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DEVELOPING EMPIRICAL RELATIONSHIPS TO PREDICT TENSILE, IMPACT AND FATIGUE STRENGTH OF GTA WELDED AA 6061 ALUMINIUM ALLOY INCORPORATING PULSED CURRENT PARAMETERS

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ABSTRACT

The preferred welding process for welding AA6061 aluminium alloy is frequently Gas Tungsten Arc (GTA) welding due to its comparatively easier applicability and better economy. In the case of single pass GTA welding of thinner section of this alloy, the pulsed current has been found beneficial due to its advantages over the conventional continuous current process. In this investigation an attempt has been made to develop empirical relationships to predict tensile strength, impact toughness and fatigue life of GTA welded AA6061 aluminium alloy joints by incorporating pulsed current parameters. One of the design of experiment concepts, full factorial design, has been used to design the number of experimental conditions. Regression analysis has been used to develop the empirical relationships. Analysis of variance technique has been used to identify the significant factors. Co-efficient of determination has been calculated to check the adequacy of the developed models. The developed relationships can be effectively used to predict mechanical properties of the GTA welded AA6061 aluminium alloy joints from pulsed current parameters.

Keywords: *Pulsed Current, Tungsten Inert Gas Welding, Aluminum Alloy, Tensile Strength, Impact Toughness, Fatigue Life, Design of Experiments, Analysis of Variance.*

1. Introduction

Weld fusion zones typically exhibit coarse columnar grains because of the prevailing thermal conditions during weld metal solidification. This often results in inferior weld mechanical properties and poor resistance to hot cracking. It is thus highly desirable to control solidification structure in welds and such control is often very difficult because of higher temperatures and higher thermal gradients in welds in relation to castings and the epitaxial nature of the growth process. Nevertheless, several methods for refining weld fusion zones have been tried with some success in the past: inoculation with heterogeneous nucleants, microcooler additions and surface nucleation induced by gas impingement and introduction of physical disturbance through techniques such as torch vibration [1].

The use of inoculants for refining the weld fusion zones was, as a matter of fact, not as successful as in castings because of the extremely high temperatures involved in welding and also due to the undesirable effects of inoculating elements on weld mechanical properties at the levels required for producing grain refinement. Other techniques like surface nucleation and microcooler additions were also turned down because of the complicated welding set-ups and procedures associated with their use. In this process, two relatively new techniques namely, magnetic arc oscillation and current pulsing, have gained wide popularity because of their striking promise and the relative ease with which these techniques can be applied to actual industrial situations with only minor modifications of the existing welding equipment [2].

Pulsed current tungsten inert gas (PCGTAW) welding, developed in 1950s, is a variation of GTA welding which involves cycling of the welding current from a high level to a low level at a selected regular frequency. The high level of the peak current is generally selected to give adequate penetration and bead contour, while the low level of the background current is set at a level sufficient to maintain a stable arc. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time producing the weld as a series of overlapping nuggets and limits the wastage of heat by conduction into the adjacent parent material as in normal constant current welding. In contrast to constant current welding, the fact that heat energy required to melt the base material is supplied only during peak current pulses for brief intervals of time allows the heat to dissipate into the base material

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leading to a narrower heat affected zone (HAZ). The technique has secured a niche for itself in specific applications such as in welding of root passes of tubes, and in welding thin sheets, where precise control over penetration and heat input are required to avoid burn through [3].

Metallurgical advantages of pulsed current welding frequently reported in literature include refinement of fusion zone grain size and substructure, reduced width of HAZ, control of segregation, etc [4, 5]. All these factors will help in improving mechanical properties. Current pulsing has been used by few investigators to obtain grain refinement in weld fusion zones and improvement in weld mechanical properties [6, 7]. However, reported research works relating the effect of pulsed current parameters on mechanical properties are very scant. Hence, in this investigation an attempt has been made to develop empirical relationships to predict tensile, impact and fatigue strength of GTA welded AA 6061 aluminium alloy joints using statistical tools such as design of experiments, analysis of variance and regression analysis.

