Optimization of TIG Welded Bead Profile Using Taguchi Method

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***Abstract*—This work presents the direct application of the Taguchi method to optimize the TIG welding process of low-carbon steel (st37) manufactured by the Libyan Iron and Steel Company. The main objectives of the experiments are to investigate the influence of some welding process parameters and to produce a weld bead with an optimal bead profile. In this case, the penetration-to-width ratio was chosen as the quality characteristic to be optimized. The welding input parameters used were welding current (I), travel speed (S), and arc length (AL). The experiments were conducted based on a three-factor-four-level L16 orthogonal array. Sixteen runs were conducted on four steel plates. The weld bead's width and penetration were measured with an optical microscope and then analyzed with Minitab 17 software. Larger-the-better was used for the signal-to-noise ratio (S/N) analysis to maximize the penetration while minimizing the width. ANOVA was used to check the statistical significance of the chosen parameters on the penetration-to-width (P/W) ratio. The mean S/N ratio and ANOVA analysis found that the Taguchi method for optimization of weld bead profiles was successful. The optimum combinations determined from the mean S/N ratio were ($I_1S_2AL_3$), I_1= 100Amp, S_2=1.6mm/s, and AL_3=2.5mm). Where the results of the ANOVA analysis showed that the current (I) and speed (S) have a significant effect, but the arc length (AL) has an insignificant effect on the P/W ratio.**

Keywords—TIG; Low carbon (st37) steel, P/W ratio, Taguchi; Orthogonal array; S/N ratio; ANOVA

I. INTRODUCTION

Among the various fabrication methods employed, fusion welding is widely used, and it is one of the most important and versatile means of fabrication available to industry. Actually, many products could not even be made without fusion welding. Fusion welding is by far the more important category of welding methods. It is a thermal joining method in which the edges of the base metal to be joined is melted and caused to fuse together with or without adding filler material [1,2].

Tungsten inert gas (TIG) welding is one of the most important fusion welding processes. TIG is an arc welding that uses a non-consumable tungsten electrode and a workpiece to produce the weld pool. Tungsten Inert Gas welding, also known as Gas Tungsten Arc welding (GTAW). The older term "*Heliarc*" was named because of helium, the first gas used for this welding process [3]. Nowadays, the shielding gas includes argon (Ar), helium (He), or a mixture of both gases, which is used to protect the weld area [3-6]. Because of the high quality of welds produced by this welding process, It has become an essential tool for many industries, including aerospace, nuclear, marine, food processing, automobile, and for maintenance work [6-8]. TIG welding is clean, cost-effective, and can be used by hand or automated. It can weld a wide range of ferrous and nonferrous metallic materials with various thicknesses by selecting several different modes. This process has made it possible to join hard-to-weld metals such as Al and Mg. This process is also used for materials, including low carbon (mild) steel, stainless steel, and Ti alloys. It has shown great potential for joining various unlike (dissimilar) metallic material combinations [5,9].

The quality of the weld relies strongly on the input welding process parameters, such as welding current, travel speed, arc length, gas composition, gas flow rate, polarity, and weld joint position [9]. Therefore, to have the best output parameters, such as weld bead geometry profile (penetration, width, penetration to width ratio, etc.), selecting the optimum welding process parameters is crucial [10]. So, the main objectives of this study were: (i) to investigate the influence of some welding process parameters on output response parameters. The input parameters used were welding current, travel speed, and arc length, where the output parameter is the penetration-to-width (P/W) ratio profile. This output criterion appears to be the most widely used and most reliable measure of penetration [9,11]; (ii) to determine the optimal combination levels of the TIG welding process parameters for the (P/W) ratio profile.

II. TAGUCHI METHOD

Taguchi method is a powerful, robust design of experiments (DOE) approach that has been widely used in engineering products and process design that focuses on minimizing variation and sensitivity to noise [12-15]. In Taguchi parameter design, the main objective is to find the parameter settings that produce the best levels of quality charactistics, while minimizing the response variation [16-21]. A process designed with this objective will produce a more consistent output value [16-19]. In recent years, a large number of applications of the Taguchi method have been used in a worldwide range of industries [13].

A. Orthogonal Arrays

The Taguchi method succeeded in utilizing orthogonal arrays from the design of experiments theory to study a large number of parameters with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental process parameters studied compared to full factorial design [16-18]. The conclusions from small-scale experiments are valid over the entire experimental range controlled by input parameters and their settings [22].

