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Prediction and Optimization of Pulsed Current Gas Tungsten Arc Welding Process Parameters to Obtain Sound Weld Pool Geometry in Titanium Alloy Using Lexicographic Method

M. Balasubramanian, V. Jayabalan, and V. Balasubramanian

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In this article the weld pool geometry of pulsed current gas tungsten arc (GTA)-welded titanium alloy was analyzed. Increase in use of pulsed current process creates dependancy on the use of mathematical equations to predict the weld pool geometry. Hence, the development of mathematical models using four factors, five levels, central composite design was attempted. The developed models were checked for their adequacy. Lexicographic method was used for optimizing the process parameters of pulsed current GTA welding technique. Optimizing the process parameters has resulted in bringing out strong weld pool geometry, which was later confirmed by conducting confirmation tests.

Keywords analysis of variance, experimental design, gas tungsten arc welding, lexicographic method, pulsed current, titanium alloy

1. Introduction

Basically, gas tungsten arc (GTA) welding 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. On the other hand, it is widely understood that the GTA welding of titanium alloy exhibits columnar grains in the weld pool, which often results in inferior mechanical properties and may lead to hot cracking. Current pulsing technique was attempted by many researchers to great success, resulting in grain refinement of fusion zone. It was reported that substantial grain refinement was possible in the case of aluminum alloys and titanium alloys (Ref 1, 2). In recent past, many researchers (Ref 3-5) have used pulsed current GTA welding technique to improve the mechanical properties and had been proven to great success. Weldability of aluminum-lithium alloys was studied with pulsing current. The results proved that current pulsing lead to relatively finer and more equiaxed grain structure in GTA welds of AA8090 type Al-Li alloy. Grain refinement was accompanied by an increase in hardness, ultimate tensile strength, and tensile ductility (Ref 5). Selection of process parameters in GTA welding of 1.6 mm titanium alloy was presented for obtaining optimum grain size and hardness. The developed models were optimized using the traditional Hooke and Jeeve's algorithm. Optimum process parameters for minimum fusion zone grain size and maximum fusion zone hardness were identified and they were in the range of 80 and 90 amps for peak current and 45-55 amps for base current, 6-9 Hz for pulsing frequency, and 40-45% for pulse on time (Ref 6). Modified Taguchi method was adopted to analyze the effect of each GTA welding process parameter on the weld pool geometry, and then to determine the process parameters with the optimal weld pool geometry. Experimental results have shown that the front height, front width, back height, and back width of the weld pool in the GTA welding of stainless steel are greatly improved by using this approach (Ref 7).

From the literature it is understood that the published information on the effect of pulsed current parameters on mechanical and metallurgical properties of titanium alloy welds could be counted with fingers. Moreover, there are no literature available relating pulsed current parameters and the weld pool geometry. To have high-quality weld with improved mechanical properties, optimization of process parameters is required. Hence, the present investigation was carried out to attain the above objective. Since pulsed current is defined by four variables (peak current, base current, pulse frequency, and pulse-on-time), it is always essential to model it and that is the aim of this article. There are few more variables which will influence bead geometry, such as travel speed, gas flow rate, torch position, etc. The article is aimed at to develop an empirical relationship between pulsed current parameter and bead geometry, keeping other variables constant.

M. Balasubramanian, Department of Mechanical Engineering, Maamallan Institute of Technology, Anna University, Sriperumpudur, Tamil Nadu 602 105, India; **V. Jayabalan**, Department of Manufacturing Engineering, Anna University, Guindy, Chennai, 600 025, India; and **V. Balasubramanian**, Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, Chidambaram 608 002, India. Contact e-mails: manianmb@yahoomail.com, manianmb@rediffmail.com, jbalan@annauniv.edu and visvabalu@yahoo.com

2. Methodology of Experimentation and Analysis

The scheme of investigation and further interpretation and analysis of results is discussed in the following section.

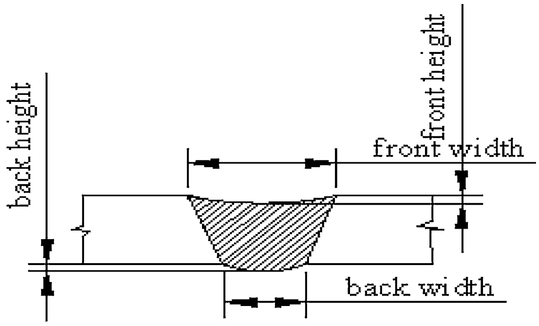

Fig. 1 Typical weld pool geometry

The material under investigation is Ti-6Al-4V alloy. To evaluate the quality of GTA welds, the measurements of the front height, back height, front width, and back width of the weld pool are considered (Fig. 1). Basically, weld penetration at the back face of the base metal must be achieved to ensure the weld strength. The front height, back height, front width, and back width of the weld have a smaller-the-better quality characteristic.