2. Scheme of Investigation

In order to achieve the desired aim, the present investigation has been planned in the following sequence:

i. Identifying the important pulsed current parameters which are having influence on tensile, impact and fatigue properties
ii. Finding the upper and lower limits of the identified parameters
iii. Developing the experimental design matrix
iv. Conducting the experiments as per the design matrix
v. Recording the responses
vi. Developing mathematical models
vii. Identifying the significant factors
viii. Checking the adequacy of the developed models

2.1 Identifying the important parameters

From the literatures [5-8] and the previous work [9] done in our laboratory, the predominant factors which are having greater influence on mechanical properties of pulsed current TIG welded joints have been identified. They are: (i) Peak current (ii) Background current (iii) Pulse frequency (iv) Pulse on time.

2.2 Finding the working limits of the parameter

A large number of trial runs have been carried out using 5 mm thick rolled plates of AA 6061 aluminium alloy to find out the feasible working limits of pulsed current TIG welding parameters. AA4043 (Al-5%Si) aluminium alloy of 3mm diameter has been used as the filler metal. Different combinations of pulsed current parameters have been used to carryout the trial runs. The bead contour, bead appearance and weld quality have been inspected to identify the working limits of the welding parameters. From the above analysis following observations have been made:

i. If peak current was less than 160 ampheres, then incomplete penetration and lack of fusion were observed. At the same time, if peak current was greater than 180 ampheres, then undercut and arc wander were observed on the weld bead surface.
ii. If background current was lower than 80 ampheres, then the arc length was found to be very short and addition of filler metal becomes inconvenient. On the other hand, if the background current was greater than 90 ampheres, then arc became unstable and arc wandering was observed due to increased arc length.
iii. If pulse frequency was less than 2 Hz, then the bead appearance and bead contours were appeared to be similar to that of constant current weld beads. Further, if pulse frequency was greater than 6 Hz, then more arc glare and arc spatter were experienced.
iv. If pulse on time was lower than 40%, then weld nugget formation was not so smooth due to incomplete melting of filler metal. On the contrary, if the pulse on time was greater than 60%, then overmelting of filler metal and overheating of tungsten electrode were been noticed. The process parameters and their levels are presented in Table 1.

Table 1: Important Factor and their Levels

Factors	Unit	Notation	Levels	
			(-1)	(+1)
Peak current	Amp	P	160	180
Base current	Amp	B	80	90
Pulse frequency	Hz	F	2	6
Pulse on time	%	T	40	60

2.3 Developing the experimental design matrix

By considering all the above conditions, the feasible limits of the parameters were chosen in such a way that the AA 6061 aluminium alloy should be welded without any weld defects. Due to narrow range of factors, it was decided to use two level, full factorial design matrix to reduce the required number of experimental conditions. Table 1 presents the ranges of factor considered and Table 2 shows the 16 set of coded conditions used to form the design matrix 2^4

(two levels and four factors) factorial design. The 16 experimental conditions (rows) have been formed for main effects by using the formula 2^{nc-1} for the low (-1) and high (+1) values; where 'nc' refers to the column number. For example, in Table 2, the first four rows are coded as -1 and next four rows are coded as +1, alternatively, in the third column [because nc=3 and therefore 2^{3-1}=4]. The method of designing such matrix is dealt elsewhere [10, 11].

For the convenience of recording and processing the experimental data, upper and lower levels of the factors have been coded as +1 and –1 respectively and the coded values of any intermediate levels can be calculated using the following expression [12].

$$X_i = X - \frac{0.5*(X_{\max} + X_{\min})}{0.5*(X_{\max} - X_{\min})} \quad (1)$$

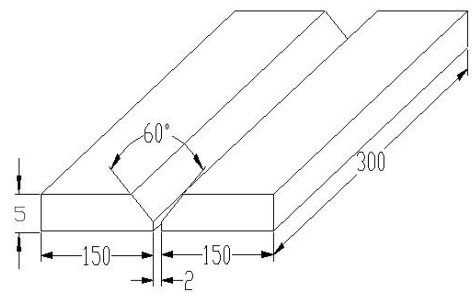
Where X_i is the required coded value of a factor of any value X from X_{min} to X_{max}; X_{min} is the lower level of the factor and X_{max} is the upper level of the factor.

