Droplet Detachment and Plate Fusion Characteristics in Pulsed Current Gas Metal Arc Welding

Uniform arc length and uniform droplet detachment were observed for the welds made with background detachment

BY S. RAJASEKARAN, S. D. KULKARNI, U. D. MALLYA AND R. C. CHATURVEDI

ABSTRACT. Molten metal droplet detachment and plate fusion characteristics, which have an important bearing on the weld quality, were influenced by the parameters of pulsed current, *viz.* peak current (I_P), peak duration (T_P), background current (I_B) and background duration (T_B). The complex interdependence of the above parameters of pulsed current makes it difficult to select the most suitable combination of parameters for welding (Refs. 1–4). To resolve this problem, a first estimate of the pulse parametric zone based on burnoff, droplet detachment and arc stability criteria was obtained. It has been further restricted taking into account the short circuit and burnback characteristics. Within this narrowed zone, the suitable combination of the pulsed current parameters has been recommended on the basis of a combined criteria, *viz.* uniformity in arc length, uniformity in droplet detachment and weld bead surface quality. This is done to obtain good quality welds. These studies have been carried out for a fixed pulse cycle time and one droplet detachment per pulse conditions.

Further studies have been carried out for different types of droplet detachments, namely background detachment, one droplet detachment per peak, two droplets detachment per peak and three droplets detachment per peak by varying pulse cycle time. The suitable type of droplet detachment has been selected on the basis of uniformity in arc length, uniformity in droplet detachment and uniformity in weld bead surface undulation. The effect of types of droplet detachment on weld bead geometry has been studied. The peak energy, arc noise level, reinforcement height and heat input were found to be low for background detachments. Also with background detachments, uniformity in arc length and weld penetration were found to be high.

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Introduction

In pulsed current gas metal arc welding (GMAW-P), spray transfer or more precisely controlled droplet transfer is obtained at low average current. This condition provides a smaller and controlled weld pool, which allows welding of thin materials in all positions (Ref. 2). Detachment of molten metal droplets from the filler metal, which transfer across the arc and flow into the weld pool, are defined as metal transfer characteristics. Droplet detachment characteristics are defined as a) the size of molten droplets; b) instance and duration at which detachment takes place; and c) number of droplet detachments per pulse.

KEY WORDS

Pulsed Current GMAW
Droplet Detachment
Metal Transfer
Plate Fusion
Pulse Parameters
Arc Stability
Parametric Zones
Weld Characteristics
Arc Length
Weld Quality

Depending on the parameters of the GMAW-P process, either a single droplet or multiple droplets may become detached. If it is a single droplet, this detachment may occur either in peak duration or background duration; if it is multiple droplets detachment, the same may occur in peak duration. This difference in the timing of droplet detachment affects the uniformity in arc length, uniformity in droplet detachment, uniformity in weld bead surface undulation, quality of the weld (Ref. 5) and weld bead geometry. These characteristics have been investigated in this study. Molten droplet diameter was assumed to be equal to the diameter of filter metal, which is reported to provide a good spray transfer and good quality welds (Refs. 6–8). Based on this assumption, a first estimate of the pulse parametric zone was obtained for four different wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min). Welding speeds were 10, 13.33, 16.67 and 20 mm/s (0.39, 0.52, 0.66 and 0.79 in./s), respectively. That is, the ratio between wire feed rate and welding speed was 10. The combination of criteria, *viz.* burnoff, droplet detachment and arc stability, have been taken into account as suggested by Amin (Ref. 1) to construct these parametric zones. These zones were obtained for a fixed pulse cycle time and one droplet detachment per pulse conditions.

Experiments were also conducted at fixed value of W_F, I_B and T_B to establish the relationship between I_P and T_P for different types of droplet detachments, namely background detachment, one droplet detachment per peak, two droplets detachment per peak and three droplets detachment per peak. To obtain the above type of droplet detachments, pulse cycle time is allowed to vary. For this, it was not assumed that the molten droplet diameter is equal to the diameter of filler metal. In addition to obtaining the above relationship between I_P and T_P, further studies have been carried out to select a suitable type of droplet detachment to obtain good quality welds.

Objectives

The objectives of this investigation were to predict the stable pulse parametric zone and to determine the suitable combination of pulse parameters to obtain a good quality weld.

Experimental Work

Materials

The filler metal used was ER 5356 Al-Mg wire with a diameter of 1.2 mm (0.047 in.). The base metal was AA 5083 Al-Mg alloy of 6.0 mm (0.236 in.) thickness. Argon gas having a commercial purity of 99.97% and a flow rate of 20 L/min (42.4 ft^3/h) was used throughout the welding as shielding gas.

Welding Equipment

Figure 1 shows the schematic layout of the experimental setup of GMAW-P. A transistorized welding power supply — Transarc Fronius 500 — was used for carrying out welding operations both in steady current and pulsed current, operating with constant voltage output characteristics. In the pulsed current mode, peak voltage, background voltage, peak duration, cycle time and wire feed rate can be varied over a range of 10 to 40 V, 10 to 30 V, 1 to 15 ms, 3.3 to 50 ms and 0 to 18 m/min (0 to 708.7 in./min), respectively.

Directly setting the levels at peak and background current is not possible with the above welding power supply. Hence, levels of peak and background voltage were adjusted by trial and error to obtain the desired peak and background current levels, and measured using a high-speed double channel digital storage oscilloscope. Wire feed rate, peak duration and cycle time could be independently adjusted using the power supply control.

In steady current mode, voltage can be varied over a range of 10 to 40 V and wire feed rate can be varied over a range of 0 to 18 m/min (0 to 708.7 in./min). Voltage was adjusted by trial and error to obtain the desired welding current for a specified wire feed rate.

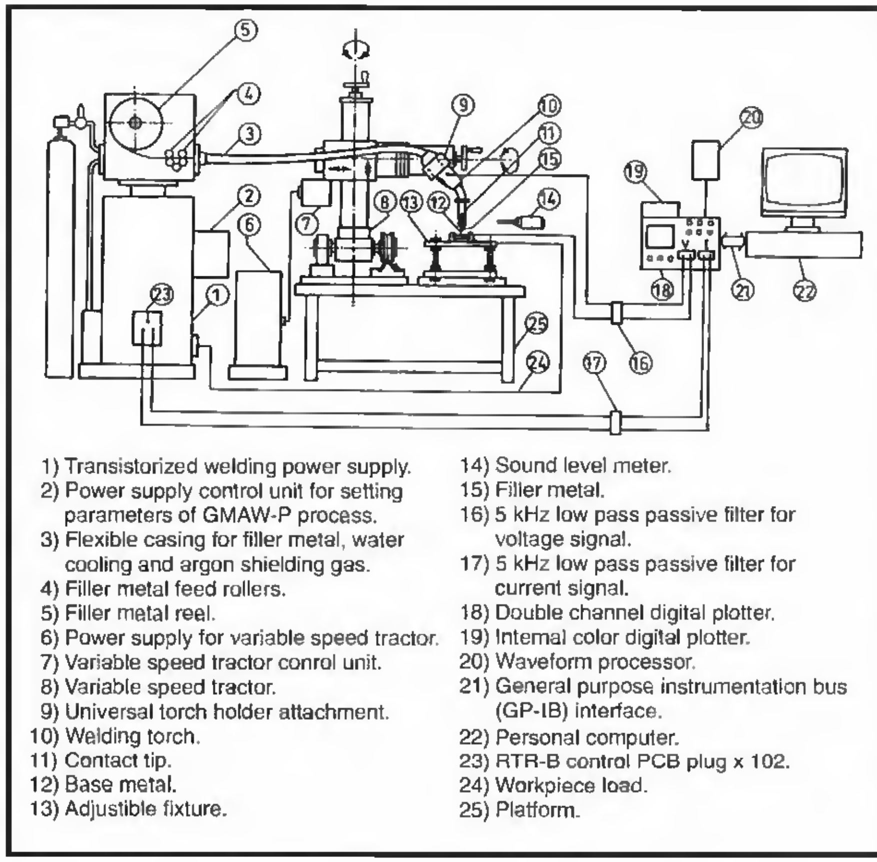


Fig. 1 — Schematic of experimental setup of pulsed current gas metal arc welding.

Filters for Voltage and Current Signals

The problem of high frequency noise and process noise in the signals of voltage and current was discussed with the manufacturer of the welding power supply (Ref. 9) and eliminated from the signals using two 5-kHz low-pass passive filters as shown in Fig. 1. These filters permit frequencies below 5 kHz to pass and reject all other frequencies that are above 5 kHz. Since expected molten droplet frequency is well within 5 kHz, droplet detachment phenomena could be clearly studied from the blips on the waveform of pulsed voltage.

Instrumentation

Welding currents were sensed from the RTR-B control PCB — plug x — 102 of welding power supply (Ref. 9) as shown in Fig. 1. Voltage levels were sensed between the base metal and the contact tip (Refs. 10 and 11) and were

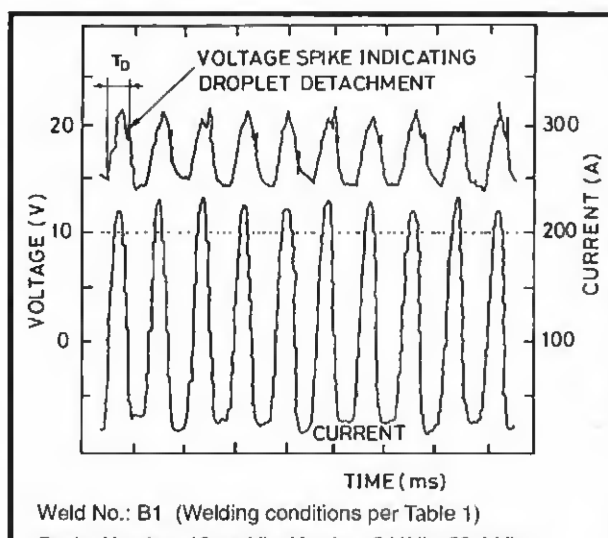


Fig. 2 — Arc voltage and current trace.

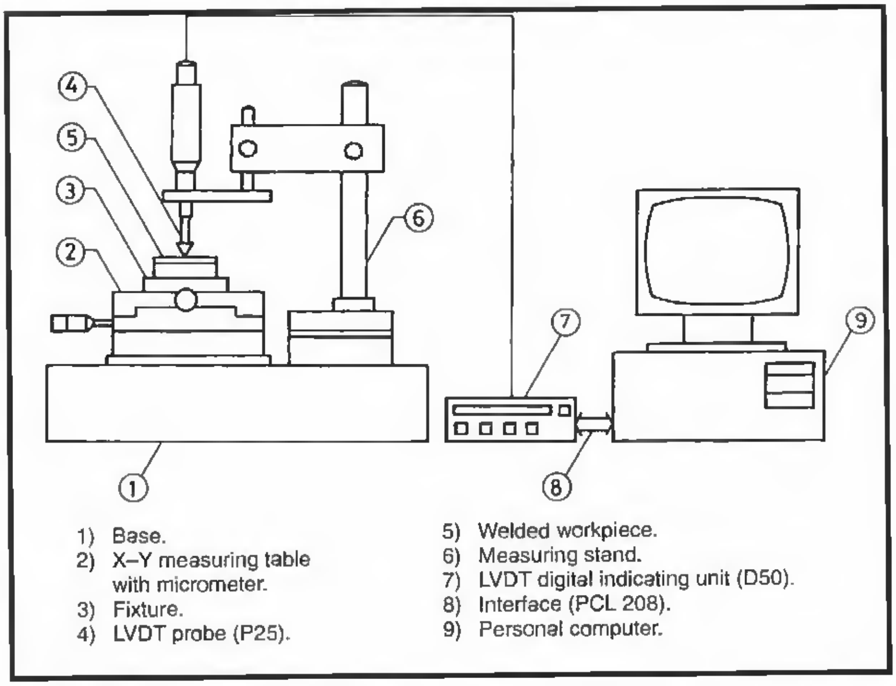


Fig. 3 — Schematic layout of the linear variable differential transformer (LVDT) experimental setup to measure weld bead surface undulations.