2.1 Identification of Important Process Variables

From the literature (Ref 4-7), the predominant factors that have greater influence on fusion zone grain refinement of pulsed current GTA welding process were identified. They are: (i) peak current; (ii) background current; (iii) pulse frequency; and (iv) pulse on time.

2.2 Identifying the Limits of the Process Variables

A large number of trial runs were carried out using 1.6 mm thick mill-annealed sheets of titanium (Ti-6Al-4V) alloy to find out the feasible working limits of pulsed current GTA welding process parameters. The working limits were decided by inspecting the bead contour, bead appearance, and for any visual defects. The upper limit of a factor was coded as +2 and the lower limit as −2; the coded values for intermediate ranges were calculated from the following relationship:

$$X_i = 2[2X - (X_{max} - X_{min})]/(X_{max} - X_{min}) \quad \text{(Eq 1)}$$

where X_i is the required coded value of a parameter of any value X from X_{min} to X_{max}; X_{min} is the lower level of the variable and X_{max} is the upper level of the variable.

2.3 Design Matrix

Due to wide range of factors, it was decided to use four factors, five levels, rotatable central composite design matrix. Table 1 presents the ranges of factors considered and Table 2 shows the 31 sets of coded conditions used to form the design matrix. The first 16 experiments have been formulated as per 2^4 (two levels and four factors) factorial design. The 16 experimental conditions (rows) have been formed for main effects. The next eight experimental conditions are called as corner points, i.e., keeping one factor at the lowest/highest level and the remaining factors at middle level. The last seven experimental conditions are known as center points, i.e., keeping all the factors at the middle level and it is normally done to know the repeatability of the experimental procedures.

Table 1 Important factors and their levels

S. No	Factor	Notation	Unit	Levels −2	−1	0	1	2
1	Peak current	p	amp	60	70	80	90	100
2	Base current	b	amp	20	30	40	50	60
3	Pulse frequency	f	Hz	0	3	6	9	12
4	Pulse-on-time	t	s	35%	40%	45%	50%	55%

Table 2 Welding conditions

Power source	Lincoln, USA
Polarity	AC
Arc voltage	22 volts
Electrode	W + 2% Thoriated (alloy)
Electrode diameter	2 mm
Shielding gas	Argon
Gas flow rate	10 L/min
Torch position	Vertical
Operation	Automatic
Welding speed	300 mm/min

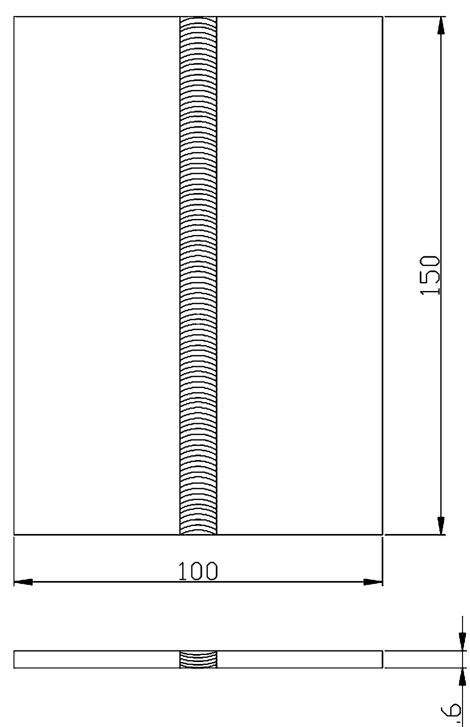

Fig. 2 Dimensions of joint configuration

2.4 Conducting Experiments According to Design Matrix

The titanium alloy (Ti-6Al-4V) plate 1.6 mm thick with yield strength (at 0.2% offset) of 910 MPa, ultimate tensile strength of 998 MPa, and elongation of 10% was single-pass autogenously welded (Fig. 2). High-purity argon gas (99.99%) was used as a shielding gas and as trailing gas right after the

