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Review

Selection of parameters of pulsed current gas metal arc welding

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Abstract

Pulsed welding is a controlled method of spray transfer, in which the arc current is maintained at a value high enough to permit spray transfer and for long enough to initiate detachment of a molten droplet. Once the droplet is transferred the current is reduced to a relatively low value to maintain the arc. These periods of low current allow the average arc current to be reduced into the range suitable for positional welding, while periodic injection of high current pulses allows metal to be transferred in the spray mode. Parameters of these current pulses, such as I_p I_b, T_p and T_b have a distinct effect on the characteristics viz., the stability of the arc, weld quality, bead appearance and weld bead geometry. Improper selection of these pulse parameters may cause weld defects including irregular bead surface, lack of fusion, undercuts, burn-backs and stubbing-in. Therefore, 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. However, arriving at such a combination of parameters without a rational base would be only a matter of chance with a fairly low probability for achieving desirable weld properties, since the complexity and interdependence of pulse parameters involved in this process. These difficulties of setting-up the welding conditions correctly has been one of the main reasons for the lack of popularity of pulsed GMA welding in industries. Hence, a detailed study is essential to arrive at a method of predicting the conditions that will give a good weld and this paper reviews various aspects of the pulsed GMA welding, the effects of pulse parameters and different methodologies adopted for selecting these parameters to obtain better quality welds.

Keywords: Peak current; Peak time; Base current; Base duration; Pulse frequency; Detachment parameter

Contents

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Nomenclature

A	area of cross-section of the wire, mm^2
d_d,	wire diameter, mm
d_e	electrode diameter, mm
D	load duty cycle, %
D_d	droplet volume, mm^3
dc	direct current, A
e	$I_p - I_b$ = excess current, A
F	frequency, Hz
I	dc steady current, A
I_{av}	average current, A
I_m	mean current, A
I_p	peak current, A
I_b	base current
k	intercept, A
K_c	detachment parameter, A^n/s
L	electrode extension, mm
M_m	melting rate in terms of mass, kg/s
M	mass of the droplet, kg
m	electrode melting rate, kg/s
m_d	electrode melting rate with pulsing, kg/s
S_m	slope, A/(m/min)
t_d	detachment time, ms
T	cycle time, ms
T_p	peak current duration, ms
T_b	base current duration, ms
V_{drop}	volume of droplet, mm^3
W_f	wire feed rate, m/min
W	wire feed rate, mm/s
x	fractional duration of peak

Greek symbols

α	factor accounting for localized arc heating, mm/(A s)
β	factor accounting for resistance heating along the wire length, A^{-2}/s
δ	T_pF = detachment parameter, A^n/s
φ	droplet volume, mm^3
ρ_d	density of the droplet, kg/mm^3

1. Introduction

The gas metal arc welding is increasingly employed for fabrication in many industries. The process is versatile, since it can be applied for all position welding; it can be easily automated and can easily be integrated into the robotized production centers. These advantageous features of this process have motivated many researchers to study the GMAW process in detail.

Despite its wide application, the gas metal arc welding (GMAW) process has some limitations regarding the control of metal transfer. Although GMA welding was initially developed as a high deposition, high welding rate process facilitated by continuous wire feed and high welding currents, susceptibility to porosity and fusion defects, limited its use to applications where weld quality was not of paramount importance [1]. However, in recent years, as the industries have striven to become more efficient, there has been renewed interest to improve quality and to overcome the limitations of conventional GMA welding which led to the development of pulsed arc technologies.

The pulsed GMAW process works by forming one droplet of molten metal at the end of the electrode per pulse. Then, just the right amount of current is added to push that one droplet across the arc and into the puddle. Unlike conventional GMAW, where current is represented by a straight line, pulsed GMAW drops the current at times when extra power is not needed, therefore cooling off the process. It is this “cooling off” period that allows pulsed GMAW to weld better on thin materials, control distortion and run at lower wire feed speeds [1].

However, it is not so easy to select the values for these pulse parameters, since for each welding condition (base material, electrode material and diameter, shielding gas type, etc.) there is an optimum parameter combination [2,3]. Also, robotics and automated applications are demanding greater consistency from the welding process, which in turn necessitates more insights into the effects that operating parameters have on weld bead shapes and extent of fusion [4,5]. Taking the above facts into consideration, this paper attempts to review the various aspects of pulse parameters and their selection to obtain good quality welds.

2. Features of pulsed GMAW

1. The main feature of pulsed GMAW is a spray type metal transfer at low average currents, which would produce globular metal transfer under steady current conditions [6].
2. Pulsed GMAW, a modified spray transfer process provides the best of both short-circuiting and spray transfer.
3. Pulsing reduces overall heat input, yet provides the fusion associated with spray transfer [4,7–9].
4. Pulsed GMAW provides good bead appearance because tiny molten droplets do not cause spatter [7,10,11].
5. Welders have better directional control over the weld bead because the weld puddle cools in between pulses and freezes faster. This minimizes puddle sag or an excessive convex bead during out-of-position welding.
6. It requires less skill to obtain good welds with GMAW-P than it does with GTAW [7].

3. Pulse parameters

The primary parameters of pulsed GMAW welding are: (1) peak current, (2) background current, (3) peak current duration, (4) background current duration, (5) pulsing frequency and (6) load duty cycle.

1. Peak current (I_p): Higher of the two current levels in the pulsing waveform (Fig. 1). It is the current level at which the spray transfer is achieved. The peak current pinches off a spray transfer droplet and propels it towards the weldment for fusion [7].

