An Investigation of TIG welding parameters on microhardness and microstructure of heat affected zone of HSLA steel

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Abstract: Nowadays a wide variety of metal joining methods are used in fabrication industries. In this study, the effect of various welding parameters of the TIG welding process on microhardness, depth, and microstructure of the heat-affected zone (HAZ) of L450 HSLA steel and optimizing these process parameters following Taguchi experimental design was investigated. The microhardness tended to increase significantly with the increase of welding speed from 1.0 to 2.5 mm/s whereas the width of HAZ decreased. The current and arc voltage was found to be less significant in relative comparison. Microstructures of the welded samples were also studied to analyze the changes in the microstructure of the material in terms of ferrite, pearlite, bainite, and martensite formations. Welding speed was found to be the most significant factors leading to changes in microhardness and metallurgical properties. The increase of welding heat input caused an increase in width (depth) of HAZ and the growth of prior austenite grains and then enlarged the grain size of coarse grain heat affected zone (CGHAZ). However, the amount of martensite in the HAZ decreased accompanied by an opposite change of paint. It was observed that the hardness properties and the microstructural feature of HAZ area was strongly affected by the welding parameters.

1. Introduction

When high strength low alloy steel is welded, non-uniform heating and cooling in weld metal and base metal create harder heat affected zone (HAZ), cold crack susceptibility and residual stress in weldments [1]. The properties of the welded metal, HAZ, and base metal have been considered with varying parameters. But there is only a little work on welded high strength low alloy steels. Hence HSLA steels become an indispensable steel category for different applications. For instance, ships, railroad equipment, building construction, boilers, offshore oil drilling platforms, pipelines, pressure vessels, aircraft, automobiles [1, 2]. However, These critical zones which created through the welding process playing an important role in the morphology of material properties of welded HSLA steels. The heat affected zone (HAZ) is one of an undesirable zone, but the inevitable region of a fusion welded joint. This region undergoes additional thermal cycle(s) that may have a detrimental effect on the microstructure and mechanical properties of the welding joints. For this reason, the properties of the HAZ, particularly the toughness, and strength, still remains a major concern for many users of these materials [2]. Also, hardness, depth of heat affected zone and microstructure of heat affect zone...
(HAZ) are extremely important for HSLA steel structural consideration in welding. These are very much important in the case of welding method, cooling rate, grain structure, and structural integrity. The process parameters like welding current, voltage, welding speed and arc length are the primary variables which control the fusion, depth of penetration, and depth of HAZ. The HAZ was more classified into three regions, i.e. grain growth region, grain refined region and transition region [3]. The hardness during weld joint is not uniform. Moreover, HSLA Steel is sensitive to thermal cycle and the metal of weld joint was having highest temperature, i.e. above the melting point and the parent metal was having temperature very less below the lower critical line. Because of the high-temperature difference between these two regions, the cooling rate was very high and the solidification of weld metal was under non-equilibrium conditions. Due to this, the transformation from austenite to pearlite micro-constituent has not occurred and austenite to martensite or bainitic lathe has happened. So, the hardness of this region was very high and HAZ has become more susceptible to catastrophic cracking [4]. Therefore, a variety of microstructures in welded HSLA steel is obtained depending on the deformation temperature and cooling rate. The proper control of these process parameters and the characteristics will give better results and fewer risks in order to guarantee the reliability and durability of the welding zones [5, 6].

To predict the optimum input welding parameters without consuming more time and raw materials in experimentation trials, there are different methods of optimization for obtaining the required output values through the development of models. A design of experiments (DOE) approach is the most significant and efficient way for optimization of process variables. The use of DOE methods over the last two decades has grown significantly and has been adapted in science and engineering experiments to optimize process parameters [7]. No research work has been done using DOE approach for optimization of TIG torch welding parameters on HSLA steel. Therefore, the main aim of this work is to study the influence of welding parameters (current, arc voltage, travel speed and heat input) on microhardness, depth, and microstructure of the heat-affected zone (HAZ) and to optimize the process parameters after accomplishment of the TIG welding process on X65 HSLA steel following Taguchi experimental design.

2. Experimental procedures
The high strength low alloy steels employed in the present work, designated as L450- HSLA steel, was procured from China in the form of plates with 10 mm in thickness. The chemical composition of this steel can be found elsewhere [8].

A Miller TIG torch source attached with a semi-automatic traversing arm was used for melting purpose. The direct current electrode negative (DCEN) mode was used and a 3.2 mm diameter tungsten electrode was used to strike an arc between the electrode and the workpiece in pure Argon atmosphere to prevent excessive oxidation [8].