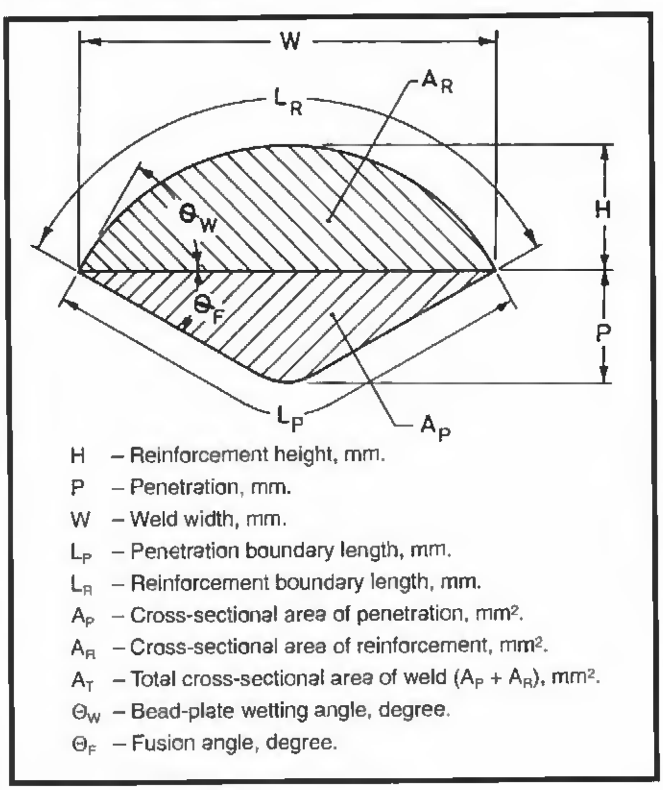


Fig. 4 — Bead-on-plate weld bead geometry.

used to measure arc voltage. Sufficient time was allowed during welding to reach a stable welding condition. For this, delay time was set in the oscilloscope. Then instantaneous current and voltage were monitored and recorded simultaneously with a high-speed double channel digital storage oscilloscope (Gould 4072) through 5 kHz low-pass passive filters — Fig. 1.

Levels of peak current were measured on the pulsed current wave form for every pulse cycle time and average peak current level was taken as a measure of peak current. Levels of background current were measured on the captured pulsed current waveform for every pulse cycle time and the average background current level was taken as a measure of background current. Droplet detachment was observed from the blips on the waveform of pulsed voltage. There are variations in the peak voltage values along peak duration except those due to the intentional pulsing. The reason for variations is that when the droplet is transferred, the instantaneous arc voltage will momentarily increase and form blips on the peak voltage levels along the peak duration (Refs. 1 and 12). Droplet detachment time and the number of droplet detachments were obtained from pulsed voltage traces.

The total area of the captured waveform of the pulsed current was measured by using a waveform processor of the oscilloscope. Average current was calculated by dividing the total area of the current waveform by total time duration that corresponded to the measured area of the waveform. Similarly, average voltage was calculated by dividing the total area of the pulsed voltage waveform by the corresponding total time. These calculated values of average current (I_{AV}) and average voltage (V_{AV}) with the known welding speed (W_S) were used to calculate the heat input using the following expression. Efficiency was not measured or assumed.

$$\text{Heat input} = (I_{AV}\,V_{AV}) / W_S \quad \text{J/mm} \qquad (1)$$

Welding Procedure

Filler metal was connected to the direct-current-electrode-positive (DCEP) polarity. A welding torch was mounted on a four-wheeled variable-speed tractor (Esab A2 Mini trac). It was moved above the base metal and the bead-on-plate welds (flat-welding-position type) were deposited in the rolling direction of base metal. The torch-to-work angle was maintained at 90 deg and contact tip-to-work distance at 15 mm (0.591 in.). Proper guiding was ensured and proper alignment was made for moving the variable-speed tractor with the welding torch over the base metal. This setup ensures constant arc length between the contact tip and base metal throughout the welding operation; this ensures that the current levels were the same throughout the length of a weld.

Quality Parameters and their Measurements

The suitable parameters of the pulsed current and the type of droplet detachment to obtain good quality welds were selected on the basis of quality parameters, *viz.* uniformity in arc length, uniformity in droplet detachment and weld bead surface quality. Method of measurements of these quality parameters are detailed below.

Uniformity in Arc Length

Uniformity in arc length was judged by the uniformity of voltage values as sug-

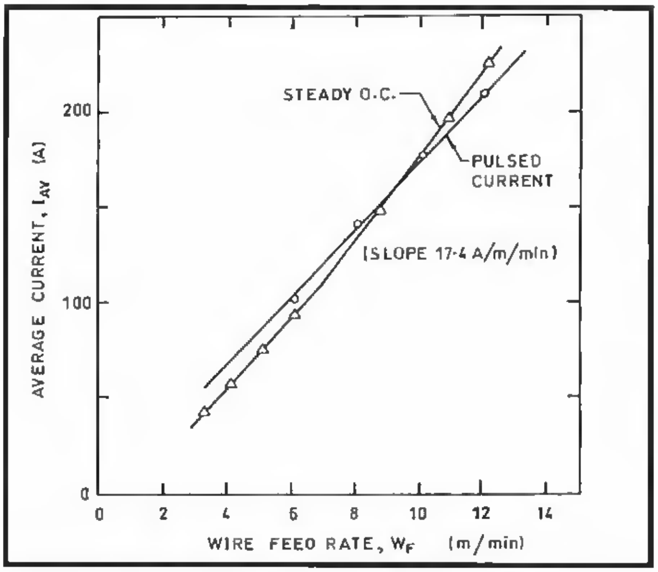


Fig. 5 — Burnoff characteristics for steady direct current and pulsed current using 1.2 mm diameter of ER 5356 filler metal.

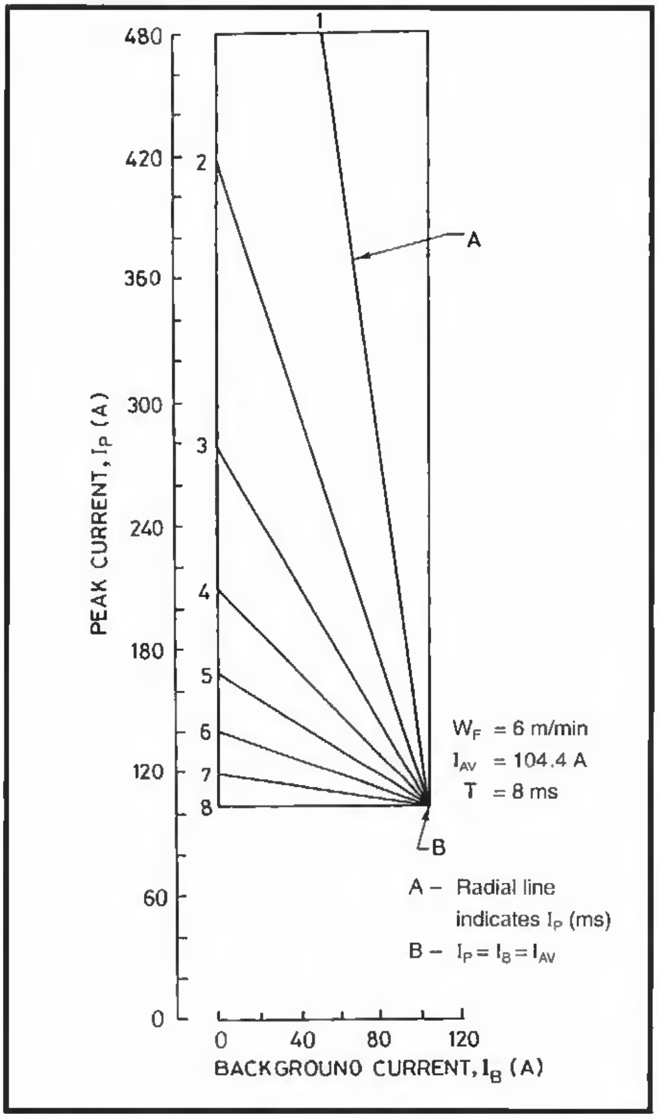


Fig. 6 — Parametric zone predicted from burnoff criterion.

gested in Ref. 13. Values of peak voltage were measured from the recorded waveform of pulsed voltage on the oscilloscope using an on-screen measurement cursor, and standard deviation and coefficient of variation of the same were calculated. The waveform with lesser standard deviation and coefficient of variation was considered to be of uniform arc length. Then, the corresponding parameters of the pulsed current were selected to obtain good quality welds.

Uniformity in Droplet Detachment

Droplet detachment time (T_D), *i.e.*, time duration between the moment at which the pulsed voltage starts to increase and the voltage blip (moment at which droplet detachment takes place from filler metal) in a pulsed cycle time (Fig. 2), was measured on the recorded waveform of pulsed voltage using an on-screen measurement cursor of the oscilloscope. The duration between the start of pulse to the time of first droplet detachment was taken as droplet detachment time for multiple droplet detachment conditions, and standard deviation and coefficient of variation of the same were calculated. The waveform with lesser standard deviation and coefficient of variation was considered to be of uniform droplet detachment. Then, the corresponding parameters of the pulsed current were selected to obtain good quality welds.

Uniformity in Weld Bead Surface Undulation

A quantitative evaluation of the quality of weld was carried out by measuring the surface characteristics of the weld bead using a computerized measuring system based on a Linear Variable Differential Transformer (Sylvac) — Fig. 3. The workpiece was mounted on an X-Y measuring table using a specially designed and fabricated fixture. The workpiece was aligned properly and moved under an LVDT probe, in the direction of welding. An LVDT probe with a standard contact point of a 2 mm (0.079 in.) diameter carbide ball was used. A sample length of weld used was 25 mm (0.984 in.). Fluctuations on the top of the weld bead surface were displayed numerically on the digital indicating unit of a LVDT (1 micron [3.94×10^{-5} in.] accuracy). All the displayed digital output values were transferred to a personal computer through a data acquisition card and analyzed statistically to calculate the standard deviation and coefficient of variation. The weld surface undulation profile with lesser standard deviation and coefficient of variation was considered to be good from the standpoint of smooth weld bead. Then, the corresponding parameters of the GMAW-P process were selected to obtain good quality welds.

