NUMERICAL MODELING OF HEAT-AFFECTED ZONE IN THE 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 the base metal, where the welded joint may have the lowest toughness and, hence, it has always been a matter of interest for numerous researchers. Our aim is to study the effects of GMAW parameters on the width of the HAZ. The Taguchi orthogonal array, signal-to-noise (S/N) ratios, and the analysis of variance (ANOVA) are used 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.

Introduction

The process of gas-metal arc welding (GMAW) is an important component in numerous industrial operations [1]. This process has various advantages over the other melting welding methods. High welding speed, large metal deposition, and spatter free welding are some of its advantages. In addition, it is applicable to 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 us to use robots [2–4]. These advantages have motivated many researchers to study the GMAW process in detail [5]. The heat-affected zone (HAZ) is a nonmelted area adjacent to the weld metal in fusion welding processes, which undergoes numerous microstructural changes as compared with the base metal. In several studies [6–11], it was indicated that the HAZ may have the lowest toughness in the welded joint and, hence, the importance of HAZ was emphasized. As the use of welded steel structures is intensified, it becomes clear that the HAZ is susceptible to various types of cracking and, especially, cold cracking, which is attributed to the formation of a very susceptible HAZ microstructure [12]. Thus, in analyzing all these problems, it makes sense to note that the minimization of HAZ width should be quite helpful. As far as we know, there is relatively little information about the minimization of HAZ width in low-carbon steels. Therefore, in the present work, we make an attempt 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 3 mm-thick plates. In addition, an AWS A5.18/ER70S-6 copper-coated solid wire with a diameter of 1 mm and

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the following composition: 0.11C-1.63Mn-0.95Si-0.5Cu was used as a filling metal. To minimize welding distortions, the plates were located in jig fixtures and welded by using the GMAW process as butt joints in a flat position. In the present work, a Revo MIG SP-1601 machine was applied for welding operations and weld pools were protected by the 100% CO₂ shielding gas. The arc voltage (V), wire feeding speed (WFS), welding speed (WS), and torch angle (Alpha) were chosen as welding parameters on three levels and their effect on the HAZ width was investigated and analyzed. The welding parameters and their values on three levels are summarized in Table 1. The design of experiments (DOE) in the present work was performed by applying the Taguchi orthogonal array L9 in which the four variables varied on three levels. The nine experiments designed on the basis of the Taguchi technique are summarized in Table 2. After termination of the welding process, the weld coupons were cut in the direction perpendicular to the direction of welding in the same situations and the cross-sectional specimens were extracted. Then these specimens were ground by using SiC-papers, polished, and etched in 2% Nital to reveal the HAZ features. In each experiment, the HAZ widths were measured with a caliper and the average width was reported. The analysis of variance (ANOVA) and signal-to-noise (S/N) ratios were

### Table 1

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

### Table 2

| 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     |
applied to identify the most significant factor and predict the optimal setting of parameters [13]. In this work, the “smaller is better” criterion was selected for the HAZ width and the S/N ratios were calculated. This means that the optimal level for a factor is the level that results in the lowest value of the S/N ratio in the experimental region. As a verification of the S/N ratio results, the ANOVA was performed to determine the effect of different parameters on the output variable. Furthermore, the percentage contribution of each control factor was determined according to the results of ANOVA [14]. Finally, a mathematical model was developed and utilized to predict the HAZ width. For this purpose, a linear regression model using the Minitab 16 software was developed for finding the relationship between the predictor variables and the response variable.

Results and Discussion

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

It follows from the Delta values presented in Table 4 that the most significant parameter affecting the HAZ width is the welding speed and the next is the wire-feeding speed. The optimal condition for the minimal HAZ width (according to the average S/N values of the process parameters on three levels) is V-2 (20 V), WFS-1 (3 m/min), WS-3 (8 mm/sec) and Alpha-1 (25 deg). The main effect plots generated by the Minitab 16 software in Fig. 2 show the variations of the HAZ width with changes in the input factors. The plot of welding speed is more divergent than for the other factors and, hence, it can be assumed that the welding speed is the most significant factor that affects the HAZ width and the next factor is the wire-feeding speed, while the arc voltage and torch angle have less pronounced effects on the HAZ width.
Table 3
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 the $S/N$ 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     |

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

This analysis is carried out for a significance level ($\alpha = 0.05$). It follows from the ANOVA that the welding speed is the most prominent factor that exerts the maximum influence on the HAZ width with a percentage contribution of 50%, while the next factor is the wire feeding speed with a percentage contribution of 31%. The percentage contribution indicates the relative power of a factor in reducing variation. For a factor with higher percentage contribution, small variations have a great influence on the performance [18]. The final linear regression model with coefficient values is represented by the following equation:

$$\text{HAZ width} = -2.4457 + 0.1717.V + 0.3967.WFS - 0.1656.WS + 0.0053.\text{Alpha}$$
**Table 5**

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 |        |        |         |         |

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

The coefficient of determination (R-squared) in the ANOVA is a measure of strength of the linear relationship between the experimental and predicted values [19]. In the regression model, the R-squared is a statistical measure of how well the regression line approximates the actual data points [20]. In 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, the higher the R-squared value, the better, which indicates a better fit to the regression model. The R-squared value equal to 91.59\% in the present work is desirable and represents a good fit; moreover, the data closely follow a straight line. The normal probability plot of residual for the HAZ width is shown in Fig. 3. It is easy to see that the data closely follow the straight line. If the value of $p$ in ANOVA is lower than the significance
level ($\alpha = 0.05$), then this means that the factor corresponding to this value of $p$ is statistically significant for the regression model. Hence, the value of $p$ lower than 0.05 for the welding speed and the wire feeding speed indicates that, unlike the arc voltage and torch angle, they have statistically significant effects on the response of HAZ width at the 95% confidence level. A low value of $p$ ($< 0.05$) means that we can reject the null hypothesis. Conversely, a higher (insignificant) value $p$ suggests that the changes in the predictor are not associated with changes in the response [21]. It follows from the ANOVA of linear regression for the HAZ width that the $p$-value in the regression equation indicates that the regression model is significant. The F-ratio (named after Fisher [22]) is used to determine the significant factors that affect the response. The higher the F-value for a factor, the greater the effect of variations of this factor on the response. The highest F-value (24.0029) verifies that the welding speed is the most effective factor as indicated in Table 4 and the next factor is the wire feeding speed with an F-value of 14.7565.