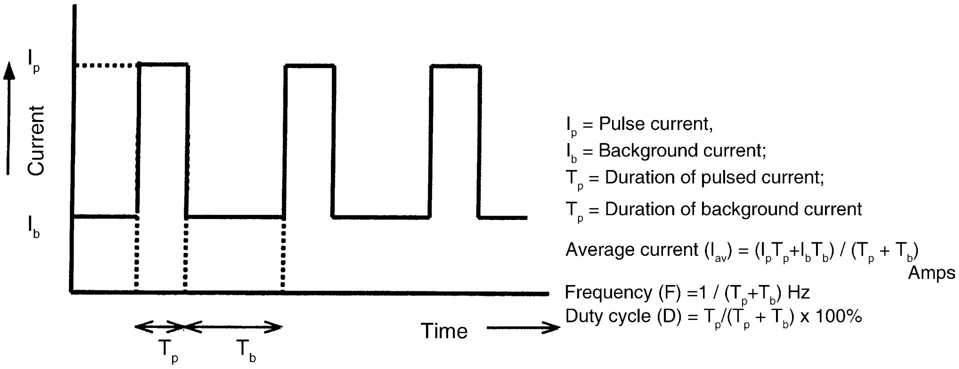

Fig. 1. Schematic representation of a current–time diagram during pulsed power welding.

2. Background current (I_b): The lower of the two current levels in the pulsing waveform. This is the current required for maintaining the arc. The background current maintains the arc but is too low for metal transfer to occur [7].
3. Pulse width (T_p): It is defined as the beginning of current rise to the beginning of current fall during a pulse. It is the time period between the moment at which the current starts to increase and the moment at which it begins to decrease at the end of the pulse [12].
4. Background current duration (T_b): It is the time spent at lower current value.
5. Pulses per second (pulse frequency, F): Pulse frequency is the number of peak current pulses, which occur in one second of time and it is given by the inverse of the cycle time, T in seconds. A pulse cycle time (T) is defined as the period from the start of a pulse to the end of the base time just before the next pulse [13].
6. Load duty cycle (D): It is defined as the ratio between the pulse width to the cycle time, i.e. $D = T_p/(T_p + T_b) \times 100\%$ [3].

3.1. Pulsed wave form

A pulsed current waveform can generally be defined by four variables: I_p, I_b, T_p and T_b (Fig. 1). In practice the background currents usually contains ripples due to characteristics of power source while the pulse current is approximately sinusoidal. These differences, however, are not particularly significant and to a large extent the actual waveforms can he represented by the equivalent rectangular current of the same average value of the two stages, respectively [14].

4. Selection of pulse parameters

For effective utilization of pulsed GMAW process, it is essential to understand the influence of pulse parameters on various aspects of weldment. However, pulsing the current introduces additional operational parameters [2] as mentioned above, other than conventional GMAW parameters, such as contact tip to work distance, nozzle to plate distance (Figs. 2 and 3), welding speed, welding current and welding voltage. These extra variables cause difficulty in selecting optimum operating conditions for pulsed current welding [3,15–23]. Smooth spray transfer, resulting in reproducible, fully fused weld deposits can be achieved by careful selection of pulsed GMAW parameters [24]. Identifying such suitable combinations of welding parameters for use with pulsed gas metal arc welding (GMAW-P) can

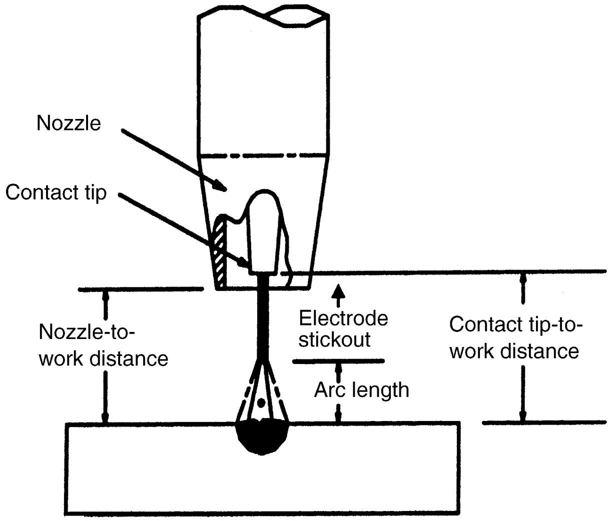

Fig. 2. GMA welding parameters.

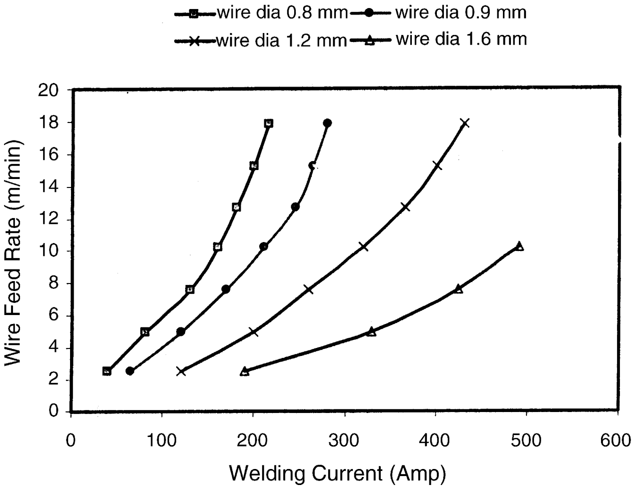

Fig. 3. Typical welding currents vs. wire feed rates for carbon steel electrodes at a fixed stickout [29].

be a time-consuming process, involving considerable trial and error [12]. However, in practice, it is not easy to establish a usable working pulse condition by trial and error when adjusting pulse parameters. This is because for a given wire feed speed the pulse amplitude and duration together must be adjusted such that at least one droplet is detached with each pulse. In addition, the mean current determined by all the parameters together must give a burn-off rate matching the wire feed speed to maintain a constant arc length. If the pulse magnitude is insufficient, the droplets do not detach in correspondence with the pulses and the metal transfer becomes unstable [23].

