Identifying the Effect of Gas Tungsten Arc Welding Parameters on the Quality of 304L Stainless Steel Weldments Using Taguchi Method

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الملخص:

تقدم هذه الورقة البحثية دراسة حول استمثال وتأثير عوامل اللحام على تغلغل اللحام، عرض خرزة اللحام والمنطقة المتأثرة بالحرارة باستخدام تقنية لحام القوس الكهربائي باستخدام قطب التنغستن (TIG) وذلك للحام وصلات من الصلب المقاوم للصدأ نوع (304L) بسمك 2مم. و قد تم إجراء التجارب العملية تحت أوضاع مختلفة وذلك بتغيير تيار اللحام، سرعة اللحام ومعدل تدفق الغاز ، حيث تم تحديد عوامل اللحام باستخدام طريقة تاغوتشي الإحصائية متمثلةً في استخدام المصفوفة المتعامدة L9 ثلاثة عوامل بثلاثة مستويات (3X3) لدراسة تأثير عوامل اللحام على جودة وصلات اللحام للصلب المقاوم للصدأ نوع (304L). أما درجة أهمية عوامل اللحام على تغلغل اللحام، عرض خرزة اللحام والمنطقة المتأثرة بالحرارة فتم تحديدها باستخدام تحليل التباين (ANOVA). أما التوليفة المثلى لعوامل اللحام فتم إيجادها بوساطة تحليل نسبة الإشارة إلى الضجيج (SNR). و قد أظهرت التجارب العملية إمكانية زيادة تغلغل اللحام، عرض خرزة اللحام بشكل ملحوظ باستخدام طريقة تاغوتشي. حيث أظهرت النتائج أن تيار اللحام له تأثير قوي على جودة وصلات اللحام، بينما لم يُظهر معدل تدفق الغاز أي تأثير على جودة وصلات اللحام، كما بينت التجارب أيضا أن المستوى الثالث المتمثل في التجربة السابعة هي أفضل تجربة أعطت أفضل عرض لخرزة اللحام بالإضافة إلى أفضل تغلغل لوصلة اللحام، حيث كانت عوامل اللحام هي 185 أمبير، سرعة اللحام 135 مم/ دقيقة ومعدل تدفق الغاز 15 لترًا / دقيقة. علاوة على ذلك، فإن أفضل تجربة أعطت أقل منطقة متأثرة بالحرارة هي التجربة الثالثة المتمثلة في المستوى الأول وذلك بتيار لحام 165 أمبير، سرعة اللحام 235 مم / دقيقة و تدفق غاز 15 لترًا / دقيقة. وهذا مما يؤكد صلاحية طريقة تاغوتشي لتحسين أداء عملية اللحام واستمثال عوامل اللحام في عملية لحام القوس الكهربائي باستخدام قطب التنغستن (TIG).

Abstract:

An attempt has been made to evaluate the effect of welding parameters on the weld penetration, weld bead width and heat effective zone of Tungsten Inert Gas (TIG) welded 2 mm 304L stainless steel joints. The welding parameters including arc current, welding travel speed and gas flow rate were used to achieve the optimum joint. Taguchi technique has been implemented to optimize the welding parameters. Orthogonal array L9 (Three factors with three levels 3x3) was used to study the effect of arc current, welding travel speed and gas flow rate on the quality of 304 stainless steel welds. Signal to a noise ratio (SNR) and the analysis of variance (ANOVA) are also used to determine the main effects of different welding parameters on the weld bead width (WB), weld penetration (WP) and heat affected zone (HAZ). Results showed that welding current has significant effect, whereas gas flow rate showed no effect on the quality of 304Lwelded joints. Welding current of 185A, welding speed of 135mm/min and gas flow rate of 15lit/min have been selected as the best process parameter of weld bead width and weld penetration at level three of experiment seven. However, the optimum process parameter for heat affected zone are level one experimental three at165 A, 235 mm/min, 15 lit/min of welding arc current ,travel speed and gas feeding rate, respectively.

