FUSION CHARACTERISTICS OF AN Al-Li ALLOY IN PULSED-GMAW PROCESS

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ABSTRACT

Fusion characteristics of high strength heat-treatable Aluminium-Lithium alloy plates, using GMAW process in continuous and pulsed mode were studied. Burn-off characteristic of the 1.6mm diameter 2319-filler wire in continuous and pulsed mode, including relation between pulse current and pulse duration for one droplet detachment per pulse was determined.

***Keywords :** Al-Li alloy, Pulsed-GMAW, Bead geometry, Aluminium welding*

INTRODUCTION

Every 1% of Li addition to aluminium alloys reduces the density by 3% and increases Young's modulus by 5% [1]. Because of the weight savings due to better specific modulus, and excellent fatigue and cryogenic toughness, most of the Al-Li alloys development is directed towards aerospace industry [2]. These alloys are also strong candidates for use in marine applications, lightweight pressure vessels, cryogenic fuel tankage for spacecrafts, armoured personnel carriers etc, in the welded condition. However, limited information is available on the weldability characteristics of these alloys and in particular with Pulsed-GMAW. Further, it has been reported for other alloys that, for a given heat input per unit length of weld the pulsed arc gives a narrower and deeper fusion zone compared with steady operation, and the HAZ is smaller [3]. Hence, it was felt that there is a need to study the fusion characteristics of this type of alloy in the steady and pulsed-GMAW and compare the fusion characteristics at similar current and arc voltage ranges.

In GMAW the composition and type of wire influences the values of arc voltage [4]. Each type of wire and dimension could have different burn-off and metal transfer characteristics. Hence, the burn-off behaviour of the filler used in the present study needs to be determined for two reasons (a) Current range for obtaining spray mode of transfer; and (b) as a guiding burn-off rate for pulse mode experiments. In a steady current GMAW where constant voltage characteristic is used for self-regulation of arc length, significant current fluctuations occur about the mean value. It is also known that plate fusion characteristics (bead penetration in particular) is more regular with a constant current characteristic [5]. Hence, for critical comparison with pulse mode of welding, constant current characteristics were used throughout the experiments.

Current pulsing consists of alternately applied high and low current, namely the pulse current (I_p) and the background current (I_p). Pulse current density should be sufficiently high to ensure that spray transfer occurs and in combination with appropriate pulse duration (T_p), detaches a single droplet of electrode material with a diameter approximately equivalent to the diameter of the electrode. If the combination of I_p and T_p does not provide sufficient energy, there may not be one droplet detachment per pulse resulting in irregular metal transfer and lesser control of the arc and welding process itself [6]. The acceleration of the droplets detached during the pulse current phase is high. These high velocity droplets impact on the weld pool with considerable momentum, which can result in greater penetration. The velocity of the droplets can influence the arc force, which is due to inertia of the droplets, the gas jet impinging on the weld pool surface, or both [7]. Hence, pulse detachment could be useful in heavier section welds where higher penetration is desirable. Further, if the detachment is at the end of the pulse, its energy is expected to be maximum. In our experiments, thicker sections are used for welding and so droplet detachment at the end of each pulse is preferred and the necessary conditions were experimentally determined.

EXPERIMENTAL PROCEDURE

Weld beads were deposited using a bead-on-plate technique on plates of 13.7 x 100 x 200 mm Aluminum-Lithium alloy Al-4.45%Cu-1.18%Li-0.48% Mg-0.44%Ag-0.14%Zr (W condition). The alloy has been developed by Defence Metallurgical Laboratory (DMRL), Hyderabad, India. 1.6 mm diameter 2319 filler wire and Argon shielding was used. Each one of the well-cleaned specimens was welded employing an electrode positive polarity (DCEP).A transistorised power source with pulsing facility and a current capacity of 500A was used. Constant current mode was used throughout the experimentation. Employing the mechanized GMAW station throughout, for depositing beads ensured the reproducibility of the data. This also eliminated the effect of welder's skill on the results.

