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Optimizing Fusion Zone Grain Size and Ultimate Tensile Strength of Pulsed Current Micro Plasma Arc Welded Inconel 625 Alloy Sheets using Hooke & Jeeves Method

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ABSTRACT

Pulsed Current Micro Plasma Arc welding (PCMPAW) process is an important joining process widely used in sheet metal fabrication industries. The paper focuses on developing mathematical models to predict grain size and ultimate tensile strength of pulsed current micro plasma arc welded Inconel 625 nickel alloy using Response Surface Method (RSM). The experiments were carried out based on Central Composite Design (CCD) with 31 combinations of experiments. The adequacy of the models is checked by Analysis of Variance (ANOVA) technique. Hooke and Jeeves method is used to minimize grain size and maximize the ultimate tensile strength.

1. Introduction

In welding processes, the input parameters have greater influence on the mechanical properties of the weld joints. By varying the input process parameters, the output could be changed with significant variation in their mechanical properties. Accordingly, welding is

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usually selected to get a welded joint with excellent mechanical properties. To determine these welding combinations that would lead to excellent mechanical properties, different methods and approaches have been used. Various optimization methods can be applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables. One of the most widely used methods to solve this problem is Response Surface Methodology (RSM), in which the unknown mechanism with an appropriate empirical model is approximated, being the function of representing a RSM.

Pulsed current MPAW involves cycling the welding current at selected regular frequency. The maximum current is selected to give adequate penetration and bead contour, while the minimum is set at a level sufficient to maintain a stable arc (Balasubramanian *et.al*,2006, Madusudhana Reddy G ert.al, 1997). This permits arc energy to be used effectively to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets. By contrast, in constant current welding, the heat required to melt the base material is supplied only during the peak current pulses allowing the heat to dissipate into the base material leading to narrower Heat Affected Zone (HAZ). Advantages include improved bead contours, greater tolerance to heat sink variations, lower heat input requirements, reduced residual stresses and distortion, refinement of fusion zone microstructure and reduced with of HAZ.

Several researchers (Balasubramanian *et.al*, 2010, Balasubramanian *et.al*, 2006, Madusudhana *et.al*, 1997) have studied the importance of using optimum pulse parameters to obtain sound mechanical properties in Gas Tungsten Arc Welding (GTAW) process. Very few works are reported on using current pulsing technique in MPAW process. From the previous works (Kondapalli Siva Prasad *et.al*, 2011a, 2011b, 2011c, 2011d, 2011e) it is decided that four important parameters, namely peak current, back current, pulse rate and pulse width affect the weld quality to a larger extent. One had to carefully balance various pulse parameters to arrive at an optimum combination. Hence in this investigation, an attempt has been made to optimize the Pulsed Current MPAW parameters to attain minimum grain size and maximum ultimate tensile strength using Hooke & Jeeves method.

2. Experimental Procedure

Inconel625 sheets of 100 x 150 x 0.25mm are welded autogenously with square butt joint without edge preparation. The chemical composition of Inconel625 stainless steel sheet is given in Table 1. Experiments were conducted using the pulsed current MPAW process. The welding has been carried out under the welding conditions presented in Table 2. From the literature four important factors of pulsed current MPAW as presented in Table 3 are chosen. A large number of trail experiments are carried out using 0.25mm thick Inconel625 sheets to find out the feasible working limits of pulsed current MPAW process parameters. Due to wide range of factors, it was decided to use four factors, five levels, rotatable central composite design matrix to perform the number of experiments for investigation. Table 4 indicates the 31 set of coded conditions used to form the design matrix. The method of designing such matrix is dealt elsewhere (Montgomery, 1991, Box *et.al*, 1978).

Table 1: Chemical composition of Inconel625 (weight %).

C	Mn	P	S	Si	Cr	Ni
0.0300	0.0800	0.0050	0.0004	0.1200	20.8900	61.6000

Al	Mo	Cb	Ta	Ti	N	Co	Fe
0.1700	8.4900	3.4400	0.0050	0.1800	0.0100	0.1300	4.6700

Table 2: Welding conditions.

Power source	Secheron Micro Plasma Arc Machine (Model: PLASMAFIX 50E)
Polarity	DCEN
Mode of operation	Pulse mode
Electrode	2% thoriated tungsten electrode
Electrode Diameter	1mm
Plasma gas	Argon & Hydrogen
Plasma gas flow rate	6 Lpm
Shielding gas	Argon
Shielding gas flow rate	0.4 Lpm
Purging gas	Argon
Purging gas flow rate	0.4 Lpm
Copper Nozzle diameter	1mm
Nozzle to plate distance	1mm
Welding speed	260mm/min
Torch Position	Vertical
Operation type	Automatic

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Table 3: Important factors and their levels.

