Bead formation research in TIG welding of AISI 304 steel

Manahil Tongov¹², Rayna Dimitrova¹ and Konstantin Konstantinov¹

¹Technical University of Sofia, Bulgaria, Faculty of Industrial Technology, Department “Materials Science and Technology”
²Institute of Metal Science, equipment, and technologies with Center for Hydro- and Aerodynamics “Acad. A. Balevski” at the Bulgarian Academy of Sciences – (IMSETHC-BAS)

E-mail: tongov@tu-sofia.bg

Abstract. On the basis of the experimental results in depositing strips of molten metal onto AISI 304 steel using the D-optimal plan of the experiment and processing of the got results, regression equations were obtained describing the dependence of the bead width and the penetration depth depending on the welding speed and the value of the welding current. In parallel, a regression equation is obtained connecting the arc voltage and the welding current.

1. Introduction

High-alloy austenitic steel AISI 304 (1.4301) is widely used in various industries. Building regression models to determine the influence of process parameters on bead formation is a common practice for analysis and optimization [1÷10]. TIG welding is one of the main methods for welding of constructions from that steel. The application of technologies and tools for solving technological problems by simulation modeling of welding process is one of the most promising areas in this field. In order to be complete realized it is necessary to modeling the heat source with subsequent calibration, verification and validation of the built model.

In the present work, on the basis of experimental results, regression equations, which are applicable for the definition of the heat source in simulation modeling of the welding process, are obtained.

2. Materials and research method

The survey was performed using a consistent quasi-D-optimal plan. In this study, the magnitude of the welding current (in the range of 80 to 180 [A]) and the welding speed (12 to 30 [cm / min]) were varied. The arc length was constant and equal to 2 [mm]. The shielding gas flow rate was 6 [l / min] at a current value up to 120 [A] and 10 [l / min] at a higher value of the welding current. Thus, the number of factors in the experiment plan was two. During the experiment, strips were surfaced onto specimens 6x100x100 [mm] from AISI 304 steel at preliminary set values of welding current and welding speed. On each specimen several strips of molten metal were deposited after natural cooling the specimen to room temperature, measuring the values of the welding current, the arc voltage and the average welding speed. Samples for metallographic analysis were prepared from the specimens with deposited strips of molten metal. The preparation includes the following stages: sectioning of a sample, wet grinding in several stages, polishing and etching with a mixture of concentrated nitric and hydrochloric acid, optimally in a molar ratio of 1:3. Metallographic analysis with an optical
metallographic microscope Neophot 21 “Carl Zeiss” were carried out. It was determined the geometric parameters for all samples – the penetration depth and the width of the welding bead.

The regression equations were sought as complete second-degree polynomials, and in the case of an inadequate model as third-degree complete polynomials. The plan of the experiment in relative coordinates is given in Table 1. In addition, seven experiments were performed in the center of the plan to verify the adequacy of the model. The value of the current was used as the first factor and the welding speed as the second factor. The processing of the obtained results was as follows:

The experiment plan matrix was specified, with each row representing the values of the factors for a particular surfaced stripe:

\[
X = \begin{pmatrix}
    x_{1,1} & x_{2,1} \\
    x_{1,2} & x_{2,2} \\
    \vdots & \vdots \\
    x_{1,21} & x_{2,21}
\end{pmatrix}
\]

Table 1. Experiment plan in relative coordinates.

| № | X1 | X2 | № | X1 | X2 | № | X1 | X2 |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 8 | 1 | -0.447 | 15 | -0.447 | -0.447 |
| 2 | -1 | -1 | 9 | -0.447 | 0.447 | 16 | 0.447 | 0.447 |
| 3 | 1 | -1 | 10 | -0.447 | -1 | 17 | -1 | 1 |
| 4 | -1 | 1 | 11 | 1 | 0.447 | 18 | -1 | -1 |
| 5 | -1 | -0.447 | 12 | -0.447 | 1 | 19 | 1 | -1 |
| 6 | 0.447 | 1 | 13 | -1 | 0.447 | 20 | 1 | 1 |
| 7 | 0.447 | -1 | 14 | 0.447 | -0.447 | 21 | 0.447 | 1 |

The sought regression equation is of the type

\[
\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1 x_2 + b_4 x_1^2 + b_5 x_2^2 + b_6 x_1^2 x_2 + b_7 x_1 x_2^2 + b_8 x_1^2 + b_9 x_2^3
\]

which can be written down as \( y = \sum_{j=0}^{9} b_j f_j(x) \) and therefore the elements of the extended matrix of plan \( F = F F^T \), where \( j \) is the function number, \( i \) – the experiment number.

