted in variability) is 77.93% for hardness.

Similarly, standard error, which quantifies the precision associated with statistical analyses, is 5.15. Mean absolute error, which is an average of absolute errors, and it quantifies how close the forecast or predictions are. Less value means less error, which is, in this case, is 2.76. Below, the Pareto chart drawn for hardness in Figure 6 shows the same.

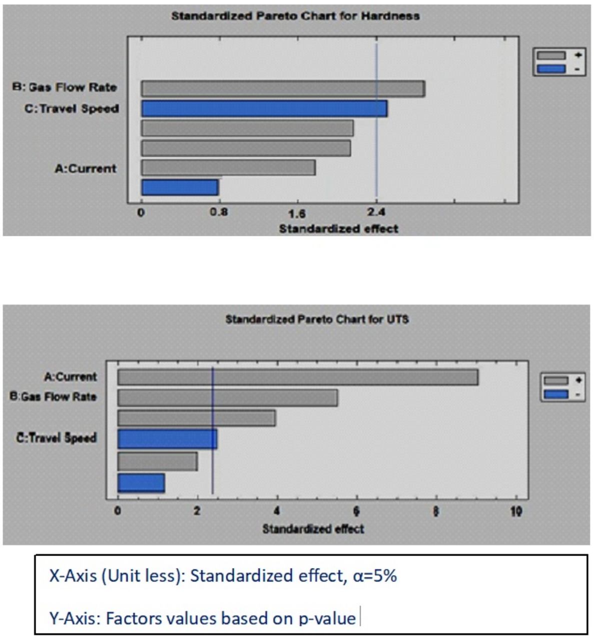


Figure 6. Standard Pareto charts for hardness and UTS

Table 9. Variance analyses for UTS

UTS	Sum of Squares	Df	Mean Square=Sum of Square/Df	F-Ratio=Mean Square/Error	P-Value
A:Current	8779.18	1	8779.18	81.81	0.0375
B: Gas Flow Rate	3265.09	1	3265.09	30.43	0.0419
C:Travel Speed	666.002	1	666.002	6.210	0.0833
AB	61.8857	1	61.8857	0.580	0.0472
AC	4.72500	1	4.72500	0.040	0.2398
BC	1138.67	1	1138.67	10.61	0.6539

R-sq. = 96.4706 %, Std. An error of Est. = 10.3591, Mean absolute error = 5.20509

ANOVA Table 9 [13] shows the ultimate tensile strength variability for each factor separately and their interactions as well. All P values of less than 0.05 can see in Table 9. From this table, we can say current has a significant effect on tensile strength along with combination (AB) with a gas flow rate. Because current also governs arc initiation, and its instability and a big change in current can also affect weld strength and weld quality by metallurgical effects as well. R-squared value (as explained in hardness analyses under Table 8) shows the model is fitted 96.4706% of variability for tensile strength. Similarly, the standard error is 10.3591, and the mean absolute error is 5.20509.

Based on the above variance analyses, standard Pareto charts draw for hardness and UTS [13]. Absolute values of the standardized effects can see from Pareto charts. The reference line depends upon the significant level and indicates the effects of significance.

The X-Axis is unitless in the graph and shows a standardized effect of affecting factors. Cut off p-value has selected 2.5 (α=5%) on a scale, and bars drawn for major affecting factors and their combinations along Y-Axis. Two colors with sign +/- shows factor's increasing/decreasing effects.

From charts, we see the gas flow rate along with travel speed has the main effect, and similarly, current, and Gas flow rates have the main effects on UTS.