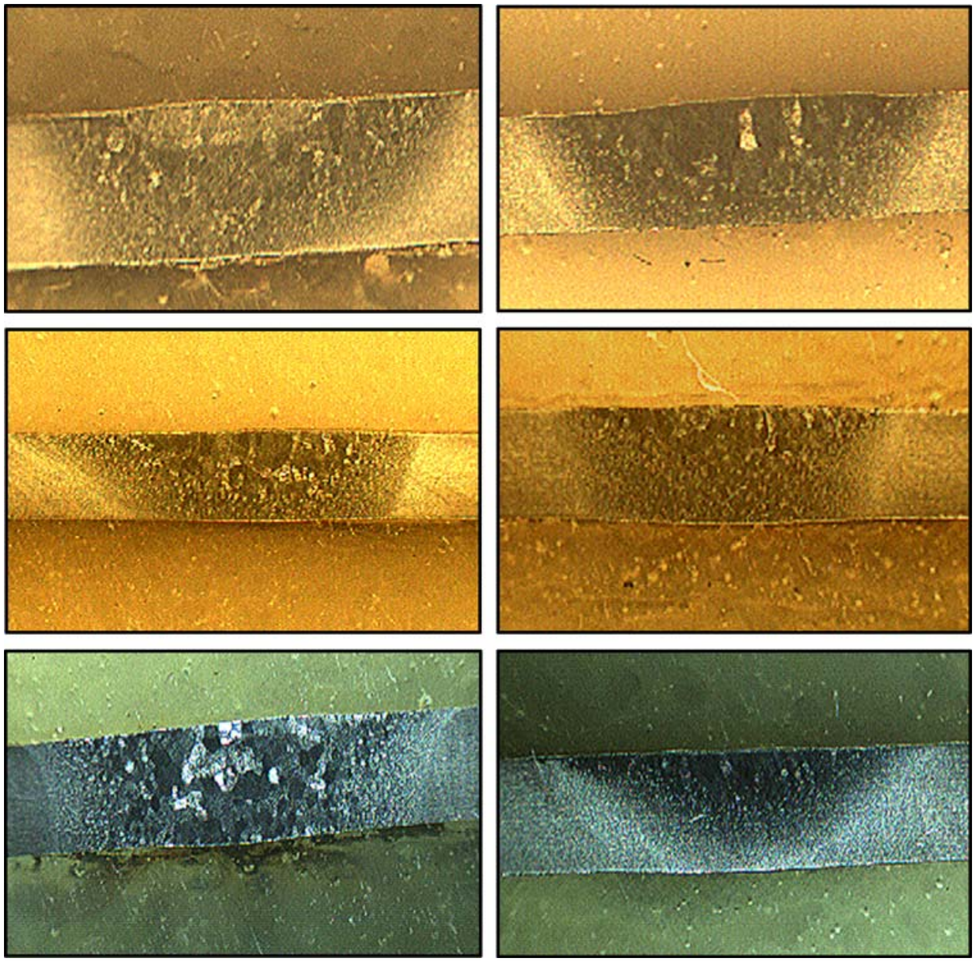

Fig. 3 Macrographs of weld pool

welding to prevent absorption of oxygen and nitrogen from the atmosphere. Backing plate and purging gas were not used since they will influence back height and back width of the weld pool. However, the titanium sheets were rigidly clamped to avoid distortion. The joints were made with 2 mm diameter tungsten electrode under the welding conditions presented in Table 2.

2.5 Recording the Responses

Three specimens were extracted at 50 mm interval along the weld line from each joint. These specimens were prepared using standard metallographic procedures to reveal the macrostructure (weld pool geometry). Specimens were etched with Krolls reagent to reveal the weld pool geometry. The profile of the weld pool was measured using a profilometer (Fig. 3). The observed values of weld pool front height, back height, front width, and back width are given in Table 3. The values are average of the three readings and the deviation is ±2%.

2.6 Development of Mathematical Models

The response function representing any of the weld pool dimensions is expressed as $Y = f\,(p, b, f, t)$.