Fisher Information Matrix is \( F^T F \), and the sought coefficients were determined as

\[
b = G^{-1} F^T y
\]

To verify the adequacy of the model according to the Fisher criterion, the ratio \( F = \frac{s_{ost}^2}{s^2} \) was used. Here \( s_{ost} \) and \( s \) are respectively the variation of adequacy and variance of experience. The variation of adequacy was determined by the obtained results \( y_i \) and the calculated value by equation

\[
\hat{y}_i:
\]

\[
s_{ost}^2 = \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}{N - k} = \frac{\sum_{i=1}^{21} (y_i - \hat{y}_i)^2}{11}
\]

where \( N \) is the number of experiments, \( k \) - the number of coefficients in equation (2).
The variance of experience $s$ was determined on the basis of further conducted experiments at the center of the plan such as:

$$s^2 = \frac{1}{n-1} \sum_{u=1}^{n} (y_u - \bar{y}_u)^2$$

where $\bar{y}$ is the average of the measured values $y_i$.

Thus, the value of $F$ was compared with the value of the Fisher distribution $F_T$ at the significance level $\alpha$ and the number of degrees of freedom $\nu_{ost} = N - k = 11$ and $\nu = n - 1 = 6$. In order to consider the model adequate, it is necessary to observe the ratio $F < F_T$.

The Student's criterion was used to check the statistical significance of the coefficients of the regression equation. For its implementation, there is a matrix $C = G^{-1}$ (it has dimensions $k \times k$) with diagonal elements $c_{jj}$ . To make a coefficient significant, it is necessary to observe the condition

$$\frac{|b_j|}{\sqrt{s^2c_{jj}}} > t(\alpha, \nu_{ost})$$

where $t(\alpha, \nu_{ost})$ is the value of the Student distribution at the significance level $\alpha$ and degrees of freedom $\nu_{ost}$.

### 3. Results and discussion

The measurement of the geometric parameters – the bead width and the penetration depth is illustrated in Figure 1. The results of the experiments are shown in Table 2 in absolute values in the sequence in which the welds are performed. The expanded plan matrix and the inverted Fisher information matrix, respectively, are shown in Table 3 and Table 4. The results for the stripes in the center of the plan are shown in Table 5, and the values of the coefficients of the regression equations are shown in Table 6. The value of Fisher distribution at significance level 0.05, number of residual degrees of freedom 11 and degree of freedom 6 is 4.027442. The ratio is 2.0926827 for the penetration depth and 2.2872729 for the bead width. This indicates that the obtained models are adequate. Statistically significant coefficients are shown in Table 6 in bold.

**Figure 1. Measurement of the bead width and the penetration depth**
### Table 2. Experimental results.

| № | X1 - welding current, [A] | X2 - welding speed, [cm/min] | bw - bead width, [mm] | hw - penetration depth, [mm] |
|---|--------------------------|-----------------------------|----------------------|-----------------------------|
| 1 | 180                      | 30                          | 7.609                | 1.24                        |
| 2 | 180                      | 12                          | 11.518               | 2.112                       |
| 3 | 80                       | 30                          | 2.801                | 0.438                       |
| 4 | 80                       | 12                          | 4.025                | 1.006                       |
| 5 | 80                       | 17                          | 3.552                | 0.767                       |
| 6 | 152                      | 30                          | 6.713                | 1.033                       |
| 7 | 152                      | 12                          | 9.358                | 1.659                       |
| 8 | 180                      | 17                          | 9.242                | 1.517                       |
| 9 | 108                      | 25                          | 5.305                | 1.017                       |
| 10| 108                      | 12                          | 6.322                | 1.377                       |
| 11| 180                      | 25                          | 8.324                | 1.221                       |
| 12| 108                      | 30                          | 4.719                | 0.804                       |
| 13| 80                       | 25                          | 2.942                | 0.538                       |
| 14| 152                      | 17                          | 8.326                | 1.221                       |
| 15| 108                      | 17                          | 5.295                | 1.046                       |
| 16| 152                      | 25                          | 7.267                | 1.074                       |
| 17| 180                      | 30                          | 7.542                | 1.23                        |
| 18| 80                       | 30                          | 1.92                 | 0.449                       |
| 19| 80                       | 30                          | 2.307                | 0.325                       |
| 20| 130                      | 12                          | 7.543                | 1.283                       |
| 21| 152                      | 30                          | 6.51                 | 1.111                       |