Keywords: Gas Tungsten Arc Welding (GTAW), 304L Stainless steel, Taguchi methods, Signal-to-Noise Ratio (S/N), tool analysis (ANOVA), Heat affected zone (HAZ) and Tungsten inert gas (TIG)

1. Introduction

Austenitic stainless steels are widely used in almost all types of industries. Stainless steel are used in typical areas such as piping systems, heat exchangers, tanks and pressure vessels [1,2]. The most important characteristics of AISI 304L austenitic Chromium-Nickel stainless steel are corrosion resistance, good weldability, formability, toughness, ductility and strength [3]. Tungsten inert gas (TIG) welding which uses an arc between work piece to be welded and non-consumable tungsten electrode under a shielding gas is an extremely important arc welding process [4].

TIG welding is most common welding process to produce a high weld quality for thin stainless-steel material. This welding technique is commonly used to weld metals such as stainless steel, magnesium, aluminum and titanium [3]. Several researches have been carried out on the optimization of optimal parameters for TIG welding of stainless using Taguchi selections. K. Kishore et al. [5] studied the effect of process parameters for AISI 1040 welded joints using MIG and TIG techniques. Five control factors have been considered including arc voltage, arc current, welding speed, nozzles to work distance and plate thickness. It has been found that the optimum current parameters for TIG are 150A and 180A for 3mm and 5mm thick plates, respectively. In addition, it has been reported that welding speed should be less than 0.4m/min for 3mm thick plates and 0.35m/min for 5mm thick plates in MIG welding process. It was also recommended the nozzle tip distance to be 10mm and 12mm for 3mm and 5mm thick plates, respectively. Prashant S Lugad et al. [6] investigated the effect of electrode gap, arc current, welding travel speed and gas feeding rate for the welding of 6mm austenitic stainless steel 304L plates. Taguchi method using L9 orthogonal array has been used and the percentage contribution of each parameter was calculated by ANOVA tool. The tensile strength percentage contribution of process parameters are 44.87%, 28.14%,20.80%,6.12% of welding speed, welding current, arc gap and gas flow, respectively. It has been also indicated that the optimum process parameters are 1mm electrode gap, 200A welding current, 100mm/min welding speed and 10 Lit/min gas flow rate. Mohamed. F et al. [7] utilized Taguchi L9 orthogonal array design with experimental characterization for mechanical properties optimization of dissimilar TIG welding metals of X-70 alloy steel and 304L. Results showed that gas flow was the main significant contributing welding parameter of tensile strength and hardness. It was also found that the result obtained at welding speed of 70m/min, welding current of 70A and gas flow of 8L/min reflecting the optimum welding parameters. G. Shanmugasundar et al.[3] investigated the optimized process parameters on AISI 304L using TIG process. The process were Three levels of current, gas flow rate and nozzle to work piece distance. Taguchi design method was implemented for parameters optimization ultimate tensile strength (UTS) of welding joints. The optimum parameters were observed at experiment no.4 at welding current of 110A, Gas flow rate of 10 *l*/min and nozzle to work piece distance of 15 mm. The ultimate tensile strength was 454MPa. Taguchi's, S/N ratio concept showed that the current at level 3 (120A), gas flow rate at level 1 (10 L/min) and nozzle to plate distance at level 3 (15 mm), gave the higher UTS values, and accordingly is the optimum process parameters.

In this present work visual examination was used to evaluate weld geometry. Visual inspection has been considered as one of the effective NDT tests for welding process. The main objective of this work is to optimize welding process parameters including welding current, welding speed and gas flow rate on weld geometry in term of the weld bead width, weld penetration and heat effective zone of AISI 304L stainless steel weldments using TIG process.

2. Experimental Procedure

2.1 Welding Technique

A number of eighteen 2 mm thick 304L stainless steel sheets of dimensions of 250mm (L) x120mm (W) were used to produce nine weld joints using TIG welding process. The two parts welded semi-automatically without gab or preparation for the edges of the sheets with one pass to produce butt joints in flat position as shown in Figure 1.