The second-order polynomial (regression) equation used to represent the response Y is given by

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{\substack{i=1 \\ i \neq j}}^{k} b_{ii} x_i^2 + \sum_{i,j=1}^{k} b_{ij} x_i x_j \qquad \text{(Eq 2)}$$

and for four factors, the selected polynomial could be expressed as

$$\begin{aligned} Y = {} & b_0 + b_1(p) + b_2(b) + b_3(f) + b_4(t) + b_{11}(p^2) + b_{22}(b^2) \\ & + b_{33}(f^2) + b_{44}(t^2) + b_{12}(pb) + b_{13}(pf) + b_{14}(pt) \\ & + b_{23}(bf) + b_{24}(bt) + b_{34}(ft) \end{aligned} \qquad \text{(Eq 3)}$$

where b_0 is the average of responses and $b_1, b_2, \ldots, b_{23}$ are the coefficients that depend on respective main and interaction effects of the parameters. The value of the coefficients has been calculated using the following expressions (Ref 8):

$$b_0 = 0.142857\,(\Sigma Y) - 0.035714\,\Sigma\Sigma(X_{ii}Y) \qquad \text{(Eq 4)}$$

$$b_i = 0.041667\,\Sigma(X_i Y) \qquad \text{(Eq 5)}$$

$$b_{ii} = 0.03125\,\Sigma(X_{ii}Y) + 0.00372\,\Sigma\Sigma(X_{ii}Y) - 0.035714(\Sigma Y) \qquad \text{(Eq 6)}$$

$$b_{ij} = 0.0625\,\Sigma(X_{ij}Y) \qquad \text{(Eq 7)}$$

All the coefficients were tested for their significance at 90% confidence level applying student's t-test using the SPSS

Table 3 Design matrix and measured values of weld pool geometry

Exp. No	p	b	f	t	Front height (F_h), mm	Back height (B_h), mm	Front width (F_w), mm	Back width (B_w), mm
1	−1	−1	−1	−1	0.103	0.075	7.500	7.180
2	1	−1	−1	−1	0.077	0.056	5.857	5.278
3	−1	1	−1	−1	0.12	0.081	8.143	5.946
4	1	1	−1	−1	0.081	0.066	6.570	4.625
5	−1	−1	1	−1	0.082	0.069	7.000	6.921
6	1	−1	1	−1	0.064	0.05	6.286	4.833
7	−1	1	1	−1	0.11	0.078	7.452	6.621
8	1	1	1	−1	0.078	0.059	6.143	5.620
9	−1	−1	−1	1	0.13	0.084	7.171	6.626
10	1	−1	−1	1	0.072	0.063	6.429	5.722
11	−1	1	−1	1	0.15	0.088	7.571	6.320
12	1	1	−1	1	0.107	0.072	7.286	6.285
13	−1	−1	1	1	0.11	0.078	7.857	5.633
14	1	−1	1	1	0.078	0.056	5.857	5.278
15	−1	1	1	1	0.17	0.094	8.286	6.481
16	1	1	1	1	0.082	0.069	7.210	6.167
17	−2	0	0	0	0.074	0.044	6.314	4.389
18	2	0	0	0	0.068	0.053	6.571	5.056
19	0	−2	0	0	0.05	0.031	5.520	3.967
20	0	2	0	0	0.062	0.047	5.286	4.620
21	0	0	−2	0	0.21	0.106	7.686	7.478
22	0	0	2	0	0.11	0.081	8.129	7.278
23	0	0	0	−2	0.088	0.038	5.771	4.482
24	0	0	0	2	0.079	0.059	7.120	5.252
25	0	0	0	0	0.061	0.022	6.130	4.620
26	0	0	0	0	0.035	0.019	5.171	3.967
27	0	0	0	0	0.052	0.034	5.143	4.480
28	0	0	0	0	0.036	0.019	5.200	4.767
29	0	0	0	0	0.052	0.028	5.610	4.910
30	0	0	0	0	0.05	0.031	5.100	4.580
31	0	0	0	0	0.066	0.025	5.300	4.550

statistical software package. After determining the significant coefficients, the final models were developed.

3. Final Mathematical Models

Front height (F_h, mm):

$$F_h = 0.050288 - 0.0145p + 0.008583b - 0.01108f + 0.006917t + 0.00655p^2 + 0.002802b^2 + 0.0288f^2 + 0.0096t^2 + 0.00175ft - 0.00425pb - 0.0066pt + 0.0018bf + 0.0035bt \quad \text{(Eq 8)}$$

Back height (B_h, mm)

$$B_h = 0.02543 - 0.00575p + 0.0045b - 0.00342f + 0.00466t + 0.00805p^2 + 0.00568b^2 + 0.0193f^2 + 0.008059t^2 + 0.001125bf \quad \text{(Eq 9)}$$

