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Experimental Investigation of Process Parameters on Weld Bead Geometry for Aluminium Using GTAW

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Abstract: ***Gas tungsten arc welding, GTAW, is one of the widely used techniques for joining ferrous and non-ferrous metals. In this study experiments were carried out as per central composite design and regression analysis was conducted to determine input – output relationships of the process. The input process parameters such as current, welding speed and gas flow rate were controlled using the control panel of the automatic welding set up for welding Aluminium AA6063 alloy. GTAW process is well known for narrow welds that means deeper penetration and narrower weld width. To consider these quality characteristics a constrained optimization problem was formulated. Genetic Algorithm with a penalty term was used to solve the said problem.***

Keywords: Aluminium TIG, Tungsten inert gas welding, GTAW, Parametric optimization in TIG. Genetic Algorithm

1. Introduction

The American Welding Society (AWS) defines weld as “A localized coalescence of metals or non-metals produced either by heating the materials to suitable temperatures, with or without application of pressure, or by pressure alone, and with or without the use of filler material.”

Indian Standard IS : 812-1957 defines the weld as “a union between two pieces of a metal at faces rendered plastic or liquid by heat or by pressure, or both. Filler metal may be used to affect the union”

International Organization for Standards (ISO) defines welding as “An operation by which two or more parts are united, by means of heat or pressure, or both, in such a way that there is continuity of the nature of the material between these parts. A filler material, the melting temperature of which is of the same order as that of the parent material, may or may not be used.”

Tungsten inert gas arc welding, as the name suggests is a process in which the source of heat is an arc formed between a non-consumable tungsten electrode and the work piece, and the arc and the molten puddle are protected from atmospheric contamination (i.e. oxygen and nitrogen) with a gaseous shield of inert-gas such as argon, helium or argon-helium mixture. Filler metal, if required, is added externally to the arc in the form of a bare wire by the welder. It is often referred to in abbreviated form as TIG welding. Some authors prefer to call it inert-gas tungsten-arc welding.

The American Welding Society refers to the process as gas tungsten-arc-welding and has given it the letter designation GTAW. While a few countries such as the U.S.A. and Canada use helium and argon-helium mixture besides argon for arc shielding, most other countries including India use only argon, as helium is not available. In the latter countries the process is sometimes called Argon arc process for the sake of simplicity.

The concept of using gases in place of fluxes to shield the welding arc was first tried out by Roberts and van Nuys in 1919 and by other scientists in the following years. Besides inert gases, hydrogen and hydrocarbons were also considered. A workable method of inert gas welding was first developed by the Northrop Aircraft Co. of the U.S.A. in 1940, using a simple tungsten electrode torch and a D.C. welding generator.

It was successfully used on thin-gauge magnesium and stainless steel. The main target of the process was Aluminium but initially it was found that the refractory oxide film on the Aluminium surface interfered with the arc unless AC was used. AC could be used successfully only when by 1946 it was found that a spark ionizer could be made to stabilize the AC arc. The high-frequency ionizer however could not remove the inherent imbalance between the voltages on alternate half-cycles, which resulted in a DC component that tended to saturate the transformer. This problem was finally overcome by using large capacitors in series with the arc, appropriately termed DC suppressors.

The Gas Tungsten arc welding process is illustrated in figure 1 here. The process uses a non-consumable tungsten (or tungsten alloy) electrode held in a torch. Shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal from contamination by the atmosphere.