This complex interdependence of those pulse parameters necessitates investigation of this process from various aspects. Smati [6] and Kim and Eager [3] determined the theoretical pulsing frequency by dividing the electrode melting rate by the mass of the droplet and showed good agreement between the predictions and experimental results.

Subramaniam et al. [25] developed a wire feed rate model to characterize the process, whereas Amin [23] and Rajasekaran et al. [26] used burn-off criteria, arc stability and weldment qualities to determine the suitable range of pulse parameters.

Ghosh and Gupta [27] proved in their work that proper selection of pulsed GMA welding parameters has been beneficial to improve the mechanical properties of weld deposit as well as HAZ in welding of Al–Zn–Mg alloys. Similar observations were made by other researchers also that, a critical and selective use of pulse parameters improved the weldment properties as compared with those of the conventional weldments.

5. Selection of average current

The average current (I_{av}) is defined as:

$$I_{av} = \frac{I_p T_p + I_b T_b}{T_p + T_b} \tag{1}$$

Although there are four parameters involved in the stepped or pulsed current waveform, the operating characteristics can be considerably simplified if the “average’ values of the higher and lower currents and their sum are considered [28].

The average current has to be always below the transition current, as it would be more profitable to weld straight with spray transfer, a condition simpler from the point of view of parameter setting (fewer variables) and equipment [2]. However, Ghosh and Gupta [27], cite that, the deposition characteristics of the pulsed process were better when the average current was higher than the transition current.

Amin [23] indicated that, there is a functional relationship that represents all the feasible pulse conditions, i.e. combinations of the pulse parameters (pulse amplitude and duration, and background current and duration), for any specified mean current. He characterized mean current for stainless steel, mild steel. NG61, Inconel and NG21 and expressed the characteristics as given by the Eq. (2).

$$I_m = S_m W_f + k \tag{2}$$

where I_m is the mean current (A), W_f the wire feed speed (m/min), S_m the slope (A/(m min)) and k is the intercept (A).

The author, have established the above relation by conducting two tests at different wire feed speeds, one at $W_1 = 2$ m/min and the other at $W_2 = 8$ m/min, for each test the pulse parameters were adjusted by trial and error, so that a required arc length was maintained. He found that the slope is 34.9 A/(m min) for stainless steel 316 (under Ar + 2% O_2), 22.1 A/(m min) for stainless steel 308 (under Ar + 2% O_2), 26.5 A/(m min) for mild steel (under Ar + 5% CO_2) and 31.7 A/(m min) for Inconel (under Ar).

Needham and Carter [14] pointed out that, the average current is related to the wire feed rate in the same way as the normal dc operating current. For example, Fig. 3 [29] shows the relationship between wire feed speed and welding current, for carbon steel. Thus to a first approximation, the average current under pulse operation for a given wire feed can be estimated from the values used in normal spray transfer welding practice.

Collard [30], in his investigations found that when all other variables are constant, current will become a function of wire feed speed and this relation does not change in pulsed GMAW. The average current will vary with wire feed speed when all other parameters are constant and may be predicted using the same relationship as in conventional GMAW [31]. When I_b, I_p and T_p are fixed, the average current will vary directly with frequency. By fixing the background current, peak current and pulse duration at appropriate levels for a given application, changes in wire feed speed can be accommodated by changes in frequency assuming shielding atmosphere, electrode extension, voltage, electrode diameter and type are constant.

Allum and Quintino [32], investigated the effects of altering mean current and welding speed on fusion characteristics of pulsed GMAW welding and found that the dilution was maximized (up to 50%) for high currents and welding speeds and minimized by using low currents at low speeds, as required in surfacing applications.

According to Stanzel [33], the pulse width adjustment had some effect on droplet size and arc cone width, and a substantial effect on average amperage. Pulse frequency controls the average amperage, overall heat input, wire burn-off rate, arc length and can also influence travel speed.

Ghosh and Gupta [27], in their investigations found that using parameters comprised of comparatively high mean current and pulse frequency with low pulse duration give rise to finer microstructure with lower dilution.

6. Selection of peak current

In pulsed GMA welding, I_p should be set above the critical current and pulse duration (T_p) should be so adjusted that the electrode tip is melted in proper size and a droplet is transferred reliably per every pulse to the base metal [34].

For GMAW-P, an applicable method to ensure the repeatability and controllability has been to detach one droplet of diameter close to that of the electrode. This can be achieved by selecting appropriate amplitude and duration for the peak current and it should be higher than the transition current to ensure detachment [12,30,34–36]. Ueguri et al. [34], have reported that, the

Table 1
Transition current for Al and mild steel [12]

Wire dia (mm)	Transition current (A)	
	Al	MS
1.0	110	120
1.2	**140**	**200**
1.6	190	260

transition current of the pulsed current is larger than that of the direct current. These transition currents are dependent on the type of filler metal wire and diameter. For example, transition current for Al and mild steel are given in Table 1 [12].