Front width (F_w, mm)

$$F_w = 5.3793 - 0.3678p + 0.1765b - 0.01875f + 0.2255t + 0.3472p^2 + 0.0873b^2 + 0.7135f^2 + 0.348t^2 - 0.1475ft + 0.1611pb + 0.1213ft \quad \text{(Eq 10)}$$

Back width (B_w, mm)

$$B_w = 4.5535 - 0.3678p + 0.1765b + 0.225t + 0.3472p^2 + 0.71349f^2 + 0.34799t^2 + 0.16112pb + 0.294pt + 0.1158bf \quad \text{(Eq 11)}$$

4. Checking the Adequacy of the Developed Mathematical Models

The adequacy of the developed models was tested using the analysis of variance (ANOVA) technique. As per this technique, if the calculated value of 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 for all the responses are presented in Table 4. From the table, it can be understood that all the developed models are adequate to predict the weld pool geometry of pulsed current GTA-welded titanium alloy at 99% confidence level.

5. Solution Methodology

Lexicographic method (Ref 9-11) optimizes one of the original objectives, subject to constraints on other objectives

Table 4 ANOVA test results

Terms	Front height	Back height	Front width	Back width
First-order terms				
Sum of squares (SS)	0.010911	0.002082	5.22467	4.082689
Degrees of freedom (dof)	4	4	4	4
Mean square (MS)	0.002728	0.000521	1.306169	1.020672
Second-order terms				
Sum of squares (SS)	0.026552	0.012814	19.00803	22.52034
Degrees of freedom (dof)	10	10	10	10
Mean square (MS)	0.002655	0.001281	1.900803	2.252034
Error terms				
Sum of squares (SS)	0.000805	0.000206	0.832445	0.527196
Degrees of freedom (dof)	6	6	6	6
Mean square (MS)	0.0001	3.43E − 05	0.138741	0.087866
Lack of fit				
Sum of squares (SS)	0.006829	0.001908	5.583633	3.777107
Degrees of freedom (dof)	10	10	10	10
Mean square (MS)	0.000683	0.000191	0.558363	0.377711
F_{ratio} (calculated)	5.08	5.565	4.024	4.298
F_{ratio} (from table) (10,6,0.01)	7.87	7.87	7.87	7.87
Whether the model is adequate?	Yes	Yes	Yes	Yes

that give a better visibility to frame a constraint for subsequent objectives. This step-by-step process first generates an objective value based on constraints discussed in model. Then, the objective function is added as another constraint for the next objective function based on the value found in the previous step.

The experimentation is continued until the final objective considered is reached. In the lexicographic method, the designer ranks the objectives in the order of importance. The optimum solution X^* is then found by minimizing the objective functions, starting with the most important and proceeding according to the order of importance of the objectives. Let the subscripts of the objectives indicate not only the objective function number, but also the priorities of the objectives. Thus, $f_1(X_1)$ and $f_k(X_1)$ denote the most and the least important objective functions, respectively.

The first problem is formulated as:

$$\text{Minimize } f_1(X_1)$$
$$\text{Subject to}$$
$$g_j(X) \leq 0, \quad j = 1, 2, \ldots, m$$

and its solution X_1^* and $f_1^* = f_1(X_1^*)$ is obtained. Then, the second problem is formulated as:

$$\text{Minimize } f_2(X)$$
$$\text{Subject to}$$
$$g_j(X) \leq 0, \quad j = 1, 2, \ldots, m$$
$$f_1(X) \leq f_1^*$$

The solution of the problem is obtained as X_2^* and $f_2^* = f_2(X_2^*)$.

This procedure is repeated until all the k objectives have been considered.

The ith problem is given by minimize $f_i(X)$ subject to $g_j(X) \leq 0$, $j = 1, 2, \ldots, m$, $f_l(X) \leq f_l^*$, $l = 1, 2, \ldots, i-1$, and its solution is found as X_i^* and $f_i^* = f_i(X_i^*)$. Finally, the solution obtained at the end (i.e., X_k^*) is taken as the desired solution X^* of the original multiobjective optimization problem.

To begin with the constraints are $-2 < p < 2$, $-2 < b < 2$, $-2 < f < 2$, $-2 < t < 2$. At each stage, optimizing the functions on priority basis, each function will add as a constraint to the other function. Say $f_1(X) = 0$ will add as another constraint while minimizing $f_2(X)$ and so on.