7. Desirability function

For optimization, desirability and loss functions are two approaches that normally use. Desirability function takes precedence over loss function due to its flexibility and applications. A desirability function approach is very useful for multi-response processes optimization. Here the idea is that quality of process having multiple characteristics with any one of them is outside the desired limit is unacceptable [8]. This method helps to find those operating conditions which provide desirable response values. Depending upon whether a maximum, minimum, or target value assigned to a particular response, different desirability functions are available to be used. For this work, larger the best (LTB) selected for UTS, and smaller the best (STB) for hardness, and desirability for each response calculated by using Equations given below. Where d_i is desirability, y is response value, Y_{max} is upper/maximum limit, and Y_{min} is the lower/minimum limit. Desirability ranges from zero to one, and the highest value will be optimal. Generally, 0.7 and above is considered satisfactory.

Individual desirability for each response obtained using equations 4 and 5 developed by Derringer and Suich for larger the best and smaller the best.

$$d_i = \begin{cases} 0, & y^{\wedge} \leq Y_{min} \\ \left(\frac{y^{\wedge} - Y_{min}}{Y_{max} - Y_{min}}\right), & Y_{min} \leq Y^{\wedge} \leq Y_{max}, r \geq 0 \\ 1, & y^{\wedge} \geq Y_{min} \end{cases} \tag{4}$$

$$d_i = \begin{cases} 1, & y^{\wedge} \leq Y_{min} \\ \left(\frac{y^{\wedge} - Y_{max}}{Y_{min} - Y_{max}}\right), & Y_{min} \leq Y^{\wedge} \leq Y_{max}, r \geq 0 \\ 0, & y^{\wedge} \geq Y_{min} \end{cases} \tag{5}$$

By using these equations, individual desirability of each response was calculated for each run and given in Table 7.

D is overall desirability and calculated by the geometric mean of all individual desirabilities.

$$D = \{d_1(Y_1).d_2(Y_2).d_3(Y_3).\cdots.d_k(Y_k)\}^{\frac{1}{k}}. \tag{6}$$

After performing this, the optimal values obtained using the above equation for each response are given in Table 10.

Here, D is overall desirability of each response, and D* shows overall process desirability and geometric means of both overall desirabilities D.

Table 10. Optimal values for responses

Response	Optimized	Optimal	95.0% Limit	Desirability (D)
UTS (MPa)	yes	562.891	570.276	0.813
Weld Hardness (HRB)	yes	70.435	79.90	0.845

Overall desirability, D*= 0.82. Optimized desirability and response values are the base that used to get the optimized settings for factors and given in Table 11, whose graphical presentation shown in Figure 7 [13].

Table 11. Optimum factors settings

Factors	Setting
Current (Amp)	145
Travel Speed (mm/Min)	90
Gas Flow Rate (L/Min)	12

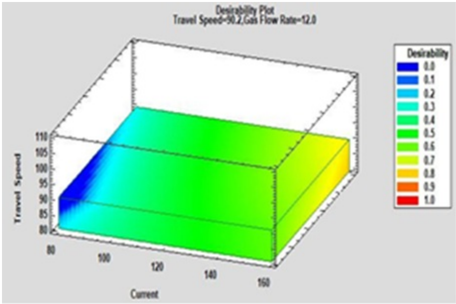


Figure 7. Desirability plots for factors

The graphical presentation of desirability plots for factors shown above showing optimal values of current, gas flow rate and travel speed, as mentioned in Table 10. Desirability (D) for both responses and overall process (D*) found about 0.8, as mentioned in Table 9 and shown as yellow/orange area in the top right portion as per the color contrast range of Figure 7.

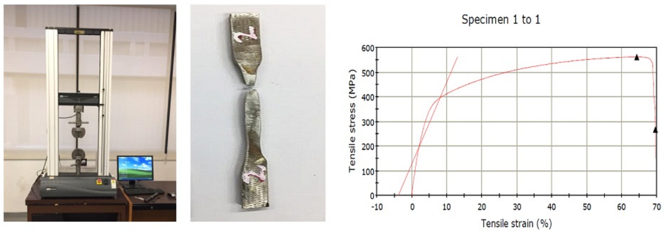
8. Validation of gtaw optimization results

After performing optimization to get optimal values as an output, then the next stage was to validate the results. Optimal factors values obtained were used to run the final weld. The same material used for welding under the same circumstances and welding conditions. Final results, including UTS and hardness values, micro and macrostructure, were found very close to the optimal responses obtained through the optimization process, as given in Table 12. Final confirmation welding and samples which have taken for testing shown in Figure 8.