B. Signal-to-Noise Ratio

Once the desired output responses are measured and collected, the signal-noise (S/N) ratios and the analysis of variance (ANOVA) techniques will be used to analyze the process input parameters' impact and optimization analysis.

Taguchi recommends using the signal-to-noise ratio (S/N) instead of simply optimizing process parameters [17-18,23]. The rationale is that while there is a need to maximize the mean (signal) in the sense of its proximity to the nominal value, minimizing the process variations (noise) is also desirable. The use of S/N ratios accomplishes both objectives simultaneously [17,23].

The signal-to-noise ratio for each control process input parameter should be calculated to investigate and determine the influence of each selected process parameter on the output responses. The signals should indicate the sensitivity of the experiment output to the noise factors.

There is three Signal-to-Noise (S/N) ratios of common interest for optimization [17,18]:

- Smaller-the-Better
  $S/N = -10 \text{ Log } (\sum(Y^2)/n)$
- Larger-the-Better
  $S/N = -10 \text{ Log } (\sum(1/Y^2)/n)$
- Nominal-is-Best
  $S/N = 10 \text{ Log } (\bar{Y}^2/\sigma^2)$

Where: Y is the observed data, n is the number of observations, σ^2 is the variation of Y, and $\bar{Y}$ is the average of the observed experimental data.

C. Analysis of Variance (ANOVA)

The primary aim of ANOVA is to examine the design parameters' characteristics and to indicate which input parameters are significantly affecting the output parameters [24]. The analysis of variance can be accomplished based on the total sum of squares (SS)T from the total mean of the (S/N) ratio. The Fisher test (F) at a 95% confidence level is used to indicate which process input parameters have a statistically significant effect on the performance quality. The large value of the F-test means that the effect is great on the performance characteristic due to the change in the process parameters. The contribution percentage for each parameter can be used to evaluate the importance of the process parameter change on the performance characteristic [17,24]. All the equations used for the analysis of variance are reported in various references, such as [17,18].

III. EXPERIMENTAL DETAIL

A. Introduction

A series of experiments were performed on an ESAB PROTIG 450 TIG welding machine shown in both Figures (I and II) to examine the effects of input process parameters, namely, welding current, travel speed, and arc length. In these experiments, the weld bead geometry characteristics (penetration and width) were measured using an optical microscope and analyzed using the Taguchi method and ANOVA analysis to find the optimal process parameters for the best bead output response (P/W) ratio.

B. Experimental Procedure

The experimental procedure steps followed in this research study were:

- The experimental samples used were four (128x70x4 mm) plates of low-carbon steel (st37) manufactured by the Libyan Iron and Steel Company (LISCO).
- The understudy experimental samples were prepared for welding by cleaning them from rust and debris with a metal brush.
- Four weld beads were performed on each plate for a total of sixteen beads, each with different input parameter values. Care was taken to let the plate cool at room temperature before the next weld to avoid overheating the plate.
- The bead-on-plate welding tests were done according to the selected input orthogonal array.
- After finishing all sixteen experimental runs, the cross sections of the welds were cut. Then metallographic samples were prepared using standard methods such as grinding, polishing, and etching using 2% Nital solution to reveal the weld bead geometry (penetration and width).
- Weld bead penetration (P) and width (W) were measured and collected. The measurement was performed using Nikon ToolMaker's Microscope V12.

FIGURE I. TIG MACHINE POWER SUPPLY

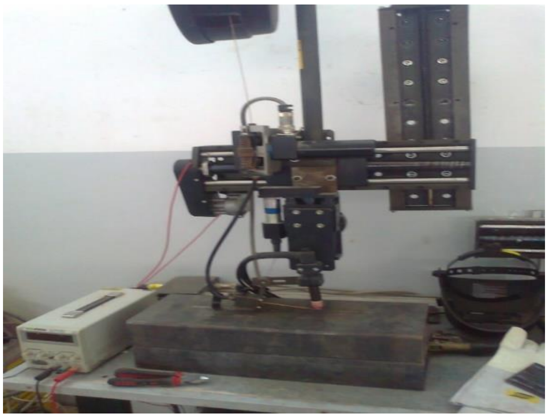

FIGURE II. TIG MACHINE

1) TIG Welding Setup

The specifications of the TIG welding machine used in this study are as shown in Table I.