Serial No	Input Factor	Units	Levels				
			-2	-1	0	+1	+2
1	Peak current	Amperes	6	6.5	7	7.5	8
2	Back current	Amperes	3	3.5	4	4.5	5
3	Pulse rate	Pulses/Second	20	30	40	50	60
4	Pulse width	%	30	40	50	60	70

Table 4: Design matrix and experimental results.

Serial No	Peak current (Amperes)	Back current (Amperes)	Pulse (Pulses/Second)	Pulse width (%)	Grain size (Micons)	Ultimate tensile strength (VHN)
1	-1	-1	-1	-1	40.812	833
2	1	-1	-1	-1	50.226	825
3	-1	1	-1	-1	41.508	838
4	1	1	-1	-1	47.536	826
5	-1	-1	1	-1	47.323	826
6	1	-1	1	-1	45.206	830
7	-1	1	1	-1	45.994	825
8	1	1	1	-1	43.491	826
9	-1	-1	-1	1	46.290	825
10	1	-1	-1	1	49.835	820
11	-1	1	-1	1	40.605	835
12	1	1	-1	1	47.764	828
13	-1	-1	1	1	50.095	818
14	1	-1	1	1	46.109	826
15	-1	1	1	1	47.385	824
16	1	1	1	1	45.013	830
17	-2	0	0	0	40.788	830
18	2	0	0	0	45.830	826
19	0	-2	0	0	51.663	821
20	0	2	0	0	47.263	828
21	0	0	-2	0	45.270	832
22	0	0	2	0	46.030	825
23	0	0	0	-2	44.626	831
24	0	0	0	2	46.626	825
25	0	0	0	0	44.845	830
26	0	0	0	0	44.845	830
27	0	0	0	0	40.145	840
28	0	0	0	0	44.845	830
29	0	0	0	0	40.045	838
30	0	0	0	0	44.845	830
31	0	0	0	0	40.445	832

3. Recording the responses

3.1 Measurement of grain size

Microstructural examinations were carried out using metallurgical microscope (Make: Carl Zeiss, Model: Axiovert 40MAT) at 100X magnification. The specimens for metallographic examination were sectioned to the required size from the weld joint and were polished using different grades of emery papers. Sample preparation and mounting is done as per ASTM E 3-1 standard. The samples are surface grounded using 120 grit size belt with the help of belt grinder, polished using grade 1/0 (245 mesh size), grade 2/0 (425 mesh size) and grade 3/0 (515 mesh size) sand paper. The specimens are further polished by using aluminum oxide initially and the by utilizing diamond paste and velvet cloth in a polishing machine. The polished specimens are etched by using Aqua regia solution to reveal the microstructure as per ASTM E407. The micrographs of parent metal zone and weld fusion zone are shown in Figure 1 & 2 (Kondapalli Siva Prasad *et.al*, 2011e).

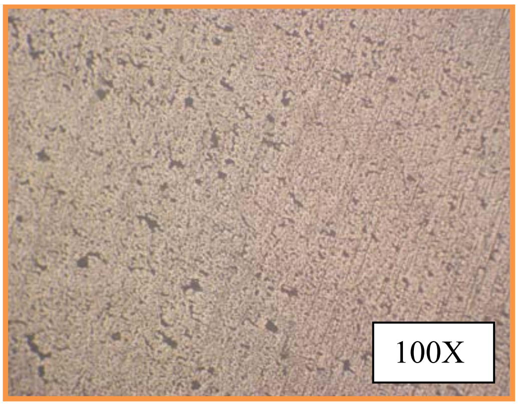

Figure 1: Microstructure of parent metal zone.

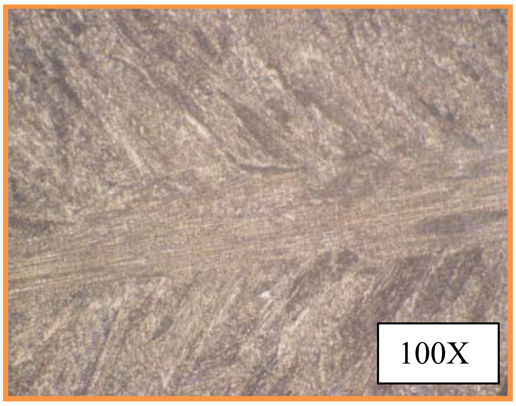

Figure 2: Microstructure of weld fusion zone.