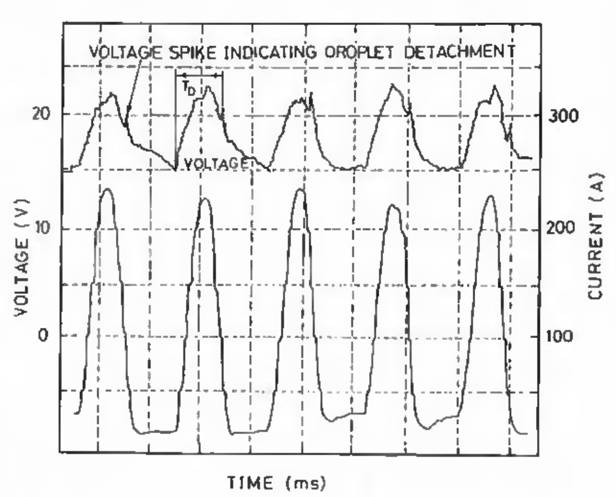
Arc Noise Level

The peak of the arc noise was measured with respect to peak, background and multiple droplet detachments by using the A scale of a sound level meter (Bruel and Kjaer-Type 2230). The sound level meter (Fig. 1) was placed horizontally at a distance of 500 mm (19.69 in.) from the arc and at right angle to the direction of welding (Ref. 14).

Weld Bead Geometry

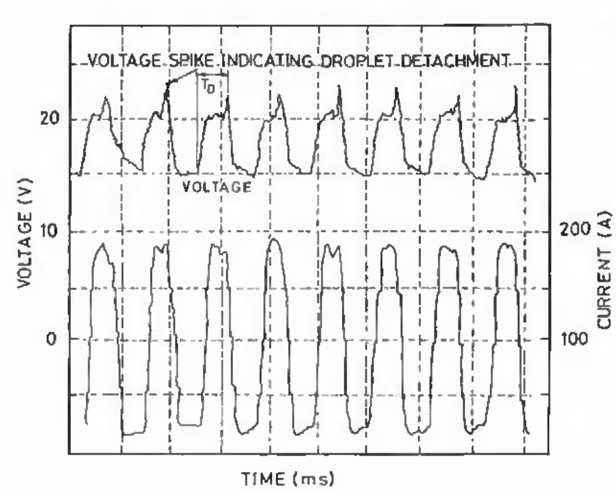
Tracing of Weld Bead Profiles

Test pieces were cut from the welded specimens, discarding the beginning and end portions. Test pieces were polished by using an abrasive belt polishing machine and etched with 10% Na OH at 70°C (158°F). The polished and etched



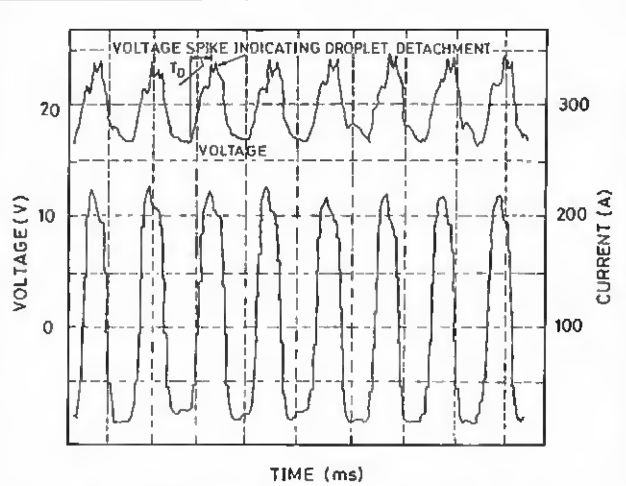
I_P = 240.5 A; T_P = 3 ms; I_B = 20 A; T_B = 6 ms (Weld No.: B17);
Scale: X-axis = 5 ms/div; Y-axis = 5 V/div and 50 A/div.

Fig. 7 — Typical arc voltage and current traces, indicating background detachment.



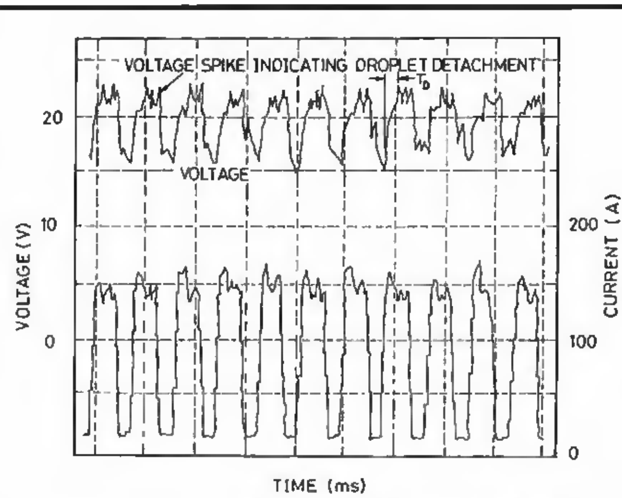
I_P = 196.8 A; T_P = 5 ms; I_B = 20 A; T_B = 6 ms (Weld No.: B20);
Scale: X-axis = 10 ms/div; Y-axis = 5 V/div and 50 A/div.

Fig. 8 — Typical arc voltage and current traces indicating one droplet detachment per peak.



I_P = 230.3 A; T_P = 5 ms; I_B = 20 A; T_B = 6 ms (Weld No.: B22);
Scale: X-axis = 10 ms/div; Y-axis = 5 V/div and 50 A/div

Fig. 9 — Typical arc voltage and current traces indicating two droplets detachment per peak.



I_P = 172.7 A; T_P = 10 ms; I_B = 20 A; T_B = 6 ms (Weld No.: B27);
Scale: X-axis = 20 ms/div; Y-axis = 5 V/div and 50 A/div.

Fig. 10 — Typical arc voltage and current traces indicating three droplets detachment per peak.

test pieces were examined with the help of a profile projector. Profiles of the weld bead cross sections were traced from the screen of profile projector at 10X magnification.

Measurement of Weld Bead Sizes

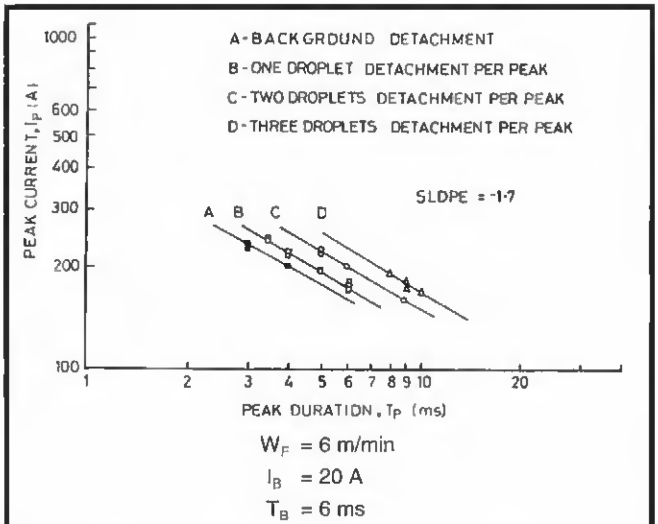
Weld penetration, reinforcement height, weld width, reinforcement boundary length, penetration boundary length, cross-sectional area of penetration and total cross-sectional area on both sides of the weld bead were measured (Fig. 4) with the help of an area curvimeter (Ushikata — Model UP 8405 D) and average values were obtained. From these measurements, weld penetration shape factor (W/P), weld reinforcement form factor (W/H) and percentage dilution were calculated.

Measurement of Weld Bead Angles

Fusion angle and bead plate wetting angle on both sides of the weld bead were measured by using a two-coordinate measuring machine (Nikon) and average values were calculated. Figure 4 shows the typical geometry of bead-on-plate weld bead.

Prediction of Parameters of the Pulsed Current

Parameters of the pulsed current are peak current (I_P), peak duration (T_P), background current (I_B) and background duration (T_B). These parameters have a distinct effect on the characteristics of arc and droplet detachment. Since these characteristics directly affect the stability of arc, uniformity in droplet detachment, weld quality, bead appearance and weld bead geometry,



TYPE OF DROPLET DETACHMENT	RELATIONSHIP
A BACKGROUND DETACHMENT	$I_P^{1.7}\ T_P = 34\ A^{1.7}\,s$
B ONE DROPLET DETACHMENT PER PEAK	$I_P^{1.7}\ T_P = 40\ A^{1.7}\,s$
C TWO DROPLETS DETACHMENT PER PEAK	$I_P^{1.7}\ T_P = 50\ A^{1.7}\,s$
D THREE DROPLETS DETACHMENT PER PEAK	$I_P^{1.7}\ T_P = 62\ A^{1.7}\,s$

Fig. 11 — Relationship between I_P and T_P for different types of droplet detachments.

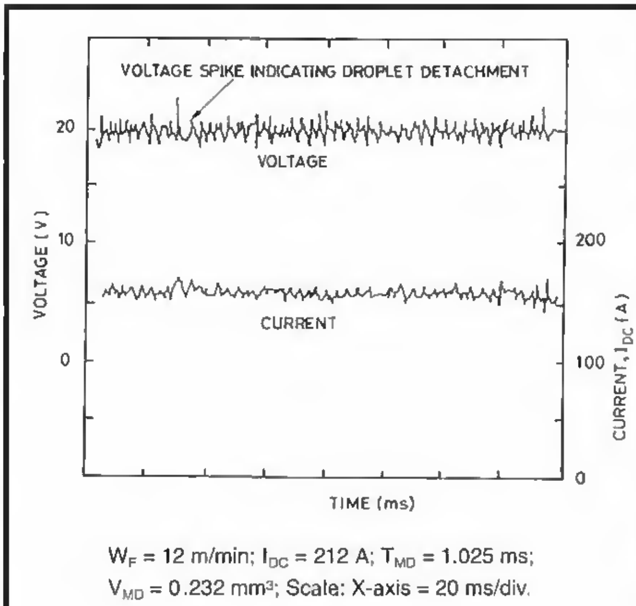


Fig. 12 — Arc voltage and current traces of steady direct current.

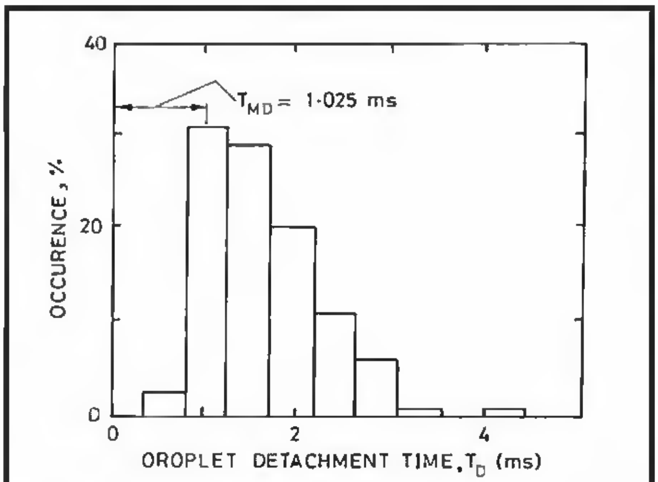


Fig. 13 — Frequency distribution of droplet detachment time intervals (welding conditions per Fig. 12).

