UDC: 621.791.75:519.876.2
Preliminary communication

OPTIMIZATION OF DOUBLE-SIDED SUBMERGED ARC WELDING PARAMETERS OF STEEL X65

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Abstract

Due to the complexity of the Submerged Arc Welding process (SAW), determining welding parameters has relied on empirical and experimental data (trial and error), which economically is not justifiable. Welded joint quality during Submerged Arc Welding (SAW) is mainly influenced by various welding parameters such as arc voltage (U), welding current (I), welding speed (v_s) and electrode stick out (l). Welded joint geometry is directly influenced by these welding parameters, so in the published literature from this field there are various data about the influence of welding parameters on the welded joint geometry. Therefore, in this paper we have developed mathematical models for our experimental data, based on the welding voltage (U), welding current (I) and welding speed (v_s) and the effect of these parameters on penetration and overlap. The models were obtained by multiple polynomial regression analysis. These models predict penetration and overlap in two-sided submerged arc welding of API 5L grade steel X65 for line pipe. The results of the established mathematical models show that the models accurately predict weld penetration and overlap. Furthermore, we must optimize welding parameters to produce high-quality welding. To do so, we used the Genetic Algorithm (GA), as a computational tool to solve the resulting constrained optimization problem. The results give us the values for penetration and overlap at their maximum/minimum values respectively.

Keywords: Submerged arc welding (SAW); Double sided welding; Welding parameters; Optimization; Genetic algorithm.

1 Introduction

Submerged Arc Welding (SAW) is mostly used in steel fabrication for structural shapes like large diameter pipes, tanks, pressure vessels and welded components for welded machinery (Aniruddha & Hloch, 2013). Since Submerged Arc Welding process (SAW) is very complex, it makes difficult determining the technological parameters that would assure high-quality welding. Welded joint quality during Submerged Arc Welding (SAW) is mainly influenced by various welding parameters such as arc voltage (U), welding current (I), welding speed (v_s) and electrode stick out (l). Having good control of these parameters allows us to do high-quality welding (S. Thiru Chitrambalam1, 2012).

Generally, in literature this problem is addressed by introducing mathematical models that describe the nature of the problem. In (S. Thiru Chitrambalam1, 2012) mathematical models for Process Control Parameters and Weld Penetration for Robotic CO2 Arc Welding using Factorial Design Approach are proposed. The Taguchi experimental method has been used in (Kumanan, J, & K, 2007) for determination of welding process parameters in submerged arc welding. In (Mostafa, 2005) statistical techniques have been used to predict weld bead penetration in flux-cored arc welding (FCAW) of a grade of high strength low alloy (HSLA) steels where the objective function has been defined and solved as linear quadratic programming problem. A mathematical model is proposed in (Marcelo Teodoro Assunção, 2017) and validated for underwater we flux cored arc welding – FCAW.

Lately, the Genetic Algorithm has been shown to give efficient results to optimization problems (Sivanandam, 2008). The paper (Karamani, 2015) shows implementations of Genetic Algorithms in optimization in data mining.

A mathematical model that captures the effects of the welding parameters is determinant when it is required to do a quality welding.

In our case Submerged Arc Welding has been used to weld pipes that are made of Steel X65 with dimensions Φ813x12 mm. SAW is an arc-welding process that uses a consumable, continuous bare wire electrode, and granular flux is used as an arc shield.

To describe the physical problem, mathematical models based on welding voltage (U), welding current (I), and welding speed (v_s) and the effect of these parameters on penetration and overlap have been established using a statistical approach. In double-sided submerged arc welding of API 5L grade steel X65 for line pipe, mathematical models predict penetration and overlap.

2 The welded joint

The measurements of geometrical dimensions of the welded joint have been made during a macroscopic investigation of the prepared specimens.

Results from the measurement of the geometrical dimensions of the welded joint are presented in the tables 1, 2, 3, 4 as presented in (Maksuti. Rr). The geometrical dimensions of the welded joint, on the other hand, are shown in figure 1.