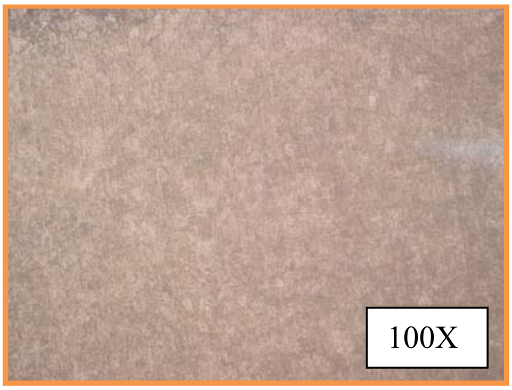

Figure 3: Grain size of parent metal at 100X.

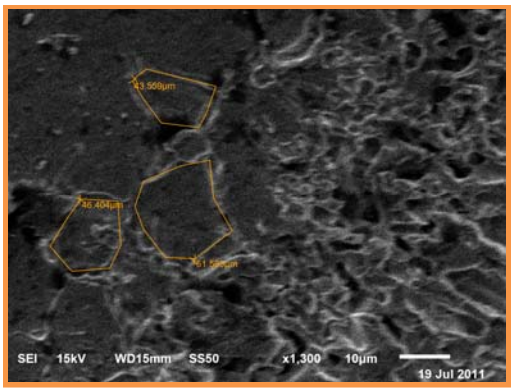

Figure 4: Grain size of weld fusion zone (SEM)

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Grain size of parent metal and weld joint is measured by using Scanning Electron Microscope (Make: INCA Penta FETx3, Model:7573). Figure 3 & 4 indicates the measurement of grain size for parent metal zone and weld fusion zone. Average values of grain size at the fusion zone are presented in Table 4.

The average grain size at the weld interface is about 45.772 Microns and that of parent metal is about 50 Microns. Smaller grains at interface indicate better strength of weld joint.

3.2 Measurement of ultimate tensile strength

Three transverse tensile specimens are prepared as per ASTM E8M-04 guidelines and the specimens after wire cut Electro Discharge Machining are shown in Figure 5. Tensile tests are carried out in 100 KN computer controlled Universal Testing Machine (ZENON, Model No: WDW-100) as shown in Figure 6 (Kondapalli Siva Prasad et.al, 2011d). The specimen is loaded at a rate of 1.5 KN/min as per ASTM specifications, so that the tensile specimens undergo deformation. From the stress strain curve, the ultimate tensile strength of the weld joints is evaluated and the average of three results for each sample is presented in Table 4.

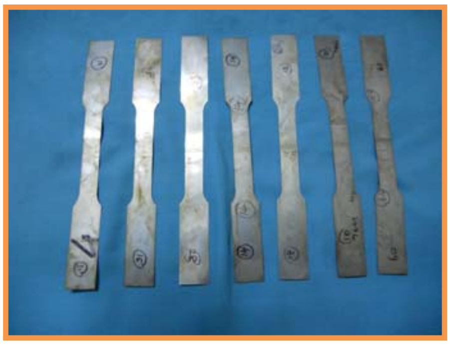

Figure 5: Tensile specimens.

Figure 6: Universal Testing Machine.

4. Developing Mathematical Models

The grain size (G) and ultimate tensile strength(T) of the weld joint is a function of peak current (A), back current (B), pulse rate (C) and pulse width (D). It can be expressed as (Cochran W G & Cox G M, 1957, Barker T B, 1985 , Gardiner W P, Gettinby G, 1998).

Grain size (G),

$$G = f(A, B, C, D) \quad (1)$$

Ultimate tensile strength (T)

$$T = f(A, B, C, D) \quad (2)$$

The second order polynomial equation used to represent the response surface 'Y' is given by (Montgomery D.C, 1991):

$$Y = b_o + \sum b_i x_i + \sum \beta_{ii} x_i^2 + \sum\sum b_{ij} x_i x_j + \in \quad (3)$$

Using MINITAB 14 statistical software package, the significant coefficients were determined and final models are developed using significant coefficients to estimate grain size and ultimate tensile strength values of weld joint.