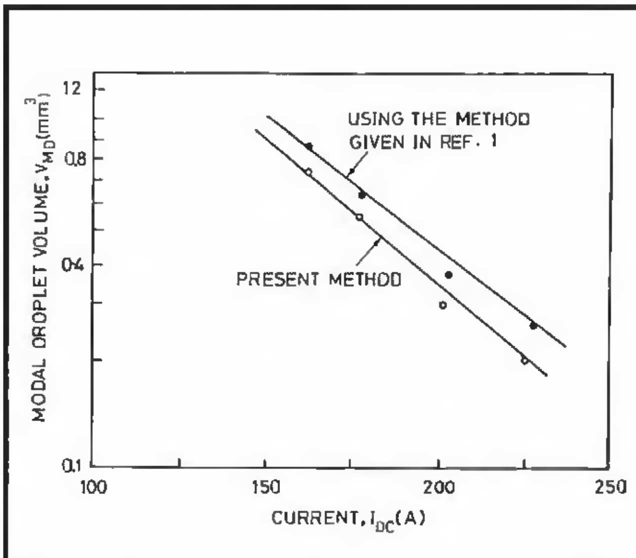


Fig. 14 — Relationship between modal droplet volume and current.

it is important to select a proper combination of parameters of the pulsed current for welding, which will ensure that the process gives proper results in all the above aspects. Arriving at such a combination of parameters without a rational base would be only a matter of chance with a fairly low probability. A detailed study is therefore essential to arrive at a method of predicting conditions that will give a good weld.

A first estimate of the pulse parametric zone was obtained for four different wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), based on burnoff, droplet detachment and arc stability criteria as suggested by Amin (Ref. 1). The reason for choosing these wire feed rates is that wire feed rates of 6 and 8 m/min (236.2, 315.0 in./min) lead to operation at average current below the spray current level of the filler metal under use, and wire feed rates of 10 and 12 m/min (393.7 and 472.4 in./min) lead to operation at the average current above the spray current level. These wire feed rates therefore cover a good range that is practical. Welding speeds were 10, 13.33, 16.67 and 20 mm/s (0.39, 0.52, 0.66 and 0.79 in./s) respectively, *i.e.*, the ratio between wire feed rate and welding speed was 10. To find the feasible set of values of the pulsed current parameters for each selected wire feed rate, the following procedure is used.

Burnoff Criterion

While current varies with time in GMAW-P, it is essential the average current that determines the burnoff rate match the wire feed rate so a constant arc length is maintained. If there is any difference between wire feed rate and burnoff rate, the arc becomes unstable,

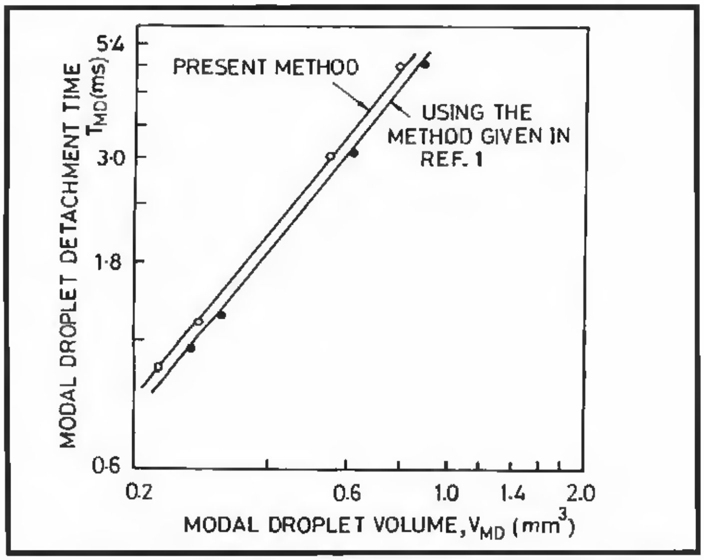


Fig. 15 — Relationship between modal droplet detachment time and modal droplet volume.

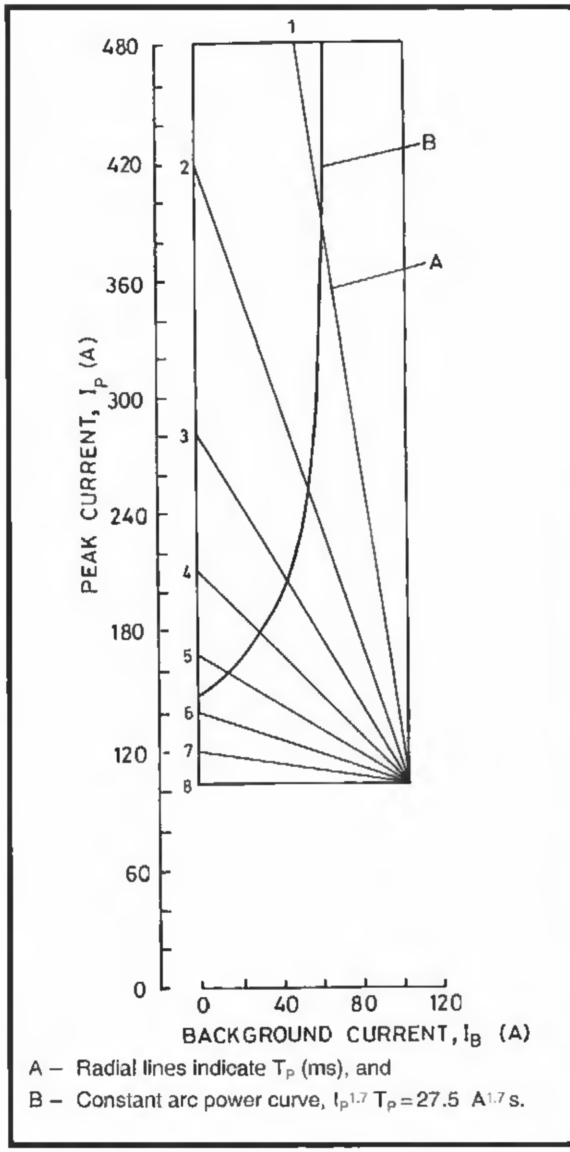


Fig. 16 — The constant arc power curve superimposed on the parametric zone predicted from burnoff criterion (welding conditions per Fig. 6).

causing burnbacks or stubbing in, which can result in defective welds as well as operator frustration (Ref. 1). This is known as the burnoff criterion.

There is a functional relationship that represents all the feasible pulse conditions for this criteria. The relationship represented by the parameters of pulsed current (I_P, T_P, I_B and T_B) is unique for any specified average current. A relationship between average current and wire feed rate for GMAW-P conditions using the experimental setup was experimentally determined using the following procedure.

Experiments were carried out for various combinations of parameters of the pulsed current, which were selected by trial and error method, for different wire feed rates of 6 (W_{F1}), 8 (W_{F2}), 10 (W_{F3}) and 12 m/min (W_{F4}) (236.2, 315.0, 393.7 and 472.4 in./min). Welding speeds were 10, 13.33, 16.67 and 20 mm/s (0.39, 0.52, 0.66 and 0.79 in./s), respectively, *i.e.*, the ratio between wire feed rate and welding speed was 10. Values of I_{AV} obtained at constant arc length were plotted against each wire feed rate, as shown in Fig. 5. The related I_{AV} for each experiment was obtained from the following expression (Ref. 15):

$$I_{AV} = (I_P\, T_P + I_B\, T_B / (T_P + T_B)\ \ A \qquad (2)$$

I_{AV} for other wire feed rates can be obtained from Fig. 5. Similar relationships between wire feed rate and average current for both steady direct current and pulsed current have been reported by Trindade (Ref. 16) for 1.2 mm (0.047 in.) diameter of 99.5% pure aluminum filler metal.

Experiments were also carried out to determine the burnoff characteristics for steady current GMA welding for the wire feed rates from 3 to 12 m/min (118.1 to 472.4 in./min) at an interval of 1 m/min (39.37 in./min); the relationship was plotted in the burnoff characteristics for steady direct current and pulsed currents using 1.2 mm diameter of ER 5356 filler metal — Fig. 5. Welding speed was varied from 5 to 20 mm/s (0.20 to 0.79 in./s) at an interval of 1.67 mm/s (0.066 in./s), *i.e.*, the ratio between wire feed rate and welding speed was 10. Results show that the burnoff characteristic line of steady current GMAW intersects with the burnoff characteristic line of GMAW-P at the wire feed rate of 8.6 m/min (338.6 in./min). The corresponding current of the same is 150 A and it coincides with the spray current level of the filler metal. Results also show that in GMAW-P, the burnoff rate per ampere is more than the steady current GMAW for the average currents above spray current level. The reason is that proportionately more heat is transferred to the filler metal in GMAW-P than in steady current GMAW. Similar relationships between wire feed rate and average current for both steady direct current and pulsed current have been reported by Trindade (Ref. 16) for 1.2 mm (0.047 in.) diameter of 99.5% pure aluminum filler metal.

Amin (Ref. 1) has not assumed droplet diameter to be equal to the diameter of filler metal. The droplet volumes therefore vary for a given size of filler metal. In the present study, molten droplet diameter was assumed to be equal to the diameter of filler metal, which is reported to provide a good spray transfer and good quality welds (Refs. 6–8). On the basis of the above assumption, the corresponding droplet volume (V_D) was calculated from the following expression:

$$V_D = (4/3)\pi r^3\ mm^3 \qquad (3)$$

where r is the radius of filler metal. For the filler metal radius of 0.6 mm (0.024 in.), the corresponding droplet volume is 0.905 mm^3 (5.52 x 10^{-5} $in.^3$). Setting droplet volume too high may cause a short circuit and then spatter (Ref. 7).

For the droplet volume of 0.905 mm^3

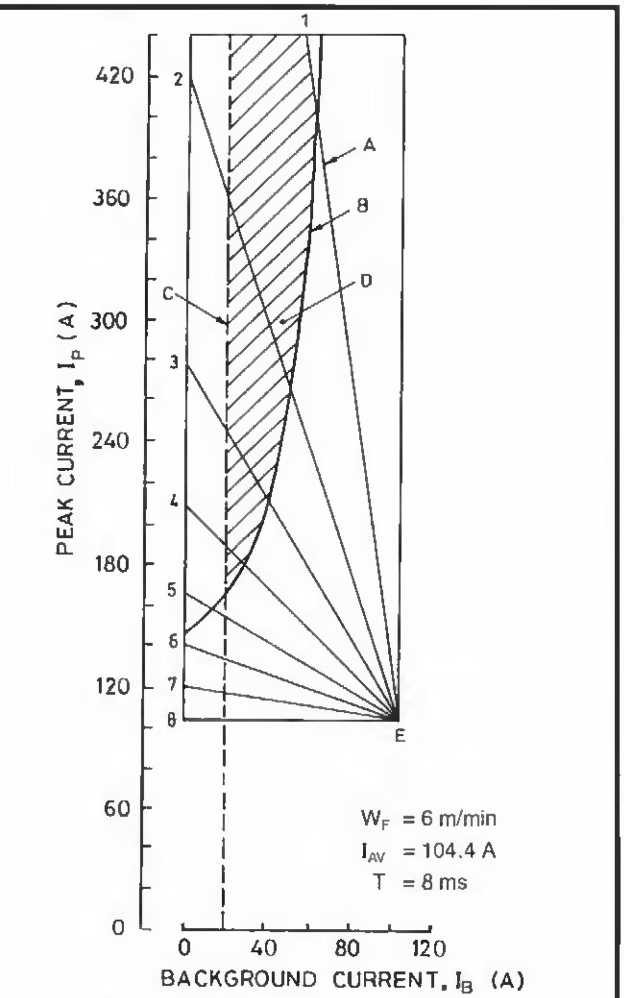


Fig. 17 — Background current limit, together with constant arc power curve, superimposed on the parametric zone predicted from burnoff criterion (welding conditions per Fig. 6).