Stable Arc of about 10.0mm was used for obtaining the suitable sets of parameters. Arc length was monitored by projecting a magnified image with a simple lens system, while control was done by manually adjusting the wire feed speed.

Experimental work was carried out in two stages, namely, determination of filler wire characteristics and study of bead geometry & shape relationships.

FILLER WIRE CHARACTERISTICS

Steady Mode : Beads-on-plate were layed at different wire feed rates and corresponding current and voltage readings were taken. The observed current (I), voltage (V) and wire feed rates (W_f) were recorded and I v/s. W_f plot is given in Fig.1. The curve is similar to that observed by Trindade et al [8] for 1.2 mm pure aluminium filler wire. The sub-threshold region is upto 144 A, Transition zone is from 144 – 177A, Normal spray transfer was observed from 194A onwards.

Pulsed Mode : Setting of pulse parametric range is done in three steps: (a) Burn-off criterion to obtain stable arc; (b) Determination of relation between pulse current and

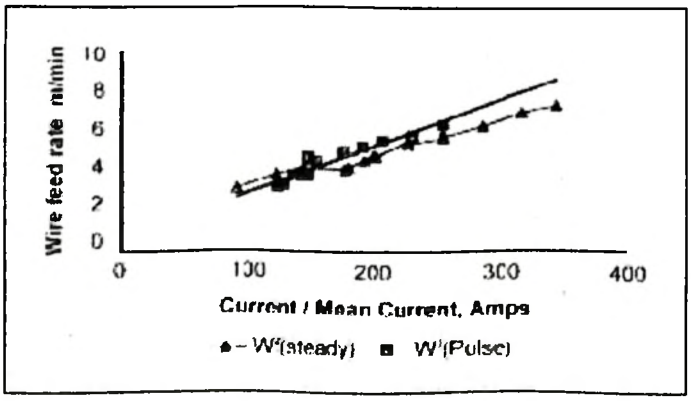

Fig.1 : Current (Steady mode)/ Mean Current (Pulse mode) v/s wire feed rate.

duration for obtaining one droplet detachment per pulse, at the end of the pulse and (c) Determination of parameters range using (a) and (b).

Burn-off rate : The pulse mode experiments were undertaken starting with some arbitrary values of pulse parameters pulse current (I_p), pulse duration (T_p), background current (I_b) and background duration (T_b) to determine the burn-off rate in the pulse mode. The initial settings of the wire feed were made using the burn-off rate in steady mode (Fig.1). As the welding proceeds, wire feed rate is manually adjusted to obtain stable arc with a hissing noise indicating spray transfer. The wire feed rate and corresponding mean current (I_m) values were recorded directly from the power source. The burn-off rate in pulse mode is plotted in Fig.1.A linear relation between the wire feed rate and mean current was obtained as follows:

$W_f = 0.0234\ I_m + 0.48$ ...1

(W_f in m/min and I_m in Amperes)

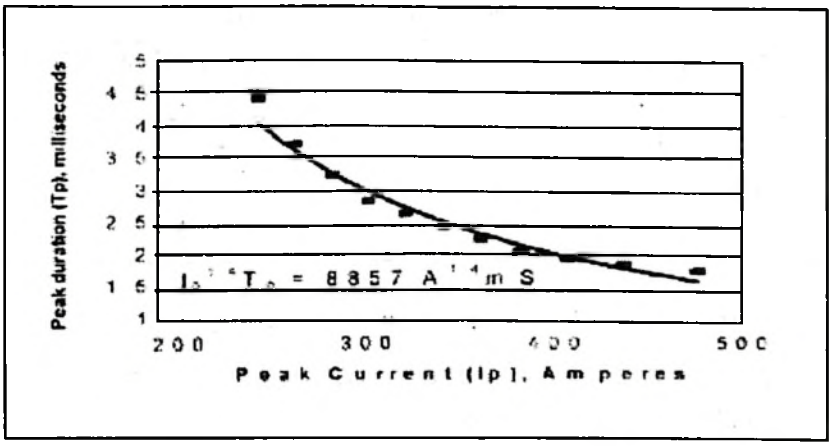

Fig. 2 : Ip-Tp relation for one drop detachment at the end of every pulse

In further experiments, mean current levels were fixed using this relation. Essentially, by fixing the wire feed rate, desired mean current value was obtained.