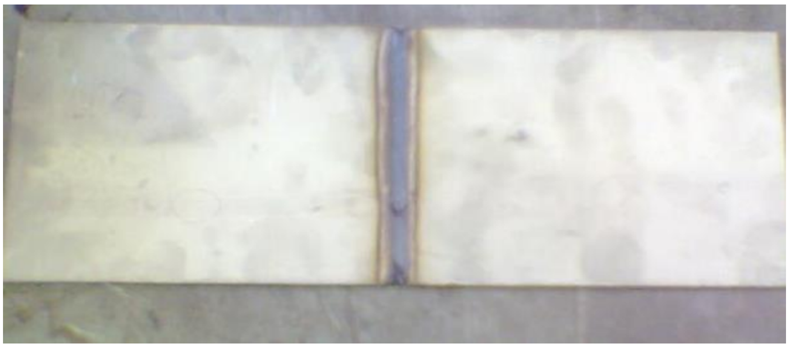

Figure 1. The primarily butt joints

A semi-automatic gas tungsten arc welding machine was used for welding all experimental specimens. All specimens were welded with pure tungsten electrode with 3.2mm diameter and using filler metal ER-308L with 1.2mm diameter. The chemical composition of the base metal plate and filler wire used in the process for welding purpose is given in Table. 1. The length of welding arc was 1.5 mm, type of welding current is (DCSP) and the pure Argon used as a shielding gas during welding, (All the experimental specimens were welded without pre-heating).

TABLE 1. Chemical composition of base metal and filler wire

Material	C	Mn	Si	P	S	Cr	Ni	N
304L	0.030	2.0	0.75	0.045	0.03	19	10	0.10
Filler Wire 308L	0.03	2.5	0.30	0.03	0.03	19.5	11.0	0.75

2.2 Weld Bead Geometry Test

This test carried out to determine the weld geometry variables obtained by welding process. Specimens were exposed to extensive etching cleaning process using concentrated HCL acid. The weld geometry was measured using projector as shown in Figure .2.

Figure 2. Etching cleaning Projector**.**

2.3 Taguchi Experimental Design

Taguchi approach was established on statistical design of experiments. Therefore, all experiments carried out according to specific design called Orthogonal Arrays (OAs) such L4, L9, L27. Table.2 shows the operation conditions considered in this study at three different levels.

TABLE 2. Process parameter levels and response factors

Symbol	Process parameters	Level 1	Level 2	Level 3
A	Welding current (A)	165	175	185
B	Welding speed (mm/min)	135	174	235
C	Gas flow rate (L/min)	5	10	15
	Process response factors			
WB	Weld bead width (mm)			
WP	Weld penetration (mm)			
HAZ	Heat affected zone (mm)			

The interaction effect between the welding parameters is neglected. There are 6 degrees of freedom owing to the three sets of three level welding process parameters. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, nine experiments carried out to construct L9 (3^3) orthogonal array with 8 degrees of freedom. Table.3 depicts all operational variables of welding process.

TABLE 3. Experimental layout (L9)

Experimental number	Factor A Welding current (A)	Factor B Welding speed (mm/min)	Factor C Gas flow rate (L/min)
1	165	135	5
2	165	174	10
3	165	235	15
4	175	135	10
5	175	174	15
6	175	235	5
7	185	135	15
8	185	174	5
9	185	235	10

1- Analysis of the Signal-to-Noise (S/N) Ratio

Statistical analysis of performance called the S/N ratio using Taguchi method to evaluate the desired output (effect of various factors on the weld bead width, weld penetration and heat affected zone in the present study). The S/N ratio used to measure the selected control levels that best cope with noise. The S/N ratio is the ratio of the mean (signal) to the standard deviation. The ratio depends on the quality characteristics of the product or process under study. S/N analysis has three categories characteristic presented below.

There are three categories of performance characteristic in the analysis of the S/N:

1.1 Lower is better (LB)

$$S/N_{LB} = -10 \log\left(\frac{1}{r}\sum_{i=1}^{r} yi^2\right) \qquad (1)$$

Where **r** is the number of measurements in the trial and $\mathbf{y_i}$ is the measured characteristic value.

1.2 Nominal is better (NB)

S/N$_{NB1}$ = -10 log Ve (Variance only)

S/N$_{NB2}$ = 10 log $\left(\frac{Vm-Ve}{rVe}\right)$ (mean and variance)

1.3 Higher is better (HB)

S/N$_{HB}$ = $-10 \log \left(\frac{1}{r} \sum_{i=1}^{r} \frac{1}{yi^2} \right)$ (2)

Where yi is the measured characteristic value.