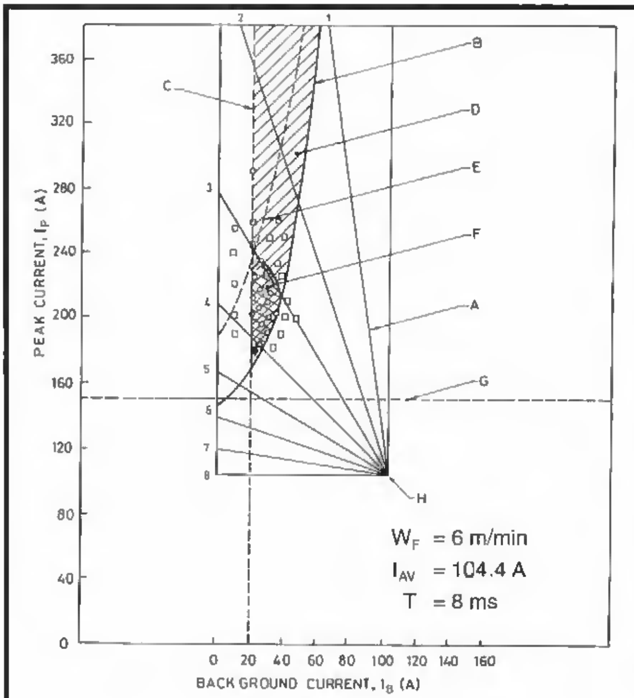


Fig. 18 — Stable pulse parametric zone (welding conditions per Fig. 6).

(5.52×10^{-5} in.³), pulse cycle time (T) was calculated for one droplet detachment (peak/background) per pulse conditions at different wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min) as 8.0, 6.0, 4.8 and 4.0 ms, respectively, using the following expression:

$$T = 240\ V_D / \pi d^2\ W_F \text{ ms} \qquad (4)$$

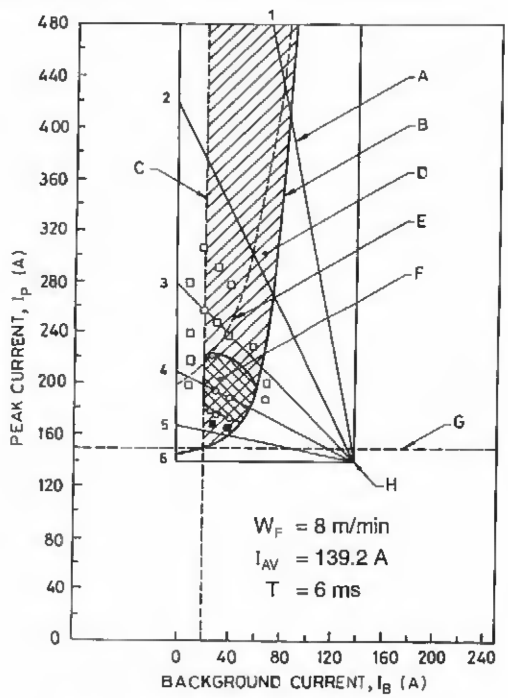
The parametric zone as shown in Fig. 6 was obtained on the basis of burnoff criterion for the wire feed rate of 6 m/min (236.2 in./min) and pulse cycle time of 8.0 ms. The zone represents a potentially feasible combination of I_P, T_P and I_B at a specific wire feed rate. Details of the construction can be found in the work of Amin (Ref. 1).

Droplet Detachment Criterion

It is desirable that spray type of metal transfer must be produced at all wire feed rates. In addition, for a given wire feed rate, both I_P and T_P must be adjusted so that at least one droplet is detached with each pulse. If the combination of I_P and T_P provides insufficient energy, a droplet does not detach for each pulse and the welding process becomes irregular (Ref. 1). This is called droplet detachment criterion. I_P, T_P, I_B and T_B combinations within the parametric zone, as shown in Fig. 6, would satisfy the burnoff criterion only. Insufficient I_P and T_P combinations would not produce spray type of metal transfer. Therefore, the parametric zone predicted from burnoff criterion was further limited to satisfy the requirement of droplet detachment during I_p. This limit is defined by the expression linking "Limiting Peak Current and Peak Duration" as discussed below.

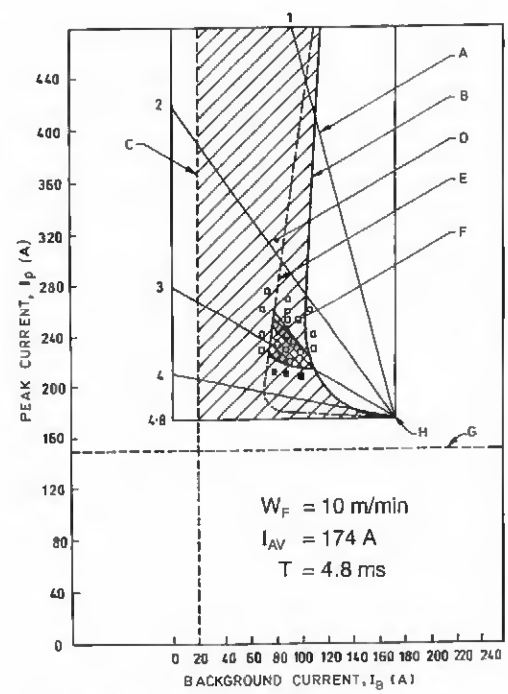
Limiting Peak Current (I_P) and Peak Duration (T_P)

Experiments were conducted at fixed value of W_F = 6 m/min (236.2 in./min), I_B = 20 A and T_B = 6 ms to establish the relationship between I_p and T_P for different types of droplet detachments, namely background detachment, and one droplet detachment, two droplets detachment and three droplets detachment per peak, respectively (Ref. 16). Welding speed was 10 mm/s (0.39 in./s). For this, levels of I_P were kept above the spray current level (Refs. 6 and 17–19), and I_P and T_P were allowed to vary — Figs. 7–10. To



A – Radial line indicates, T_P (ms);
B – Constant arc power curve ($I_P^{1.7}\,T_P = 27.5$ $A^{1.7}$ s ($V_{MD} = 0.905$ mm³);
C – Background current limit;
D – Predicted stable zone;
E – Constant arc power curve, $I_P^{1.7}\,T_P = 18.2$ $A^{1.7}$ s ($V_{MD} = 0.5$ mm³);
F – Stable pulse parametric zone;
G – Spray current level: 150 A and
H – $I_P = I_B = I_{AV}$.
□ – Short circuit;
■ – Burnback;
○ – Welds in stable pulse parametric zone.

Fig. 19 — Stable pulse parametric zone.



A – Radial line indicates, T_P (ms);
B – Constant arc power curve, $I_P^{1.7}\,T_P = 27.5$ $A^{1.7}$ s ($V_{MD} = 0.905$ mm³);
C – Background current limit;
D – Predicted stable zone;
E – Constant arc power curve, $I_P^{1.7}\,T_P = 18.2$ $A^{1.7}$ s ($V_{MD} = 0.5$ mm³);
F – Stable pulse parametric zone;
G – Spray current level: 150 A; and
H – $I_P = I_B = I_{AV}$.
□ – Short circuit;
■ – Burnback;
○ – Welds in stable pulse parametric zone.

Fig. 20 — Stable pulse parametric zone.

obtain the above types of droplet detachments, pulse cycle time was allowed to vary. For this, it was not assumed in this study that molten droplet diameter would he equal to the diameter of filler metal.

The values of I_P and T_P were grouped according to the type of droplet detachment and plotted on the logarithmic scale — Fig. 11. Slope between I_P and T_P was found to be –1.7 for all types of droplet detachments, *i.e.*, $T_P \propto I_P^{-1.7}$. Amin (Ref. 1) found the slope as –2.3 for 1.6 mm (0.063 in.) diameter of pure aluminum filler metal, and Trindade and Allurn (Ref. 16) found the slope as –2.0 for the filler metal diameter of 1.2 mm (0.047 in.) pure aluminum. However, Araya, Endo, Imamiya, Ando and Sejima (Ref. 14) found the slope as –1.54 for the filler metal diameter of 1.6 mm (0.063 in.) ER 4043 Al-Si alloys. This shows that the slope varies depending on chemical composition and diameter of filler metal. The relationship between I_P and T_P can be expressed as follows:

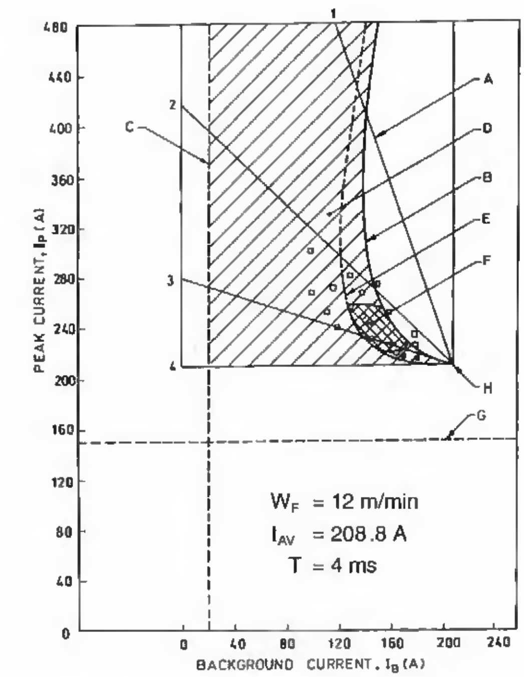
$$I_P^{1.7}\,T_P = K_v\,A^{1.7}\,s \qquad (5)$$

where K_v is a constant called detachment parameter. The values of a constant vary depending on the droplet volume to be detached from a given filler metal and diameter. Determination of K_v is essential for evaluating the limiting I_P and T_P.

Detachment Parameter

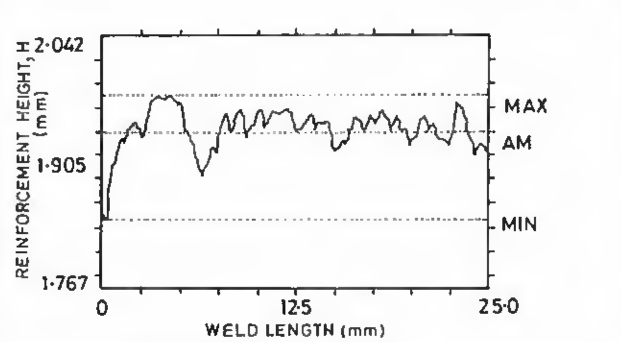
A few experiments were conducted with steady direct current for different wire feed rates of 9, 10, 11 and 12 m/min (354.3, 393.7, 433.1 and 472.4 in./min), in which spray type of metal transfer is expected to occur, for estimating the value of K_v for any requisite droplet volume. Welding speeds were 15, 16.67, 18.33 and 20 mm/s (0.59, 0.66, 0.72 and 0.79 in./s), respectively, *i.e.*, the ratio between wire feed rate and welding speed was 10. For each experiment, wire feed rate was set and voltage was adjusted to maintain a required arc length. Corresponding wave forms of arc voltage and current were obtained from a double channel digital storage oscilloscope.