The final mathematical models are given by

Grain Size (G)

$$G = 42.859+1.052X_1-1.058X_2+0.3150X_3+0.625X_4+1.640X_2^2-2.320X_1X_3 \quad (4)$$

Ultimate tensile strength (T)

$$T=833.143-0.875X_1+1.792X_2-1.625X_3-1.458X_4-1.296X_1^2-2.171X_2^2-1.296X_4^2 +3.187X_1X_3 \quad (5)$$

Where X_1, X_2, X_3 and X_4 are the coded values of peak current, back current, pulse rate and pulse width respectively.

5. Checking the adequacy of the developed models

The adequacy of the developed models was tested using the analysis of variance technique (ANOVA). As per this technique, if the calculated value of the F_{ratio} of the developed model is less than the standard F_{ratio} (from F-table) value at a desired level of confidence (say 99%), then the model is said to be adequate within the confidence limit. ANOVA test results are presented in Table 5 & 6 for all the models. From the table it is understood that the developed mathematical models are found to be adequate at 99% confidence level. The value of

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co-efficient of determination ‘ R^2 ’ for the above developed models is found to be about 0.86 .

Figures 7 and 8 indicate the scatter plots for grain size and ultimate tensile strength of the weld joint and reveal that the actual and predicted values are close to each other with in the specified limits.

Table 5: ANOVA test results for grain size.

Grain Size						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	249.023	249.023	17.7873	6.10	0.000
Linear	4	65.207	65.207	16.3018	5.59	0.005
Square	4	91.443	91.443	22.8608	7.84	0.001
Interaction	6	92.372	92.372	15.3954	5.28	0.004
Residual Error	16	46.639	46.639	2.9149		
Lack-of-Fit	10	9.750	9.750	0.9750	0.16	0.994
Pure Error	6	36.889	36.889	6.1481		
Total	30	295.661				

Table 6: ANOVA test results for ultimate tensile strength.

Ultimate tensile strength						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	679.070	679.070	48.5050	6.89	0.000
Linear	4	209.833	209.833	52.4583	7.45	0.001
Square	4	211.362	211.362	52.8405	7.51	0.001
Interaction	6	257.875	257.875	42.9792	6.11	0.002
Residual Error	16	112.607	112.607	7.0379		
Lack-of-Fit	10	1.750	1.750	0.1750		
Pure Error	6	110.857	110.857	18.4762	0.01	1.000
Total	30	791.677				

Where SS=Sum of Squares, MS=Mean Squares, DF =Degree of Freedom, F= Fisher’s ratio

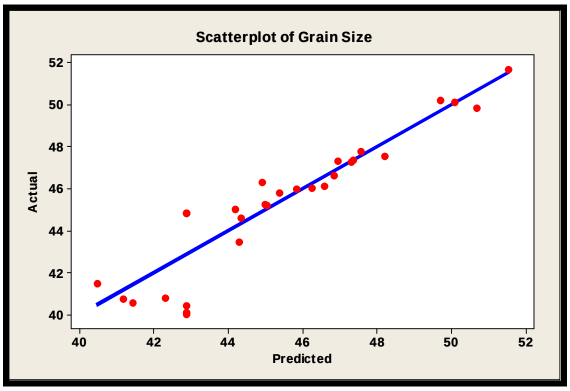

Figure 7: Scatter plot of Grain size.

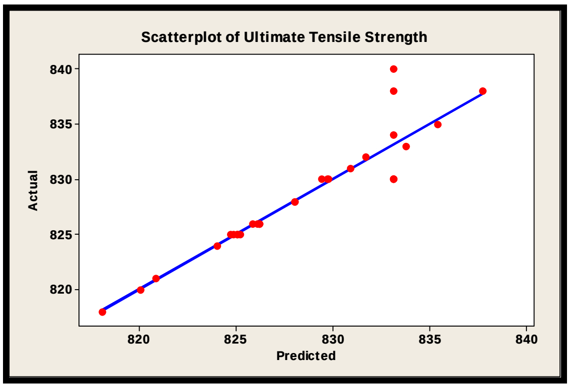

Figure 8: Scatter plot of Ultimate tensile strength.

6. Optimizing Using Hooke & Jeeves algorithm

Hooke and Jeeves method (Kalyanmoy.D, 1988) is used to search the optimum values of the process variables. In this paper the algorithm is developed to optimize the pulsed current MPAW process variables. The objective is to minimize grain size & maximize ultimate tensile strength. The coding for the Hooke Jeeves method is written in MATLAB software.