Determination of I_p -T_p relation : Pulse parameters I_p, T_p, I_b, and T_b were arbitrarily chosen. From the burn-off rate model as given by equation-1, the wire feed rates were fixed and the welding runs carried out. As the burn-off criterion (viz., sufficient supply of filler wire for the mean current levels used) was being satisfied,a stable arc could be obtained. The Voltage transient is recorded using an oscilloscope. Droplet detachments were identified by the spikes on voltage transients recorded. The pulse current was first fixed at a particular value and the pulse duration varied until the required condition is achieved. All such conditions yielding one drop per pulse detachment, that too at the end of the pulse were taken. The mean current range used for these experiments is 128-160 A. The droplet volume is 1.56 – 1.8 mm^3 . This droplet volume corresponds to a droplet diameter approximately equal or less than the diameter of

Table I : Effect of background conditions on droplet detachment time measured from recorded V-Transients during pulse-GMAW

Pulse Current, A	Pulse duration, mS	Background duration, ms time, ms	Actual detachment
300	2.9	2	2.93
300	2.9	7.3	2.63
380	2	3.1	1.9
380	2	9.5	2
405	1.9	4.8	1.96
405	1.9	10	2

Table II : Welding parameters and their limits

Parameter	Units	Symbol	Limits	
			Low(-1)	High(+1)
Welding Current	A	I	194	248
Welding speed	cm/min.	S	30	45
Pulse Current	A	Ip	300	380

the filler wire. Plotting the experimentally determined I_p and T_p values above,a parabolic curve as shown in Fig.2 is obtained. Regression analysis of the I_p -T_p curve yielded a relation:

$I_p^{1.4}\ T_p = 8857\ \text{Amp}^{1.4}.$ ms 2

In subsequent experimentation, this relation was found to hold good for higher mean currents as well. It was also observed that the influence of the background conditions on droplet detachments was minimal at higher pulse currents as shown in Table I.

EFFECT OF WELDING PARAMETERS ON BEAD GEOMETRY

All the conditions like arc length/arc voltage, type of shielding, nozzle-to-plate-distance, electrode stickout remaining same, the main parameters that affect the welded joint from the point of view of bead geometry and metallurgy are welding current and welding speed.

The bead geometry and shape relationships (BG&SR) could be described by penetration (p), crown height (h), width (w), weld penetration shape factor (WPSF) defined as the ratio of width to penetration (w/p), weld reinforcement form factor (WRFF) defined as the ratio of width to crown height (w/h) and %dilution (D) defined as the ratio of area of penetration (A) to the total bead area (A) at a given cross section.

The bead geometry variations with the important heat input factors like welding current and speed were taken. In the case of steady GMAW these two parameters would describe the overall heat being put into the welded joint. But, in the case of Pulsed-GMAW, there are four parameters I_P, T_P , I_b and T_b together representing the mean/average welding current (Im). They are related to each other as given below:

Mean Current $I_m = (I_PT_P+I_bT_b)/T_p+T_b$...3

The experiments were designed

Other experimental parameters kept constant throughout the experiments are as follows :

Background current, I_b	150 Amp
Arc voltage range. V	23 - 27 V
Polarity	DCEP
Nozzle to plate distance, NPD	15 mm
Electrode stick out	10-12 mm
Nozzle diameter	18 mm
Shielding gas & flow rate	Argon, 22 litres/minute
Torch angle	90°
Calculated parameters	
Pulse current duration,T_P , ms	Equation $I_PT_P = 8857$ A.mS
Background duration, T_b , ms	Equation $I_m = (I_PT_P+I_bT_b)/(T_P+T_b)$
Frequency, F	$1/(T_P + T_b)$