Data such as estimated droplet detachment time, droplet volume and current level (I_{DC}) were obtained from the waveforms of arc voltage and current. Typical waveforms are shown in Fig. 12, where the droplet detachments are indicated by the voltage blips. Although the



A – Radial line indicates, T_P (ms);
B – Constant arc power curve, $I_P^{1.7}\,T_P = 27.5\ A^{1.7}$ s (V_{MD} = 0.905 mm³);
C – Background current limit;
D – Predicted stable zone;
E – Constant arc power curve, $I_P^{1.7}\,T_P = 18.2\ A^{1.7}$ s (V_{MD} = 0.5 mm³);
F – Stable pulse parametric zone;
G – Spray current level: 150 A; and
H – $I_P = I_B = I_{AV}$.
□ – Short circuit;
■ – Burnback;
○ – Welds in stable pulse parametric zone.

Fig. 21 — Stable pulse parametric zone.



ARITHMETIC MEAN : 1·9330
STANDARD DEVIATION : 0·0257 MAXIMUM VALUE: 1·973
COEFFICIENT OF VARIATION: 0·0133 MINIMUM VALUE: 1·836

I_P = 245.9 A; T_P = 2.6 ms; I_B = 141.5 A; T_B = 1.4 ms; W_F = 12 m/min; W_S = 20 mm/s.

Fig. 22 — Typical weld bead surface undulation recorded by LVDT (Weld No. B15).

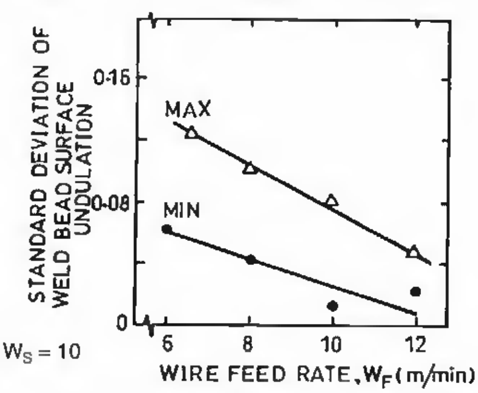


Fig. 23 — Effect of wire feed rate on weld bead surface undulation.

time interval between successive droplets varies from detachment to detachment, the average time interval is approximately constant, which may be taken as the estimated droplet detachment time. However, a better estimate is given by the modal droplet detachment time, T_{MD}, as shown by the frequency distribution.

Experimentally determined modal detachment time values (T_{MD}) are required while calculating modal droplet volumes (V_{MD}). For this, two experiments were conducted for the same wire feed rate and average values of I_{DC} and T_{MD} were obtained. Amin (Ref. 1) had used the end point (largest) of the class interval of maximum frequency as the modal value. In the present study, the midpoint of class interval has been used — Fig. 13. This is recommended by most of the statisticians, *e.g.*, Bowker (Ref. 20). The following expression was used to calculate V_{MD}.

$$V_{MD} = (\pi d^2\, W_F\, T_{MD})/240 \text{ mm}^3 \qquad (6)$$

Using the above calculated values, the relationship between I_{DC} and V_{MD} is obtained as shown in Fig. 14; the relationship between V_{MD} and T_{MD} is obtained as shown in Fig 15. Similar relationships, obtained using a method given in Ref. 1, were superimposed on Figs. 14 and 15. Values of I_{DC} and T_{MD} for any required droplet volume to be detached can be determined from Figs. 14 and 15. These values are expected to satisfy the pulse controlled metal transfer — that is, for evaluating detachment parameter, Kv, the predicted pulse combination is I_{DC} and T_{MD}, which can be expressed as follows:

$$I_{DC}^{1.7}\, T_{MD} = K_v\, A^{1.7} \text{ s} \qquad (7)$$

The values of I_{DC} and T_{MD} were obtained from the relationship, shown in Figs. 14 and 15 as 150 A and 5.5 ms respectively, for detaching the droplet volume of 0.905 mm³ (5.52 x 10^{-5} in.³). These values were substituted in Equation 7 and K_v was obtained as 27.5 ($A^{1.7}$ s).

Constant Arc Power Curve

The value of K_v was substituted in

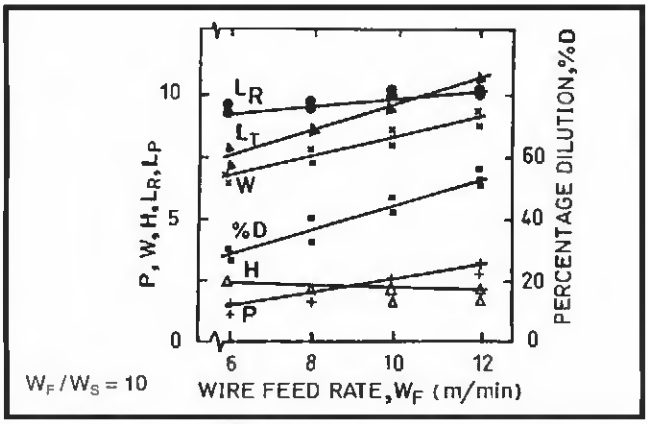


Fig. 24 — Effect of wire feed rate on penetration, reinforcement height, weld width, percentage dilution, penetration boundary length and reinforcement boundary length.

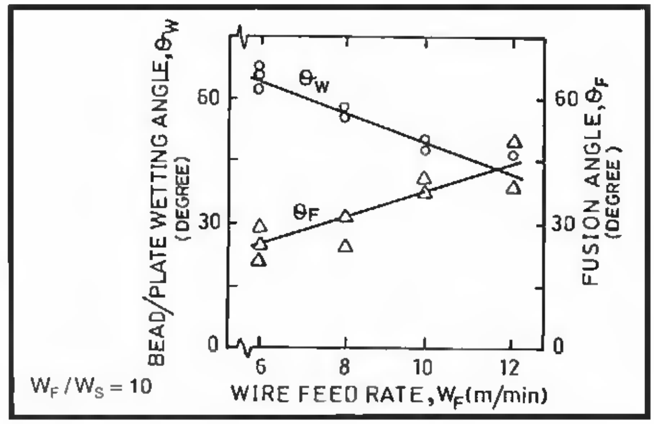


Fig. 25 — Effect of wire feed rate on bead-plate wetting angle and fusion angle.

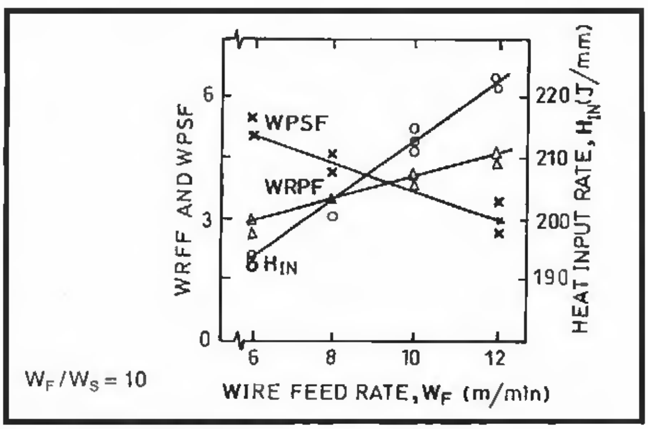


Fig. 26 — Effect of wire feed rate on heat input, WRFF and WPSF.

Equation 5 and constant arc power curve was obtained as

$$I_P^{1.7}\, T_P = 27.5\ A^{1.7}\ s \qquad (8)$$

The constant arc power curve, superimposed on Fig. 6, is shown in Fig. 16. Only the combination of parameters of pulsed current above the constant arc power curve would satisfy the droplet detachment criterion.

Arc Stability Criterion

The minimum background current (I_B) for the stable arc is 20 A (Ref. 6). This limit can be expressed as

$$I_B \geq C \qquad (9)$$

The limiting I_B value of 20 A for stable arcing was superimposed on Fig. 16 and is shown in Fig. 17. The parametric zone for 6 m/min (236.2 in./min) is included between the constant arc power curve and I_B limit, which is a set of range of values of each of the pulsed current parameters. This set satisfies a combination of the criteria, *viz.* burnoff, droplet detachment and arc stability.

Results and Discussion

Determination of New Stable Pulse Parametric Zone

Stable pulse parametric zone is defined as the set of range of values of each of the parameters of pulsed current (I_P, T_P, I_B and T_B) that satisfies burnoff, droplet detachment and arc stability criteria. Even though the stable parametric zone (Fig. 17) was predicted on the basis of burnoff, droplet detachment and arc stability criteria, it does not define the most suitable combination of pulse parameters within the stable parametric zone, capable of providing the most stable arc and the most desirable weld bead characteristics such as penetration profile and weld bead surface, etc. Therefore, experiments were carried out for various combinations of pulse parameters within the predicted stable parametric zone and points are marked in the graphs — Fig. 18. All those points representing the pulse parameter combinations that did not short circuit or burnback are joined by a curve to give the new stable pulse parametric zone. Short circuits were observed above the zone and burnbacks were observed below the zone. It is obvious from Fig. 18 that the new stable pulse parametric zone is much smaller than what was predicted by Amin (Ref. 1). The parametric zone, predicted on the basis of burnoff, droplet detachment and arc stability criteria has been further restricted taking into account the short circuit and burnback characteristics. The set of ranges for values of each of the pulsed current parameters within the new stable parametric zone (Fig. 18) is expected to provide proper welds without short circuit or burnback, in addition to satisfying the criteria, namely burnoff, droplet detachment and arc stability.