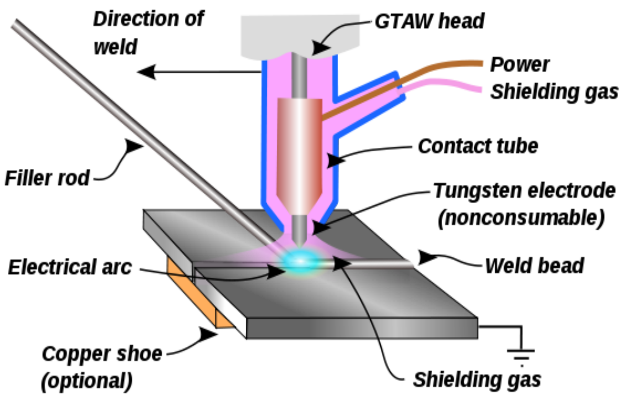

Figure 1: Schematic of a GTAW torch

2. Literature Survey

Mohd. Shoeb, Prof. Mohd. Parvez and Prof. Pratibha Kumari studied the various welding parameters such as welding speed, voltage and gas flow rate on HSLA steel.The effects of these parameters on weld bead geometry such as penetration, width & height have been studied. MIG welding was carried out on DC electrode (welding wire) positive polarity (DCEP). However DCEN in used (for higher burn off rate) with certain self- shielding and gas shield cored wires. Mathematical equations have been developed using factorial technique and the result of various effects are indicated [1].

Prachya Peasuraa, Anucha Watanapab studied the effect of shielding gas parameter on mechanical properties and microstructures of heat-affected zone and fusion zone on gas tungsten arc welding (GTAW) in aluminium alloy AA 5083. The factorial experiment was designed for this research. The factors of AA 5083 weld used in the study types of shielding gas in argon and helium, gas flow rate at 6, 10 and 14 litres per minute. Then the results were using microstructure and Vickers hardness test. The result showed that types of shielding gas and gas flow rate interaction hardness at heat-affected zone and fusion zone with a P–value < .05. The factor which was the most effective to the hardness at heat-affected zone and fusion zone was argon with a flow rate of 14 litres per minute at heat-affected zone with 74.27HV and fusion zone with 68.97HV. Experimental results showed that the argon condition provided smaller grain size, suitable size resulting in higher hardness both in weld metal and HAZ. They also indicated that the grain size and precipitation Mg affect the hardness of sample [2].

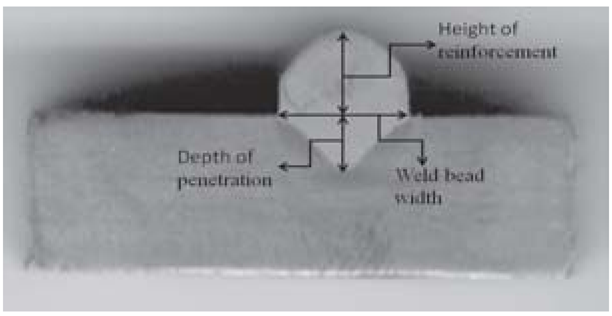

Figure 2: Weld bead geometry

Vipin Kumar, Gajendra Singh and Mohd. Zaheer Khan Yusufzai carried out an experimental study carried out to analyse the effects of process parameters of gas metal arc welding (GMAW) on dilution in a single layer stainless steel cladding on mild steel. Factors i.e. open circuit voltage, nozzle to work distance and welding current were taken an account to analyse dilution. The analysis of the results obtained from the experiment was done on MINITAB 15 [3].

G. Haragopal, P V R Ravindra Reddy, G Chandra Mohan Reddy and J V Subrahmanyam presented a method to design process parameters that optimize the mechanical properties of weld specimen for aluminium alloy (Al-65032), used for construction of aerospace wings. The process parameters considered for the study were gas pressure, current, groove angle and pre-heat temperature. Process parameters were assigned for each experiment. The experiments were conducted using the L9 orthogonal array. Optimal process parameter combination was obtained. Along with this, identification of the parameters which were influencing the most was also done. This was accomplished using the S/N analysis, mean response analysis and ANOVA. They indicated that the Gas pressure is the most significant factor for proof stress. Optimum mechanical properties are found at a groove angle of 60 degrees. Current is the most influencing factor on UTS. Effect of pre-heat has a considerable effect on proof stress, % elongation and impact energy. Optimum condition for maximization of mechanical properties can be found using S/N analysis, mean response analysis and mechanical properties at optimum conditions can be predicted using this method [4].