Many researchers [15,23,26,30,37–40] have used power law relations ($I_p^n T_p = \text{constant}, n = 2$), for determining the amplitude of peak current and duration. Assuming that all other parameters are fixed, the equation $I_p^2 T_p = \text{constant}$ [41] may be used to determine the range of pulse amplitudes and durations to detach a single consistent droplet. A general inverse relationship between limiting pulse amplitude and duration was established by Amin [23], on the current and duration necessary just to detach a droplet size from the wire tip. For example for 1.5 mm^3 droplets from 1.2 mm diameter mild steel and 1.6 mm diameter aluminum wires, he found the relationship appear virtually linear with substantially the same slope of −2.3, i.e. $T_p \alpha I_p^{-2.3}$. Thus, the relationship between I_p and T_p, for constant droplet volume is an isoparametric equation: $I_p^{2.3} T_p = K_v$, where K_v, the detachment parameter is 1.8×10^3 A$^{2.3}$/s for 1.6 mm diameter aluminum wire and for Inconel wire of 1.2 mm diameter, it is 2.73×10^3 A$^{2.3}$/s [23]. The combination of the highest I_p and lowest T_p was found to be capable of providing both uniform arc length and uniform droplet detachment when compared to the combination of lowest I_p and highest T_p [26].

Needham and Carter [14] had taken the pulse amplitude and duration as that required to detach a droplet of size equal to wire diameter, then the background current and duration were adjusted to give the requisite average current, and hence the average burn-off rate.

Boughton and Lucey [42] had found that the minimum peak value of pulse current necessary for a given type of wire was constant and was independent of average total welding current. It had also been found that this current should not exceed the minimum value by any significant amount otherwise the arc would tend to exhibit some of the less desirable properties associated with abnormally high current density arcs, e.g. undercutting. They had also shown that, for a given wire size and type, the peak pulse current could be maintained constant at a level just exceeding the minimum necessary to obtain control of transfer. With a fixed value of peak pulse current its mean value is also fixed for a given repetition frequency, hence any variations in average total current are effected solely by varying the background current.

Stanzel [33], indicated that, pulsed current parameters for stainless steel were likely to have slightly higher peaks and lower background currents compared with mild steel because of surface tension characteristics; while aluminum requires much higher peak and background currents because of its heat absorption characteristics.

7. Selection of peak time

As has been discussed in the previous section, pulse duration depends upon the pulse amplitude, and it should be selected in such a way to ensure the detachment of the droplet with the diameter close to that of the electrode [23,36]. A high narrow pulse tends to produce a more constricted arc than a low wide pulse, and therefore offers some distinct advantages [30]. Jilong and Apps [43], had used the Eq. (3), to determine the detachment time (t_d), for mild steel wire of size 1.2 mm diameter.

$$t_d = t_1 + t_2 + t_3 \tag{3}$$

where t_1 is the heating time for preparing for the necking process, it depends on current = 1–1.5 ms; t_2 the necking and drop growth time and t_3 is the detachment time during which part of the neck is heated to the boiling point and leads to drop detachment; normally lasts less than 0.2 ms and t_d is inversely proportional to the peak current magnitude but is independent of the current duration. It has been confirmed that the necking process is an unidirectional process; after its commencement it will go on to the end of detachment, even if the current is reduced to low level; after the detachment of the first drop, the liquid string will be formed and if the current level is kept unchanged, the occurrence of stream transfer will be unavoidable. Even though the current level was reduced before the drop detachment, the metal transfer still continued and, moreover, stream spray transfer was prevented completely [44].

Thus, the correct duration, T_p for the peak current can be expressed as:

$$t_1 < T_p < t_1 + t_2 \tag{4}$$

i.e. if $T_p < t_1$, the necking process is not triggered so that no drop can be formed, and if $T_p > t_1 + t_2$, a string will be formed and stream spray will occur after first drop.

Subramaniam et al. [25], have used experiments to characterize the peak current and time to achieve desirable metal transfer for aluminum. An equation was formed, relating the peak and background conditions by a combination of exponential and Lorentzian function, as given by Eq. (5), where T_p and T_b are peak and background times in millisecond.

$$T_p = \left[(496.1 \times (1 - e^{-0.003 \times I_b T_b})) + \frac{270.1}{\frac{(I_b T_b - 188.2)^2}{8423.5}} \right] / I_p \tag{5}$$

This can be used to define the minimum time at peak required for droplet detachment at a desired peak current level.

Several researchers [2,15,23,26,37,45,46] have used the Eq. (6), to determine the pulsation period (T), needed to have the cylinder changed into a spherical of diameter equal to the wire diameter.

$$T = \frac{240 V_{drop}}{\pi d_e^2 W_f} \tag{6}$$

where V_{drop} is the droplet volume, $(\pi d_{\mathrm{d}}^3)/6\,(\mathrm{mm}^3)$, D_{d} the droplet diameter (mm) and W_{f} is the wire feed speed (m/min).

Once, T is calculated, T_{p} can be determined when T_{b} is fixed or pre-selected as $T = T_{\mathrm{p}} + T_{\mathrm{b}}$.