In this study the quality characteristics are the weld bead width, weld penetration and HAZ [8]. Hence, for both characteristics, the HB ratio is used to evaluate of various factors on weld bead width and weld penetration characteristics, and LB to evaluate of various factors on the HAZ.

2- Analysis of variance (ANOVA)

ANOVA has been used to evaluate the effect of process parameters on the quality characteristic. ANOVA can be calculated based on the total sum of squares **(**SS**)** from the total mean of (S/N) ratio and given by equation (3):

$$SS := \sum_{i=1}^{m} \left[\left(\frac{S}{N} \right)_i \right]^2 - \frac{1}{m} \cdot \left[\sum_{i=1}^{m} \left(\frac{S}{N} \right)_i \right]^2 \quad (3)$$

Where m is the total number of experiments, and (S/N) is the calculated value in a row. The (SS) is decomposed in to the sum of the squares due to each factor (SS_F) and the sum of squares due to the error (SSe), which are given by equations (4 and 5) respectively:

$$SS_F = \sum_{j=1}^{q} \frac{((S/N)_j)^2}{q} - \frac{1}{m} \left[\sum_{i=1}^{m} (S/N)_i \right]^2 \quad (4)$$

$$SS_e = SS_T - \sum SS_F \quad (5)$$

Where (F) represents one of the experiment factors (parameters), j is level number of the specific factor (F), q is the repetition of each level of the factor.

The Expected sum of the squares $(SS')_F$ is given by:

$$(SS')_F = SS_F - (DF)_F V_e \quad (6)$$

Where $(DF)_F$, is the degree of freedom for each factor is the number of its levels minus one $(DF)_e$, is the $(DF)_T$ minus the sum of the $(DF)_F$. The variance (V_F) for each factor is defined as the (SS_F) for each factor divided by $(DF)_F$, and variance due to the error (V_e) is determined as the $(SS)_e$ divided by $(DF)_e$.

Statistically, there is a tool called an F test, named after R.A. Fisher, to see which process parameter has a significant effect on the quality characteristic. The F- value defines as the (V_F) for each factor divided by (V_e). Usually, when the calculated F- value is greater than the tabulated F- value, it means that a change in process parameter has a significant effect on the quality characteristic (weld bead width, penetration and HAZ).

The percentage (P) of the contribution to the total variation is determined for each factor using equation (7)

$$P = \frac{(SS')F}{(SS)} x100 \qquad (7)$$

3. Results and Discussion

3.1 Weld Bead Width Test Results

The experimental results of weld bead width test and corresponding signal-to-noise ratio (S/N) are tabulated in Table. 4.

TABLE 4. S/N ratio of the weld bead width

Experimental number	Measured Weld Bead width (mm)					Mean Weld Bead width (mm)	S/N Ratio
1	6.3	5.5	5.2	5.4	5.6	5.6	28.963
2	3.2	4	3.9	3.1	-	3.55	23.101
3	3.3	3	3.3	3.5	-	3.27	22.358
4	5.5	5.6	5.8	5.2	-	5.53	26.895
5	5	4.9	5.7	5.6	-	5.3	26.546
6	4.8	4.5	5	5.1	4.6	4.8	27.614
7	7.3	7.5	7	6	7.3	7.02	30.931
8	6.4	6.3	5.9	6.5	6.4	6.3	29.971
9	5.1	5	4.9	5	4.6	4.9	27.824

The results of the weld bead width are ranged from 3.27 to 7.02mm, and the Experimental number seven has the highest weld bead width measurements value 7.02mm, which is corresponding to the greatest calculated value of S/N ratio. It is evident that the variations of weld bead width are due to the different levels used for each experiment. The main factors affecting the weld bead width based on the S/N ratio are shown in Figure 3.