### Table 3. Expanded experiment plan matrix for penetration depth.

| № | b0 | b1 | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 |
|---|----|----|----|----|----|----|----|----|----|----|
| 1 | 1  | 180| 30 | 5400| 32400| 900 | 972000| 162000| 5832000| 27000|
| 2 | 1  | 180| 12 | 2160| 32400| 144 | 388800| 25920 | 5832000| 1728 |
| 3 | 1  | 80 | 30 | 2400| 6400 | 900 | 192000| 72000 | 512000 | 27000|
| 4 | 1  | 80 | 12 | 960 | 6400 | 144 | 76800 | 11520 | 512000 | 1728 |
| 5 | 1  | 80 | 17 | 1360| 6400 | 289 | 108800| 23120 | 512000 | 4913 |
| 6 | 1  | 152| 30 | 4560| 23104| 900 | 693120| 136800| 3511808| 27000|
| 7 | 1  | 152| 12 | 1824| 23104| 144 | 277248| 21888 | 3511808| 1728 |
| 8 | 1  | 180| 17 | 3060| 32400| 289 | 550800| 52020 | 5832000| 4913 |
| 9 | 1  | 108| 25 | 2700| 11664| 625 | 291600| 67500 | 1259712| 15625|
| 10| 1  | 108| 12 | 1296| 11664| 144 | 139968| 15552 | 1259712| 1728 |
| 11| 1  | 180| 25 | 4500| 32400| 625 | 810000| 112500| 5832000| 15625|
| 12| 1  | 108| 30 | 3240| 11664| 900 | 349920| 972000| 1259712| 27000|
| 13| 1  | 80 | 25 | 2000| 6400 | 625 | 160000| 50000 | 512000 | 15625|
| 14| 1  | 152| 17 | 2584| 23104| 289 | 392768| 43928 | 3511808| 4913 |
| 15| 1  | 108| 17 | 1836| 11664| 289 | 198288| 31212 | 1259712| 4913 |
| 16| 1  | 152| 25 | 3800| 23104| 625 | 577600| 95000 | 3511808| 15625|
| 17| 1  | 180| 30 | 5400| 32400| 900 | 972000| 162000| 5832000| 27000|
| 18| 1  | 80 | 30 | 2400| 6400 | 900 | 192000| 72000 | 512000 | 27000|
| 19| 1  | 80 | 30 | 2400| 6400 | 900 | 192000| 72000 | 512000 | 27000|
| 20| 1  | 130| 12 | 1560| 16900| 144 | 202800| 18720 | 2197000| 1728 |
| 21| 1  | 152| 30 | 4560| 23104| 900 | 693120| 136800| 3511808| 27000|
Table 4. Matrix C (inverted matrix G) for penetration depth.

| Ci  | Ci0 | Ci1 | Ci2  | Ci3  | Ci4  | Ci5  | Ci6  | Ci7  | Ci8  | Ci9  |
|-----|-----|-----|------|------|------|------|------|------|------|------|
| C0  | 597.577 | -8.663 | -37.715 | 0.1484 | 0.05583 | 1.3731 | -0.0003 | -0.0017 | -0.0001 | -0.0178 |
| C1  | -8.663 | 0.18749 | 0.1665 | -0.0015 | -0.0014 | -0.0033 | 4E-06 | 1E-05 | 3E-06 | 3E-05 |
| C2  | -37.715 | 0.1665 | -4.81024 | -0.0127 | -0.0003 | -0.196 | 2E-05 | 0.0002 | -3E-07 | 0.0027 |
| C3  | 0.14841 | -0.0015 | -0.0127 | 0.0001 | 1.9E-06 | 0.0002 | -2E-07 | -2E-06 | 8E-09 | -2E-07 |
| C4  | 0.05583 | -0.0004 | -0.0003 | 2E-06 | 1.1E-05 | 9E-06 | -1E-08 | 2E-08 | -3E-08 | -2E-07 |
| C5  | 1.37309 | -0.0033 | -0.196 | 0.0002 | 8.5E-06 | 0.009 | -1E-07 | -4E-06 | -1E-08 | -0.0001 |
| C6  | -0.0003 | 3.9E-06 | 1.6E-05 | -2E-07 | -1E-08 | -1E-07 | 8E-10 | 3E-10 | 2E-11 | 5E-10 |
| C7  | -0.0017 | 1.2E-05 | 0.0002 | -2E-06 | 2.2E-08 | -4E-06 | 3E-10 | 3E-08 | -7E-11 | 7E-10 |
| C8  | -0.0001 | 3.2E-06 | -3E-07 | 8E-09 | -3E-08 | -1E-08 | -2E-11 | -7E-11 | 7E-11 | 4E-10 |
| C9  | -0.0178 | 2.9E-05 | 0.00266 | -2E-07 | -2E-07 | -0.0001 | 5E-10 | 7E-10 | 4E-10 | 2E-06 |