8. Selection of base current

This is the current required for maintaining the arc, but it is too low for metal transfer to occur [7,23]. The Background current is pre-programmed just to maintain an arc between each pulse without extinguishing the arc [26,37,38,47,48] and it is the least critical waveform parameter [30]. According to Needham [28], the background current duration is not independent and Allum and Quintino [32], had chosen the background conditions on the basis of a 50 Hz per 100 A rule, for example, at 200 A the frequency is 100 Hz with a background duration of 6 ms background current level of 100 A, if the peak structure is fixed at 350 A, 4 ms.

According to Allum [39], though the peak parameters appear to be largely responsible for metal transfer, the size of the droplet transferred is of course strongly influenced by background conditions. This may be quantified by noting that the volume of metal (φ) detached per pulse is given by Eq. (7).

$$\phi = \frac{AW}{F} \tag{7}$$

where A is the wire cross-sectional area (mm^2) and W is the wire feed speed (mm/s). If peak conditions correspond to values of $I_{\mathrm{p}}^2 T_{\mathrm{p}}$ appropriate to one drop per pulse then ϕ may be identified as the droplet volume. Further to a first approximation

$$W \sim K\langle I\rangle$$

where $\langle I\rangle$ is the average current over a pulse cycle and $\langle I^2\rangle = \langle I\rangle^2 + x(1-x)I_{\mathrm{e}}^2$ and K is the constant.

Hence, Eq. (7) is given by

$$\phi \approx \frac{AK\langle I\rangle}{F} \tag{8}$$

The definition of $\langle I\rangle$ then suggests that

$$\Phi \approx AK(I_{\mathrm{p}}T_{\mathrm{p}} + I_{\mathrm{b}}T_{\mathrm{b}}) \tag{9}$$

This expression shows that, background conditions generally influence droplet size [39]. Perhaps more importantly, Eq. (8) shows that if the mean current is varied under conditions of constant I_{p} and T_{p} then Φ will only remain constant if $I_{\mathrm{b}}T_{\mathrm{b}}$ = constant. The background current and duration should therefore be varied in inverse proportion.

Several researchers have suggested that, in order to minimize the overall heat input the background current is set to a minimum value but this may result in a high crowned welding bead and poor sidewall fusion. Background current levels can vary substantially, but for mild steel this will range from 30 to 50 A [30], 50 A for austenitic stainless steel [49] and for aluminum alloys it is 20 A [15] and the selection of base duration depends on average current and will be less than the peak time for achieving ODPP.

Subramaniam et al. [50], in their work, developed a model for ODPP transfer in 4047 aluminium taking into account the background conditions, which proved to be significant. However, Vilarinho and Scotti [2] observed that, the base parameters did not have significant influence on the pulse detachment phenomenon, since it did not alter the one-drop per pulse condition.

9. Selection of feed rate

In GMAW, the current depends on the rate at which, the wire is fed into the arc [10,23,48,51], The wire feed rate must match the melting rate for stable operation. Good arc stability is achieved under good metal transfer conditions, particularly when the wire feed rate is exactly matched by the wire-melting rate [15,23,26]. Low wire feed rate causes melt back, and a high feed rate can cause the arc to extinguish through short-circuiting [25]. The wire feed rate is determined by the size of droplet to be transferred and the transfer or repeat frequency, i.e. at low feed rates, the frequency must be low [28]. At a constant wire feed speed, a large value of frequency is preferable for practical use [34].

Most wire feed rate models are based on experiments or computations of arc and resistance heating of the wire during welding. When all other variables are constant, wire feed speed will become a function of current and the wire feed rate may be predicted using the same relationship as in conventional GMAW [30].

The most common equation used for determining wire feed is based on the Eq. (10), given below [25,39].

$$W = \alpha I + \beta L I^2 \tag{10}$$

where W is the wire feed rate, L the electrode extension, α the factor accounting for localized arc heating at the wire tip and β is the factor describing resistance heating along wire length. Experimental values of α and β for 1.2 mm carbon steel wires are 0.3 mm/(A s) and 5×10^{-5} A^{-2}/s, respectively, for aluminum, α is 0.75 mm/(A s) and β is negligible [39], and for mild steel wire (1.0 mm diameter), the values are, $\alpha \approx 0.47$ mm/(A s) and $\beta \approx 10.02 \times 10^{-5}$ A^{-2}/s[24]. Vilarinho and Scotti [2], found that, for AWS ER 4043 wire, shielded under pure Ar, the values of α as 12.8×10^{-4} m/(A s) and β as -8.84×10^{-5} A^{-2}/s.

Smati [6] and Amin and Ahmed [17], shown that the wire melting rate for pulsed GMA, which was controlled by both arc and wire resistance heating effects, matched the wire feed speed, W, as given by the Eq. (11).

$$W = \alpha I_{\mathrm{av}} + \beta L F(I_{\mathrm{p}}^2 T_{\mathrm{p}} + I_{\mathrm{b}}^2 T_{\mathrm{b}}) \tag{11}$$

At low mean currents, resistance heating due to background current is negligible. For example, when I_{av} is 100 A, it is only 5% of the total resistance heating [17], consequently the relation can be simplified to get the Eq. (12).

$$W = \alpha I_{\mathrm{av}} + \beta L F I_{\mathrm{p}}^2 T_{\mathrm{p}} \tag{12}$$

where W is the burn-off rate, α and β related to the arc and ohmic heating effects, I_{av} the average current (A), F the frequency (Hz) and L is the electrode stick out.

