Robust parameter design of shielded metal arc welding (SMAW) for optimum tensile strength

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Abstract. Shielded Metal Arc Welding (SMAW), an arc welding process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding, is widely used in engineering applications. SMAW parameters that usually applied in practice is still possible to be optimized to improve the process to become robust. This work is focus on an optimization of SMAW process on ASTM A500 Hollow Square Pipe, as it is widely found in applications. The welding parameters such as welding current, electrode angle, root gap, and electrode type are adopted as process parameters. Taguchi robust optimization is applied as optimization strategy, and L9 fractional orthogonal array is selected as design of experiment. The optimization objective is to maximize tensile strength of SMAW welded joint. The optimization results found that welding current 100A, electrode angle 90°, root gap 2 mm, and electrode type E7018 of SMAW parameters give the optimum tensile strength. The tensile strength gain of robust design based on the initial design was carried out by 98,39 MPa (from 259,45 MPa of initial design to 357,84 MPa of optimum design).

1. Introduction
Welding becomes an essential process on manufacturing sector because of its low cost, lightweight, high strength-to-weight ratio, and high flexibility. In construction sector, it is needed to improve the quality of welding process as a main part of engineering metal construction [1]; [2]. SMAW is one of the most popular arc welding techniques because of its flexibility and efficiency [3]; [4]. The most used materials on construction sector is hollow square pipe ASTM A500 standard, which has many applications in the engineering field. The output expected from this weld joint is the tensile strength, which is defined as maximum strains that can be hold by materials before it fractures [5]; [6].

The tensile strength of weld joint is influenced by several parameters process [7]. The most used SMAW parameters are welding current (I), electrode angle (θ), root gap (d), and electrode type (E). Thus, it is needed to find the best combination of parameters by an optimization method to produce the optimum tensile strength [8]. One of the most efficient optimizations methods is Taguchi method [9]. Taguchi method is used to improve a design process or product to become “robust” [10]. To determine the robust design, Taguchi used S/N ratio, as a comparison between signal (output is expected) with noise (error is unexpected). Robustness is according to a design which is insensitive to the influence of noise factors (uncontrollable factors) [11].

Previous works were conducted by some authors, and some of them was Nair (2016) who optimized the tensile strength of SMAW welded joint of SS316L plates using Taguchi method and found the optimum parameters which were welding current (100A), welding angle (15o), and filler electrode
On the other hand, Ahire (2018) who optimized the welded strength and deposition rate on SS304 and mild steel plates welded joint using Taguchi method assisted by RSM and GA based techniques found the optimum parameters which were welding current (91.4A), welding speed (6.7 mm/s), angle (30\degree), and root gap (1 mm). Also, Qazi (2019) who optimized the tensile strength on SA516 using Taguchi method and found the optimum parameters which were welding current (120A), welding speed (4 mm/s), root face (2 mm).

Based on most of the previous works, there are still many works that do not fully adopt the robust design concept of the Taguchi method, which can be seen from the absence of the uses of replication in data generation. In this work, the replication will be used in data generation to estimate the effect of noise factor and fully adopt the robust design concept [12]. On the other hand, the welding speed parameter will not be used in this work because of the difficulty of the controlling speed in manual welding.

The main goal of this work is to optimize the welding current, electrode angle, root gap, and electrode type in order to obtain the SMAW “robust” design parameter using L9 fractional orthogonal array Taguchi design within three replicated on each parameter combination to accommodate the fluctuation on the tensile strength due to the noise factors effect.

2. Material and method

2.1. Material and Tensile Testing Specimens

The specimens for tensile testing are obtained from the hollow square pipe of ASTM A500 with detailed composition as shown in Table 1, with dimensions of 50 mm x 50 mm x 2.8 mm. Two sections of hollow square pipe with dimensions of 150 mm in length will be welded together into a welded joint.

| C    | Cu  | Fe  | Mn  | P   | S    |
|------|-----|-----|-----|-----|------|
| 0.3% | 0.2%| 99% | 1.3%| 0.05%| 0.063%|

Then, from this welded joint will be cut off into a specimen for tensile testing according to the IACS weldments standard as shown in Figure 1. The diameter of the electrode used in this work is 2.6 mm. The universal testing machine is used to obtain the tensile strength of specimens [13].