Table III : Experimental design matrix along with other calculated parameters

Bead No.	Direct Parameters			Dependent / Calculated Parameters		
	Im	Ip	S	Tp	Ib	Tb
Pulse-GMAW						
BOP-1	248	380	45	2.0	150	3.1
BOP-2	194	380	45	2.0	150	9.5
BOP-3	248	300	45	2.9	150	2.0
BOP-4	194	300	45	2.9	150	7.3
BOP-5	248	380	30	2.0	150	3.1
BOP-6	194	380	30	2.0	150	9.5
BOP-7	248	300	30	2.9	150	2.0
BOP-8	248	300	30	2.9	150	7.3
Continuous-GMAW						
BOP-9	248		45			
BOP-10	194		45			
BOP-11	248		30			
BOP-12	194		30			

using two level factorial design.

Selection of parametric range for two levels :

Welding current : The lower level of current was chosen to be 194 Amps., which is the spray transition temperature. The same lower level current for I_m was chosen for P-GMAW also, so as to compare the bead geometries etc in GMAW and P-GMAW. The higher level current was limited by the pulse parametric zone, beyond which there were no practical combinations for I_b and T_b (for eg: I_b values are very near or above the spray transition temperature, which is undesirable).

Welding speed : This was done by trial and error. Beyond 45 cm/min the lower level current was resulting in unacceptable overlaps. Below 30 cm/min, the bead width was increasing excessively without much increase in the penetration.

Pulse current in case of P-GMAW : It was felt that high pulse currents should be chosen in order to minimise the influence of background parameters as elaborated in earlier sections. The intended purpose of pulse current is to detach a droplet with good kinetic energy, which is higher at higher pulse currents. However, too high a pulse current may result in streaming transfer. So, 300-380A was found to be optimum range.

The range of parameters for the experiments planned is given in Table II.

Experimental design matrix and calculated parameters are given in Table III

The plates were sectioned at three places and bead dimensions measured using image analysis software on digitally stored macrostructure of the cross sections.

RESULTS AND DISCUSSION

(i) Comparison of bead profiles using GMAW and Pulsed-GMAW :

Burn-off rate of the filler wire is higher in case of pulsed GMAW, is lower than continuous GMAW at current levels below the transition zone. However, burn-off rate with Pulse-GMAW is higher than with

Table IV : Mean values of measured bead dimensions for beads-on-plate in P-GMAW and GMAW based on factorial design

Expt no.	Im	Ip	S	Penetration, p, mm	Weld width, W, mm	Reinforcement height h,mm	Total Fusion area A_f mm^2	Penetration area Ap mm^2
P-GMAW								
BOP-1	+1	+1	+1	5.6	14.09	3.02	62.85	37
BOP-2	-1	+1	+1	3.6	10.98	2.6	45.3	23.2
BOP-3	+1	-1	+1	5.73	13.13	2.87	63.05	38
BOP-4	-1	-1	+1	3.36	9.64	2.81	37.15	17.45
BOP-5	+1	+1	-1	6.89	16	3.73	93.05	50.15
BOP-6	-1	+1	-1	4.41	12.34	3.22	57.71	29.3
BOP-7	+1	-1	-1	5.82	15.74	3.59	86.63	47.05
BOP-8	-1	-1	-1	4.81	13.66	3.0	64.5	35
GMAW								
BOP-9	+1		+1	4.4	12.1	2.73	50.8	28.5
BOP-10	-1		+1	2.22	8.51	2.71	38.25	12.55
BOP-11	+1		-1	4.43	15.86	3.17	81.63	46.8
BOP-12	-1		-1	2.9	14.55	2.71	55.15	25.64

continuous GMAW for current levels above transition zone, by about 10%. Hence, deposition rate and heat transfer efficiency in case of P-GMAW is higher than in case of GMAW, which may enable higher welding speeds, in current range above transition current, which is the range used for the present study.