Similarly, Allum and Quintino [32], used Eq. (13), to predict the burn-off rates, for Bostrand LW1 wires, neglecting ohmic heating during the background period, i.e.

$$W = \alpha I_{\mathrm{av}} + \beta L \delta F \tag{13}$$

δ is the detachment parameter $I_{\mathrm{p}}^2 T_{\mathrm{p}}$ and the authors have used $\alpha = 0.27\,\mathrm{mm/(A\,s)}$, $\beta = 5.93 \times 10^{-5}\,\mathrm{A^{-2}/s}$, $L = 15\,\mathrm{mm}$, $\delta = 490\,\mathrm{A^2/s}$ and $I_{\mathrm{av}}/F = 2\,\mathrm{A/Hz}$ for their calculations.

However, Allum [39], have adopted a different approach to determine the wire feed speed, which is given by Eq. (14),

$$W\,(\text{pulse}) = W\,(\text{dc equiv}) + \beta L x (1 - x) I_{\mathrm{e}}^2 \tag{14}$$

where,

$$W\,(\text{dc equiv}) = \alpha I_{\mathrm{av}} + \beta L I_{\mathrm{av}}^2 \tag{15}$$

x is the fractional duration of peak ($T_{\mathrm{p}}F$) and I_{e} is the excess current (i.e. $I_{\mathrm{e}} = I_{\mathrm{p}} - I_{\mathrm{b}}$).

From the Eq. (14), it is apparent that, the burn-off rate in pulse welding is higher than dc steady current welding for the same equivalent current. However, Rajasekaran et al. [26], have reported that, the burn-off characteristic line of steady current GMAW intersects with the burn-off characteristic line of pulsed GMAW at the transition current and also that, the burn-off rate per ampere is more than the steady current GMAW for the average currents above the spray current level (i.e. burn-off rate per ampere is less than the steady current GMAW for the average currents below the spray current level).

Subramaniam et al. [25], developed a linear wire feed rate model using data on the values of wire feed rate obtained from the experiments conducted using a two level factorial experimental design. It has been reported by Rajasekaran [15] that, penetration, percentage dilution, reinforcement boundary length, weld width and heat input 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 increase in wire feed rate.

10. Selection of frequency

A pulse cycle is defined as the period from the start of a pulse to the end of the base time just before the next pulse. Repeat frequency (1000/cycle-time, Hz) of current pulses is adjusted to give the correct electrode burn-off rate in relation to wire feed rate to obtain constant arc length [5]. Since the frequency is a function of average current (calculated from wire feed speed under constant conditions), the appropriate frequency for a given condition can be pre-selected and as the conditions change, variations in average current will be necessary to maintain a stable arc. These changes in average current can be facilitated by continually varying pulse parameters such as frequency [30].

Kim and Eagar [3], calculated a theoretical frequency by dividing the electrode melting rate by the mass of one drop as given by Eq. (16).

$$\text{Theoretical frequency} = \frac{m_{\mathrm{pulse}}}{V_{\mathrm{drop}}(I_{\mathrm{p}})\rho_{\mathrm{d}}} \tag{16}$$

where m_{pulse} is the electrode melting rate with current pulsing, $V_{\mathrm{drop}}(I_{\mathrm{p}})$ the volume of the drop at the peak current and ρ_{d} is the density of the drop.

The average melting rate for the square wave current may be estimated as the weighted sum of the melting rate at the peak current and at the base current, as given by Eq. (17).

$$m_{\mathrm{pulse}} = D m(I_{\mathrm{p}}) + (1 - D) m(I_{\mathrm{b}}) \tag{17}$$

where D is the load duty cycle, $m(I_{\mathrm{p}})$ the melting rate at peak current and $m(I_{\mathrm{b}})$ is the melting rate at base current.

In the same way, Zhang et al. [35], determined the frequency using the Eq. (18).

$$F = \frac{M_{\mathrm{m}}}{m_{\mathrm{d}}} \tag{18}$$

where F is the theoretical drop detachment frequency, M_{m} the melting rate in terms of mass and m_{d} is the mass of the droplet.

For a given frequency, the base time T_{b} will be fixed (assuming that peak time T_{p} is known before), then the base current can be chosen according to the required melting rate, where the frequency range versus wire feed rate is obtained by experiment.

When the pulse frequency is increased above the theoretical pulsing frequency, with other operational parameters held constant, not every pulse can detach one drop. In other words, when the droplet size and the melting rate remain the same, it is impossible to produce more drops than predicted by theoretical frequency. Boughton and Lucey [42], have indicated that it is preferable to use a frequency over 33 cycles (but below 100 cycles/s) to improve wetting, particularly when the welding speed is increased above about 20 in./min (51 cm/min). The longer interval between pulses and the larger droplet that is obtained when using a lower frequency make it necessary to keep the welding speed down in order to obtain fully satisfactory wetting. However, Rajasekaran et al. [26] and Subramaniam et al. [25], in their work have shown that ODPP can be achievable even at frequencies as high as 400 Hz with duty cycle as high as 62.5%.

Some authors [3,25,42] have also used load duty cycle in addition to frequency. It is reported by Kim and Eagar [3] that the employment of pulse frequency and load duty cycle as the operational parameters, eliminates some of the complexities of adjusting the process, for instance, if the load duty cycle is kept constant, the pulse frequency can be changed without affecting the average welding current, which may lead to constant electrode melting rate. In this manner it is possible to determine a range of optimum pulsing frequency at a constant electrode melting rate.