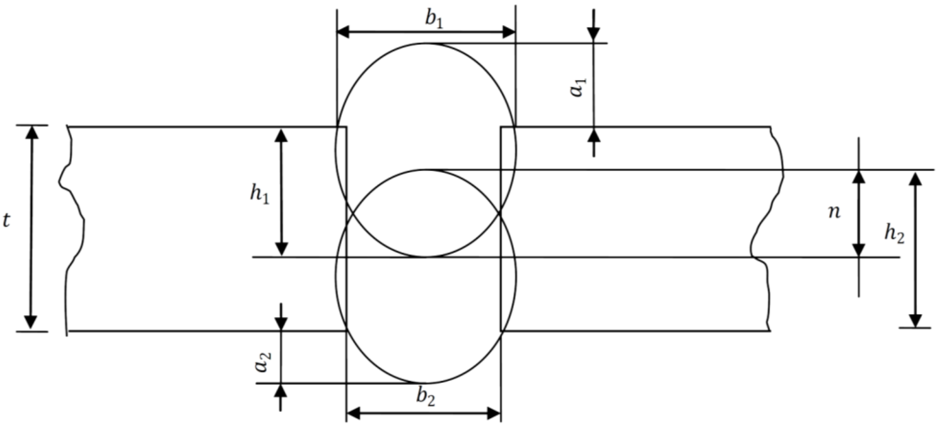

Figure 1. The welded joint

Table 1. Results from the measurement of the geometrical dimensions of the welded joint

Sample nr.	b_1	b_2	h_1	h_2	a_1	a_2	t
653505	12.9 mm	11.4 mm	6.9 mm	7.0 mm	1.9 mm	2.2 mm	12.3 mm
653417	14.1 mm	11.9 mm	7.9 mm	5.8 mm	2.5 mm	2.4 mm	12.3 mm
653504	12.6 mm	12.1 mm	8.5 mm	5.6 mm	2.6 mm	1.9 mm	12.3 mm
653597	12.5 mm	10.0 mm	8.0 mm	7.0 mm	2.6 mm	2.5 mm	12.3 mm
653508	13.0 mm	11.5 mm	8.2 mm	6.8 mm	3.5 mm	2.7 mm	12.3 mm

The welded pipes analyzed are made of Steel X65 with dimensions Φ813x12 mm, welded with the following welding parameters (shown in tables 2,3,4):

Table 2. The welding parameters analyzed for steel X65

Inner welded joint	
Current: 550-600A	$550 \leq I \leq 600$
Voltage: 27-28V	$27 \leq U \leq 28$
Welding speed: v_s =0.8 m/min	v_s =0.8 m/min
Outer welded joint	
Current: 650-700A	$650 \leq I \leq 700$
Voltage: 29-30V	$29 \leq U \leq 30$
Welding speed: v_s =0.8 m/min	v_s =0.8 m/min

Table 3. The inner welded joint

Sample nr.	U_1-Voltage	I_1-Current	h_1-Penetration	v_s=Welding speed
653505	29 V	650 A	6.9 mm	0.8 m/min
653417	30 V	680 A	7.9 mm	0.8 m/min
653504	29 V	700 A	8.5 mm	0.8 m/min
653597	29 V	690 A	8.0 mm	0.8 m/min
653508	30 V	695 A	8.2 mm	0.8 m/min

Table 4. The outer welded joint

Sample nr.	U_2-Voltage	I_2-Current	h_2-Penetration	v_s= Welding speed
653505	28 V	600 A	7.0 mm	0.8m/min
653417	28 V	555 A	5.8 mm	0.8m/min
653504	28 V	550 A	5.6 mm	0.8m/min
653597	27 V	595 A	7.0 mm	0.8m/min
653508	28 V	590 A	6.8 mm	0.8m/min

