Process Parameter Optimization in TIG Welding of AISI 4340 Low Alloy Steel Welds by Genetic Algorithm

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Abstract Weld quality is an essential requirement to the fabrication and construction industries. In this present investigation, an attempt has been made to optimize the process parameters of Tungsten Inert Gas (TIG) welding of AISI 4340 low alloy steel. Taguchi L9 orthogonal array is used to design the experiment and response surface methodology was used to develop mathematical model and the process parameters were optimized using Genetic Algorithm (GA). The important process parameters namely welding current, voltage, welding speed, and gas flow rate are considered. The results indicate that the current and voltage have a maximum influence on improving Ultimate Tensile Strength (UTS) in TIG-welded joint.

1. Introduction
Tungsten Inert Gas (TIG) welding is one of the usual arc welding processes where arc produces between non-consumable tungsten electrode and workpiece and metal fusion happens. TIG welding is broadly utilized for joining alloy steels, stainless steels in numerous fabrication industries due to high caliber and great appearance. Be that as it may, one potential issue related to traditional TIG is the constraint on workpiece thickness that can be welded in single pass thus offers limited efficiency. And, TIG welding should have the following characteristics, (1) a straight polarity direct current, (2) high frequency arc starting, and (3) power supply reduction device (1). Increment in current may not be shrewd dependably as it will prompt increment in bead width with relatively low pick up in infiltration. Nickel-Chromium-Molybdenum steels are broadly utilized for joining as a part of various applications including marine, automotive and machine instruments, pressure vessels, transport, mining and so on. Impressive measures of spotlight on accomplishing high caliber welded joints of such materials for similar and dissimilar joining are being investigated at quicker production rates with higher amount of infiltration. Exertion has been made by a few researchers to modify the TIG welding process by utilizing fluxes to increase the weld penetration. The depth of penetration amid TIG welding could be altogether expanded laying an activated flux layer on workpiece surface before welding, accordingly eliminates the need of edge preparation, reduces number of passes required and improves efficiency. The procedure is instituted as flux activated TIG welding. Numerous analysts directed experimental studies to assess the impact of various oxide, halide or mixture of fluxes on increase in DOP and relating decrease in width or width-to-penetration (WP) on various high nickel-chromium-molybdenum steels at various instances (2–4). Be that as it may, the welding innovation has not been exceptionally fruitful to join nickel-chromium-molybdenum steels in commercial ventures in this way, and related studies are likewise to a great degree constrained. So, it gets to be important to explore the relevance of welding innovation in joining little scale parts.

2. Materials and Methods
The base materials used for the present investigation were AISI 4340 (ASTM A29), produced by M/s ALOKINGOTS India Pvt. Ltd, Mumbai, India is a medium carbon, low alloy steel. The chemical compositions of base metal as received is C – 0.39, Mn – 0.72, Cr – 0.7, Ni – 1.65, Si – 0.15, Mo – 0.2, P – 0.035 and S – 0.04. All AISI 4340 steel plates were sized into 150mm (L) × 75mm (W) × 5mm (t) were butt welded at different process parameters as per the design matrix. Figure 1 demonstrate the AISI 4340 steel plates to be welded. Before welding, acetone was used to eradicate the oils that remained on the surface of the specimens. Extensive welding trials were conducted in autogenous mode with ESAB make A-TIG power source having capacity of 250A with 25% duty cycle to examine the performance and appearance of the weld.
Figure 1. Test specimens of AISI 4340 – medium carbon, low alloy steels

Then, all the steel plates were welded by TIG welding as per the variables designed by orthogonal array using Taguchi technique. A 3 mm diameter and 2.2 % thoriated tungsten electrode with an air-cooled torch was used. The welding variables and their corresponding ranges are presented in Table 1. All the samples were welded under full penetration. The electrode angle was kept as 19 – 22° pure argon was used as a shielding gas during welding. The flux paste was applied later welding, acetone evaporated, parting a layer of flux on the surface. The torch was moved along the center line of the weld specimens.

| Process Factors | Current (A) | Voltage (V) | Welding Speed (WS) (mm/sec) | Gas Flow Rate (GFR) (lpm) |
|-----------------|-------------|-------------|-----------------------------|---------------------------|
| Levels          | 70 - 80     | 12 - 14     | 55 - 65                     | 8-12                      |