It has been reported by some researchers that, when the load duty cycle is increased to 10%, tapering of the electrode occurs even at low base currents, for instance, with 10% load duty cycle, taper was observed at a base current of 180 A and at a peak current of 400 A for mild steel electrode [3]. As the base current and load duty cycle increase, the tapering becomes larger and will decrease the equilibrium droplet size (i.e. the droplet size is no longer similar to droplet size of projected spray transfer).

11. Selection of shielding gas

Air in the weld zone is displaced by a shielding gas in order to prevent contamination of the molten weld puddle. This contamination is caused mainly by nitrogen, oxygen and water vapor present in the atmosphere.

The shielding gas used must possess the following properties [1]:

- Generate the arc plasma and stable arc root mechanism.
- Produce smooth detachment of molten metal from the tip of the wire.
- Protect the wire tip, molten pool and welding head in the immediate vicinity of the arc from oxidation.

To avoid the problems associated with contamination of the weld puddle, three main gases are used for shielding. These are argon, helium and carbon dioxide. In addition, small amounts of oxygen, nitrogen and hydrogen have proven beneficial for some applications. Of these gases, only argon and helium are inert gases, compensation for the oxidizing tendencies of other gases are made by special wire electrode formulations. Argon, helium and carbon dioxide can be used alone, in combinations or mixed with others to provide defect free welds in a variety of weld applications and weld processes. Pulsed arc technique is an artificial method of producing spray transfer at currents below those at which spray transfer occurs naturally. However, to obtain this, it is essential to select a particular electrode/shielding gas combination, which will give a natural spray transfer. For example, a mild steel electrode used with CO_2 will not give a natural spray transfer, but the same electrode used with argon will.

It is reported by some researchers that the breakup length (length of the tapering column before droplet detachment) becomes shorter as the carbon dioxide content increases from 0 to 25% in an Ar mixture [45]. The droplet frequency decreases accordingly because the drop size increases with the carbon dioxide content. The reason for this is due to the fact that the increase of carbon dioxide will increase the gas energy potential, due to the dissociation energy of the diatomic gas. A higher energy potential causes a current density increase, fact that leads the arc to be limited to the lower portion of the drop. As there is no tapering effect, the drops are allowed to enlarge before detaching.

It has been observed by researchers that, the transfer changed into predominately repelled (deflected) in both globular and spray modes when the content of CO_2 exceeded 10% [45]. As pulsed GMAW is essentially a spray type process, pure CO_2 cannot be used for pulsed GMAW because an unstable arc with excess spatter occurs.

Thus, pulsed GMAW is limited by the shielding gases used. Argon is the gas, which will give spray transfer and, therefore it is the basis of the family of gas mixtures used for pulsed arc [30]. Arc parameter can be applied to both solid and flux cored wire welding provided a gas mixture that supports true axial spray transfer is used. For example, argon and argon–oxygen or argon–carbon dioxide mixtures containing low levels of active gas (for CO_2 up to about 18%) can be used [51].

99.95% commercially pure argon is used primarily for welding aluminum, but is not recommended for material such as steels because of poor arc stability. Argon + O_2 gas mixture produces a constrictive arc, which makes it ideal for stabilizing the spray or pulsed metal transfer modes. The ‘tight’ arc, however, means that attention must be paid to joint fit-up and is less tolerant to surface contamination on thin sheet than argon 5% CO_2, 2% O_2.

For general applications, additions of CO_2 are preferred to O_2 as the arc is less constricted and the resulting weld bead has a better profile. For material of less than 6 mm thickness, argon with 5% CO_2, 2% O_2 produces minimal spatter. For thicker materials, higher CO_2 contents are preferred to reduce risk of sidewall fusion defects, but unfortunately spatter does increase. For this argon 15% CO_2, 2% O_2 has been found to produce the best performance in terms of good weld bead penetration and low spatter generation. Apart from pure argon itself there are two mixtures, Argonex 1 (99% pure Ar 1% O_2) for high alloy ferrous materials and Argoshield 5 (95% low cost Ar and 5% CO_2), for low alloy ferrous materials including MS and stainless steels used for welding SS to mild steels or for overlaying of SS on mild steel are commonly used for pulsed arc [52].

Ninety nine percent pure argon, 1% O_2 mixture is mainly used with the high alloy ferrous materials. The purpose of O_2 addition is to improve “wetting” of the weld pool without leading to any significant loss of the more reactive elements. Ninety five percent low cost argon and 5% CO_2 gas mixture has been designed to suit low alloy ferrous materials including mild steel. The 5% CO_2 is added to give improved “wetting” and also to prevent the formation of gas pores in the weld metal. A mixture of 95% Ar and 5% CO_2 has been found to give least spatter and best bead appearance [6].

Bosworth [53], have studied the effect of gas composition on thermal transfer efficiency in pulse welding using solid steel wire under argon-base shielding gas containing 5% CO_2 and argon containing 18% CO_2. These gas compositions were chosen as being representative of the types of gas compositions normally used. The use of an argon-based shielding gas with low concentration of CO_2 resulted in a considerable reduction in heat generated at the arc and received by the weld. However, it was observed (Table 2) that there was not a significant difference in the thermal transfer efficiencies [1].