The Hooke & Jeeves method incorporates the past history of a sequence of iterations into the generation of a new search direction. It combines exploratory moves with pattern moves. The exploratory moves examine the local behavior of the function & seek to locate the direction of any stepping valleys that might be present. The pattern moves utilize the information generated in the exploration to step rapidly along the valleys.

Exploratory Move:

Given a specified step size which may be different for each co - ordinate direction and change during search. The exploration proceeds from an initial point by the specified step size in each coordinate direction. If the function value does not increased the step is considered successful. Otherwise the step is retracted and replaced by a step in the opposite direction which in turn is retained in depending upon whether it success or fails. When all N coordinates have been investigated, the exploration move is completed. The resulting point is termed a base point.

Pattern Move:

A pattern move consists of a single step from the present base point along the line from the previous to the current base point.

A new pattern point is calculated as:

$$x_p^{(k+1)} = x^{(k)} + (x^{(k)} - x^{(k-1)})$$

where, $x_p^{(k+1)}$ is temporary base point for a new exploratory move.

If the result of this exploration move is a better point then the previous base point (x^k) then this is accepted as the new base point $x^{(k+1)}$. If the exploratory move does not produce

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improvement, the pattern move is discarded and the search returns to x(k), where an exploratory search is undertaken to find a new pattern.

Various steps involved in Hooke & Jeeves method is discussed below.

Step 1: Starting point $x^{(0)}$

The increments Δ_i for i=1,2,3, …, N

Step reduction factor $\alpha > 1$

A termination parameter $\varepsilon > 0$

Step 2: Perform exploratory search

Step 3: Was exploratory search successful (i.e. was a lower point found)

If Yes go to step (5)

Else continue

Step 4: check for the termination $||\Delta|| < \varepsilon$ current pint approximation x0

$$\Delta_i = \Delta_i / \alpha \text{ for } i = 1,2,3, \ldots, N$$

Go to step 2

Step 5: Perform pattern move

$$x_p^{(k+1)} = x^{(k)} + (x^{(k)} - x^{(k-1)})$$

Step 6: Perform exploratory research using $x_p^{(k+1)}$ as the base point; let the result be $x^{(k+1)}$.

Step 7: This step decides whether you are doing this operation for minimization or maximization.

If you applied the condition “Is $f(x^{(k+1)}) < f(x^{(k)})$?” then it is to find the maximum ultimate tensile strength.

If “Is $f(x^{(k+1)}) < f(x^{(k)})$?” then it is to find minimum grain size.