Table 2: Experimental Design Matrix and the Test Results

Expt No.	P	B	F	T	TS (MPa)	IT (J)	FL (cycles) x 10^5
1.	-1	-1	-1	-1	250	10	9.32
2.	+1	-1	-1	-1	290	11	19.42
3.	-1	+1	-1	-1	190	7	3.65
4.	+1	+1	-1	-1	220	9	6.46
5.	-1	-1	+1	-1	270	11	14.23
6.	+1	-1	+1	-1	320	12	22.11
7.	-1	+1	+1	-1	230	9	7.32
8.	+1	+1	+1	-1	250	10	10.72
9.	-1	-1	-1	+1	220	9	6.67
10.	+1	-1	-1	+1	260	10	12.33
11.	-1	+1	-1	+1	170	7	2.45
12.	+1	+1	-1	+1	200	8	4.65
13.	-1	-1	+1	+1	230	9	7.38
14.	+1	-1	+1	+1	280	11	16.24
15.	-1	+1	+1	+1	210	8	5.17
16.	+1	+1	+1	+1	230	9	8.26

2.4 Conducting the experiments and recording the responses

AA6061 Aluminum alloy (Al-Mg-Si alloy) has gathered wide acceptance in the fabrication of light weight structures such as transportable bridge girders, military vehicles, road tankers and railway transport systems. Rolled plates of AA6061 of 5 mm thickness was used as the base material. Single V butt joint configuration (Fig. 1) was prepared for joining the plates.



(All the dimensions are in mm)

Fig. 1 Single V Butt Joint Configuration

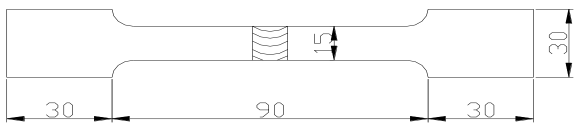
The filler metal used for joining the plates was AA 4043 (Al-5%Si) grade aluminium alloy. Tungsten Inert Gas (TIG) welding process has been used to fabricate the joints. Argon (99.99% pure) has been used as the shielding gas. In this investigation, 16 joints were fabricated using different combination of pulsed current welding parameters as prescribed by the experimental design matrix (Table 2). The chemical composition and mechanical properties of base metal and weld metals are presented in Table 3. The welding conditions and other process parameters used in the fabrication of the joints are given in Table 4.

Table 3(a): Chemical Composition (wt %) of Base Metal and all Weld Metal

Material	Mg	Mn	Fe	Si	Cu	Al
Base metal AA6061	0.68	0.33	0.23	0.53	0.31	Bal
All WM AA4043	0.05	0.22	0.05	5.00	0.12	Bal

Table 3(b): Mechanical Properties of Base Metal and All Weld Metal

Joint Type	Yield strength	Tensile strength	Elongation (%)	Vicker hardness (0.05) kg
BM AA6061	270	310	10	240
All WM AA4043	140	210	7	260

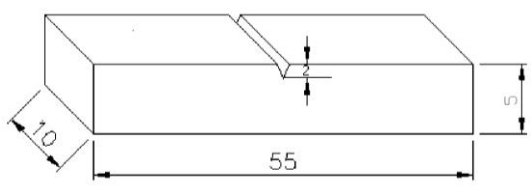


(All the dimensions are in mm)

Fig. 2 Dimensions of Tensile Specimen

Tensile specimens (Fig. 2) were prepared as per the ASTM E8M-90a guidelines. Tensile tests were carried out in 100 kN, electro-mechanical controlled Universal Testing Machine (Make: FIE-BLUE STAR). The specimen was loaded at the rate of 1.5 kN/min as per ASTM specifications, so that tensile specimen undergoes deformation. The specimen finally fails after necking and the load versus displacement was recorded. At each experimental condition, three specimens were tested and average values are presented in Table 2.

Sub-size charpy impact specimens (Fig. 3) were prepared to evaluate the toughness of the welded joints and ASTM E23-91 specifications were followed.