The macrographs of the cross section of the weld beads made of GMAW and P-GMAW were compared. Macrographs at low current and high speeds are given in Fig.3. P-GMAW weldments show a finger-like penetration, whereas the GMAW weldments show more shallow penetration. Only at higher currents and higher speed,a tendency for finger type penetration is observed in case of GMAW. For the same current level and welding speed, pulse-GMAW showed a significantly higher penetration, which is evident from the values shown in Table IV, perhaps aided by the tendency towards finger like penetration. The difference is higher at lower current level (194A), approximately 1.4 mm at higher welding speeds and 2 mm at lower speeds. Higher electromagnetic force and velocity of the droplets transferred into the weld due to pulse current, could

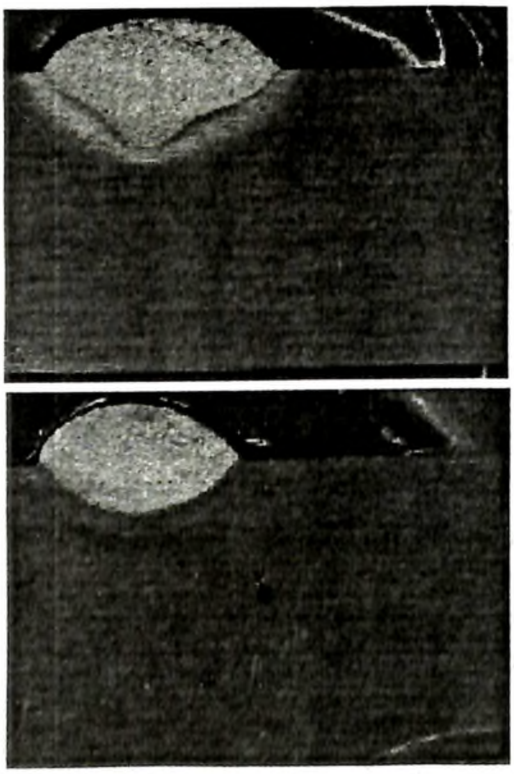

Fig-3: Weld beads at 194 A and 45cm/min P-GMAW (a) and GMAW (b)

Table V : Co-efficients of correlation between measured bead dimensions and welding parameters for Pulse-GMAW beads-on-plate used for mathematical modelling

Bead dimension Parameter	/Mean Value	Im.Ip.S	Im	Ip	S	Im.Ip	Im.S	Ip.S
Penetration, p	4.9	-0.11	0.86	0.10	-0.46	0.14	0.11	0.05
Width, w	13.19	-0.25	1.54	0.16	-1.24	0.15	0.11	0.42
Reinforcement height, h	3.10	0.05	0.20	0.04	-0.28	0.04	-0.08	-0.05
Dilution, D	54.25	-6.27	8.07	5.12	-4.57	-5.51	7.31	6.06
WPSF	2.84	-0.01	-0.16	-0.01	0.01	-0.04	-0.06	0.05
WRSF	4.56	-0.17	0.24	0	-0.03	-0.01	0.16	0.22

be the reasons for higher penetration using P-GMAW. This means, lower currents could be used with P-GMAW compared to GMAW for same level of penetration. Further, it is possible to get good spray metal transfer at much lower mean currents than in case of GMAW. This will be advantageous while welding heat treatable alloys.