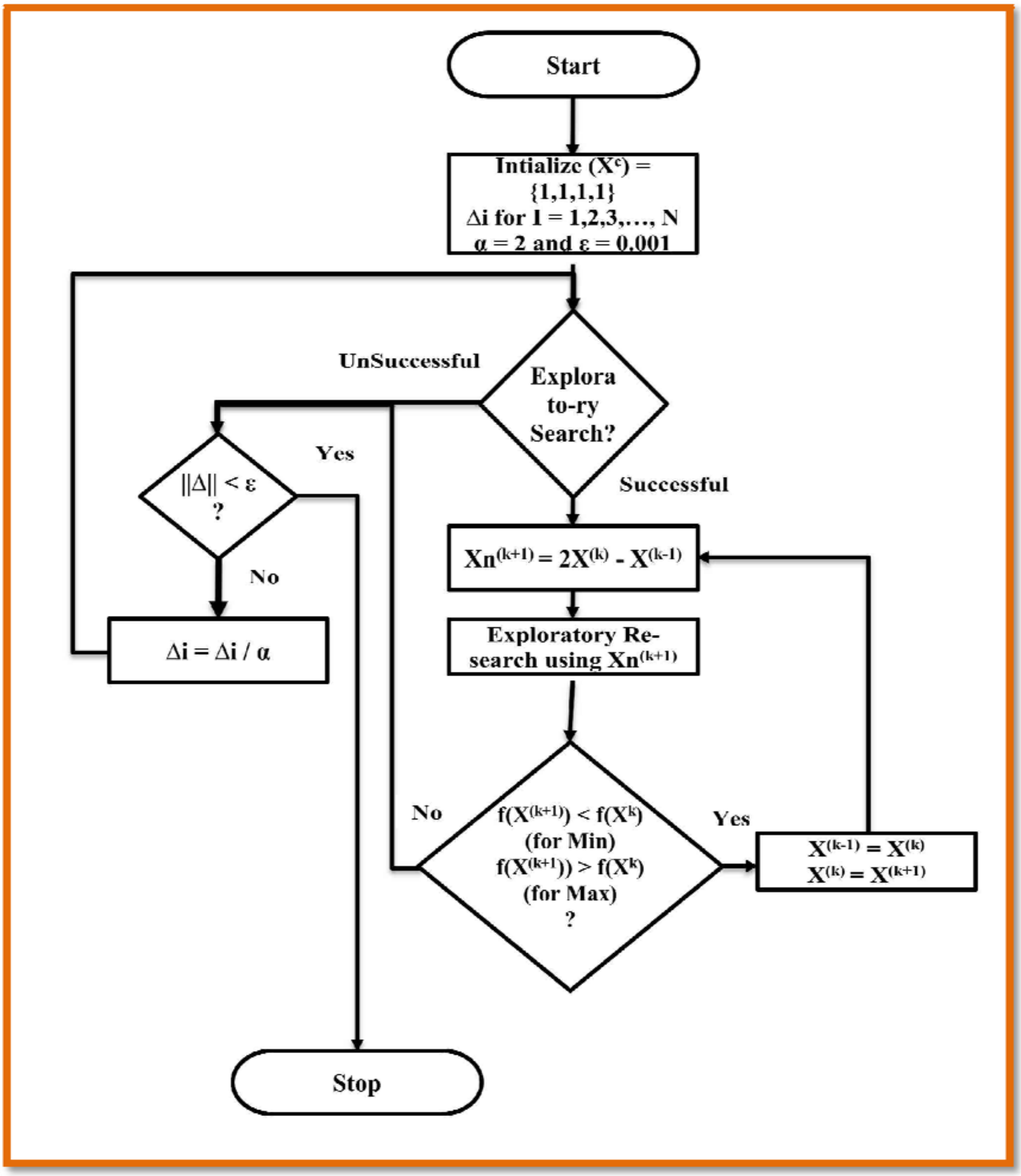

Figure 9: Flow chart of Hooke & Jeeves method.

Step (i) & (ii) results either Yes or No basing on the requirement of minimum grain size or maximum tensile strength. After getting the result continue with the following process.

If Yes Set $x^{(k-1)} = x^{(k)}$

$x^{(k)} = x^{(k+1)}$ go to step (5).

Else go to step (4)

Detailed flow chart of Hooke & Jeeves method is presented in Figure 9.

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Table 7: Optimized pulsed current MPAW parameters for grain size.

	Hooke & Jeeves	Experimental
Peak current(Amperes)	7.1196	7
Back current(Amperes)	4.1196	4
Pulse rate (Pulses/econd)	42.3911	40
Pulse width (%)	52.3911	50
Ultimate Tensile Strength(Mpa)	41.1640	40.045

Table 8: Optimized pulsed current MPAW parameters for ultimate tensile strength.

	Hooke & Jeeves	Experimental
Peak current(Amperes)	7.2177	7
Back current(Amperes)	4.2177	4
Pulse rate(Pulses/Second)	44.3545	40
Pulse width (%)	54.3545	50
Ultimate Tensile Strength(Mpa)	844.3545	840

From Tables 7 and 8, it is understood that the values predicted by Hooke and Jeeves method and experimental values are very close to each other.

7. Conclusions

The developed empirical models can be effectively used to predict grain size and ultimate tensile strength of Pulsed Current Micro Plasma Arc Welded Inconel 625 joints. The developed models are valid within the range of selected weld input parameters. A minimum grain size of 40.045 microns and maximum ultimate tensile strength of 840 Mpa is obtained for the input parameter combination of peak current of 7 Amperes, back current of 4 Amperes, pulse rate of 40 Pulses /Second and pulse width of 50% experimentally. From Hooke and Jeeves method, the minimum grain size obtained is 41.1640 microns for the input parameter combination of peak current of 7.1196 Amperes ,back current of 4.1196 Amperes, pulse rate of 42.3911 Pulses /Second and pulse width of 52.3911%. The maximum ultimate tensile strength obtained is 844.3545 MPa for the input parameter combination of peak current of 7.2177Amperes, back current of 4.2177 Amperes, pulse rate of 44.3545 Pulses /Second and pulse width of 54.3545%. The values of grain size and ultimate tensile strength obtained experimentally closely matches with the values obtained using Hooke & Jeeves method.

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