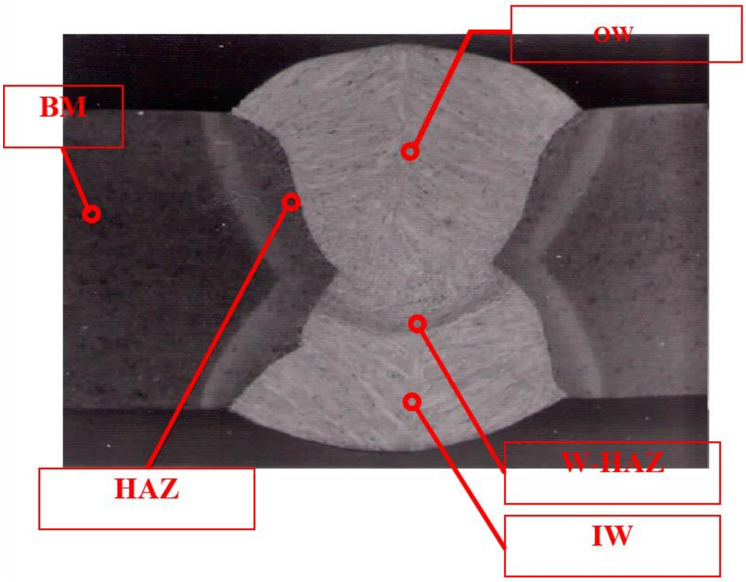

Figure 2. Macro photography of the welded joint (sample 653504)

3 Mathematical model for the outer welded joint

Three mathematical models are developed for the outer welded joint that explains the influence of the welding parameters on penetration.

To begin, the tabular data in table 4 are used to derive an expression via linear regression which results in a linear model.

$$P = -8.875 \ - 0.06028U + 0.02936I \quad (1)$$

If the results from the measured data and the results obtained from equation (1) are compared; a crude approximation can be noticed. However, in our case, one needs an expression that in terms of practical implementation will provide more accurate results than the equation by linear regression.

To demonstrate this, the following example is considered.

Example: Let us compare the results from equation (1) and the measured values. Substituting in equation (1) the values for the parameters of the case number 653417, respectively U=27 V and I=560 A.

Result: Results in P=5.7320 mm. In the table the penetration for those values is 5.8 mm, therefore the error is e=0.0625 mm.

Secondly, a custom equation to approximate penetration has been used, respectively equation (a); which can be found in literature, and it is used to determine the penetration in welding processes(Bytyçi & Osmani, Saldimi I, 1996).

$$P = k\sqrt[3]{\frac{I^4}{U^2V_s}} \quad (a)$$

When the curve is fit by the model given in equation (a),it should be considered that *k* is a constant and it can have different values. However, it has been noted that the two values for *k* that better approximate the curve are *k=0.01398* and *k=0.01249*. As a result, we get equation (2) that predicts the penetration.

$$P = 0.01398\ (or\ 0.01279)\sqrt[3]{\frac{I^4}{U^2V_s}} \quad (2)$$

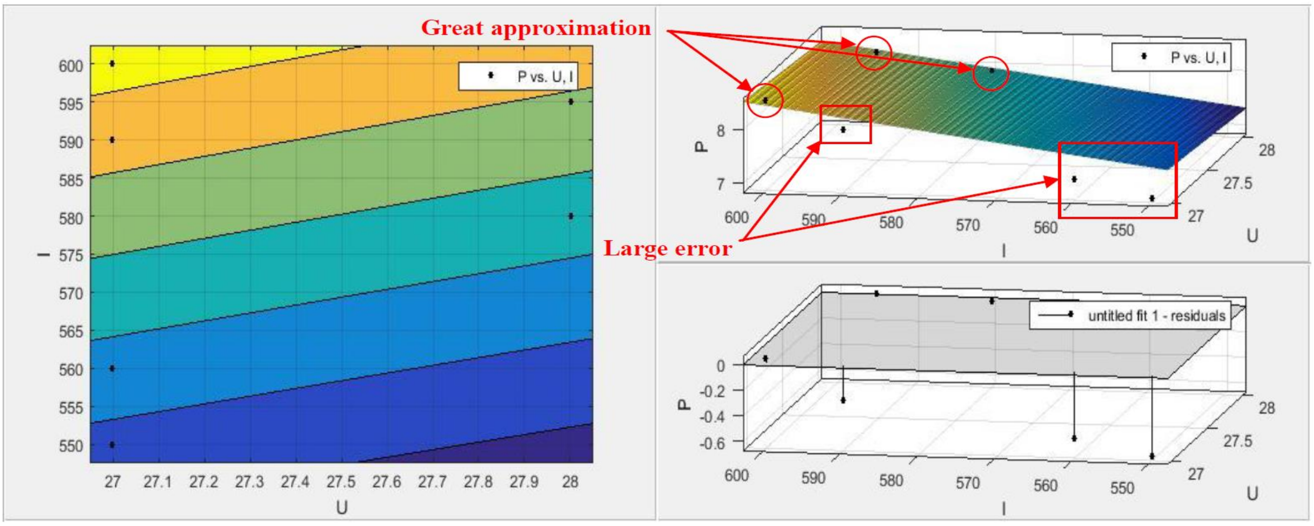

Figure 3. Results from the model given by equation (2)

