

## NUMERICAL MODELING OF HEAT-AFFECTED ZONE IN GMAW PROCESS

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Low-carbon steel St37-2 is widely used in the bus production industry. The gas metal arc welding (GMAW) is strongly applied to join steel components due to its ease and low cost. Heat-affected zone (HAZ) is the area between the weld and base metal where can have the lowest toughness in a welding joint and hence it has always been a matter of interest for many researchers. This work aims to study the effects of GMAW parameters on HAZ width. The Taguchi orthogonal array, signal-to-noise (S/N) ratios, and analysis of variance (ANOVA) are employed to investigate and analyze the effect of the welding parameters on the HAZ width.

**Keywords:** *St37-2 steel, gas metal arc welding, heat-affected zone, analysis.*

Низьковуглецеві сталі St37-2 широко використовують в автомобілебудівній промисловості. Газодугове зварювання металу (ГДЗМ) успішно застосовують для зварювання сталевих елементів через його простоту та дешевизну. Зона термічного впливу (ЗТВ) – це ділянка між зварним з'єднанням та основним металом, де з'єднання може мати найменшу в'язкість і тому цікавить багатьох дослідників. Досліджено вплив параметрів ГДЗМ на ширину ЗТВ. Використано ортогональний масив Тагучі, відношення сигнал/шум (S/N) та дисперсійний аналіз (ANOVA) для аналізу впливу параметрів зварювання на ширину ЗТВ.

**Ключові слова:** *сталь St37-2, газодугове зварювання, зона термічного впливу, аналіз.*

**Introduction.** The gas metal arc welding (GMAW) process is an important component in many industrial operations [1]. This process has various advantages over other melting welding methods. High welding speed, large metal deposition, and spatter free welding are some of its advantages. In addition, it is applicable for a wide variety of commercial metals and alloys such as carbon steel, stainless steel, copper and aluminum. Furthermore, it is a mechanized method and allows the use of a robot [2–4]. These advantages have motivated many researchers to study the GMAW process in detail [5]. The heat-affected zone (HAZ) refers to a non-melted area adjacent to weld metal in the fusion welding processes which undergoes a lot of microstructural changes compared to the base metal. Several studies [6–11] have indicated that HAZ can have the lowest toughness in the weld joint and hence emphasize the importance of the HAZ. With increasing use of welded steel constructions, it became apparent that the HAZ showed susceptibility to various types of cracking, especially cold cracking which had been attributed to the formation of a very susceptible HAZ microstructure [12]. So, with considering all these problems, it makes sense that the minimizing of the HAZ width will only help. From what we know, there is relatively little information in order to minimize the HAZ width in low-carbon steels. Therefore, an attempt has been made in the present work to investigate and analyze the effect of GMAW parameters on the HAZ width in St37-2 steel.

**Materials and methods.** Due to its industrial importance, DIN 17100 St37-2 steel was chosen as a base material in the form of a plate 3 mm thick. In addition, AWS A5.18/ER70S-6 copper-coated solid wire with 1 mm diameter and composition of 0.11C-1.63Mn-0.95Si-0.5Cu was used as a filling metal. To minimize the welding distortion, the plates were located in the jig fixtures and welded using the GMAW process as butt joints in a flat position. A Revo MIG SP 1601 machine was applied for welding operations in this study and weld pools were protected by 100 % CO<sub>2</sub> shielding gas. The arc voltage (V), wire feeding speed (WFS), welding speed (WS) and torch angle (Alpha) were chosen as welding parameters at three levels and their effect on the HAZ width was investigated and analyzed. The welding parameters and their values at three levels are summarized in Table 1. Design of experiments (DOE) in this work was performed based on an application of Taguchi orthogonal array L9 in which the four variables were varied at three levels. The nine experiments designed based on Taguchi technique are summarized in Table 2. Having finished the welding process, the weld coupons were cut perpendicular to the welding direction in the same situations and the cross-sectional specimens were extracted. Then, these specimens were ground using SiC-papers, polished, and etched in 2% Nital for appearing the HAZ features. For each experiment, the HAZ widths were measured by caliper and the average width was reported. The analysis of variance (ANOVA) and signal-to-noise (S/N) ratios were applied to identify the most significant factor and predicted optimal parameters setting [13]. In this work the “smaller is better” criterion was selected for the HAZ width and the S/N ratios were calculated. It means that the optimum level for a factor is the level that results in the lowest value of the S/N ratio in the experimental region. As verification for the S/N ratio results, the ANOVA was performed to determine the effect of different parameters on the output variable. Furthermore, contribution percentage of each control factor was determined from the results of ANOVA [14]. Finally, a mathematical model was established and utilized for predicting the HAZ width. For this purpose, a linear Regression model using Minitab 16 software was developed for finding the relationship between the predictor variables and the response variable.