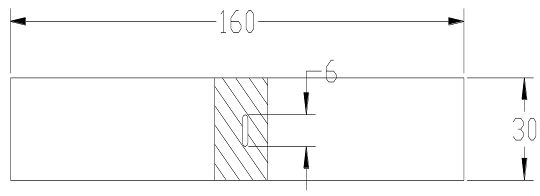
(All the dimensions are in mm)

Fig. 3 Dimensions of Sub-Size Impact Specimen

Impact test was conducted at room temperature using pendulum type impact testing machine (Make: ENKAY) with a maximum capacity of 300 J. The amount of energy absorbed in fracture is recorded and the absorbed energy is defined as the impact toughness of the material. Three specimens were tested and the average values are given in Table 2.

Table 4: Welding Conditions and Other Parameters

Welding machine	Make:Lincoln; Model: Precision TIG-375
Polarity	AC (alternating current)
Electrode	Thoriated Tungsten rod of 3 mm diameter
Filler rod	AA 4043 (Al-5% Si) of 3 mm diameter
Gas flow rate	14 lpm
Welding speed	70 mm/min
Arc voltage	20 volts
Torch angle	90 deg (vertical)



(All the dimensions are in mm)

Fig. 4 Dimensions of CCT Specimen

Centre Cracked Tension (CCT) fatigue test specimen (Fig. 4) were prepared to evaluate fatigue life of the welded joints. The slices derived from the single pass welded joints were reduced to a thickness of 4 mm by shaping and grinding processes to obtain flat and required surface roughness.

Then the sharp notch was machined in the WM region to the required length using the wire cut electric-discharge machine (EDM). Procedures prescribed by the ASTM E647-91 standard were followed for the preparation of the specimens. Fatigue experiments were conducted using a servo hydraulic controlled (INSTRON make), 100 kN capacity UTM with a frequency of 10 Hz under constant amplitude loading (R= stress ratio = $\sigma_{min}/\sigma_{max} = 0$). Fatigue experiments were carried out at a stress level of 100 MPa and three specimens were tested and the average fatigue life values are presented in Table 2.

3. Developing Empirical Relationships

Representing tensile strength of the joint by TS, the response function can be expressed as [10-12]

TS = f (Peak current, Base current, Pulse frequency, Pulse on time)

$$TS = f(P, B, F, T) \quad (2)$$

The model selected includes the effects of main factors and first order interaction of all factors. It is a portion of power series polynomial expressed as follows:

$$TS = b_0 + b_1(P) + b_2(B) + b_3(F) + b_4(T) + b_5(PB) + b_6(PF) + b_7(PT) + b_8(BF) + b_9(BT) + b_{10}(FT) + b_{11}(PBF) + b_{12}(PBT) + b_{13}(PFT) + b_{14}(BFT) + b_{15}(PBFT) \quad (3)$$

where b_0 is the average of responses (fatigue life); $b_1, b_2, b_3, \ldots b_{15}$ are the coefficients that depend on respective main and interaction factors which are calculated by using following expression [10].

$$b_i = \sum \frac{X_i Y_i}{n} \quad (4)$$

Where 'i' varies from 1 to n, in which X_i is the corresponding coded value of a factor and Y_i is the corresponding response output value (tensile strength) obtained from the experiment and 'n' is the total number of combinations considered (in this case n =16). Analysis of Variance (ANOVA) method has been applied to find out the significance of main factors and interaction factors.

Table 5: Yate's Algorithm to Calculate Sum of Squares (SS) for Tensile Strength (TS)

	Y	[1]	[2]	[3]	[4]	SS	
	250	540	950	2020	3820	912025	1
	290	410	1070	1800	280	4900	P
	190	590	850	140	-420	11025	B
[+]	220	480	950	140	-80	400	PB
	270	480	70	-240	220	3025	F
	320	370	70	-180	0	0	PF
	230	510	70	-40	60	225	BF
	250	440	70	-40	-40	100	PBF
	220	40	-130	120	-220	3025	T
	260	30	-110	100	0	0	PT
	170	50	-110	0	60	225	BT
[-]	200	20	-70	0	0	0	PBT
	230	40	-10	20	-20	25	FT
	280	30	-30	40	0	0	PFT
	210	50	-10	-20	20	25	BFT
	230	20	-30	-20	0	0	PBFT

Table 6: Yate's Algorithm to Calculate Sum of Squares for Impact Toughness (IT)