When the equation (2) results are compared to the real values, unacceptable values in terms of practical applications are obtained. Even why it provides a reasonable estimate for the three values shown in figure 3 with red circles. Still large error can be observed for the other points. Hence, this equation is not considered because it fails to adequately represent the welding process considered.

4 Mathematical model via multiple polynomial regressions

Since equations (1,2) do not give satisfactory results, multiple polynomial regression was used to determine a mathematical model that approximates the welding process. To use multiple polynomial regression ,it must have an additional data point, particularly are needed at least six data points. Therefore, another value is found in between. To accomplish so, an estimate value for U = 27 V and I = 560 A, was obtained using the model obtained via linear regression.

After substitution of the values for current and voltage into the equation (1) the value for penetration is obtained, P= 5.9 mm.

Table 5. The outer welded joint with six values

Sample nr.	U_2-Voltage	I_2-Current	h_2-Penetration	v_s= Welding speed
1.	28 V	600 A	7.0 mm	0.8m/min
2.	28 V	555 A	5.8 mm	0.8m/min
3.	28 V	550 A	5.6 mm	0.8m/min
4.	27 V	595 A	7.0 mm	0.8m/min
5.	28 V	590 A	6.8 mm	0.8m/min
6.	27 V	560 A	5.9 mm	0.8m/min

By multiple polynomial regression the following model is obtained

$$h_2(U_2, I_2) = -91.19 + 1.421 \cdot U_2 + 0.2441 \cdot I_2 - 0.002546 \cdot U_2 \cdot I_2 - 0.001257 \cdot {I_2}^2 \quad (3)$$

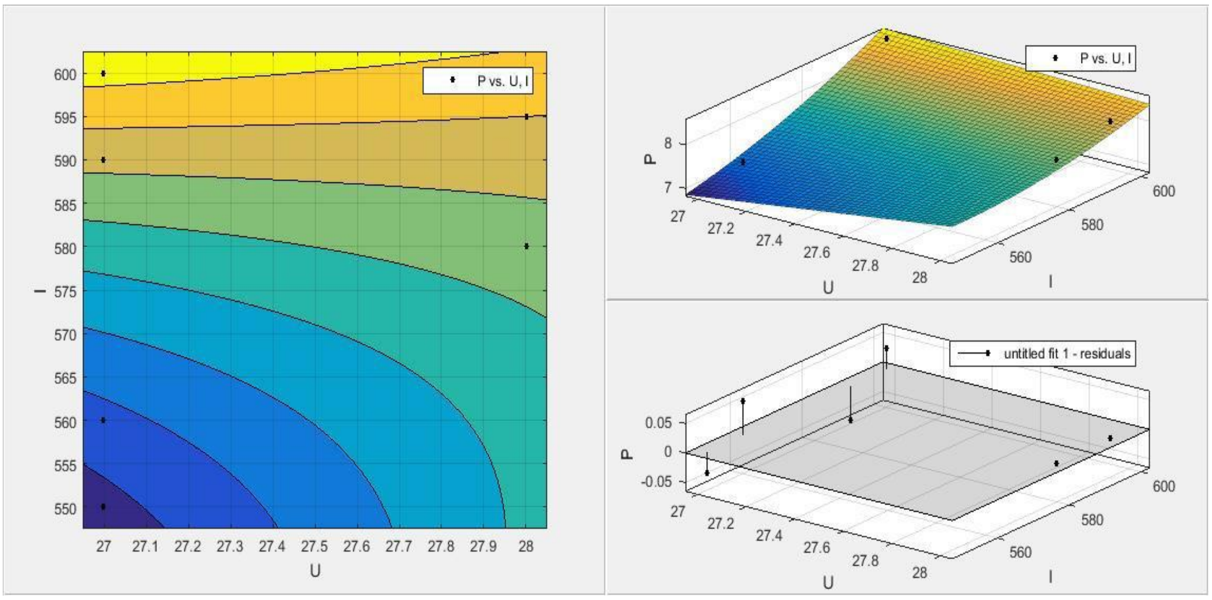

Figure 4. Graphical representation of the approximated model equation (3)