As can be seen from Fig. 18, the boundary on the right side of the new zone is a constant arc power curve ($I_P^{1.7}\, T_P = 27.5\ A^{1.7}\ s$) that has been plotted for the droplet volume of 0.905 mm³ (5.52 x 10⁻⁵ in.³). Another constant arc power curve was superimposed, as shown in Fig. 18, to find the boundary on the left side of the new zone. It is given by $I_P^{1.7}\, T_P = 18.2\ A^{1.7}\ s$ and the corresponding droplet volume is 0.500 mm³ (3.05 x 10⁻⁵ in.³). It has been observed from Fig. 18 that the new stable zone of pulse parameter is bound by

1) Short circuit and burnback characteristics;

2) Two peak duration values;

3) Two constant arc power curves, explained as follows:

The arc power curve $I_P^{1.7}\, T_P = 27.5\ A^{1.7}\ s$ corresponds to the droplet volume of 0.905 mm³ (5.52 x 10⁻⁵ in.³); and the other constant arc power curve $I_P^{1.7}\, T_P\ 18.2 = A^{1.7}\ s$ corresponds to the droplet volume of 0.500 mm³ (3.05 x 10⁻⁵ in.³); and

4) A background current that de-

Table 1 — GMAW-P Parameters and Statistical Analysis of Peak Voltage, Droplet Detachment Time and Weld Bead Surface Undulation

Weld No.	I_P (A)	T_P (ms)	I_B (A)	T_B (ms)	W_F m/min	W_S mm/s	I_{AV} (A)[a]	V_{AV} (V)[a]	V_P	T_D	WBSU	P.E (J)
B1	238.6	3.0	29.6	5.0	6.0	10.0	108.2	18.2	22.4[b]	4.3[b]	0.059[c]	16.0
									0.2516[c]	0.3647[c]	0.023[d]	
									0.0112[d]	0.0850[d]		
B2	225.0	3.3	25.0	4.7	6.0	10.0	106.3	18.3	22.7	4.1	0.1340	16.9
									0.5401	0.8288	0.0558	
									0.0238	0.2025		
B3	209.0	3.5	27.8	4.5	6.0	10.0	104.9	18.3	22.2	3.8	0.1190	16.2
									0.4359	0.6022	0.0527	
									0.0196	0.1591		
B4	200.1	3.7	25.1	4.3	6.0	10.0	104.5	18.7	23.3	3.9	0.0780	17.3
									0.7869	0.6863	0.0318	
									0.0338	0.1745		
B5	187.3	4.0	23.5	4.0	6.0	10.0	103.5	18.9	22.3	4.2	0.1130	16.7
									0.6557	0.5172	0.0483	
									0.0294	0.1227		
B6	220.6	3.5	24.7	2.5	8.0	13.3	139.5	20.0	22.6	3.8	0.0673	17.5
									0.5146	0.4814	0.0309	
									0.0229	0.1279		
B7	201.1	4.0	21.8	2.0	8.0	13.3	129.5	21.0	23.0	4.3	0.0604	18.5
									1.2381	0.5536	0.0290	
									0.0539	0.1286		
B8	172.7	4.5	38.1	1.5	8.0	13.3	133.8	22.0	24.8	4.6	0.0427	19.3
									0.5063	0.4389	0.0234	
									0.0204	0.1014		
B9	242.1	2.7	89.6	2.1	10.0	16.7	173.0	19.5	21.8	3.4	0.0703	14.3
									0.5142	0.7211	0.0384	
									0.0236	0.2121		
B10	235.3	2.7	93.0	2.1	10.0	16.7	172.1	20.4	23.5	4.0	0.0817	14.9
									0.5757	0.6996	0.0441	
									0.0245	0.1753		
B11	235.0	2.8	94.5	2.0	10.0	16.7	173.7	19.9	22.7	3.8	0.0510	14.9
									0.5291	0.6333	0.0270	
									0.0233	0.1681		
B12	224.9	3.2	76.6	1.6	10.0	16.7	168.1	20.9	23.1	3.7	0.0567	16.6
									0.5701	0.6337	0.0273	
									0.0247	0.1722		
B13	211.6	3.2	95.7	1.6	10.0	16.7	168.2	20.8	22.6	3.8	0.0148	15.3
									0.5139	0.4800	0.0063	
									0.0228	0.1260		
B14	258.2	2.6	119	1.4	12.0	20.0	202.5	21.9	21.8	3.4	0.0477	14.6
									0.4428	0.2600	0.0208	
									0.0203	0.0769		
B15	245.9	2.6	141	1.4	12.0	20.0	206.0	21.6	23.2	3.1	0.0257	14.8
									0.4281	0.4029	0.0133	
									0.0185	0.1285		
B16	235.4	3.0	142	1.0	12.0	20.0	203.7	21.8	23.3	3.1	0.0406	16.5
									0.3426	0.3992	0.0191	
									0.0147	0.1278		

(a) Measured value
(b) Average value
(c) Standard deviation
(d) Coefficient of variation
W.B.S.U.: Weld Bead Surface Undulation
P.E.: Peak Energy = $I_P \times T_P \times V_P$ (J)

Table 2 — Types of Droplet Detachment and Statistical Analysis of Peak Voltage, Droplet Detachment Time and Weld Bead Surface Undulation

Weld No.	I_P (A)	T_P (ms)	(a) I_{AV} (A)	(a) V_{AV} (V)	TY	V_P (V)	T_D (ms)	WBSU	P.E (J)	ANLR dB(A)
B17	240.5	3.0	96.0	18.6	A	23.2[b] 0.2944[c] 0.0127[d]	4.38[b] 0.2482[c] 0.0567[d]	0.0611[c] 0.0283[d]	16.7	84.6 to 88.9
B18	211.5	4.0	96.4	19.1	A	23.1 0.4822 0.0209	6.00 0.4546 0.0758	0.0714 0.0334	19.5	84.6 to 88.9
B19	226.0	4.0	101.8	18.2	B	23.6 0.5535 0.0235	3.86 0.3611 0.0743	0.0616 0.0300	21.3	86.5 to 88.3
B20	196.8	5.0	99.7	18.1	B	2.9 0.6466 0.0283	4.80 0.3571 0.0693	0.0553 0.0252	22.5	86.5 to 88.3
B21	180.5	6.0	99.4	18.6	B	22.8 0.9887 0.0435	5.11 0.6173 0.1207	0.1540 0.0657	24.7	86.5 to 88.3
B22	230.3	5.0	109.4	18.3	C	23.0 0.3258 0.0142	3.86 0.3662 0.0948	0.0756 0.0352	26.5	88.8 to 90.3
B23	207.8	6.0	109.5	18.3	C	23.7 0.6534 0.0276	4.61 0.3370 0.0731	0.0976 0.0406	29.6	88.8 to 90.3
B24	160.0	9.0	105.7	18.7	C	22.8 0.9082 0.0398	5.36 1.0432 0.1947	0.0792 0.0320	32.8	88.8 to 90.3
B25	192.9	8.0	109.8	19.9	D	23.9 0.4924 0.0206	3.74 0.4204 0.1123	0.0736 0.0291	36.9	86.6 to 90.5
B26	180.2	9.0	109.2	19.6	D	23.6 0.1562 0.0491	4.43 1.1160 0.2517	0.0992 0.0432	38.3	86.6 to 90.5
B27	172.7	10.0	104.6	20.2	D	23.6 0.4936 0.0210	4.63 0.4534 0.0979	0.0740 0.0318	40.8	86.6 to 90.5

(a) Measured value
(b) Average value
(c) Standard deviation
(d) Coefficient of variation
I_B = 20 A
T_B = 6 ms
W_F = 6 m/min
W_S = 10 mm/s

TY: Type of droplet detachment
A: Background detachment, $I_P^{1.7}\,T_P = 34.0\ A^{1.7}\,s$
B: One droplet detachment per peak, $I_P^{1.7}\,T_P = 40.0\ A^{1.7}\,s$
C: Two droplets detachment per peak, $I_P^{1.7}\,T_P = 50.0\ A^{1.7}\,s$
D: Three droplets detachment per peak, $I_P^{1.7}\,T_P = 62\ A^{1.7}\,s$
P.E: Peak Energy = $I_P \times T_P \times V_P$ (J)
A.N.L.R: Arc Noise Level Range
W.B.S.U: Weld Bead Surface Undulation

pends on the wire feed rate.

Figures 19–21 show the similar new stable pulse parametric zones at different wire feed rates of 8, 10 and 12 m/min (315.0, 393.7 and 472.4 in./min), respectively. Results show that as the wire feed rate increases, the operating ranges of I_P and I_B increase and that of T_P and T_B decrease.

Selection of Suitable Pulse Parameter Combinations and Suitable Type of Droplet Detachment

The new stable parametric zone as shown in Fig. 18 contains a set of ranges of pulse parameters. However, there are other criteria, namely uniformity in arc length, uniformity in droplet detachment and weld bead surface undulation, that have been considered for selection of the suitable pulse parameter combinations from the new stable parametric zone to obtain good quality weld. Also, on the basis of the above criteria, the suitable type of droplet detachment was recommended for the four different types of droplet detachments, *viz.* background detachment, one droplet detachment, two droplets detachment and three droplets detachment per peak (per peak not applicable to background detachment).

Uniformity in Arc Length

Weld Nos. B1, B8, B13 and B16 were found to have more uniformity in arc length than other welds for the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively. Hence, the corresponding parameters of pulsed current are recommended to obtain uniform arc length. Refer to Table 1 for details. Table 1 also shows that at a low wire feed rate [6 m/min (236.2 in./min)], uniformity in arc length was found to be good for the highest I_P. At higher wire feed rates, uniformity in arc length was found to be good for the lowest I_P. Welds made at higher wire feed rates were found to have good weld metal wetting. The welds were also free of porosity.

Figures 7–10 show typical arc voltage and current waveforms for different types of droplet detachment. Uniformity in the peak voltage values was determined for different types of droplet detachments on the basis of minimum value of standard deviation and coefficient of variation of the peak voltage values (Table 2). Results show that the Weld No. B17 has the uniform arc length for background detachment, whereas Weld No. B19 has the uniform arc length for one droplet detachment, Weld No. B22 has the uniform arc length for two droplets and Weld No. B25 has the uniform arc length for three droplets detachment per peak. Among these droplet detachments, standard deviation (0.2944) and coefficient of variation (0.0127) of Weld No. B17 has the lowest values, suggesting that background detachment is a preferable one to obtain uniform arc length. The result also shows that the combination of the highest I_p and the lowest T_P (Weld No. B17) provides more uniform arc length (stable arc) than the combination of the lowest I_p and the highest T_P (Weld No. B18). Hence, the corresponding parameters of pulsed current are recommended to achieve uniform arc length (Table 2).

Uniformity in Droplet Detachment

Weld Nos. B1, B8, B13 and B14 have been found to be uniform in droplet detachment when compared to the other welds that were produced for the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively (Table 1). Hence, the corresponding parameters of pulsed current are recommended to obtain uniform droplet detachment. Table 1 also shows that the highest I_P at lower wire feed rate and the lowest I_P at higher wire feed rate are preferable to obtain uniform droplet detachment. Both uniformity in arc length and uniformity in droplet detachment were found to be good for the Weld Nos. B1, B8 and B13 when compared to all other welds. For Weld No. B8, droplet detachment occurs during peak, but in all other cases this occurs during the background period.

The standard deviation and the coefficient of variation of droplet detachment time were calculated for different types of droplet detachments, given in Table 2. The lowest standard deviation (0.2482) and coefficient of variation (0.0567) were found for the weld made with background detachments (Weld No. B17). Hence, background detachment can be considered to be capable of providing more uniform droplet detachment than other types of droplet detachments. The combination of the highest I_P and the lowest T_P (Weld No. B17) was found to be capable of providing a uniform droplet detachment when compared to the combination of the lowest I_P and the highest T_P (Weld No. B18), for the weld produced by background detachment. Hence, the corresponding parameters of pulsed current used to produce Weld No. B17 can be considered suitable to obtain a uniform droplet detachment.

Uniformity in Weld Bead Surface Undulation

Typical surface undulation of the weld bead as revealed by LVDT traverse is shown in Fig. 22. Standard deviation and coefficient of variation of the weld bead surface undulation are given in Table 1. Results indicate that Weld Nos. B1, B8, B13 and B15 were found to have smoother weld surface than other welds for the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively.