Figure 8. Final confirmation run and samples used for testing

Instron-model#3367 UTS machine was used to perform tensile testing. The actual response value of UTS found 561.78 MPa as compared to an optimal value obtained from desirability analyses was 562.891 MPa. Tensile test results, TS machine, broken sample, and graph shown in Figure 9.

Vicker hardness tester of Buehler USA, model Micromet-3 advance, was used for hardness testing. Actual hardness values observed 72∼74HRB, whereas the optimal value was 71.365 HRB. The hardness tester model and sample used shown in Figure 10.



	Maximum Load (kN)	Tensile Strength (MPa)	Elongation (%)	Modulus (MPa)
1	26.74	561.78	69.51	3318.68
Min	26.74	561.78	69.51	3318.68
Mean	26.74	561.78	69.51	3318.68
Max	26.74	561.78	69.51	3318.68

Figure 9. Tensile test machine, sample and graph

Figure 10. Hardness tester and sample

Three samples were taken for the GTAW process to find base metal, HAZ, and weld metal hardness. In final results, only weld metal hardness included where the average value of weld metal hardness readings was considered i-e 73.048 HRB.

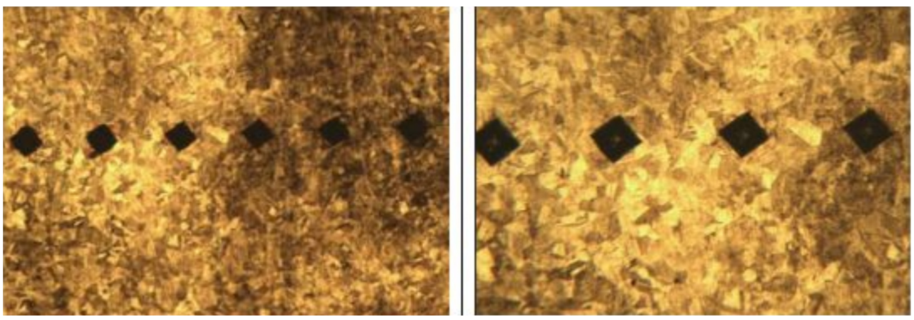


Figure 11. hardness testing locations

Ametek brand spectrometer was used to find the chemical composition of weld metal and found as follows, as shown in Figure 12.

Type	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co
	%	%	%	%	%	%	%	%	%	%
<x>	0.0118	0.430	1.82	0.0035	< 0.00050	18.61	2.46	11.38	0.0033	0.0851
Type	Cu	Nb	Ti	V	W	Pb	Sn	As	Ca	Sb
	%	%	%	%	%	%	%	%	%	%
<x>	0.111	< 0.0040	0.0066	0.0308	0.0137	< 0.0020	0.0089	< 0.0015	0.00039	< 0.0020
Type	Se	Ta	B	N	Fe					
	%	%	%	%	%					
<x>	< 0.0020	< 0.0200	0.00069	0.0728	64.9					

Figure 12. Chemical composition reading of final weld

The microstructure of final weld, HAZ, and base metal observed by using an optical microscope of brand Zeiss, model-Axioplan 2 Imaging. The microscope used and microstructures observed are shown in Figure 13.