Palani. P.K, Saju.M applied Response Surface Methodology was used to conduct the experiments. The parameters selected for controlling the process are welding speed, current and gas flow rate. Strength of welded joints were tested by a UTM. Percent elongation was also calculated to evaluate the ductility of the welded joint. From the results of the experiments, mathematical models have been developed to study the effect of process parameters on tensile strength and percent elongation. Optimization was done to find optimum welding conditions to maximize tensile strength and percent elongation of welded specimen. Confirmation tests were also conducted to validate the optimum parameter settings [5].

Dinesh Mohan Arya, Vedansh Chaturvedi, Jyoti Vimal studied to search out the optimum process parameters for Metal inert gas welding (MIG). The optimization of MIG welding process parameters was carried out for alloy steel work piece using grey relational analysis method and Taguchi method. The effect of welding parameters like wire diameter, welding current, arc voltage, welding speed, and gas flow rate were optimized based on bead geometry of welding joint. The objective function was chosen in relation to parameters of MIG welding bead geometry Tensile strength, Bead width, Bead height, Penetration and Heat affected zone (HAZ) for quality target. The signal to noise ratio (S/N ratio) is also applied to identify the most significant factor and predicted optimal parameter setting. Optimal parameters collection of the MIG operation was obtained via grey relational analysis for this study [6].

H. K. Narang, U. P. Singh, M. M. Mahapatra and P. K. Jha implemented fuzzy logic simulation of tungsten inert gas welding (TIG) process to predict the weldment macrostructure zones' shape profile characteristics. The prediction of the weld pool geometry together with the shape of the heat affected zone (HAZ) was accomplished taking into account of TIG welding process parameters such as arc traverse speed, welding current and arc length. Structural steel plates of 8 mm thickness were used for the experiments. Full factorial design of experiment methodology was followed while selecting the input process parameters (control factors). These control factors were having three levels. The TIG weld pool geometry profiles' (boundaries of thermal cycle zones) like the weld bead reinforcement, penetration and heat affected zones were the responses from the experiment. A series of 27 experiments were carried out for collecting the data. The experimental data were then used for building a fuzzy logic model to predict the effects of control factors on the responses. A graphical mapping scheme was employed for the graphical representation of the macrostructure zones' shape profiles including that of HAZ. The model was also tested for a number of test cases to establish it's adequacy [7].

D. S. Nagesh, G.L. Datta, studied and explained an integrated method with a new approach using experimental design matrix of experimental designs technique on the experimental data available from conventional experimentation, application of neural network for predicting the weld bead geometric descriptors and use of genetic algorithm for optimization of process parameters[8].

Vidyut Dey, Dilip Kumar Pratihar, G.L. Datta, M.N. Jha, T.K. Saha, A.V. Bapat appied advanced optimization technique for obtaining maximum penetration in Electron Beam Welding. Bead-on-plate welds were carried out on austenitic stainless steel plates using an electron beam welding machine. Experimental data were collected as per central composite design and regression analysis was conducted to establish input–output relationships of the process[9].

3. Problem definition

Basically, TIG weld quality is strongly characterized by the weld pool geometry. This is because the weld pool geometry plays an important role in determining the mechanical properties of the weld. Therefore, it is very important to select the welding process parameters for obtaining an optimal weld pool geometry. Usually, the desired welding process parameters are determined based on experience or from a handbook. However, this does not ensure that the selected welding process parameters can produce the optimal or near optimal weld pool geometry for that particular welding machine and environment.

The aim of this dissertation work is to obtain optimum process parameters for welding aluminium using TIG (Tungsten Inert Gas) Welding process. An attempt is made to minimize the weld area, after satisfying the condition of maximum bead penetration. Thus, it was posed as a constrained optimization problem and solved utilizing a Genetic Algorithm with a penalty function approach.