Table 5. Results of measuring the penetration depth and the bead width for the experiments carried out at the center of the plan I=130[A] u v_w = 21[cm/min].

| u   | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|-----|------|------|------|------|------|------|------|
| hw, [mm] | 1.08 | 1.142 | 1.127 | 1.033 | 1.095 | 1.002 | 1.095 |
| bw, [mm] | 6.697 | 6.869 | 6.572 | 6.494 | 6.369 | 6.353 | 6.588 |

Table 6. Regression equations coefficients values.

| b0  | -0.7979 | 0.40782 | b5  | 0.0089 | 0.044 |
|-----|---------|---------|-----|--------|-------|
| b1  | 0.08334 | 0.16434 | b6  | -7E-06 | -2E-05 |
| b2  | -0.2401 | -0.9219 | b7  | 4E-05  | 0.0001 |
| b3  | 0.0001  | -0.0006 | b8  | 2E-06  | 2E-06 |
| b4  | -0.0006 | -0.0005 | b9  | -0.0002 | -0.0009 |

A graphical representation of the experimental and calculated results is shown on Figure 2 and Figure 3.

Figure 2. Comparison of experimental and calculated results for penetration depth.
To determine the dependence of the arc voltage on the current magnitude, a D-optimal plan for the second-degree full polynomial was used (Table 7). The processing of these data and taking into account only statistically significant coefficients the following arc voltage equation was obtained:

$$U_a = 7.0996 + 0.043345J_w$$

Table 7. Arc voltage data.

| №  | Welding current, A | Welding speed, cm/min | Arc voltage, V | №  | Welding current, A | Welding speed, cm/min | Arc voltage, V |
|----|--------------------|-----------------------|---------------|----|--------------------|-----------------------|---------------|
| 1  | 180                | 30                    | 13.7          | 10 | 180                | 30                    | 12.8          |
| 2  | 180                | 12                    | 13.7          | 11 | 180                | 12                    | 13.3          |
| 3  | 80                 | 30                    | 10.1          | 12 | 80                 | 30                    | 9.9           |
| 4  | 80                 | 12                    | 10.1          | 13 | 80                 | 12                    | 10.1          |
| 5  | 130                | 30                    | 11.8          | 14 | 130                | 21                    | 11.4          |
| 6  | 180                | 21                    | 13.2          | 15 | 130                | 12                    | 11.6          |
| 7  | 130                | 12                    | 12            | 16 | 180                | 30                    | 13            |
| 8  | 80                 | 21                    | 10.1          | 17 | 80                 | 30                    | 10            |
| 9  | 130                | 21                    | 12            | 18 | 180                | 12                    | 13.2          |

The influence of the welding current magnitude on the penetration depth and the bead width for different values of the welding speed is shown on Figure 4 and Figure 5. As expected, with increasing welding current, the penetration depth is increasing. This increase is nonlinear depending on both the current magnitude and the welding speed (Figure 6). The bead width increases almost linearly with increasing current at a constant welding speed.
Figure 4. Influence of the current magnitude on the penetration depth for different values of the welding speed.

Figure 5. Influence of the current magnitude on the bead width for different values of the welding speed.
Figure 6. Influence of welding speed on penetration depth for different values of the welding current.

4. Conclusions
On the basis of experimental results for the conditions of TIG welding in argon and arc length 2 [mm], regression equations for the penetration depth, the bead width and the arc voltage were obtained. The penetration depth and the bead width depend on both the current magnitude/value and the welding speed, and these dependencies are described by third-degree polynomials. The arc voltage depends only on the current and the dependence is linear.

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