TABLE I. WELDING MACHINE SPECIFICATIONS

Mains Connection	230/400/500 V 3~ 50 Hz or 208/230/460/475 V 3~ 60 Hz
Permissible Load at 100% Duty Cycle 60% Duty Cycle 45% Duty Cycle	 360 Amp / 24.4 V 425 Amp / 27 V 450 Amp / 28 V
Setting range, welding current	5 A / 10 V – 450 Amp / 28 V
No-load Power	310 W
Efficiency	83%
Power factor	0.90
Enclosure class	IP 23
Weight	159 Kg
Dimensions, l x w x h	734 x 486 x 695 mm
Application class	S

The shielding gas used was 100% pure argon with a flow rate of (10 L/min). The flow rate should be just enough to shield the weld pool from atmospheric contaminants adequately. A 1.6 mm EWTh-2 (2% Thorium) electrode was used in the experiments. This electrode has an amperage range of (50–160 Amp) for a DCEN polarity power supply which was within the selected amperage range for the welding current parameter. No filler wire was used in the experiments as they were simple bead-on-plate welds.

2) Calibration of the Welding Speed

By using the voltage/current regulator connected to the machine motor, the travel speed of the welding torch was calibrated. Table II shows various speed values and their corresponding voltages.

TABLE II. VOLTAGE AND TRAVEL SPEED

Motor Voltage (V)	***Torch Speed (mm/s)***
7	1.3
8	1.6
9	1.9
10	2.2
11	2.4
12	2.7

C. Design of Experiments

A standard Taguchi DOE of the L16 (4^3) orthogonal array matrix (shown in Table III) with three welding process parameters and four levels for each parameter was used to study the influence of TIG process input parameters and to determine the contribution of each parameter on the weld bead geometry profile. The interactions between the parameters were neglected. The input parameters used in this research study were welding current, travel speed, and arc length. Reviewing the literature indicates that these parameters have the most significant effect on weld bead geometry. The level values and operating range for each parameter were determined using preliminary experimentation. The orthogonal array, as shown in Table IV, was then determined according to Taguchi L16 and Minitab 17 software.

TABLE III. INPUT PARAMETERS AND LEVELS

Factor	***Level 1***	***Level 2***	***Level 3***	***Level 4***	***Unit***
Current (I)	100	110	120	130	Amp
Speed (S)	1.3	1.6	1.9	2.2	mm/s
Arc Length (AL)	1.5	2	2.5	3	mm

IV. RESULTS AND DISCUSSION

After the weld bead penetration (P) and width (W) were measured and collected, the S/N ratios of the selected (P/W) quality characteristic selected were calculated, as shown in Table V. The quality characteristic chosen for this study is the maximum penetration and minimum width. The optimal parameter values for the best (P/W) ratio were determined using the analysis of signal-to-noise (S/N). The main effects plot of the mean S/N ratios for the output parameter (P/W) was obtained using Minitab 17 software and is shown in Table VI.

TABLE IV. L16 OA DESIGN MATRIX FAND PARAMETERS VALUES

Run	***I***	***S***	***AL***
1	100	1.3	1.5
2	100	1.6	2
3	100	1.9	2.5
4	100	2.2	3
5	110	1.3	2
6	110	1.6	1.5
7	110	1.9	3
8	110	2.2	2.5
9	120	1.3	2.5
10	120	1.6	3
11	120	1.9	1.5
12	120	2.2	2
13	130	1.3	3
14	130	1.6	2.5
15	130	1.9	2
16	130	2.2	1.5

Signal-to-noise ratio and analysis of variance were applied to the experimental data to identify the significant TIG welding process parameters expected to influence the output response (P/W) ratio profile. Table VI shows the mean S/N ratio values of the P/W profile that were calculated to rank the various welding process parameters. By examining the delta values, the welding current (I) has the most significant parameter, followed by travel speed (S), and then to a lesser extent, the arc length (AL).