4. Methodology

To meet the objective, experimental set up was searched first of all. The experimental setup consists of semi-automatic welding machine with control over welding parameters such as welding current, welding speed, shielding gas flow rate, etc. The experiment will be done by establishing the range of process parameters based on trial experiments and theoretical background of process parameter range selection from AWS (American Welding Society) Handbook titled "Weldability of metals and alloys".

The DOE (Design of Experiment) method applied for the experiments is Response Surface method (RSM) with Central Composite Design (CCD). The DOE will be prepared using MINITAB16 software. The experimental readings will be then taken like weld penetration, weld width and weld bead height and ultimate tensile strength of the weld joint. Moreover Radiographic Testing (RT) will be performed to check the weld quality. Optimization of process parameters will be been carried out using the genetic algorithm approach. This will be done using the soft computing tool MATLAB. A confirmatory experiment was also carried out based on optimal process parameter, to illustrate and validate the proposed approach.

5. Experimental set up

The experiments have been conducted using a Unitor UWI 400 Power Source and an Automated Welding Set up. In this welding machine automated Tungsten Inert Gas torch as well as automatic feeler wire feeding units are provided. For expe rimentation, servo motors are used for maintaining welding speed during actual welding. This would be rather different with hand held manual torch. While using automated TIG torch welding speed can be set to specific value directly on this machine as it is a controlled automation.

Figure 3: Experimental Set up

6. Design of experiment

In the present work, the Response Surface methodology has been used to plan the experiments. In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The method was introduced by G. E. P. Box and K. B. Wilson in 1951. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response.

An effective alternative to factorial design is Central Composite Design (CCD) requires many fewer tests than the full factorial design and has been shown to be sufficient to describe the majority of steady-state process responses. Hence in this study, it was decided to use CCD to design the experiments. Hence the total number of tests required for the three independent variables is 23 + (2x3) + 6 = 20. Once the desired ranges of values of the variables are defined, they are coded to lie ±1 for the factorial points, 0 for the center points and ±p for the axial points. The version 16 of the MINITAB software was used to develop the experimental plan for RSM.

7. Results & Analysis

To meet the objective, experimental set up was searched first of all. The experimental setup consists of semi-automatic welding machine with control over welding parameters such as welding current, welding speed, shielding gas flow rate, etc. Following are the results obtained for the experiments carried out as per the Design of experiment mentioned above.

Table 1 : DOE Table

Run Order	*Welding Speed (cm/min)*	*Current (Amps)*	*Gas flow rate (lit/min)*
	S	*I*	*F*
1	25.0	274	15.0
2	22.5	259	15.0
3	20.0	274	20.0
4	22.5	259	20.0
5	22.5	259	17.5
6	22.5	274	17.5
7	20.0	259	17.5
8	20.0	274	15.0
9	22.5	259	17.5
10	25.0	259	17.5
11	22.5	259	17.5
12	20.0	228	20.0
13	22.5	228	17.5
14	25.0	274	20.0
15	22.5	259	17.5
16	20.0	228	15.0
17	25.0	228	15.0
18	25.0	228	20.0
19	22.5	259	17.5
20	22.5	259	17.5

Table 2: Experimental Results

Run Order	*Bead Ht.(mm)* **BH**	*Bead Pene.(mm)* **BP**	*Bead Width(mm)* **BW**
1	0.68	7.21	8.72
2	0.72	7.45	9.23
3	0.88	7.51	9.50
4	0.73	7.35	9.25
5	0.73	7.56	9.26
6	0.75	7.51	9.20
7	0.87	7.85	9.72
8	0.90	8.04	9.51
9	0.74	7.36	9.26
10	0.65	7.10	8.80
11	0.73	7.52	9.23
12	0.78	7.50	10.01
13	0.70	7.50	9.45
14	0.68	7.15	8.71
15	0.73	7.51	9.22
16	0.81	7.96	9.98
17	0.60	7.15	9.00
18	0.56	7.12	9.00
19	0.72	7.53	9.25
20	0.74	7.51	9.27