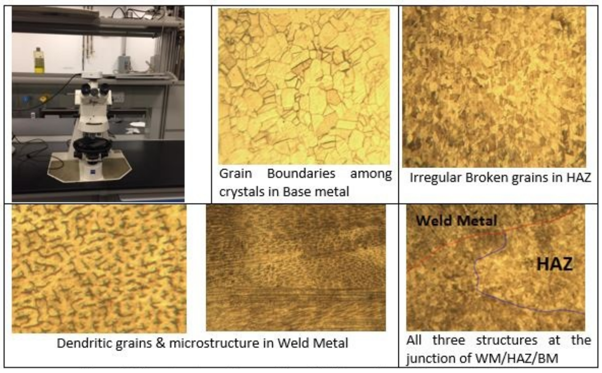


Figure 13. Microstructures of base, weld and HAZ area [Image Magnification 100X]

Because of little or no heat effect on base metal other than of weld metal and HAZ area, a fine austenitic grain crystalline structure observed for solution annealed stainless steel base material. In HAZ, irregular and broken austenitic grains were observed due to temperature changes during welding and then suddenly cooling in air. In the weld metal area, dendritic austenitic grains observed due to the melting of base metal and the addition of filler with subsequent cooling to form a new structure that changed the weld metal composition and its microstructure.

To check the quality of the Macro weld examination also performed. Here for examination, one cross-section of the weldment was polished and then etched by using the etchant of Aqua Rega (HNO3 + HCL in the ratio of 1:3, respectively). Macro test performed to find any possible imperfections like porosity, lack of penetration, and sidewall fusion and weld profile, mainly hot weld cracks or sensitization due to the formation of carbides precipitates. Macrograph has shown in Figure 14, where examination performed at less than 20x magnification.

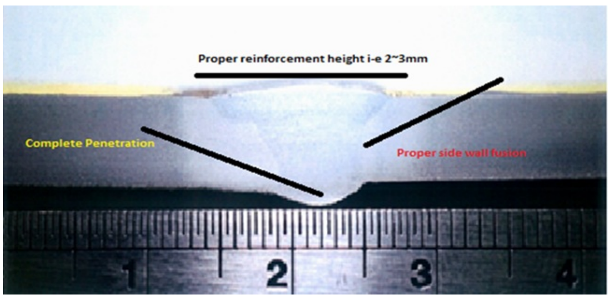


Figure 14. Macrograph examination of the final weld (GTAW)

Now final optimal results obtained from Taguchi analyses, desirability analyses, and obtained from actual testing are summarized in Table 12. From this table, we can say results are very close to each other by using both techniques. This minor difference in results (optimal factors values & and then the subsequent effect on response values) is obviously due to the different approaches and levels deployed for experiments by each statistical technique.

Table 12. Comparison table for optimal and actual results

Optimized Factors By Desirability Function	Optimized Response values Desirability Function	Taguchi array of factors giving desire results	Desire Results by Taguchi S/N Analyses	Actual Results (Responses)
Current = 145 amp	UTS = 562.89 MPa	Current 150 amp	UTS 564 MPa	UTS = 561.78 MPa
Gas Flow Rate = 12 L/Min	Hardness = 70.43 HRB	GFR 12 L/Min	Hardness 72.66	Hardness = 73.048
Travel Speed = 90 mm/Min		Travel speed 95 mm/Min		

9. Conclusion

Conclusion of this research work can be summarized as follow:

1. The study highlights the important role of standards and welding best practices deployed in the contemporary welding world. And describes the GTAW process and various controlling variables as well as Standards compliant tolerance zone on these variables acceptable window of Welding Process parameters selection, which give good quality welds.
2. The study provides a framework of exploring the best combination of conditions that provide the Highest Quality (or Enhanced Quality), Weld, by optimizing within this standard based acceptable zone of welding conditions. This constrained optimization is essentially multi-criteria optimization. The statistical tools used for this purpose in Studying the GTAW process are; the Design of Experiments (DOE) through Signal over Noise i-e S/N ratio and Desirability Function (DF) analyses to further narrowing down the optimum region for process parameters settings within welding standard-based recommended search space.
3. The above framework of the analyses can be applied for any such welding case. It can be combined in a single software package to find optimal weld conditions leading to enhanced weld quality.

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