Equation (3), in which penetration is a function of welding voltage and welding current, yields more accurate approximated penetration values that are quite comparable to those in table 4. The welding voltage is first order in this case, while the welding current is second order. Results from this predictive formula are acceptable for these purposes resulting with an average arithmetic error of e = 0.0228 mm.
Figure 4 illustrates the approximation obtained by this model given in equation (3).

The equation for the inner welded joint, that predicts welding penetration based on welding parameters, is developed in a similar manner.

$$h_1(U_1, I_1) = -237 + 11.65 \cdot U_1 + 0.1814 \cdot I_1 - 0.01684 \cdot U_1 \cdot I_1 - 0.00025 \cdot {I_1}^2 \quad (4)$$

Equation (4) is the equation that predicts welding penetration for the inner welded joint.

Table 6. The inner welded joint with six values

Sample nr.	U_1-Voltage	I_1-Current	h_1-Penetration	V_S-Welding speed
1.	29 V	650 A	6.9 mm	0.8 m/min
2.	30 V	695 A	8.2 mm	0.8 m/min
3.	30 V	680 A	7.9 mm	0.8 m/min
4.	29 V	700 A	8.5 mm	0.8 m/min
5.	29 V	690 A	8.0 mm	0.8 m/min
6.	29 V	660 A	7.2 mm	0.8 m/min

The average arithmetic error is e = 0.0366 mm.

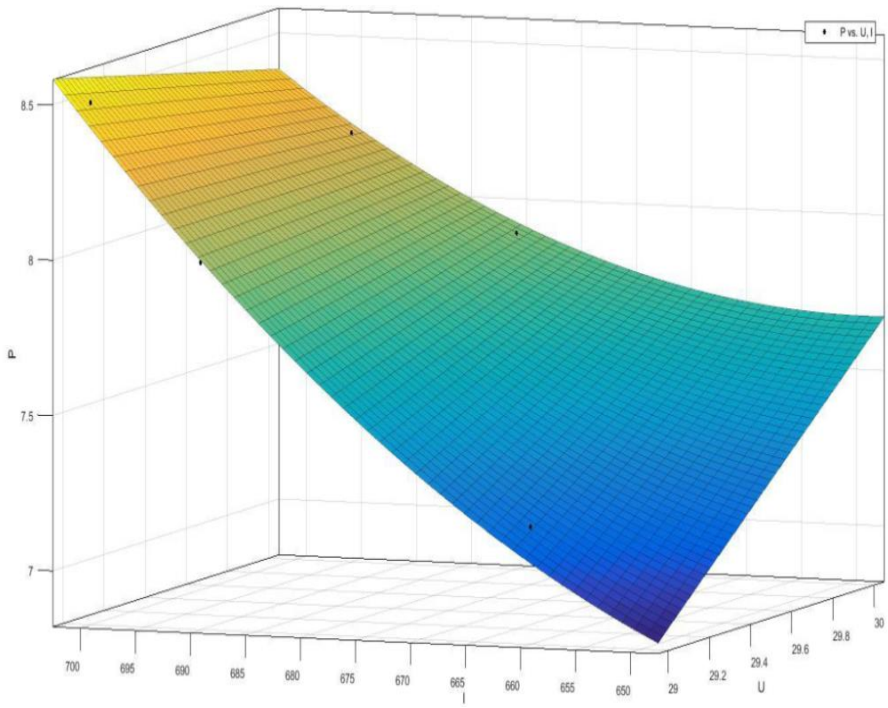

Figure 5. Graphical illustration of the model given by the equation (4)

5 Determining the mathematical model for the overlap

Based on the geometry of the welded joint in figure1, an expression that controls the overlap of the outer and inner welded joint is derived.

$$n = h_1 + h_2 - t \tag{5}$$

$$n(U_1, I_1, U_2, I_2) = -237 + 11.65 \cdot U_1 + 0.1814 \cdot I_1 - 0.01684 \cdot U_1 \cdot I_1 - 0.00025 \cdot {I_1}^2 - 91.19 + 1.421 \cdot U_2 + 0.2441 \cdot I_2 - 0.002546 \cdot U_2 \cdot I_2 - 0.001257 \cdot {I_2}^2 - t \tag{6}$$

Equation (6) represents the equation that predicts the overlap of the two welded joints. This equation is valid in the neighborhood of the points to which this function was approximated as shown in figure 5.