A. Effect of process parameters on Bead Height (BH)

Figure 4 here shows the main effect plot of process parameters on bead height at different parameters like welding speed, current and gas flow rate in GTAW process of for welding 6063 alloy of Aluminium. From the figure, it can be seen that:

- Effect of welding speed : Bead height decreases with the increase in welding speed
- Effect of current : Bead height increases with the increase in current
- Effect of gas flow rate: There is a slight decrease in bead height with the increase in gas flow rate.

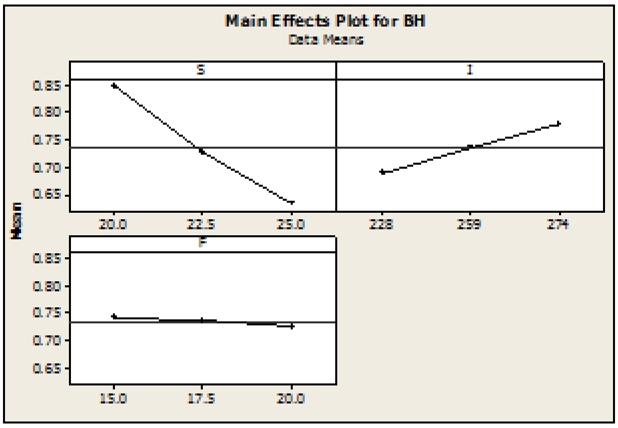

Figure 4: Main effect plots of process parameters for Bead Height

Regression equation for Bead Height is

BH = 1.29 - 0.0428 S + 0.00182 I - 0.00320 F

Table 3: Estimated Model Coefficients for BH

Predictor	Coef	SE Coef	T	P
Constant	1.29036	0.08439	15.29	0.000
S	-0.0428	0.00215	-19.90	0.000
I	0.00181	0.00022	8.01	0.000
F	-0.0032	0.002150	-1.49	0.156

S = 0.0170010 R-Sq = 96.7% R-Sq(adj) = 96.0%

B. Effect of process parameters on Bead Penetration (BP)

Figure 5 here shows the main effect plot of process parameters on bead penetration at different parameters like welding speed, current and gas flow rate in GTAW process of for welding 6063 alloy of Aluminium. From the figure, it can be seen that:

- Effect of welding speed: Bead penetration decreases with the increase in welding speed
- Effect of current : Bead penetration is almost constant with the increase in current
- Effect of gas flow rate: There is a decrease in bead penetration with the increase in gas flow rate.

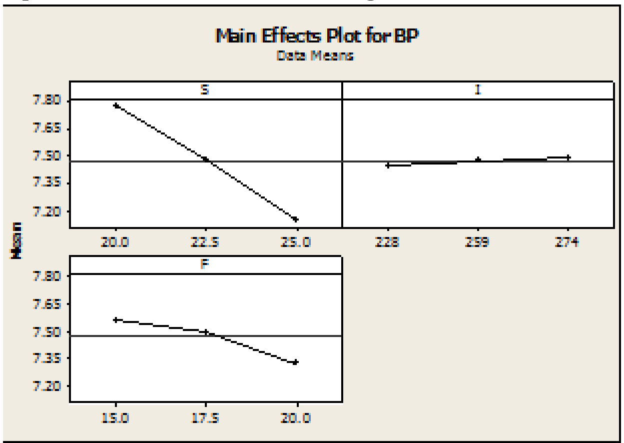

Figure 5: Main effect plots of process parameters for Bead Penetration

Regression equation for Bead Penetration is

BP = 10.9 - 0.125 S + 0.00084 I - 0.0472 F

Table 4: Estimated Model Co-efficients for BP

Predictor	Coef	SE Coef	T	P
Constant	10.8975	0.5080	21.45	0.000
S	-0.12520	0.01295	-9.67	0.000
I	0.000843	0.001366	0.62	0.546
F	-0.04720	0.01295	-3.65	0.002