**Table 1. Welding parameters and their levels**

Parameter	Notation	Level-1	Level-2	Level-3
V	V	19	20	21
WFS, m/min	WFS	3	4	5
WS, mm/s	WS	2	4	8
Alpha, degree	Alpha	25	45	80

**Table 2. Taguchi orthogonal array L9**

Experimental Run	V	WFS	WS	Alpha
#1	1	1	1	1
#2	1	2	2	2
#3	1	3	3	3
#4	2	1	2	3
#5	2	2	3	1
#6	2	3	1	2
#7	3	1	3	2
#8	3	2	1	3
#9	3	3	2	1

**Results and discussion.** The results obtained in the nine experimental tests are shown in Fig. 1. According to this figure, the average HAZ width has changed from 1.23 to 3.04 mm in various welding conditions. The S/N ratio for each experiment is calculated and tabulated in Table 3. The average values of S/N ratios of the four control factors at each of the levels are calculated and presented in Table 4. Higher the difference between their maximum and minimum values designates higher relative effect of parameter on the response [15].

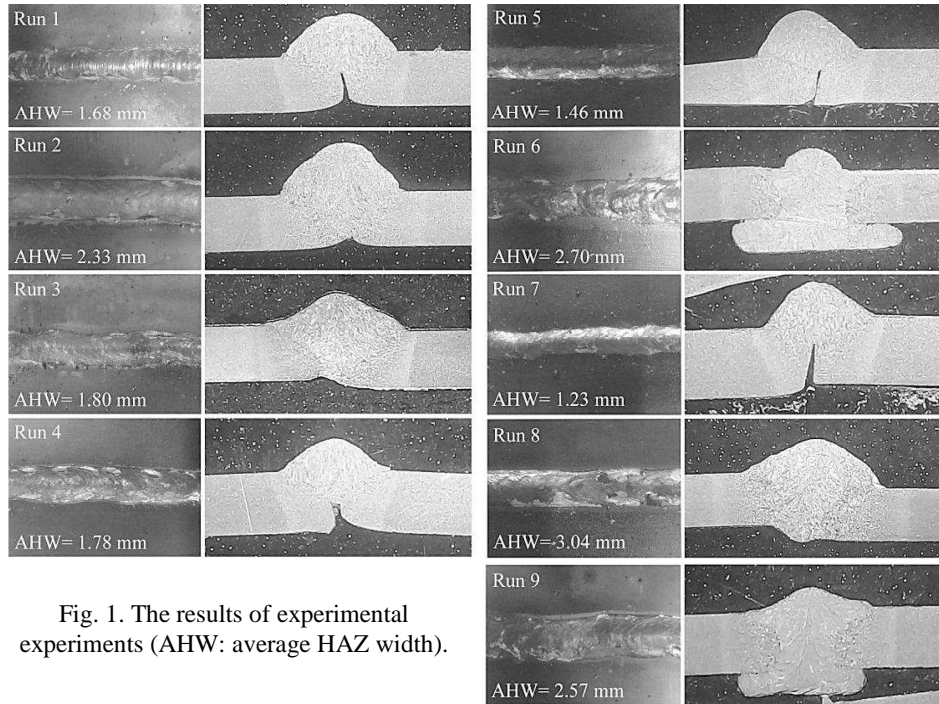


Fig. 1. The results of experimental experiments (AHW: average HAZ width).