(ii) Effect of parameters on Bead geometry & Shape relationships : The bead dimensions measured using image analysis software Image C are given in Table IV . Co-efficients of correlation calculated as per standard statistical procedures for factorial designs are given in Table V. The mathematical models for important bead parameters using the co-efficients of correlation calculated from factorial design experiments for coded values of –1 to +1 of each of the parameters Im, Ip and S are as follows:

$$p = 4.9 + 0.86\ I_m + 0.1\ I_P - 0.46\ S + 0.14\ I_m\ I_P + 0.11\ I_P\ S + 0.05\ S - 0.11\ I_m I_P\ S$$

$$w = 13.19 + 1.54\ I_m\ 0.16\ I_{Pm} - 1.24\ S + 0.15\ I_m\ I_P + 0.11\ I_m\ S + 0.42\ I_P\ S - 0.25\ I_m I_P S$$

$$h = 3.1 + 0.2\ I_m + 0.05\ I_P - 0.28\ S + 0.04\ I_m\ I_P - 0.08\ I_m\ S - 0.05\ I_P\ S + 0.05\ I_m I_P S$$

Based on the above model, effect of weld parameters on bead penetration is graphically represented in Fig.4 a & b. While I_m and S have a prominent effect on penetration, viz., penetration increases with increasing mean current and reducing welding speed. Increased pulse current is found to increase the penetration slightly, at higher current levels (Fig. 4a). Similarly at a particular mean current, pulse current increases the penetration at higher speeds (Fig. 4b). However, the effect of mean current

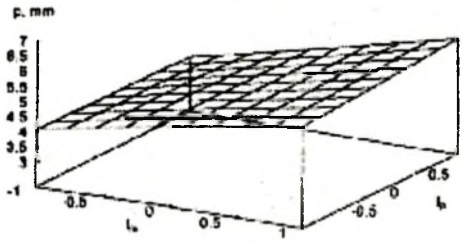

Fig-4a: Effect of I_m and I_P on p, at S=37.5cm/min

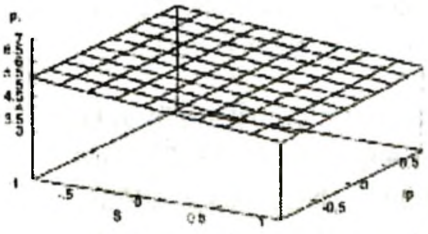

Fig-4b: Effect of I_m and S on p, at I_P=220 Amperes

Welding parameters represented with their coded values (-1 equal to lower level and 1 equal to higher level used in the factorial design of experiements) is higher than the welding speed. But, in both the cases the effect is upto a maximum of 0.8 mm. As the pulse current is increased, the electromagnetic pinch effect increases and it could increase the velocity of the droplets reaching the weld pool, thus increasing the momentum of the droplets reaching the weld pool. This could be the reason for slightly higher penetration at higher pulse current.

Similarly, variation of weld bead width with welding parameters was plotted. It was found that width increases with increasing mean current and decreases with increasing welding speed. Increase in pulse current increased the weld width at higher speed, more than at lower speeds. However, the effect was found to be insignificant.

Effect of welding parameters on weld bead reinforcement height was also evaluated based on the mathematical model. It increases with increasing mean current and decreases with increasing welding speed. Pulse current also has some effect. At a particular mean current, with increase in speed the reinforcement height decreases. This decrease was higher at lower pulse currents than at higher pulse current.

Only the mean current seems to be having any effect on WPSF Weld penetration shape factor (WPSF) and Weld reinforcement form factor (WRFF).

CONCLUSIONS

One droplet detachment at the end of the pulse could be obtained during pulsed-GMAW with 2319 filler wire of diameter 1.6mm, using the relation I tp = 8577A.mS for a useful range of welding parameters.

In the mean current range 194-248A, P-GMAW showed higher filler burn-off rate than in GMAW, indicating better heat transfer efficiency.

P-GMAW yielded higher penetration than GMAW, especially at lower mean currents.

Reasonably acceptable weld beads were obtained on 13.7mm thick plates of Al-Li alloy at a mean current as low as 194A and a welding speed of 45 cm/min.

In P-GMAW, pulse current has some effect on penetration of the weld bead, at higher mean currents. However, effect of pulse current on other weld bead dimensions is insignificant.

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