S = 0.102340 R-Sq = 87.0% R-Sq(adj) = 84.6%

C. Effect of process parameters on Bead Width (BW)

Figure 6 shows the main effect plot of process parameters on bead width at different parameters like welding speed, current and gas flow rate in GTAW process of for welding 6063 alloy of Aluminium. From the figure, it can be seen:

- Effect of welding speed : Bead width decreases with the increase in welding speed
- Effect of current : Bead width decrease with the increase in current
- Effect of gas flow rate: Bead width is almost constant with change in gas flow rate.

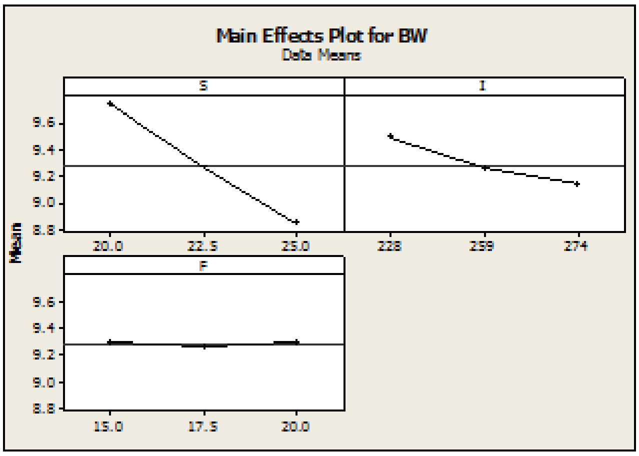

Figure 6 : Main effect plots of process parameters for Bead Width

Regression equation for Bead Width is

BW = 15.3 - 0.180 S - 0.00780 I + 0.00120 F

Table 5: Estimated Model Coefficients for BW

Predictor	Coef	SE Coef	T	P
Constant	15.2876	0.2241	68.22	0.000
S	-0.17960	0.0057	-31.45	0.000
I	-0.00780	0.0006	-12.94	0.000
F	0.001200	0.0057	0.21	0.836

S = 0.0451466 R-Sq = 98.6% R-Sq(adj) = 98.4%

8. Optimization

The aim of present study was to determine the set of optimal parameters of GTAW process to ensure minimum weldment area after satisfying the condition of maximum penetration. The weldment area can be obtained in terms of bead height, width and penetration (refer to Fig. 7) based on the assumption that it follows the parabolic curves.

A. Fitness function formulation

The above constrained optimization problem can be mathematically stated as follows:

Minimize,

f = 2/3 (BH+BP) BW

Regression model formulae for BH, BP and BW are

BH = 1.29 - 0.0428 S + 0.00182 I - 0.00320 F

BP = 10.9 - 0.125 S + 0.00084 I - 0.0472 F

BW = 15.3 - 0.180 S - 0.00780 I + 0.00120 F

Empirical model formulae for BH, BP and BW are

Weld bead height: BH = 0.10 x BP

Weld bead width: BW = 1.24 x BP

So fitness function becomes,

f=2/3 (0.10BP+BP) (1.24BP)

f=2/3 (1.364BP)

Weld bead penetration: BP = $\sqrt[3]{(I^4 / SV^2)}$

Where

P = Penetration of weld (mm)

I = Current (Amps)

S = Welding speed

V = Voltage (Volts)

B. Constraints

Subject to the condition that BP takes the maximum value and

$S_{min} \leq S \leq S_{max}$, i.e., $20 \leq S \leq 25$cm/min,

$I_{min} \leq I \leq I_{max}$, i.e., $228 \leq I \leq 274$A,

$F_{min} \leq F \leq F_{max}$, i.e., $15 \leq F \leq 20$lit/min

C. Penalty term

If the above condition was not maintained by a Genetic Algorithm-solution, its fitness value was penalized by using a term given below.