6 Optimization problem definition

The objective function represents the goal of the model, which is either going to be minimized or maximized. All these parameters are mapped to a scalar resulting from the objective function.

$$Objective function = f(I, U),$$

Subject to constraints

Where, $U, I \in \mathbb{R}^2$ are the optimization variables and $f \in \mathbb{R}$ is the objective function.

The objective here is to find values for I and U that give us the maximal and minimal penetration for the inner (h_1) andouterweld (h_2), analyzing both aspects when Vs=constant. The formulated optimization problem is given in equation (7).

$$\min_{U_i, I_i}/\max \boldsymbol{h_i}(U_i, I_i) \quad (7)$$

s.t:

$$I_{imin} \le I_1 \le I_{imax}$$

$$V_{imin} \le U_1 \le V_{imax}$$

Where, $i = 1, 2$.

Minimization and maximization problem formulation for the overlap can be written as

$$\min_{U_1, I_1, U_2, I_2}/\max \boldsymbol{n}(U_1, I_1, U_2, I_2)$$

s.t:

$$650\ A \le I_1 \le 700\ A$$

$$550\ A \le I_2 \le 600\ A$$

$$29\ V \le U_1 \le 30\ V$$

$$27\ V \le U_2 \le 28\ V \quad (8)$$

Optimization problem can be formulated as afore with constraints in current and voltage, the problem becomes a constrained optimization problem.

7 Genetic Algorithm

An algorithm is a series of steps for solving a problem. A genetic algorithm is a search technique that is efficient, robust, and accurate for finding approximate solutions to search and optimization problems. Its model for problem-solving is based on genetics (Sivanandam, 2008).

Chromosome is a sequence of genes. Genes represent a possible solution to a specific problem. A single gene represents a single factor (variable) that must be controlled, which must have an upper and a lower bound (Karamani, 2015).

$$x = [x_1, x_2, x_3, \dots, x_n] \tag{9}$$

The chromosome is a set of genes or strings of a finite length that provide a solution to a problem. Genes are the components of a chromosome, and an allele is the value of a gene. A simple n x m matrix is used to describe the arrangement of data on a chromosome. Where n denotes the number of individuals in a population and m denotes the genotype length (Karamani, 2015).

$$Chromosome = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,m} \\ g_{2,1} & g_{2,2} & \cdots & g_{2,m} \\ g_{n,1} & g_{n,2} & \cdots & g_{n,m} \end{bmatrix} \qquad)$$

The Genetic Algorithm pseudo code (Chruszczyk, 2017):

1 population = random
2 fitness = evaluate(population)
3 parents = selection(population)
4 offspring = crossover(parents)
5 offspring' = mutation(offspring)
6 population = succession(offspring)
7 if not stop, go to 2

8 Results from genetic algorithm optimization

In the table and figure below are represented the results gained from the genetic algorithm (GA) from the MatLab optimization toolbox. The objectives are to maximize the penetration of the inner welded joint, maximization of the penetration of the outer welded joint, and maximization of the overlap.

Table 7. Results from GA optimization - Maximization

Inner welded joint	Outer welded joint	Overlap
I_1 = 700 A	I_2 = 600 A	I_1 = 700 A; I_2= 600 A;
U_1 = 29 V	U_2 = 27 V	U_1 = 29 V; U_2= 27 V;
h_1 = 8.4780 mm	h_2 = 7.1398 mm	h_1 = 8.4780 mm; h_2= 7.1398 mm;
		n = 3.3178 mm
t = 12.3 mm		

Typically, the best fitness value improves rapidly in the early generations, when the individuals are farther from the optimum. The best fitness value improves more slowly in later generations, whose populations are closer to the optimal point.