	Y	[1]	[2]	[3]	[4]	SS	
	10	21	37	79	150	1406.3	1
	11	16	42	71	10	6.25	P
	7	23	34	5	-16	16	B
[+]	9	19	37	5	0	0	PB
	11	19	3	-9	8	4	F
	12	15	2	-7	0	0	PF
	9	20	2	1	2	0.25	BF
	10	17	3	-1	-2	0.25	PBF
	9	1	-5	5	-8	4	T
	10	2	-4	3	0	0	PT
	7	1	-4	-1	2	0.25	BT
[-]	8	1	-3	1	-2	0.25	PBT
	9	1	1	1	-2	0.25	FT
	11	1	0	1	2	0.25	PFT
	8	2	0	-1	0	0	BFT
	9	1	-1	-1	0	0	PBFT

The higher order interactions (three factor interactions and four factor interactions) are practically insignificant and hence not considered [13]. Yate's algorithm has been used to calculate sum of squares. Tables 5-7 represent the Yate's algorithm and in the column marked (1), the upper half is obtained by adding successive pairs of treatments and the lower half is obtained by subtracting successive pairs.

Table 7: Yate's Algorithm to Calculate Sum of Squares (SS) for Fatigue Life (Fl)

	Y	[1]	[2]	[3]	[4]	SS	
	9.3	28.7	38.8	93.2	156.4	1528.40	1
	19.4	10.1	54.3	63.2	44.0	121.00	P
	3.6	36.3	26.1	24.2	-5.9	217.71	B
[+]	6.46	18.0	37.1	19.8	-21	27.56	PB
	14.2	19.0	12.9	-36.9	26.5	43.82	F
	22.1	7.1	11.2	-22.1	2.5	0.38	PF
	7.3	23.6	7.8	-11.8	2.0	0.26	BF
	10.7	13.4	12.0	-9.2	0.5	0.02	PBF
	6.6	10.1	-18.6	15.5	-30.1	56.55	T
	12.3	2.8	-18.3	11.0	-4.4	1.20	PT
	2.4	7.8	-11.9	-1.6	14.8	13.76	BT
[-]	4.6	3.4	-10.2	4.1	2.5	0.40	PBT
	7.3	5.6	-7.2	0.3	-4.6	1.31	FT
	16.2	2.2	-4.4	1.7	5.7	2.05	PFT
	5.17	8.8	-3.4	2.8	1.4	0.12	BFT
	8.26	3.0	-5.7	-2.3	-5.1	1.64	PBFT

Table 8: ANOVA (Analysis of Variance) Test Results for Tensile Strength

Factors	(SS)	(d.o.f)	[SS/d.o.f]	F_{ratio} [MS/Error]
		Main Factors		
P	4900	1	4900	196
B	11025	1	11025	441
F	3025	1	3025	121
T	3025	1	3025	121
		Two Factors		
PB	400	1	400	16
*PF	0	1	0	0
*PT	0	1	0	0
BF	225	1	225	9
BT	225	1	225	9
*FT	25	1	25	1
Error	125	5	125	
Total	22975	15		

Column (2), (3) and (4) are obtained in the same manner from the entries in column (1), (2) and (3) respectively. Each sum of square is obtained by squaring the corresponding effect total and dividing the result by **r. 2^{nf}**, where 'r' is number of replicates (trials) and 'nf' is the number of chosen factors. Further details regarding ANOVA method and Yate's algorithm are dealt with elsewhere [10, 11].

Table 9: ANOVA Test Results for Impact Toughness

Factors	(SS)	(d.o.f)	[SS/d.o.f]	F_{ratio} [MS/Error]
Main Factors				
P	6.25	1	6.25	41.667
B	16	1	16	106.67
F	4	1	4	26.667
T	4	1	4	26.667
Two Factors				
PB	0	1	0	0
*PF	0	1	0	0
*PT	0	1	0	0
BF	0.25	1	0.25	1.667
BT	0.25	1	0.25	1.667
*FT	0.25	1	0.25	1.667
Error	0.75	5	0.15	
Total	31.7	15		