![Figure 1. Specimen Design](image)

2.2. Experimental Procedure

The experimental procedure is started with identifying SMAW parameters, formulating the optimization problem, designing the experiment, performing the experiment as shown in the Table 2, analyzing the results using analysis of mean and effect plot to predict the optimum parameter, verifying the predicted optimum parameter, and analyzing the gain of optimization. The final step is using the ANOVA to determine the effect of each SMAW parameter and the effect of uncontrollable factors in this work.

2.3. Optimization Problem Formulation

The problem formulation of this optimization case is:
Objective: Maximize ($\sigma_u$)
Factors: Welding Current
          Electrode Angle
          Root Gap
          Electrode Type

The main objectivity is to obtain optimal tensile strength ($\sigma_u$) which is influenced by welding current ($I$), electrode angle ($\theta$), root gap ($d$), electrode type ($E$). The range of each control factor is adopted from practical application and listed as shown in Table 2.

2.4. Design of Experiment (DoE)
Three levels of each control factor are selected with lower and upper bounds as level 1 and level 3, while the middle of the range factors is selected as level 2, as shown in Table 2.

| Parameters             | Level 1 | Level 2 | Level 3 |
|-----------------------|---------|---------|---------|
| Welding current ($I$) | 60A     | 80A     | 100A    |
| Electrode angle ($\theta$) | 30°     | 60°     | 90°     |
| Root Gap ($d$)        | 0 mm    | 1 mm    | 2 mm    |
| Electrode type ($E$)  | E6013   | E7016   | E7018   |

Taguchi method suggests $L_9$ fractional orthogonal array as the smallest number of total samples for four 3-level factors, which only 9 parameter combinations are selected from 81 total possible combinations as shown in Table 3 [14]. Three replications are conducted in tensile strength testing to accommodate the fluctuation due to the effect of noise factors in the SMAW welding process [15]. Since the optimization of the objective is to maximize the tensile strength, larger the better S/N ratio is adopted as robustness index in this work as shown in Equation 1 [16]; [17].

$$S / N_{LTB} = -10 \cdot \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \quad \text{(Equation 1)}$$

3. Result and discussion
3.1. Tensile Strength
Experimental tensile testing data is designed using $L_9$ fractional orthogonal array which can accommodate for four 3-level experimental factors. Tensile testing results with three replications are listed as shown in Table 3. Mean and standard deviation are estimated from three replications and larger the better S/N ratio is deployed as robustness index.
Table 3. Completed Design of Experiment L9

| Parameter | Exp Replicates | Mean | Standard Deviation | S/N Ratio |
|-----------|----------------|------|--------------------|-----------|
| I 0 d E   | 1 2 3 4 5 6 7 8 9 | 154.67 | 15.53 | 44.74 |
| 1 1 1 1 1 | 1 2 2 2 2 2 2 2 2 | 261.61 | 49.86 | 47.90 |
| 1 1 1 1 1 | 3 3 3 3 3 3 3 3 3 | 328.02 | 22.20 | 50.26 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 312.38 | 52.31 | 45.54 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 259.45 | 10.14 | 48.26 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 261.61 | 24.78 | 47.95 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 305.61 | 35.23 | 45.93 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 276.81 | 36.23 | 48.63 |
| 1 1 1 1 1 | 1 2 3 4 5 6 7 8 9 | 312.20 | 29.80 | 49.77 |

As shown in Table 3, the best design from L9 sample is experimental 3 with 50.26 in S/N ratio. On the other hand, experimental 5 is the often used in current practice, and it is called as initial design.

3.2. Optimum Parameter Analysis

Based on the experiment data using fractional orthogonal array L9, an analysis of mean (ANOM) is conducted to evaluate effect of each SMAW parameter to the tensile strength response. The ANOM is performed for both average tensile strength and S/N ratio. From the analysis, the main effect for each SMAW parameter can be plotted as shown in Figure 2.