Observing the experimental data it is easy to find the maximal values of penetration, however, for specific implementation if we want to have a certain overlap, one can modify the objective function in order to obtain a specific desired value for the penetration (n) and the respective U, I.

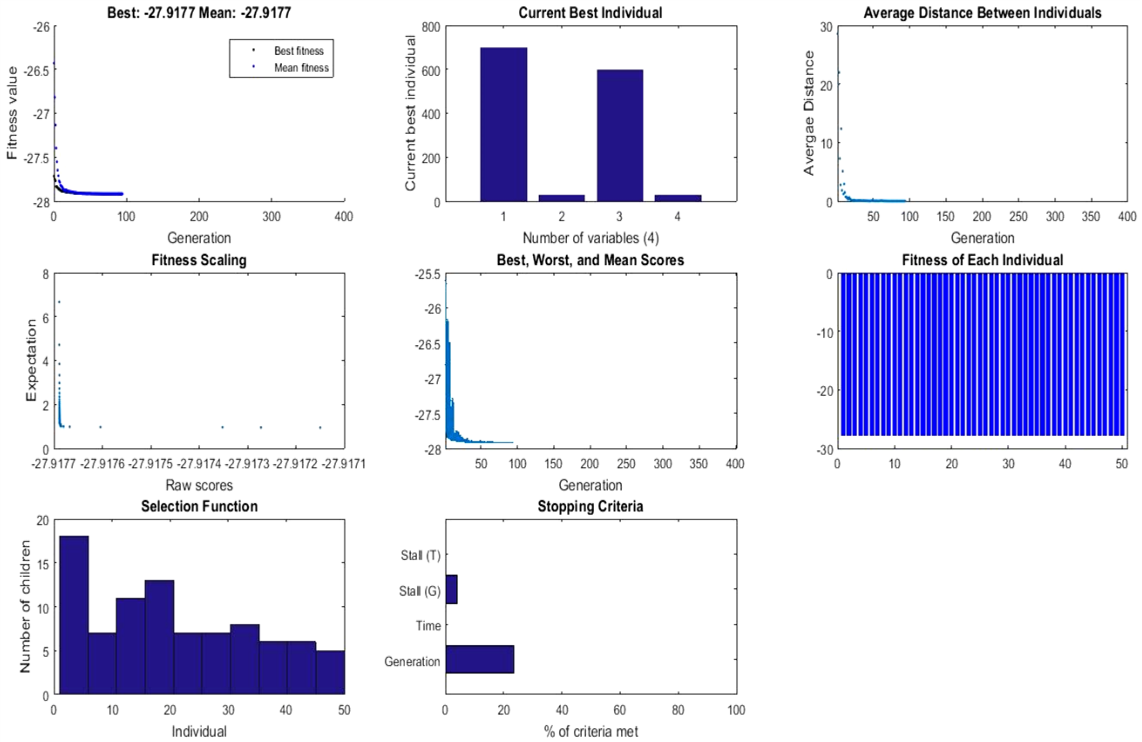

Figure 6. The GA optimization process

9 Conclusion

The mathematical models predict penetration and overlap in two-sided submerged arc welding of API 5L grade steel X65 for line pipe. The results obtained from the developed mathematical models indicate that the model predicts the weld penetration and overlap adequately; therefore they are acceptable for practical purposes. To make high-quality welding one needs to optimize welding parameters. And therefore, a formulation of the objective functions is needed to use the genetic algorithm for optimization. The results from GA optimization give us the values for penetration and overlap at their maximum/minimum values respectively. In this case are shown only the results for maximization. However, one needs to simply negate the objective function (cost function) to be able to minimize it via the genetic algorithm. This approach can also be used for specific implementation when one wants to have a certain overlap n; one can modify the objective function to obtain specific value as desired and the corresponding U and I.

Nomenclature

t the thickness of the material.

h_1 penetration in the outer welded joint.

h_2 penetration in the inner welded joint.

b_1 the width of the outer welded joint.

b_2 the width of the inner welded joint.

n the overlap.

BM base metal

OW outside weld

HAZ heat affected zone

W-HAZ weld metal heat affected zone

IW inside weld

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