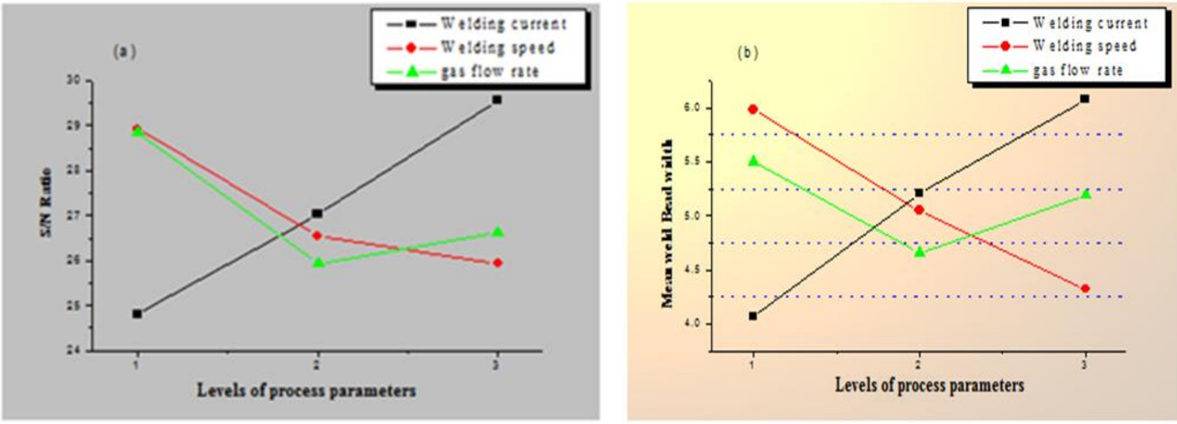

Figure 3. The average effect response for factors of the L9 (OA), (a) S/N ratio. (b) Weld bead width.

The response data drawing in Figure 3. indicate the welding current has the most significant factor affecting on the weld bead width, the second significant factor is welding speed and the gas flow rate (Factor C) has the least effect on the weld bead width as strong as the other parameters.

The results of ANOVA based on the S/N ratio are shown in Table 5.

TABLE 5. ANOVA results for S/N ratio of weld bead width

process parameters	**Degree of freedom $(DF)_F$**	**Sum of squares $(SS)_F$**	**Variance**	**Expected sum of squares $(SS')_F$**	**F-value**	**Contribution percentage**
Welding current	2	34.161	17.08	31.314	12	47.45
Welding Speed	2	15.069	7.535	12.222	5.29	18.52
Gas flow rate	2	13.923	6.962	11.076	4.89	16.78
Error	2	2.847	1.4235			17.25
Total	8	66				100

The percent of contribution of each factor is determined by analyzing of variance using equations (3) to (7). The results indicate that the welding current (47.45%) and welding speed (18.52%) are the main significant factors among the three factors that affect the weld bead width. The F- value obtained is the highest for the welding current and the welding speed represents the second higher value. Thus, the analyses of the signal-to-ratio (S/N), variance (ANOVA) and F- value results indicate that the optimal welding parameters for this set of experiments are 185 A welding current, 135 mm/min welding speed, and 15 L/min gas flow rate or (A3-B1-C3).

3.2 Weld Penetration Test Results

The experimental results of penetration test and corresponding signal-to-noise ratio (S/N) are presented in Table. 6.

TABLE 6. Mean and S/N ratio of the weld penetration test

Experimental number	Measured Weld Penetration (mm)					Mean Weld Penetration (mm)	S/N Ratio
1	1	0.5	0.7	1.1	0.7	0.80	12.355
2	0.9	0.6	0.8	0.66	-	0.74	9.534
3	0.6	0.8	0.5	0.58	-	0.62	8.025
4	1.4	1.3	1.2	1.62	-	1.38	14.894
5	1.1	1.2	1	1.06	-	1.09	12.809
6	1	0.9	0.7	0.9	0.75	0.85	12.639
7	1.9	2.1	2	1.8	1.75	1.91	19.620
8	1.7	1.8	1.7	1.6	1.8	1.72	18.698
9	1.4	1.5	1.7	1.64	-	1.56	15.928

The results for the penetration are ranged from 0.62 to 1.91mm, and the experimental number seven has the greatest penetration measurements of 1.91mm, which is corresponding to the greatest calculated value of S/N ratio. It is evident that the variations of penetration are due to the different levels used for each experiment. The main factors affecting the penetration based on the S/N ratio are shown in Figure 4.