**CONCLUSIONS**

A Taguchi orthogonal array L9 was used to design experiments in the present work and the effect of the parameters of GMAW on the HAZ width in St37-2 steel was investigated and analyzed. According to the accumulated results, the most significant parameter that affects the HAZ width is the welding speed and the next factor is the wire feeding speed. At the same time, the arc voltage and torch angle exert weaker effects on the HAZ width. The ANOVA results show that the welding speed affects the HAZ width with a percentage contribution of 50% and the next factor is the wire feeding speed with a percentage contribution of 31%. In addition, the optimal condition predicted in the present work for the minimum HAZ width is as follows: $V$-2 (20 V), WFS-1 (3 m/min), WS-3 (8 mm/sec) and Alpha-1 (25 deg).

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**REFERENCES**

1. G. Hun, S. Yun, X. Cao, and J. Li, “Acquisition and pattern recognition of spectrum information of welding metal transfer,” *Mater. Des.*, 24, 699–703 (2003).
2. S. C. Absi Alfaro, G. C. Carvalho, and S. A. de Melo Junior, “Stand offs indirect estimation in GMAW,” *J. Mater. Proc. Technol.*, 157–158, 3–7 (2004).
3. M. Suban and J. Tusek, “Dependence of melting rate in MIG/MAG welding on the type of shielding gas used,” *J. Mat. Proc. Technol.*, 119, 185–192 (2001).
4. R. Kacar and K. Kokemli, “Effect of controlled atmosphere on the MIG-MAG arc weldment properties,” *J. Mater. Des.*, 26, 508–516 (2005).
5. R. W. Messler, *Principles of Welding, Processes, Physics, Chemistry, and Metallurgy*, Chapter 3, New York: Wiley & Sons (1999).
6. R. E. Dolby, *Met. Const. Brit. Weld. J.*, 3, 99 (1971).
7. J. D. Harrison, *Why Does Low Toughness in the HAZ Matter?*, Welding Institute Seminar, Coventry, England, 1983.
8. D. P. Fairchild, “Local brittle zones in structural welds,” in: J. Y. Koo (editor), *Welding Metallurgy of Structural Steels*, TMS, CO, Denver (1987), pp. 303–318.
9. T. Haze and S. Aihar, *Proc. of the 7th Conf. on the Offshore Mechanics and Arabic Engineering (OMAE)*, Houston (1988).
10. P. L. Harisson and P. H. M. Hant, *Proc. of the Internat. Conf. on Weld Failures*, Welding Institute, London (1988).
11. R. M. Denys, *Proc. of the Internat. Conf. on Weld Failures*, Welding Institute, London (1988).
12. T. Boniszewski and F. Watkinson, “Effect of weld microstructure on hydrogen-induced cracking in transformable steels,” *Met. Mater.*, 7, 91–96/145–151 (1973).
13. S. D. Ambeaker and S. R. Wadhokar, “Influence of process parameters on depth of penetration in GMAW process by using Taguchi method,” *Int. J. Sci. Res.*, 4, 3065–3069 (2015).
14. A. Khalkhali, H. Noraie, and M. Sarmadi, “Sensitivity analysis and optimization of hot-stamping process of automotive components using analysis of variance and Taguchi technique,” in: *Proc. of the Institution of Mechan. Eng., Part E, J. Process Mech. Eng.* (2016).
15. M. Sailender, G. Chandra Mohan Reddy, and S. Venkatesh, “Influences of process parameters on heat affected zone in submerged arc welding of low carbon steel,” *Amer. J. Mater. Sci.*, 6, 102–108 (2016).
16. R. Kumar and S. Kumar, “Study of mechanical properties in mild steel using metal inert gas welding,” *Int. J. Res. Eng. Techn.*., 3, 751–756 (2014).
17. A. S. Jadon, N. S. Kushwah, Agrawal, and P. Mittal, “Parametric optimization of GTAW welding using Taguchi and ANOVA,” *Int. J. Res. Appl. Sci. Eng. Technol.*, 5, 650–655 (2017).
18. H. Mohamed, M. H. Lee, M. Sarabintu, S. Salleh, and B. Sanugi, “The use of Taguchi method to determine factors affecting the performance of destination sequence distance vector routing protocol in mobile Ad Hoc networks,” *J. Math. Stat.*, 4, 194–198 (2008).
19. A. Rajendran, M. Thirugnanam, and V. Thangavelu, “Statistical evaluation of medium components by Plackett-Burman experimental design and kinetic modeling of lipase production by Pseudomonas fluorescens,” *Ind. J. Biotechnol.*, 6, 469–478 (2007).
20. S. A. Patil, F. Baratzadeh, and H. Lankarani, “Modeling of the weld strength in spot weld using regression analysis of the stress parameters based on the simulation study,” *J. Mater. Sci. Res.*, 6, 51–61 (2017).
21. *Design-Expert Software*, Version 6, User’s Guide, Technical Manual, Stat-Ease, Minneapolis, MN– 2000.
22. H. R. Lindman, *Analysis of Variance in Experimental Design*, 1st Ed, Springer-Verlag, New York (1992).