TABLE V. THE P/W PROFILE AND S/N RATIO USING L16 OA

Run	P	W	P/W	S/N (P/W)
1	3.15	5.80	0.543	-5.302
2	2.60	5.61	0.463	-6.68
3	2.30	5.42	0.424	-7.445
4	1.12	3.56	0.315	-10.045
5	4.00	6.76	0.592	-4.558
6	3.02	5.73	0.527	-5.563
7	2.73	5.60	0.488	-6.241
8	2.34	5.09	0.46	-6.75
9	4.37	7.12	0.614	-4.24
10	3.67	6.80	0.54	-5.357
11	3.42	6.64	0.515	-5.763
12	3.08	6.50	0.474	-6.487
13	4.63	7.56	0.612	-4.259
14	4.34	7.00	0.62	-4.152
15	4.23	6.76	0.626	-4.072
16	3.86	6.62	0.583	-4.685

TABLE VI. RESPONSE TABLE FOR S/N RATIO OF P/W

Level	I	S	AL
1	-7.368	-4.590	-5.328
2	-5.778	-5.438	-5.449
3	-5.462	-5.880	-5.647
4	-4.292	-6.992	-6.475
Delta	3.076	2.402	1.147
Rank	1	2	3

By using the mean S/N ratio values given in Table VI, the main effect plots have been made using Minitab 17 software and shown in Figure III. In the

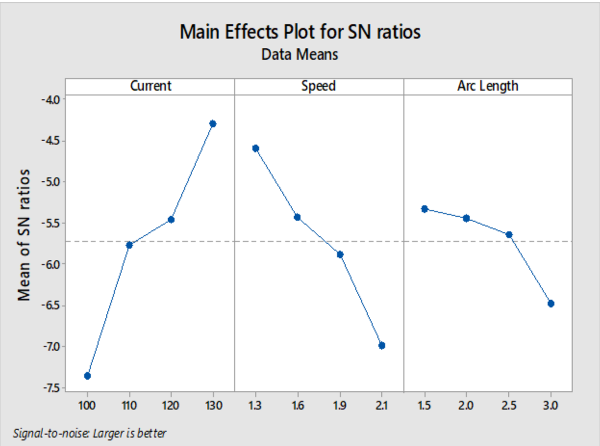

FIGURE III. MAIN EFFECT PLOTS FOR MEAN S/N RATIO FOR P/W

main effect plots, if the inclination of the line is higher, then the corresponding parameter is more significant. If the inclination is lower, then the effect of the corresponding parameters is insignificant. From the three plots shown in Figure III, it is found that welding current and travel speed have the most significant effect on the P/W ratio profile, respectively. In contrast, arc length has an insignificant impact. The optimum parametric setting can be observed from the main effect plots at the highest S/N ratio values of P/W corresponding to each factor. Table VI and Figure III show the optimum condition ($I_4S_1AL_1$): the welding current is (130 A), travel speed is (1.3 mm/s), and arc length is (1.5 mm).

In the ANOVA, the F-test values of the parameters are compared with the standard F table values at a 5% significance level (95% confidence level). If the P-values in the Table are less than 0.05, then the corresponding parameters are considered statistically significant. It is found from Table VII that P-values for welding current and travel speed are less than 0.05, indicating they have a significant effect on the P/W ratio. At the same time, the P-value of the arc length (AL) is greater than 0.05, which means that it has an insignificant effect on the P/W ratio at a 95% confidence level.

TABLE VII. ANALYSIS OF VARIANCE FOR THE P/W RATIO PROFILE

Source	DF	Adj SS	Adj MS	F-value	P-value
I	3	0.06126	0.02042	25.59	0.001
S	3	0.03628	0.01209	15.16	0.003
AL	3	0.00731	0.00244	3.05	0.114
Error	6	0.00479	0.00080		
Total	15	0.10963			

V. CONCLUSIONS

This research study deals with applying the Taguchi method to optimize the TIG welding output parameter penetration-to-width ratio profile, employing the most influencing input parameters, welding current, travel speed, and arc length. From this study, it was concluded that with automated TIG welding, controlled and reliable welding of low-carbon steel is possible. It is proven from previous studies and this study that the Taguchi method can be applied successfully to optimize and improve the welding processes. The results of the mean (S/N) ratio analysis showed that welding current significantly influences the penetration-to-width (P/W) ratio, followed by travel speed, and then arc length, with delta values of 3.076, 2.402, and 1.147, respectively. The optimum condition is ($I_4S_1AL_1$), welding current is (130 A), travel speed is (1.3 mm/s), and arc length is (1.5 mm). The results of the ANOVA analysis showed that both the welding current (I) and travel speed (S) have statistical significance since both parameters have P-value less than 0.05. Where the arc length has an insignificant effect, since the P- value is larger than 0.05.

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