Table 1 – Welding variables and their range

Figure 2. Fabricated AISI 4340 low alloy steel

The fabricated AISI 4340 steel plates after welding are presented in Figure 2 and their corresponding design matrix is presented in Table 2. After welding, specimens were collected from the center of the welded plate and subjected to Ultimate Tensile Strength (UTS). Subsequently, for conducting the hardness test, samples were allowed for grinding and polishing followed by etching in a solution of 35% concentrated HCL at 60 - 80°C for 12–15 minutes to produce a bright surface. Scanning electron microscope (SEM) (Make: FEI Quanta FEG 200 high resolution – Micro lab, Chennai, Tamilnadu, India) is used to develop the microstructure of the welded samples. Further, hardness variation in HAZ, NZ and TMAZ on the effect of TIG welding process parameters the specimens were subjected to vickers hardness and Izod impact test. Micro-hardness measurements were taken across the specimen at 300 gf load and 15 s dwell time on Vickers micro-hardness tester (Make: Fuel Instruments and Engineers (FIE), Mettax laboratory, Chennai, Tamilnadu, India). Indentations were typically performed at 3 mm spacing.
Table 2. Experimental results

| Std | Current (A) | Voltage (V) | Welding speed (WS) (mm/min) | Gas Flow Rate (GFR) (lpm) | Ultimate tensile strength (UTS) |
|-----|-------------|-------------|------------------------------|--------------------------|-------------------------------|
| 1   | 70          | 12          | 55                           | 8                        | 972                           |
| 2   | 70          | 13          | 60                           | 10                       | 961                           |
| 3   | 70          | 14          | 65                           | 12                       | 951                           |
| 4   | 75          | 12          | 60                           | 12                       | 970                           |
| 5   | 75          | 13          | 65                           | 8                        | 933                           |
| 6   | 75          | 14          | 55                           | 10                       | 943                           |
| 7   | 80          | 12          | 65                           | 10                       | 938                           |
| 8   | 80          | 13          | 55                           | 12                       | 952                           |
| 9   | 80          | 14          | 60                           | 8                        | 915                           |

3. Optimization of welding parameters

3.1. Response surface methodology
Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques for process development optimization (5). RSM is often accomplished directly for the objectives of quality improvement including reduction of variability, process enhancement and product performance (6). The RSM is widely used for setting the parameter and optimization such as chemical, electronics, manufacturing and metal cutting industries. Lot of process parameters may affect the output quality responses in the TIG welding process. Therefore, optimization and finding several independent variables affecting the TIG welding process is quite complex and time-consuming process. However, using design of experiments and applying regression analysis, process modeling of the favorite response to numerous independent input variables can be gained. The response surface can be expressed if all the variables are assumed to be measurable,

\[ y = f(x_1 + x_2 + ... + x_k) + \epsilon \]

In many engineering analysis, there is a relationship between an output variable on interest ‘y’ and set of controllable variables \( (x_1, x_2, ..., x_k) \), \( \epsilon \) is a noise or experimental error. Usually in most of the engineering and non-engineering RSM problems the relationship between the input and output variable are unknown. Thus, finding the suitable approximation for the true functional relationship between ‘y’ and set of the independent variables is the first step in RSM. Usually the second order model is utilized in RSM,

\[ y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ij} x_i x_j + \sum \beta_{ijk} x_i x_j x_k + \epsilon \]

The \( \beta \) coefficients can be calculated by means of using least square method in above model. The second-order model is normally used when the response function is not known or nonlinear (7).

3.2 Genetic algorithm
Genetic algorithm (GA) is used for stochastic problems, which is introduced by Holland (8) based on mechanics of a biological evolution process. Usually, a decision variable of a coded gene is represented by a real number, a bit or a string in genetic algorithm. And a corresponding gene of each parameter creates a chromosome which represents a binary of strings or an array of a problem that can be varied depending on a treated problem (9). A set of chromosomes is called population. Among solutions, one population is preferred through a selection operator such as roulette wheel or tournament selection, where the probability is to be selected relative to individual fitness. The selected set of individuals is used further to create a new population through genetic operators called mutation and crossover. Crossover chooses genes from parent chromosomes and builds a new offspring. Besides, the mutation is preventing all the solutions of the population get trapped into a local
optimum. This procedure is repeated under some situations are satisfied, until goodness of best solution is attained. The GA parameters used in the present investigation is presented in Table 3.

| Parameters            | Setting value |
|-----------------------|---------------|
| Population size       | 50            |
| Crossover rate        | 0.8           |
| Mutation rate         | 0.7           |
| Selection operator    | Adaptive feasible |
| Fitness operator      | Tensile strength |