Table 10: ANOVA Test Results for Fatigue Life

Factors	(SS)	(d.o.f)	[SS/d.o.f]	F_{ratio} [MS/Error]
Main Factors				
P	121	1	121	143.325
B	217.7	1	217.71	257.878
F	43.82	1	43.8244	51.9101
T	56.55	1	56.5504	66.9841
Two Factors				
PB	27.56	1	27.5625	32.6479
*PF	0.378	1	0.37822	0.44800
*PT	1.199	1	1.19903	1.42025
BF	0.260	1	0.2601	0.30809
BT	13.76	1	13.7641	16.3036
*FT	1.311	1	1.31103	1.55291
Error	4.221	5	0.8442	
Total	22975	15		

3.1 Final relationships

ANOVA test results are presented in Tables 8-10. From the ANOVA test results (Table 8), it is evident that all the main factors (P, B, F, T) and few interaction factors (PB, BF and BT) are considered to be significant. Hence the final model is developed including only these significant factors and it is given below:

Tensile Strength,

$$TS = \{239 + 17.5(P) - 26.3(B) + 13.75(F) - 13.75(T) - 5(PB) + 3.75(BF) + 3.75(BT)\}\ MPa \quad (5)$$

Similarly mathematical models have been developed to predict the impact toughness and fatigue life of the TIG welded joints by incorporating pulsed current parameters and they are given below:

Table 11: Co-efficient of Correlation for the Developed Empirical Relationships

S.No.	Name of the Relationship	Co-efficient of determination (r^2)
1	Tensile Strength (TS)	0.94
2	Impact Toughness (IT)	0.91
3	Fatigue Life (FL)	0.92

Impact Toughness,

$$IT = \{9.4 + 0.625(P) - 1(B) + 0.5(F) - 0.5(T)\}\ J \quad (6)$$

Fatigue Life,

$$FL = \{9.8 + 2.75(P) - 3.69(B) + 1.66(F) - 1.88(T) - 1.31(PB) + 0.93(BT)\} \times 10^5\ cycles \quad (7)$$

3.2 Checking adequacy of the relationships

Coefficient of determination 'r^2' is used to find how close the predicted and experimental values lie and it is calculated using the following expression [13];

r^2 = Explained variation / Total variation

$$= \Sigma (TS_p - \overline{TS})^2 / \Sigma (TS_e - \overline{TS})^2 \quad (8)$$

Where TSp is predicted (using the above model) tensile strength value for the given factors; TSe is the experimental value for the corresponding factors; $\overline{TS}$ is the average of experimental tensile strength life values. The value of 'r2' for the above-developed relationship is found to be 0.92, which indicates high correlation exist between experimental values and predicted values. Similarly co-efficient of determination has been calculated for all the developed relationships

Table 12: Comparison between Experimental Values and Predicted Values

S.No.	Pulsed Current Parameters				Tensile Strength (MPa)		Impact Toughness (Joules)		Fatigue Life 10^5 (cycles)	
	P	B	F	T	Exp	Pre	Exp	Pre	Exp	Pre
1.	170	80	3	40	260	270	9	10	11.2	11.5
2.	170	85	5	50	230	238	7	7	6.4	6.2
3.	160	90	4	50	220	210	6	7	4.5	4.8
4.	160	80	6	50	190	195	5	6	2.1	2.4
5.	180	85	4	60	300	292	12	12	20.2	21
6.	180	85	3	40	280	294	11	10	17.4	16.8
7.	175	90	2	60	240	232	8	8	8.3	8.6
8.	175	90	6	50	270	264	10	10	14.5	14
Co-efficient of determination					0.92		0.94		0.90	

and their values are presented in Table 11. To validate the developed models, few more joints were prepared and their tensile, impact and fatigue properties were evaluated. The experimental values and the corresponding predicted values (obtained from the developed relationships) are compared as shown in Table 12. From the comparison, it is understood that the developed empirical relationships can be used to predict mechanical properties of the joints with high accuracy.

4. Conclusions

Mathematical models have been developed to predict tensile strength, impact toughness and fatigue life of TIG welded AA6061 aluminium alloy joints by incorporating pulsed current parameters such as peak current, base current, pulse frequency and pulse on time. The developed mathematical models can be effectively used to predict mechanical properties of TIG welded AA6061 aluminium alloy joints within the range of pulsed current parameters investigated.

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