Using argon with a small percentage of oxygen, alloy recovery is improved compared with using CO_2 while carbon content lowered. CO_2 is not very satisfactory as a shielding gas for weld-

Table 2
Thermal transfer efficiency, effect of gas composition, steel wire 1.2 mm diameter [1]

Burn-off rate (kg/h)	Gas composition Ar % (remaining CO_2)	Arc voltage (V)	Efficiency (%)
2.06	82	23.7	82
	95	20.3	80
4.13	82	31.1	80
	95	25.5	81
5.11	82	33.7	76
	95	27.5	78

ing stainless steel because the weld metal generally contains an unacceptable level of carbon. This is reduced using an 80% argon 20% CO_2 gas mixture, but the use of this gas mixture has largely been limited to single pass sheet metal welds because the carbon content of a multi pass weld is not always regarded as acceptable [42].

Scotti [45] analysed the transfer modes for stainless steel GMAW with Ar and Ar + O_2 mixtures. He found that an increase in the oxygen content in the shielding gas reduces the values of the transition current and reduces the droplet size at the globular/spray transition. It has also been reported that, in argon/argon–oxygen gas mixtures, the SS wires behave very similar to mild steel [14].

Jacobsen [54] investigated the drop detachment process in pulsed welding using the shielding gas mixtures of Ar with various amounts of CO_2, O_2, H_2 and He. The authors found ample evidence for an upward force on the pendent drop, most likely caused by the recoil force of evaporating metal and this force increases with CO_2 concentration, base current and base current duration. The recoil force gives rise to a critical concentration of the molecular additive, above which it is impossible to detach the drop almost regardless of pulse width. This critical concentration decreases with increasing base current and base current duration. It also seems to decrease with increasing dissociation energy of the molecular additive. It was also observed that the drop velocity decreases with increasing CO_2 concentration.

Because pure helium produces globular metal transfer it is not suitable for pulsed GMA welding, as the threshold level for droplet transfer rises to more than 500 A. For this reason, in spray or pulsed metal transfer it is more common to use helium contents less than 70% to combine the advantages of the hotter helium arc with the more constricted argon arc characteristics for droplet detachment. Fenaresi et al. [55], in their investigations found that, change of shielding gas from pure argon to argon with 25% of helium, for welding of aluminum, there was an increase in the globular/spray transition current and frequency.

After their studies, Kim and Eagar [3] had reported that when welding with steel electrodes tapering will be suppressed by using a shielding gas consisting of Ar–He mixtures. Also the use of helium mixtures is expected to widen the range of frequency over which OPOD can be obtained. It has been established that, 30% He improves fluidity and arc stability and allows a higher welding speed, 1–2% O_2 or 2–3% CO_2 increases the arc stability and 1–2% N_2 can improve mechanical and corrosion properties when welding nickel based and super duplex alloys [49]. Kane et al. [56], reported that, welding of high nickel stainless steel alloy by pulsed GMAW was impossible using 100% argon due to arc instability also, it was reported that, the weldability improved when 1% CO_2 was added to the shielding gas mixture. Recommended shielding gas mixtures for various wire materials are given in Tables 3 and 4.

Table 3
Shielding gas recommendations [49]

Steel type	Gas flow 12–16 (l/min)
Duplex	Ar + 2% O_2 or Ar + 30% He + 2.5% CO_2
Standard austenite	Ar + 2% O_2 or Ar + 2–3% CO_2
Heat resisting	Ar orAr + 30% He
Fully austenite	Ar or Ar + 30% He

Table 4
Recommended combinations of shielding gases and electrodes for pulsed arc welding [52]

Electrode type	Gas type
Simple Mn–Si deoxidized mild steel	Argoshield 5
Cr–Mo steel	Argoshield 5
Low and extra low C stainless and heat resisting steels	Argonox 1
Medium carbon heat resisting steels	Argoshield 5
Stainless steel (used for welding SS to mild steels) or for overlaying on mild steel	Argoshield 5
Aluminium and alloys	Argon
Ni alloys	Argon
Copper	Argon
Bronzes	Argon
Bronzes used for overlaying steels	Argonox 1

12. Conclusions

Effect of pulse parameters on weld qualities and various approaches adopted by researchers to select these parameters were reviewed in detail.

Several researchers have reported that, achieving ODPP is a complex process, requiring a lot of trial and error experimentation and the process of determining the parameters that will provide ODPP with a droplet diameter approximately equal to the wire diameter is very time consuming and complicated.

Although ODPP is usually considered to be the ideal in GMAW-P, some authors have reported that, good quality welds can be made under conditions of more than one droplet per pulse also.

Of the pulse parameters, peak current and peak duration, plays a dominant role in determining the weld bead properties.

Burn-off rate, droplet detachment and arc stability have been the primary criteria for selecting the parameters for pulsed gas metal arc welding.

Most of the researchers had not taken the effect of base current while selecting the parameters, to characterize the feasible parametric zone. Though some researchers reported that, the effect of background condition is significant in modeling the ODPP; other researchers asserted that, the background condition had no significant effect.

Different authors had adopted different approaches to determine the wire feed speed and they had indicated that the wire feed rate depended on the wire materials composition, size of wire and electrode extension.

Only a very few had used design of experiments to carry out their experiments for selecting the pulse parameters and to study their effect on weld metal properties.

It has been reported by some authors, that, the dynamic response (dI/dt), of the power source also affects the pulse parameter selection. The fusion rate is remarkably influenced by the dynamic characteristics and smaller droplets had been observed for faster dynamic response.

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