$P = C \times [(BH/BH_{min})^a + (BW/BW_{min})^b + (BP_{max}/BP)^c]$

The values of a, b, c and C were adopted from the research paper as 2, 2, 22 and 10, respectively. Thus, the penalty term P took the form as shown below.

$P = C \times [(BH/0.56)^a + (BW/8.72)^b + (10.01/BP)^c]$

D. Optimization using MATLAB Toolbox

The objective optimization function GA from the GENETIC OPTIMIZATION and DIRECT SEARCH tool box of MATLAB is used for defining and solving the problem. Following were the settings done for GA

Probability of mutation = Uniform rate 0.008

Population size = 100

Max. Number of generations = 100

Table 6 : Results of GA

Factors	*Range*	*GA Optimized Value*	
		Regression	*Empirical*
Welding speed	20-25 cm/min	25 cm/min	20 cm/min
Welding current	228-274 A	274 A	271 A
Gas flow rate	15-20 lit/min	20 lit/min	*

*Gas flow rate was not predicted using empirical co-relations.

9. Validation

The results obtained through optimization had to be validated. This was done through practical performance of the experiment in the same manner as the practicals performed earlier as per DOE. The results showed that Genetic Algorithm was able to reach near the optimal solution, after satisfying the constraints. This was validated in present work practically, after performing a confirmatory experiment as per process parameters optimized by GA. Maximum error of 5% was found between the predicted weld geometry parameters and the actually measured weld geometry parameters.

10. Conclusion

In this study, weld runs were performed using an automatic GTAW setup. Experiments were carried out as per central composite design and regression analysis was conducted to determine input–output relationships of the process. A constrained optimization problem was formulated to minimize weldment area after ensuring the condition of maximum bead penetration.

Genetic Algorithm with a penalty term was used to solve the said problem. Following are the important conclusions of the dissertation work. Following are the major conclusions of the work.

Effect of process parameters on bead height was concluded as under:

- Effect of welding speed : Bead height decreases with the increase in welding speed
- Effect of current : Bead height increases with the increase in current
- Effect of gas flow rate: There is a slight decrease in bead height with the increase in gas flow rate.

Effect of process parameters on bead penetration was concluded as under:

- Effect of welding speed : Bead penetration decreases with the increase in welding speed
- Effect of current : Bead penetration is almost constant with the increase in current
- Effect of gas flow rate: There is a decrease in bead penetration with the increase in gas flow rate.

Effect of process parameters on bead width was concluded as under:

- Effect of welding speed : Bead width decreases with the increase in welding speed
- Effect of current : Bead width decrease with the increase in current
- Effect of gas flow rate: Bead width is almost constant with change in gas flow rate.

The Genetic Algorithm was used for optimization. Following was concluded:

- Both the regression and empirical models were subjected to optimization process and both have given near about same optimal values.
- Genetic Algorithm was able to reach the optimal solution, after satisfying the constraints. This was validated in present work practically, after performing a confirmatory experiment as per process parameters optimized by GA.
- Maximum error of 5% was found between the predicted weld geometry parameters and the actually measured weld geometry parameters.

11. Future Scope

As is known, there is always some future scope of any research work. For the present work, the futuristic proposal of work to be included is summarized as under.

- In the present work both the regression and the empirical models were used. However, the empirical model used included the process parameters namely - Voltage, Current and Welding Speed. However, Gas flow rate was not included in the empirical model used for optimization. It is proposed to develop an empirical which correlates the weld bead parameters (bead height, bead penetration and bead width) with the process parameters namely – Current, Welding speed and Gas Flow Rate.
- In the present work, the welding has been carried out in 1G i.e. flat groove position welding. As a futuristic scope of this work, it is proposed to go for any other position welding such as vertical or overhead welding.

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[25] ANSI / AWS 5.10-92, "Specification for Bare Aluminium and Aluminium Alloy Welding Electrode"