Table 5 Optimized values

Optimum process parameters				Optimum weld pool geometry			
p	***b***	***f***	***t***	F_h	B_h	F_w	B_w
83.62	35.93	6.29	43.55%	0.0418	0.0226	5.1870	4.346

6. Computational Results

The models developed in Section 3 are solved considering four factors. The first preference is given to back height, the second to front height, the third to front width, and the fourth to back width (Ref 7, 12). The results are generated with the use of Lindo Systems' Lingo 7.0. The Lingo has limitations for integer variables, nonlinear variables, constraints, etc. Hyper Version can accept 800 integer variables, 800 nonlinear variables, 4000 constraints, and 8000 total variables. Optimized levels of process parameters are given in Table 5.

7. Validation of Results

Three joints were fabricated using optimized pulsed current parameters and two more joints were fabricated using randomly chosen pulsed current parameters (nonoptimized values but within the feasible working limit). Then the joints were tested for weld pool geometry and the results are presented in Table 6. The joints fabricated using optimized pulsed current parameters exhibited smaller-the-better quality characteristics compared to other joints and it is evident from the results. Thus, the optimized pulsed current parameters obtained by the above procedure were checked for their repeatability and it is confirmed that the optimized values are valid.

Table 6 Validating the developed models

					F_h, mm			B_h, mm			F_w, mm			B_w, mm		
Exp. No.	*p*, amp	*b*, amp	*f*, Hz	*t*, %	*A*	*P*	%*D*	*A*	*P*	%*D*	*A*	*P*	%*D*	*A*	*P*	%*D*
1	85	35	6	45	0.040	0.041	2.43	0.023	0.022	−4.5	5.29	5.187	−1.98	4.41	4.346	−1.37
2	85	35	6	45	0.041	0.042	2.38	0.021	0.022	4.5	5.06	5.190	2.5	4.18	4.340	3.68
3	85	35	6	45	0.041	0.042	2.38	0.029	0.028	−3.57	5.111	5.195	1.61	4.26	4.346	2.06
4	90	45	6	45	0.047	0.045	4.44	0.030	0.031	−3.22	5.520	5.549	0.70	4.76	4.701	−1.27
5	60	55	10	50	0.222	0.214	3.73	0.130	0.133	2.25	9.112	9.262	1.61	8.09	7.944	−1.88

% Error = ((actual value − predicted value)/predicted value) × 100

8. Benefits of the Pulsed Current Welding

Pulsed current tungsten inert gas welding is a variation of continuous current tungsten inert gas welding that involves cycling the welding current at a 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. In contrast to constant current welding, in pulsed GTA heat energy is supplied only during peak current pulses, allowing it to dissipate into the base metal during the background current and thus lowering heat build up in the adjacent base material, thus leading to a narrower heat-affected zone. 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 width of HAZ. Current pulsing has been used by several investigators to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties of aluminum alloys. Cast and hot-rolled Al-Li alloy sheets were fabricated in to weld coupons of size 75 × 200 mm using pulsed current GTA welding. It was revealed that current pulsing lead to relatively finer and more equiaxed grain structure in pulsing current when compared to continuous current (Ref 5). Grain refinement was accompanied by an increase in hardness, ultimate tensile strength, and tensile ductility in AA6061 aluminum alloy. Pulsed current TIG welding parameters have been optimized to attain maximum grain refinement in the fusion zone of AA 7075 aluminum alloy using statistical tools such as design of experiments, response table, and ANOVA. A minimum grain diameter of 21.62 μm was obtained for a peak current of 200 amp, background current of 70 amp, pulse frequency of 6 Hz, and pulse on time (Ref 13). Grain refinement with equiaxed grains was observed in the case of titanium also leading to reduction in grain size, increase in hardness, and tensile strength, which has been already discussed elsewhere (Ref 14, 15).

9. Conclusions

1. A five-level factorial technique can be employed effectively for developing mathematical models to predict weld pool geometry within the region of control process parameters. The developed models can be employed in automated processes for obtaining pool geometry of required quality level.
2. Pulsed current GTA welding process parameters have been optimized to attain optimal weld pool geometry in titanium alloy using statistical tools such as design of experiments, ANOVA, and multiobjective optimization tool namely, lexicographic method.
3. The optimal weld pool geometry of back height 0.0226 mm, front height 0.0418 mm, front width 5.1870 mm, and back width 4.346 mm was obtained at a peak current of 84 amp, background current of 36 amp, pulse frequency of 6.3 Hz, and pulse on time of 44%.

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