Minitab 17 software was used to determine the no. of experiments to be conducted with the predetermined variables and their levels [9]. Taguchi method provides a set of well minimum experimental runs. This method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio takes both the mean and the variability into account. The optimum setting is the parameter combination, which has the highest S/N ratio [10]. Based on Taguchi’s orthogonal array design, experiments have been conducted with four different levels of process parameters as listed in table 1: welding current, welding voltage, welding speed and shielded gas obtain bead-on-plate weldment on L450 HSLA steel plates (60x40x10) mm³. The experiments have been carried out as per Taguchi’s L16 orthogonal array (OA) design.
Table 1. Process parameters and their limits.

| No. | Parameters | Notation | Unit | Level 1 | Level 2 | Level 3 | Level 4 |
|-----|------------|----------|------|---------|---------|---------|---------|
| 1   | Current    | C        | A    | 70      | 80      | 90      | 100     |
| 2   | Voltage    | V        | V    | 25      | 30      | 35      | 40      |
| 3   | Speed      | S        | mm/sec | 1       | 1.5     | 2       | 2.5     |
| 4   | Shielding Gas | SG   | L/min | 15      | 20      | 25      | 30      |

Taguchi technique was used for the analysis of results obtained after testing and to find out the main effect of the process parameters and the percentage contribution of each parameter on the output.

After welding, a complete cross section of the weldments composed of the parent plate and weld metal was removed transverse to the welding direction to produce specimens for microstructural examination and hardness measurements. All specimens were ground on silicon carbide “wet” papers from P320 to P1200 grade and polished sequentially on diamond wheels using 3, 1 and 0.25 µm grades. The weld metal microstructure was revealed by using 2% Nital solution. An average of three readings was taken to determine the hardness and the width of HAZ. The microstructure was evaluated using a standard optical microscope and JMS 5600 scanning electron microscope.

Table 2. Design matrix with experimental results for Hardness and width of HAZ

| Run | Current (A) | Voltage (V) | Speed (mm/sec) | Shielded Gas flow rate (L/min) | Hardness of HAZ (Hv) | Width of HAZ (mm) |
|-----|-------------|-------------|----------------|-------------------------------|----------------------|------------------|
| 1   | 70          | 25          | 1              | 15                            | 249.30               | 1.39             |
| 2   | 70          | 30          | 1.5            | 20                            | 280.20               | 1.20             |
| 3   | 70          | 35          | 2              | 25                            | 289.50               | 0.75             |
| 4   | 70          | 40          | 2.5            | 30                            | 333.90               | 0.70             |
| 5   | 80          | 25          | 1.5            | 25                            | 283.70               | 1.52             |
| 6   | 80          | 30          | 1              | 30                            | 243.60               | 1.19             |
| 7   | 80          | 35          | 2.5            | 15                            | 354.90               | 0.85             |
| 8   | 80          | 40          | 2              | 20                            | 256.30               | 1.15             |
| 9   | 90          | 25          | 2              | 30                            | 282.00               | 1.30             |
| 10  | 90          | 30          | 2.5            | 25                            | 339.60               | 0.84             |
| 11  | 90          | 35          | 1              | 20                            | 218.50               | 1.67             |
| 12  | 90          | 40          | 1.5            | 15                            | 219.20               | 1.84             |
| 13  | 100         | 25          | 2.5            | 20                            | 350.70               | 1.12             |
| 14  | 100         | 30          | 2              | 15                            | 251.28               | 1.57             |
| 15  | 100         | 35          | 1.5            | 30                            | 225.90               | 1.41             |
| 16  | 100         | 40          | 1              | 25                            | 209.00               | 2.04             |
3. Results and Discussion
Based on the DOE runs the experiments are conducted and the values of the responses are shown in table 2. The objective of the parameter design is to optimize the settings of the process parameter values for improving HAZ characteristics and From the output variables, the effect of the process parameters on these variables can be identified. [11]. In this paper, the characteristic values are selected by the hardness of HAZ and the width of HAZ, since a good result is obtained by the smaller HAZ width and lower hardness, the lower the better (LB) is preferred.

3.1 Effect of parameters on Hardness of HAZ
Hardness is one of the most important critical factors indicating the quality of the welding and its performance in service. From the Main effect plot for means of the hardness of HAZ of welded L450 HSLA steel, figure 1 established that there was a significant increase in the hardness of HAZ with the increase of the welding speed, while a little decrease with increasing voltage and current, respectively. This is due to the fact that as the welding speed increases the amount of the heat input will decrease causing high cooling rates lead to increase of hardness levels in the HAZ [12, 13].

![Main effect plots](image1.png)

Figure 1. Main effect plots a) for the means and b) for S/N ratio for Hardness of HAZ.

3.2 Effect of parameters on width of HAZ
The width of HAZ as shown in Figure 2 was influenced by the speed and current factors, the width of HAZ is smaller as the current decreased and the speed increased. The high speed causes low heat input and this causes the formation of a smaller HAZ region, the literature survey supports this result [4,14]. Whereas the results of the welding voltage and shielded gas flow rate have a less significant effect on the HAZ width. The welding speed has significantly influenced the HAZ width, this was due to the amount of molten on the base metal influences the HAZ area. It can be said that an increase in welding speed and a decrease in welding current decreases the HAZ area compared to voltage or shielded gas flow rate and by controlling them the size of the HAZ can be controlled.