4. Results and Discussion

4.1. Mathematical design of the problem

The maximization of the present fitness function values is subjected to the boundaries of weld parameters. The weld parameters and their range are shown in Table 4 is selected to show the limitations of the optimization solution and is given as follows,

| Parameters              | Range            |
|-------------------------|------------------|
| Current                 | 70≤A≤80          |
| Voltage                 | 12≤V≤14          |
| Welding speed           | 55≤WS≤65         |
| Gas flow rate           | 8≤GFR≤12         |

In order to apply GA several parameters to be considered while initiating the problem toward the objective function of the problem. The MATLAB optimization toolbox is used to maximize the TIG welded AISI4340 steels. The optimal values for the maximization of UTS of TIG welded parameters obtained from GA is Current (A) = 70A, Voltage (V) = 12V, Welding speed = 55mm/min and Gas flow rate = 11.807 lpm and it is indicated that the optimal solution is obtained in 52nd iteration. The best fitness value obtained from GA for maximizing the UTS of TIG welded AISI 4340 is 988.816 MPa.

![Figure 3. GA Convergence plot](image)

Fitness value of the convergence result obtained using GA is graphically presented in Figure 3 that shows a dotted line signifies that there is no infringement of constrains in each generation. The maximum tensile strength by GA optimization was observed to be low current (70 A), low voltage (12 V), welding speed (55 mm/s), and the high gas flow rate (11.80 lpm). The optimal values of the process parameters obtained by the GA is 988.816 MPa. Based on Taguchi L9 orthogonal array nine
experimental data was assessed from the experiments. Regression analysis was carried out model for UTS is,

\[ \text{UTS} = +1345.5-2.63 \times \text{Current} -11.83 \times \text{Voltage} -1.50 \times \text{Welding speed} + 4.41 \times \text{Gas flow rate} \]

The analysis of variance (ANOVA) test was employed to determine the percentage contribution of the parameters at 95% confidence level and to investigate which process factor significantly affected the quality characteristic of TIG welding. The result of ANOVA is presented in Table 5. The significance of each process factor was tested using \(F\)–test. In general, if \(F\) of experimental runs are higher than the table 10.128 (from the Standard Fishers table), which means that the varying the process factor makes a big change on the process performance. In addition, the percentage contribution (P) indicates the significance of process factors for the response. For a factor with a high values of P, a small variation will have a great influence on the performance (10). The graphical representation of percentage contribution is presented in Figure 4, it observed that, current (A) was found to be a major factor affecting the welding process significantly the mean average of UTS of 38.64%. The voltage (V), gas flowrate (GFR) and welding speed (F) have an effect on the UTS of 31.21%, 17.39% and 12.54% respectively. And, the predicted and adjusted coefficient of determination (R-Squared) are 99.78% and 99.55% respectively. The “predicted R-Squared” of 99.78% is in reasonable agreement with the “Adjusted R-Squared” of 99.55%.

![Figure 4 Contribution plot](image)

| Source       | df | Adj SS  | Adj MS  | F value | p value | Significant |
|--------------|----|---------|---------|---------|---------|-------------|
| Regression   | 4  | 2686.00 | 671.50  | 447.67  | < 0.0001 | Significant |
| A – Current  | 1  | 1040.17 | 1040.17 | 693.44  | 0.003   |             |
| B – Voltage  | 1  | 840.17  | 840.17  | 560.11  | <0.0001 |             |
| C – Welding speed | 1 | 337.50  | 337.50  | 225.00  | <0.0001 |             |
| D – Gasflow rate | 1 | 468.17  | 468.17  | 312.11  | 0.0002  |             |
| Error        | 4  | 6.00    | 1.50    |         |         |             |
| Total        | 8  | 5378.01 |         |         |         |             |

\[ S = 1.22 \quad \text{R-Sq} = 99.78\% \quad \text{R-Sq (adj)} = 99.55 \quad \text{R-Sq (Pre)} = 98.95\% \]