Figure 2. (a) Effect Plot for Mean, (b) Effect Plot for S/N Ratio

As shown in the Figure 2 both for average tensile strength and S/N ratio, high level (level 3) of each SMAW parameters give the optimum response. From these effects plot we can predict that the optimum parameters that produce the optimum tensile strength for welding square pipe is welding current level 3 (100A), electrode angle level 3 (90°), root gap level 3 (2 mm), and electrode type level 3 (E7018). The optimum SMAW parameter is still estimated based on analysis of mean from L9 experimental data. To verify this predicted optimum, an experimental field is needed to conduct the prediction.

3.3. Verification Optimal Design

Verification tensile testing is conducted to verify the optimum parameter. The result of the verification is included tensile strength by 365 MPa, 376 MPa, and 333 MPa in replications, and 357.84 MPa for average tensile strength with 22.05 standard deviation. Also, the S/N ratio value is 51.02. To evaluate the optimization results, this verified optimum needed to be compared with the initial SMAW parameter design.

3.4. Optimization Gain

The results of this work clearly show that the improvement of SMAW robust parameter compared to the initial design that is usually used in practice is shown in Table 4, which can be concluded that the
robust parameter will grant a gain bonus about 98,39 MPa (from 259,45 to 357,84 MPa) in tensile strength and 2,76 (from 48,26 to 51,02) in S/N ratio.

| Design Parameters | Welding Current | Electrode Angle | Root Gap | Electrode Type | Mean | S/N Ratio |
|-------------------|-----------------|-----------------|----------|----------------|------|-----------|
| Initial Design    | 80A             | 60°             | 2 mm     | E6013          | 259.45 | 48.26     |
| Robust Design     | 100A            | 90°             | 2 mm     | E7018          | 357.84 | 51.02     |
| Gain              |                 |                 |          |                | 98.39 | 2.76      |

3.5. Analysis of Variance (ANOVA)

Analysis of variance is conducted for further contribution evaluation for each SMAW parameter. Main effect of each parameter is considered, but not for any variable interaction effects. ANOVA for average tensile strength response is presented as shown in Table 5.

| Source of Variation | SS    | DoF | MS   | F₀   | F₁   | P-Value  |
|---------------------|-------|-----|------|------|------|----------|
| I                   | 8505.04 | 2   | 4252.52 | 3.78 | 3.55 | 11.70%   |
| θ                   | 6433.86 | 2   | 3216.93 | 2.86 | 3.55 | 8.85%    |
| d                   | 22833.98 | 2  | 11416.99 | 10.16 | 3.55 | 31.41%   |
| E                   | 14686.47 | 2  | 7343.23 | 6.53 | 3.55 | 20.20%   |
| Error               | 20230.06 | 18 | 1123.89 |      |      | 27.83%   |
| Total               | 72689.41 | 26 |      |      |      | 100.00%  |

As shown in Table 5, root gap (d) is the most significant SMAW parameter to the tensile strength because it allows for the maximum weld penetration than none root gap. The second is the electrode type because of each electrode type has different composition and cost, which level 3 is the highest cost. Furthermore, it is the welding current which also affects to the weld penetration. On other hand, the electrode angle (θ) does not have a significant effect on the tensile strength. The ANOVA results confirms the Taguchi Method results as presented in the previous sections in the figure of effect plot for mean response as shown in figure 2.

4. Conclusion

Optimization results of SMAW parameters to maximize tensile strength of welded joints can be concluded as following:

- The robust optimum parameter design of SMAW is 100A in welding current, 90° in electrode angle, 2 mm root gap, and electrode type E7018.
- The Improvement (gain) of the optimization SMAW parameter compared to initial SMAW parameter is 98,39 MPa in tensile strength and 2,76 in S/N Ratio.
- Contribution of each SMAW parameters to tensile strength of the weld joint are welding current 11,70%, electrode angle 8,85%, root gap 31,41%, and electrode type 20,20%.
- All optimum SMAW parameters are at highest level (level 3). This optimum SMAW parameters are at the boundary of variable space which give opportunity to improve SMAW process by revising the variables.

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