The relationship between standard deviation of weld bead surface undulation and wire feed rate is shown in Fig. 23. This is plotted for the ratio W_F/W_S = 10. The results show that variations in weld bead surface undulation is less at a high wire feed rate. It indicates that carrying out welding at a high wire feed rate is beneficial because it provides smooth weld bead surface. The reason for this is that, at a high wire feed rate, size of the droplet decreases and droplet frequency increases. Uniformity in arc length also increases and results in a smooth weld bead surface. Also, the fluidity of the weld pool improves because of the large current. Therefore, smoothness of the weld surface increases.

The standard deviation and the coefficient of variation of the weld surface undulation were calculated for different types of droplet detachments and given in Table 2. The lowest standard deviation and the lowest coefficient of variation were observed for Weld Nos. B17, B20, B22 and B25, which were produced at different welding conditions, *viz.* background detachment, and one droplet detachment, two droplets detachment and three droplets detachment per peak, respectively. Among these, the lowest standard deviation (0.0553) and the lowest coefficient of variation (0.0252) were found for the weld made with one droplet detachment per peak (Weld No. B20). The smaller the standard deviation and the coefficient of variation, the smoother the weld bead surface. Hence, one droplet detachment per peak was considered to be capable of providing a more smooth weld surface than other types of droplet detachments. Based on this, the corresponding parameters of the pulsed current that were used to produce Weld No. B20 were found to be more suitable than other combinations of pulsed current. However, standard deviation and coefficient of variation of the weld made with background detachment (Weld No. B17) was found to be second in the order of smooth weld surface. Weld Nos. B17, B22 and B25 were found to have both uniform arc length and smooth weld surface.

Plate Fusion Characteristics

Plate fusion characteristics are described with regard to penetration, weld width, percentage dilution, fusion angle, reinforcement height and beadplate wetting angle. As seen in Fig. 24, with the increase in wire feed rate, penetration, percentage dilution, reinforcement boundary length, penetration boundary length and weld width increase and the reinforcement height decreases. As the wire feed rate increases, the operating range of I_P and I_{Av} also increases (Figs. 18–21) and results in more penetration. The reason for the increase in weld width and decrease in the reinforcement height is that, at a high wire feed rate, voltage level is also to be increased to match the wire feed rate with the burnoff rate. The high arc voltage widens the weld width and decreases the reinforcement height. Figure 24 also shows that L_P is more sensitive than L_R to wire feed rate. Figures 25 and 26 show that, as the wire feed rate increases, WRFF, heat input and fusion angle increase, and bead-plate wetting angle and WPSF decrease. The results shown in Figs. 24–26 is for the ratio W_F/W_S = 10 (welding condition per Table 1). The above results indicate that welding operation should be carried out at high wire feed rate to obtain desirable weld characteristics such as larger depth of penetration, larger weld width, high-percentage dilution, large fusion angle, less reinforcement height and less bead-plate wetting angle.

The measured values of penetration, weld width, reinforcement height, fusion angle, bead-plate wetting angle and percentage dilution were listed in Table 3 for different types of droplet detachment conditions. These values indicate that the desirable weld characteristics, as mentioned in the previous paragraph, are obtained when welding is carried out using background detachment. Hence, background detachment is preferable among all the four types of droplet detachments.

Table 3 — Weld Bead Geometry and its Shape Relationships[a]

Weld No.	H mm	P mm	W mm	WPSF (W/P)	WRFF (W/H)	L_R mm	L_P mm	W/L_R ratio	W/L_P ratio	A_P mm^2	A_T mm^2	%D	θ_W (Degree)	θ_F (Degree)	H_{IN} J/mm
B17	2.05	1.47	7.28	4.95	3.55	8.92	7.94	0.82	0.92	5.23	16.25	32.18	60°14′	23°28′	178.6
B18	2.07	1.62	7.12	4.40	3.44	9.02	7.93	0.79	0.90	5.84	17.27	33.82	58°05′	27°19′	184.1
B19	2.03	1.16	7.04	6.07	3.47	8.82	7.52	0.80	0.94	4.09	14.96	27.34	69°27′	20°49′	185.3
B20	2.13	1.08	7.00	6.48	3.29	8.78	7.53	0.79	0.93	3.24	13.84	23.41	59°47′	18°35′	180.5
B21	2.35	1.27	6.82	5.37	2.90	8.91	7.37	0.77	0.93	4.51	16.36	27.57	65°43′	23°50′	184.9
B22	2.20	1.26	6.94	5.50	3.15	9.08	7.54	0.76	0.92	4.15	16.16	25.68	73°41′	21°45′	200.2
B23	2.48	1.36	6.73	4.95	2.71	9.16	7.34	0.73	0.92	5.12	17.61	29.07	73°27′	24°13′	200.4
B24	2.42	1.02	6.81	6.68	2.81	8.90	7.21	0.77	0.94	3.21	14.86	21.60	61°49′	17°49′	197.7
B25	2.48	1.22	6.49	5.32	2.15	8.90	7.09	0.73	0.92	3.35	15.55	21.54	70°14′	22°16′	218.5
B26	2.32	1.07	6.73	6.29	2.90	8.81	7.17	0.76	0.94	3.24	14.55	22.27	66°08′	19°42′	214.0
B27	2.36	0.99	6.65	6.72	2.82	8.63	7.07	0.77	0.94	2,94	13.77	21.35	59°06′	18°32′	211.3

(a) W_F/W_S = 10. Other welding conditions per Table 2.
%D: Percentage Dilution = $(A_P/A_T) \times 100$
H_{IN}: Heat Input = $V_{AV} \times I_{AV}) / W_S$ (J/mm)

Peak Energy

The peak energy was determined for the various droplet detachment conditions and given in Table 2. Results show that peak energy required for background detachment is less but the peak energy required for other types of droplet detachments is high. The reason is that the combination of the highest I_p and the lowest T_P is used during background detachments and results in low peak energy. Hence, background detachment is preferable.

Arc Noise

The measurement of arc noise level (Table 2) reveals that there is no significant difference in the arc noise level among all the four types of droplet detachments. However, the lowest arc noise level was observed for background detachment conditions (84.6 to 88.9 dB [A]). The reason for this is that droplets are transferred across the arc during background period, which is considered to be quiet.

Conclusions

The most significant findings of this study can be summarized as follows:

1) The stable pulse parametric zone, predicted on the basis of burnoff, droplet detachment and arc stability criteria, was further narrowed to a smaller stable parametric zone by taking into account short circuit and burnback characteristics. The new stable pulse parametric zone is limited by

a) short circuit and burnback characteristics;

b) two constant arc power curves that correspond to the droplet volumes of 0.905 mm^3 (5.52×10^{-5} $in.^3$) ($I_P^{1.7}$ T_P = 27.5 $A^{1.7}$ s) and 0.500 mm^3 (3.05×10^{-5} $in.^3$) ($I_P^{1.7}$ T_P = 18.2 $A^{1.7}$ s)

c) two peak duration values; and

d) a background current that depends on the wire feed rate.

2) The set of range of values of each of the pulsed current parameters within the new stable parametric zones is expected to provide proper welds without short circuit or burnback, in addition to satisfying burnoff, droplet detachment and arc stability criteria.

3) As the wire feed rate increases, operating ranges of I_P and I_B increases and that of T_P and T_B decreases.

4) The suitable combination of pulse parameters within the new stable zone was selected on the basis of uniformity in arc length, uniformity in droplet detachment and weld bead surface undulation.

5) Weld Nos. B1, B8, B13 and B16 have been found to be uniform in arc length for the welds made at the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively. Hence the corresponding parameters of pulsed current are recommended to obtain uniform arc length.

6) Weld Nos. B1, B8, B13 and B14 have been found to be uniform in droplet detachment for the welds made at the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively. Hence, the corresponding parameters of pulsed current are recommended to obtain uniform droplet detachment.

7) Both uniformity in arc length and uniformity in droplet detachment were found to be better (Weld Nos. B1, B8 and B13) at highest I_P for lower wire feed rate (6 m/min [236.2 in./min]) and at lowest I_P for the higher wire feed rates (8 and 10 m/min [315.0 and 393.7 in./min]).

8) Welds made at higher wire feed rates, whose average current is higher than spray current level, were found to have good weld metal wetting. The welds were also free of porosity.

9) Background detachment is preferable to obtain both uniform arc length (more stable arc) and uniform droplet detachment.

10) The combination of the highest I_P and the lowest T_P was found to be capable of providing both uniform arc length and uniform droplet detachment (Weld No. B17) when compared to the combination of the lowest I_P and the highest T_P, for the weld (Weld No. B18) made with droplet detachment during background.

11) Weld Nos. B1, B8, B13 and B15 were found to have smooth weld surfaces at the wire feed rates of 6, 8, 10 and 12 m/min (236.2, 315.0, 393.7 and 472.4 in./min), respectively. Hence, the corresponding parameters of pulsed current are recommended to obtain uniform weld surface.

12) Carrying out welding at higher wire feed rate is desirable as it provides a smooth weld surface.

13) A smoother weld surface was observed for the welds made with one droplet detachment per peak (Weld No. B20) than with background detachment, two droplets detachment per peak and three droplets detachment per peak conditions.

14) Penetration, percentage dilution, reinforcement boundary length, penetration boundary length, weld width, weld reinforcement form factor, heat input and fusion angle were found to be increased with increasing wire feed rate. Reinforcement height, bead-plate wetting angle and weld penetration shape factor were found to be decreased with increasing wire feed rate.

15) Background detachment is preferable among four types of droplet detachments because it provides a large depth of penetration, a large weld width, high-percentage dilution, high fusion angle, small reinforcement height, less heat input and small bead-plate wetting angle.

16) Peak energy required for background detachment is less, but one droplet detachment per peak, two droplets detachment per peak and three droplets detachments per peak conditions require high peak energy.

17) Measurement of arc noise level for the various types of droplet detachments, *viz.* background detachment, one droplet detachment per peak, two droplets detachment per peak and three droplets detachment per peak showed no significant difference among them. However, the lowest arc noise level was observed for background detachment conditions (84.6 to 88.9 dB[A]).

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Nomenclature

A_P	Cross-sectional area of penetration
A_R	Cross-sectional area of reinforcement
A_T	Total cross-sectional area of weld
C.V	Coefficient of Variation
DCEP	Direct Current Electrode Positive
d	Filler metal diameter
H	Weld reinforcement height
GMAW-P	Pulsed Current Gas Metal Arc Welding
H_{IN}	Heat input
I	Welding current
I_B	Background current
I_P	Peak current
I_{AV}	Average current
I_{DC}	Steady direct current
L_P	Penetration boundary length
L_R	Reinforcement boundary length
LVDT	Linear Variable Differential Transformer
Mg	Magnesium
P	Weld penetration
T	Pulse cycle time
T_B	Background duration
T_D	Droplet detachment time
T_P	Peak duration
T_{MD}	Modal droplet detachment time
V	Voltage
V_B	Background voltage
V_D	Droplet volume
V_P	Peak voltage
V_{AV}	Average arc voltage
V_{MD}	Modal droplet volume
W	Weld width
W_F	Wire feed rate
W_S	Welding speed
WPSF	Weld Penetration Shape Factor, W/P
WRFF	Weld Reinforcement Form Factor, W/H

Greek Symbols

θ_F	Plate fusion angle
θ_W	Bead-plate wetting angle
σ	Standard deviation