4.2. **Ultimate tensile strength**

A SEM image of base materials were taken in order to understand primary phases of the materials and to ascertain morphological changes in various phases of materials after TIG welding. The developed SEM images of base materials as presented in Figure 5(a) and Figure 5(b). The temperature of weld metal with a much lower amount of hot molten mass comparatively to surrounding temperatures were always low. Hence an air-cooling effect was experienced by the weld metal produces irregular harder
(martensite) phases owing to insufficient solidification time. Moreover, a couple of micro holes have been observed on the weld zone due to rapid solidification of molten metals as shown in Figure 5(a). This phenomenon is observed in all samples being welded irrespective to the process parameters. Besides that, from over all micro structures a clear elongated grain of irregular harder martensitic interfaces was seen in all the fabricated weld joints as shown in Figure 5(b). And in the HAZ region, exhibited fine acicular ferrite and coarse harder martensitic structure was seen, hence a lower hardness was observed. The readings were taken in Vickers hardness scale is plotted. Figure 6 shows the hardness distribution at the cross section of the welded joints of AISI 4340 steel plates. The weld zone from -5mm to +5mm showed lower hardness value when compared to base materials of AISI 4340 steel plates. Due to more heat capacity of the argon gas flame quickly softening the metals thus leads the formation of micro holes on the weld zone as shown in Figure 5(a). This tendency in nature, decreasing the hardness on the weld zone and HAZ. However, the obtained hardness plot is mostly owing for ductile nature of the joints as evidenced from the fracture locations of welded plates. At weld nugget zone, the weld metal hardness is achieved was maximum due to the formation of irregular and harder martensitic structures. The HAZ region exhibited a mix of coarse and fine microstructures. And due to full penetration welding, cooling rate is slow hence there is no noticeable changes in the micro structures were observed in the metallurgical properties (4).

Figure 5. (a) Micro holes in TIG weld zone, (b) Harder martenstic interface

Figure 6. Rockwell hardness distribution of fabricated TIG welded samples

The main effects plot for UTS with individual effect of current, welding speed, voltage, and gas flow rate are presented in Figure 7. It indicates lower current, welding speed, and voltage maximizing tensile strength because of lower heat input. The tensile strength increases with increase in gas flow rate. The reason is that shielding gases are used to prevent atmospheric contamination of the weld metal. A too low heat input result more weld defects thus tensile strength reduced in the fabricated weld joints. On the other hand increasing gas flow rate increasing tensile strength of the weld joint. Since, shielding gas has low ionization potential and is heavier than air, subsequently it giving exceptional shielding of the molten weld pool which improves the mechanical properties of the weld joint.
The interaction effect of welding speed versus current on UTS of TIG welding process parameters is presented in Figure 8. It can be seen that increasing welding current increases UTS from 927 MPa to 954 MPa. Increasing welding current increases weld penetration therefore heat input increases subsequently. Moreover, increasing weld penetration improves fluid flow in the weld pool, which is driven by the electromagnetic force, surface tension gradient, buoyancy force, and impinging force. Thus UTS is increases with increasing welding current of the fabricated weld joints.

Figure 7. Main effect plot

Figure 8. Welding speed, Current vs UTS

Figure 9. Welding speed, Gas flow rate vs UTS

Figure 10. Voltage, Gas flow rate vs UTS

Figure 9. shows the welding current, voltage vs UTS. It is observed that the voltage is directly responsible to the UTS. For voltage, F value is 694.44 in the ANOVA which is the most significant
term and consequential term in the TIG welding. In the surface plot, it can be observed that the incrementing current will decrease the UTS values from 961 MPa to 943 MPa. A change in microstructure directly affects the mechanical properties of the weld. Consequently, when the heat input increases highly, the hardness of the welded joint decreases slightly due to microstructure coarsening. Figure 10. shows surface plot of welding speed, gas flow rate vs. on UTS. When the voltage varies from 12 to 13.5 V, the UTS extremely decreases from 970 MPa to 950 MPa. In addition to that, an increasing gas flow rate from 8 to 12 lpm, the UTS increases slightly from 927 MPa to 948.5 MPa. Gases with low ionization potential encourage the ignition of the electric arc, and those with low thermal conductivity tend to build the arc stability. The corresponding F value is 560.11, which implies that voltage is the most critical term in the conducted A-TIG welding process.

5. Conclusion

In this present investigation, an attempt has been made to optimize the process parameters of A-TIG welding of AISI 4340 steel. Taguchi L9 orthogonal array has been utilized in the present investigation to optimize the process parameters of TIG welding process. The mathematical model has been developed to understand the relationship between the ultimate tensile strength and the individual factors considered in the experiment namely welding current, voltage, welding speed, and gas flow rate were used and the ultimate tensile strength of AISI 4340 steel has predicted at 95% confidence level. ANOVA has been employed to determine the percentage contributions of the process parameters. Optimization was carried out with the response surface method based genetic algorithm. Confirmation test reveals that GA can be utilized effectively to evaluate input process parameters to get the required ultimate tensile strength.

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