3.3 S/N Ratio Analysis
Based on S/N ratio analysis, the process parameters which significantly affect the hardness and width of HAZ are shown in table 3 and table 4. The level of a factor with the highest S/N ratio was the optimum level of responses measured. From the Table 4 it is clear that the optimum value levels for
lower HAZ hardness are at a Current (100 A), Voltage (40 V), speed (1 mm/sec) and Gas flow rate (15 L/min), and from Table 4 the optimum value levels for lower HAZ width are at a Current (70 A), Voltage (35 V), speed (2.5 mm/sec) and Gas flow rate (30 L/min). The response tables include ranks based on Delta statistics, which compare the relative magnitude of effects. The Delta statistic is the highest minus the lowest average for each factor [11]. Minitab indicates ranks based on Delta values; rank one to the highest Delta value, rank two to the second highest, and so on.

![Main Effects Plot for Means and S/N ratio for width of HAZ](image)

**Figure 2.** Main effect plots a) for the means and b) for S/N ratio for width of HAZ.

3.4 The microstructure of the HAZ
The microstructure of the HAZ depends on the chemical composition and the peak welding temperature. Higher heat-input welding produces wider coarse grain HAZ (CGHAZ). The extent of grain growth in the HAZ depends on the local thermal cycle, which can be controlled by adjusting the welding parameters [6]. The prior austenite grains corresponding to different locations of the HAZ are displayed in figure 3(a–d), and are characterized by distinct grain boundaries. When a welding speed

### Table 3. Hardness of HAZ Response Table for S/N Ratios.

| Level | Current (A) | Voltage (V) | Speed (mm/sec) | Shielded gas flow rate (L/min) |
|-------|-------------|-------------|----------------|-------------------------------|
| 1     | -49.15      | -49.22      | -47.21         | -48.44                        |
| 2     | -48.99      | -48.83      | -47.98         | -48.7                         |
| 3     | -48.31      | -48.53      | -48.6          | -48.83                        |
| 4     | -48.1       | -47.97      | -50.75         | -48.57                        |
| Delta | 1.05        | 1.26        | 3.53           | 0.39                          |
| Rank  | 3           | 2           | 1              | 4                             |

### Table 4. Width of HAZ Response Table for S/N Ratios.

| Level | Current (A) | Voltage (V) | Speed (mm/sec) | Shielded gas flow rate (L/min) |
|-------|-------------|-------------|----------------|-------------------------------|
| 1     | 0.3         | -2.45       | -3.76          | -2.67                         |
| 2     | -1.24       | -1.37       | -3.38          | -2.05                         |
| 3     | -2.62       | -0.87       | -1.21          | -1.45                         |
| 4     | -3.52       | -2.39       | 1.27           | -0.91                         |
| Delta | 3.82        | 1.57        | 5.03           | 1.76                          |
| Rank  | 2           | 4           | 1              | 3                             |
is high (low heat input), the microstructure of weld metal and HAZ changes, it will cause the martensite phase transformation and the microhardness increased as shown in figure 3b.

On the contrast, increasing the welding heat input (lower welding speed and higher welding current), this corresponded low cooling rate and beneficial for the formation of bainite and the ferrite was coarsened in HAZ region leading to decreased the microhardness of HAZ phases as shown in Figure 3c. Also, the increasing of welding heat input caused an increase in width (depth) of HAZ and the growth of prior austenite grains and then enlarged the grain size of coarse grain heat affected zone (CGHAZ). However, the amount of martensite in HAZ decreased accompanied by an opposite change of bainite as indicated in figure 3d.

**Conclusion**

From the present study, the HAZ area was strongly affected by the welding parameters and the welding speed being the most significant parameter on the hardness of HAZ. The increasing in welding speed cause a significant increase in the hardness of HAZ, while a slight decrease with increasing current and voltage. Moreover, the width of HAZ is influenced by the current and the welding speed. It means that an increase in welding speed and a decrease in welding current cause smaller HAZ area compared to voltage or shielded gas flow rate.

The application of Taguchi approach was successful in this study, and from the Taguchi S/N ratio the optimal parameters setting for lower HAZ hardness are at a Current (100 A), Voltage (40 V), speed (1 mm/sec) and Gas flow rate (15 L/min), and the optimal value levels for lower HAZ width are at a Current (70 A), Voltage (35 V), speed (2.5 mm/sec) and Gas flow rate (30 L/min).

When the welding heat input is low, the martensitic phases transformation occurred. Whereas increasing the welding heat input the formation of bainite and the ferrite was coarsened in HAZ region.
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