It is found from Delta values in Table 4 that the most significant parameter that affects the HAZ width is welding speed and the next is wire feeding speed. The optimal condition for minimum HAZ width (from the average S/N values of process parameters at three levels) is V-2 (20 V), WFS-1 (3 m/min), WS-3 (8 mm/s) and Alpha-1 (25 degree). The main effect plots generated by Minitab 16 software in Fig. 2 show the variation in the HAZ width with change in input factors. The welding speed graph is more diverging than the other factors, so it can be assumed that welding speed is the most significant factor that affects the HAZ width, the next is wire feeding speed while arc voltage and torch angle have less effect on the HAZ width.

**Table 3. The average HAZ width and the corresponding S/N ratio**

Experimental Run	Average HAZ width, mm	S/N ratio
1	1.68	-4.51
2	2.33	-7.35
3	1.80	-5.11
4	1.78	-5.01
5	1.46	-3.29
6	2.70	-8.63
7	1.23	-1.80
8	3.04	-9.66
9	2.57	-8.20

**Table 4. Response Table for S/N ratios – smaller is better**

Level	V	WFS	WS	Alpha
1	-5.66	-3.77	-7.60	-5.33
2	-5.64	-6.77	-6.85	-5.93
3	-6.55	-7.31	-3.40	-6.59
Delta	0.91	3.54	4.2	1.26
Rank	4	2	1	3

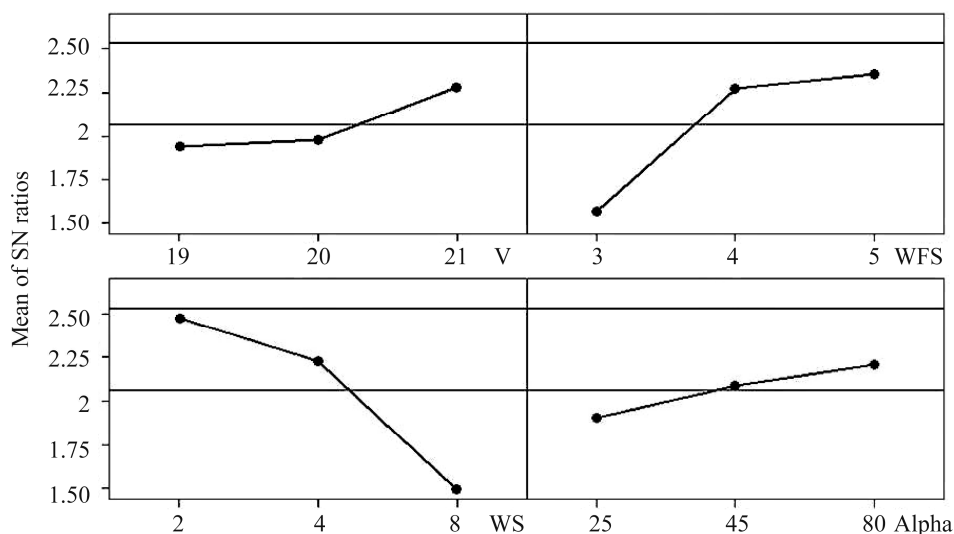


Fig. 2. Main effect plots for S/N ratios for the HAZ width.

The ANOVA is a statistical tool used to analyze the S/N ratios [16], and shows the percentage contribution of given input parameters on the measurable output parameter [17]. The ANOVA values for the S/N ratios and Regression model are calculated at 95% confidence using Minitab 16 software and tabulated in Table 5.