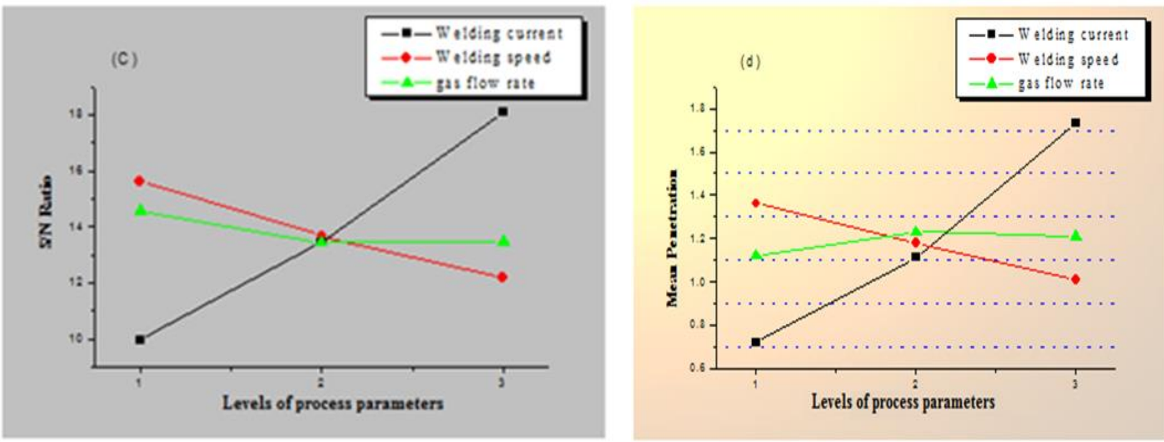

Figure 4. The average effect response for factors of the L9 (OA), (c) S/N ratio. (d) Penetration.

The response data drawing in Figure. 4 indicate the welding current (factor A) has the most significant factor affecting on the penetration at level three, experimental seven, the second factor is welding speed (factor B) and the effect of gas flow rate (Factor C) was very limited. The results of ANOVA based on the S/N ratio are presented in table 7.

TABLE 7. ANOVA results for S/N ratio of Penetration

process parameters	Degree of freedom $(DF)_F$	Sum of squares $(SS)_F$	Variance	Expected sum of squares $(SS')_F$	F-value	Contribution percentage
Welding current	2	99.346	49.67	99.253	1068.17	83.02
Welding Speed	2	17.708	8.85	17.615	190.32	14.73
Gas flow rate	2	2.403	1.20	2.31	25.81	1.93
Error	2	0.093	0.046			0.32
Total	8	119.55				100

The percent of contribution of each factor is determined by analyzing of variance using equations **(**3**)** to **(**7**)**. The results indicate that the main significant factors among the three factors that affect the penetration are the welding current and welding speed at a contribution percentage of 83.02% and 14.73%**,** respectively. The F- value obtained is the highest for the welding current. Thus, the analyses of the signal-to-ratio (S/N), variance (ANOVA) and F-value results indicate that the optimal welding parameters for this set of experiments are 185 A welding current, 135mm/min welding speed, and 15 L/min gas flow rate or **(**A3-B1-C3**)**.

3.3 Heat Affected Zone Test Results

The experimental results of HAZ test and corresponding signal-to-noise ratio (S/N) are presented in Table 8.

TABLE. 8 Mean and S/N Ratio of the HAZ test

Experimental number	Measured HAZ (mm)					Mean HAZ (mm)	S/N Ratio
1	3.6	2.7	3.8	3	2.5	3.12	-9.995
2	3	2.7	2.4	3	-	2.775	-8.900
3	2.1	2.4	3	2.5	-	2.5	-8.031
4	3.2	3.5	3	-	-	3.23	-10.210
5	2.9	2.8	3	2.74	-	2.86	-9.133
6	2.8	3	2.7	3.1	2.4	2.8	-8.976
7	2.8	3.4	3.8	3.5	3.5	3.4	-10.669
8	3.2	3.4	3.1	3	-	3.175	-10.044
9	3	2.9	2.9	2.8	2.8	2.88	-9.191

The results for the HAZ ranged from 2.5 to 3.4mm, and the experimental number three has the lowest HAZ measurements of 2.5mm, which is corresponding to the greatest calculated value of S/N ratio. It is evident that the variations of HAZ are due to the different levels used for each experiment. The main factors affecting the HAZ based on the S/N ratio are shown in Figure 5.