**Table 5. The Results of ANOVA**

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Regression	4	2.78612	2.78612	0.69653	10.8873	0.020040
V	1	0.17682	0.17682	0.17682	2.7638	0.171755
WFS	1	0.94407	0.94407	0.94407	14.7565	0.018437
WS	1	1.53562	1.53562	1.53562	24.0029	0.008048
Alpha	1	0.12961	0.12961	0.12961	2.0260	0.227723
Error	4	0.25591	0.25591	0.06398		
Total	8	3.04202				

**Note:**  $S = 0.252936$ ;  $R-Sq = 91.59\%$ ;  $R-Sq(adj) = 83.18\%$ .

This analysis is carried out for a significance level ( $\alpha = 0.05$ ). From the ANOVA is observed that the welding speed is the most prominent factor which affects the HAZ width maximum with percent contribution of 50%, and the next is wire feeding speed with percent contribution of 31%. Percent contribution indicates the relative power of a

factor to reduce variation. For a factor with a higher percent contribution, a small variation will have a great influence on the performance [18]. The final linear Regression model with coefficient values is represented by the Equation.

$$\text{HAZ width} = -2.4457 + 0.1717.V + 0.3967.WFS - 0.1656.WS + 0.0053. \text{Alpha}$$

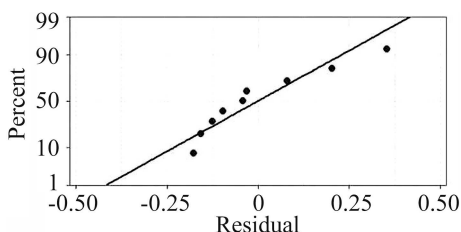


Fig. 3. Normal probability plot of residuals for the HAZ width.

The coefficient of determination (R-squared) in the ANOVA is a measure of the strength of the linear relationship between the experimental and predicted values [19]. In Regression model, the R-squared is a statistical measure of how well the Regression line approximates the real data points [20]. In the other words, it indicates the ability of a model to make predictions. The R-squared value is always between 0 and 100% and in general, a higher R-squared value is better and indicates a better fit for the Regression model. The R-squared value equal to 91.59% in this work is desirable and represents a good fit and the data closely follow the straight line. The normal probability plot of residual for the HAZ width is shown in Fig. 3. As seen, the data closely follow the straight line. If the  $p$ -value in ANOVA is less than the significance level ( $\alpha = 0.05$ ), this means that the factor corresponding to that value of  $p$  is statistically significant for the Regression model. So the value of  $p$  less than 0.05 for welding speed and wire feeding speed indicates that unlike arc voltage and torch angle, they have statistically significant effect on the response HAZ width at 95% confidence level. A low  $p$ -value ( $<0.05$ ) indicates that we can reject the null hypothesis. Conversely, a larger (insignificant)  $p$ -value suggests that changes in the predictor are not associated with changes in the response [21]. From the ANOVA of linear Regression for the HAZ width, the  $p$ -value of Regression equation indicates that the Regression model is significant. F-ratio named after Fisher [22], is used in order to find out the significant factors that affect the response. The higher the F-value for a factor specifies that the variation of that factor makes a greater effect on the response. The highest F-value (24.0029) verifies that the welding speed is the most effective factor as ranked in Table 4 and the next is wire feeding speed with F-value of 14.7565.

### CONCLUSION

A Taguchi orthogonal array L9 was used to design experiments in this work and the effect of the GMAW parameters on the HAZ width in St37-2 steel was investigated and analyzed. According to the results, the most significant parameter that affects the HAZ width is welding speed and the next is wire feeding speed while arc voltage and torch angle have less effect on the HAZ width. The ANOVA results showed that the welding speed affects the HAZ width with percent contribution of 50%, and the next is wire feeding speed with percent contribution of 31%. Also, the optimal condition predicted in this work for the minimum HAZ width was: V-2 (20 V), WFS-1 (3 m/min), WS-3 (8 mm/s) and Alpha-1 (25 degree).

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