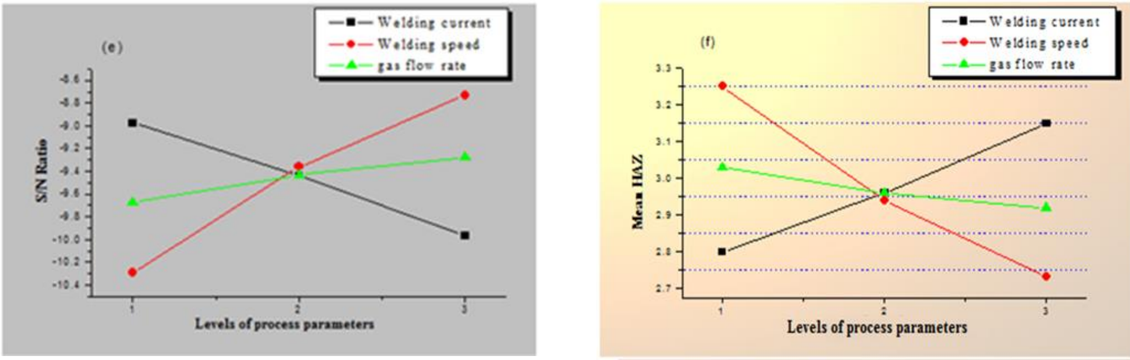

Figure 5. The average effect response for factors of the L9 (OA), (e) S/N ratio. (f) HAZ.

The response data drawing in Figure. 5 indicate the welding speed (factor B) has the most significant factor affecting on the HAZ, the second factor is welding current (factor A) and the less affecting factor is gas flow rate (Factor C).

The results of ANOVA based on the S/N ratio are tabulated in Table 9.

TABLE 9. ANOVA results for S/N ratio of HAZ

process parameters	Degree of freedom $(DF)_F$	Sum of squares $(SS)_F$	Variance	Expected sum of squares $(SS')_F$	F-value	Contribution percentage
Welding current	2	1.480	0.740	1.466	105.71	27.04
Welding Speed	2	3.691	1.845	3.677	263.57	67.83
Gas flow rate	2	0.236	0.118	0.222	16.86	4.09
Error	2	0.014	0.007			1.04
Total	8	5.421				100

The percent of contribution of each factor is determined by analyzing of variance using equations (3) to (7). The results indicate that the welding speed (67.83%) and welding current (27.04%) are the main significant factors that affect the HAZ. The F- value obtained is the highest for the welding speed and the welding current represents the second higher value. Thus, the analyses of the signal-to-ratio (S/N), variance (ANOVA) and F- value results indicate that the optimal welding parameters for this set of experiments are 165 A welding current, 235mm/min welding speed, and 15 L/min gas flow rate or (A1-B3-C3).

4. Conclusion

The optimization of welding parameters of 304L stainless welded joints using Tungsten arc welding on the weld bead width, weld penetration and HAZ were investigated using Taguchi orthogonal design. The following conclusion can be presented:

1. Results showed that welding current and welding speed are the most significant parameter effecting the weld bead width and weld penetration. However, gas flow rate showed less significant effect on weld quality.
2. On contrary, HAZ was essentially affected by welding speed and welding current with negligible gas flow rate effect according to the S/N ratio.
3. The best combination or the best setting of the welding process is determined based on S\N ratio where the parameter levels are: the welding speed is 135 mm/min, welding current is 185A, and gas flow is 15lit/min.
4. Taguchi technique to be used to evaluate same welding parameters on the mechanical properties including the hardness and hardness.

The best acceptable results of welding geometry obtained by the combinations effects of welding parameters, since the experiment number three shows the lowest heat affected zone due to the maximum welding speed, but experiment number seven shows the effective combination of welding parameters on final welding geometry.

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