Chapter 2
Concept of Pulse Current Gas Metal Arc Welding Process

Abstract The unique features of pulsing the current flow in GMAW process that led to development of pulse current gas metal arc welding (P-GMAW) have been discussed. The concept of the P-GMAW process has been explained in terms of its basic process variables. Fundamentals of the control of pulse parameters that can precisely influence the welding process primarily in terms of variation in phenomena of metal transfer has been thoroughly described. The mechanism of drop detachment as a function of pulse parameters that classifies the use of P-GMAW process in two different segments of one drop transfer per pulse and multiple drop transfer pulse has been critically explained with respect to its utility. In the light of all such variations the thermal characteristics of the P-GMAW process have been stated in reference to the wire melting and thermal behaviour of depositing droplet as a function of pulse parameters.

Keywords P-GMAW · Process parameters · Fundamentals of control · Metal transfer · Drop detachment · Thermal characteristics · Wire melting · Thermal nature of droplet

Using conventional GMAW is not favoured in various applications due to its inherent limitation in control of the characteristics of weld deposition. The stable spray mode of metal transfer that offers maximum ease of operation with high weld quality is possible to employ only at relatively higher welding current. Thus, metal transfer in conventional GMAW cannot be regulated as independent of heat input. In pulse current gas metal arc welding (P-GMAW) process, the current is periodically modulated between a relatively low base current and high peak current, as schematically shown by a typical square wave pulse (Fig. 2.1). The mean current level generally falls within the range normally associated with the globular transfer and the peak current level far exceeds the transition value giving axial spray transfer of smaller droplets. By repeated application of current pulses a synthetic spray mode of metal transfer is produced at a comparatively low level of heat input primarily due to intermittent pulses of high current [1, 2] for short duration. Due to this synthetic spray mode of metal transfer of intermittent nature there is a distinct

P.K. Ghosh, *Pulse Current Gas Metal Arc Welding*, Materials Forming, Machining and Tribology, DOI 10.1007/978-981-10-3557-9_2

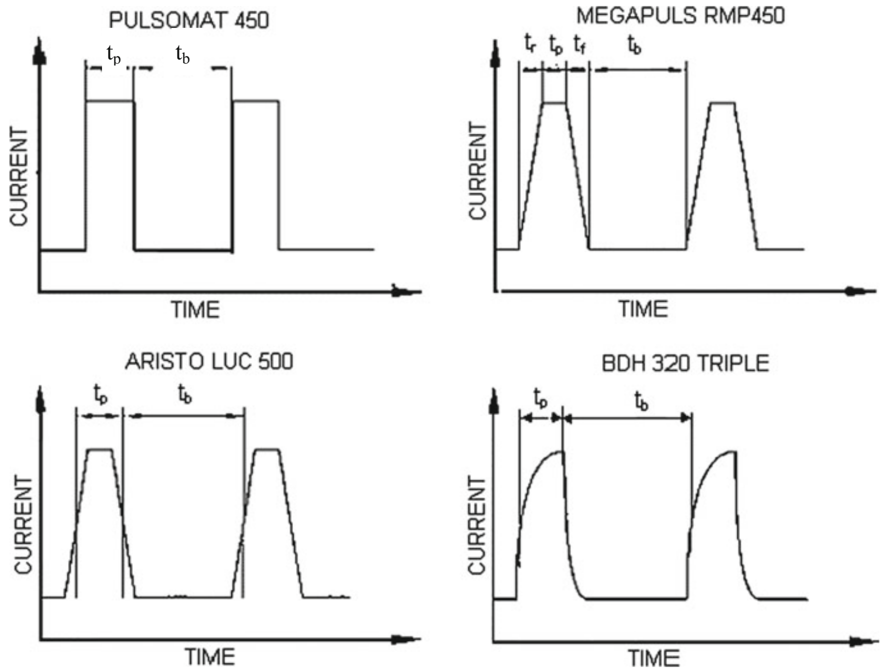

Fig. 2.1 Typical modes of pulsation of various power sources

possibility of availing more precisely controlled weld thermal cycle and metal transfer in this process than that available in conventional GMAW process. The process offers greater ease of operation for welding in any position, for root passes without backing and in case of welding of heat sensitive materials and thin sheets [3]. The use of pulsing enables control of drop size and frequency of its transfer to eliminate spatter and modify penetration without changing average or mean current [4]. The mean current of P-GMAW as of welding current of GMAW is primarily controlled by regulation of feeding rate of filler wire which is correlated almost linearly within the working range of parameters for various ferrous and non ferrous materials (Fig. 2.2a–e). The process facilitates the use of comparatively lower diameter of filler wire and reduces the wire feed problem at relatively high current of spray mode of metal transfer. Due to such operational ease the P-GMAW process is widely accepted in weld fabrication of various ferrous and non-ferrous metals requiring high weld quality.

The P-GMAW process is suitable for depositing high quality welds at relatively low heat input [5] but, the favourable characteristics of this process are primarily governed by the pulse parameters. It introduces additional welding parameters such as, mean current (I_m), peak current (I_p), base current (I_b), pulse frequency (f), peak current duration (t_p) and base current duration (t_b) in the process over those involved in conventional GMAW. It has also been realized that a change in any

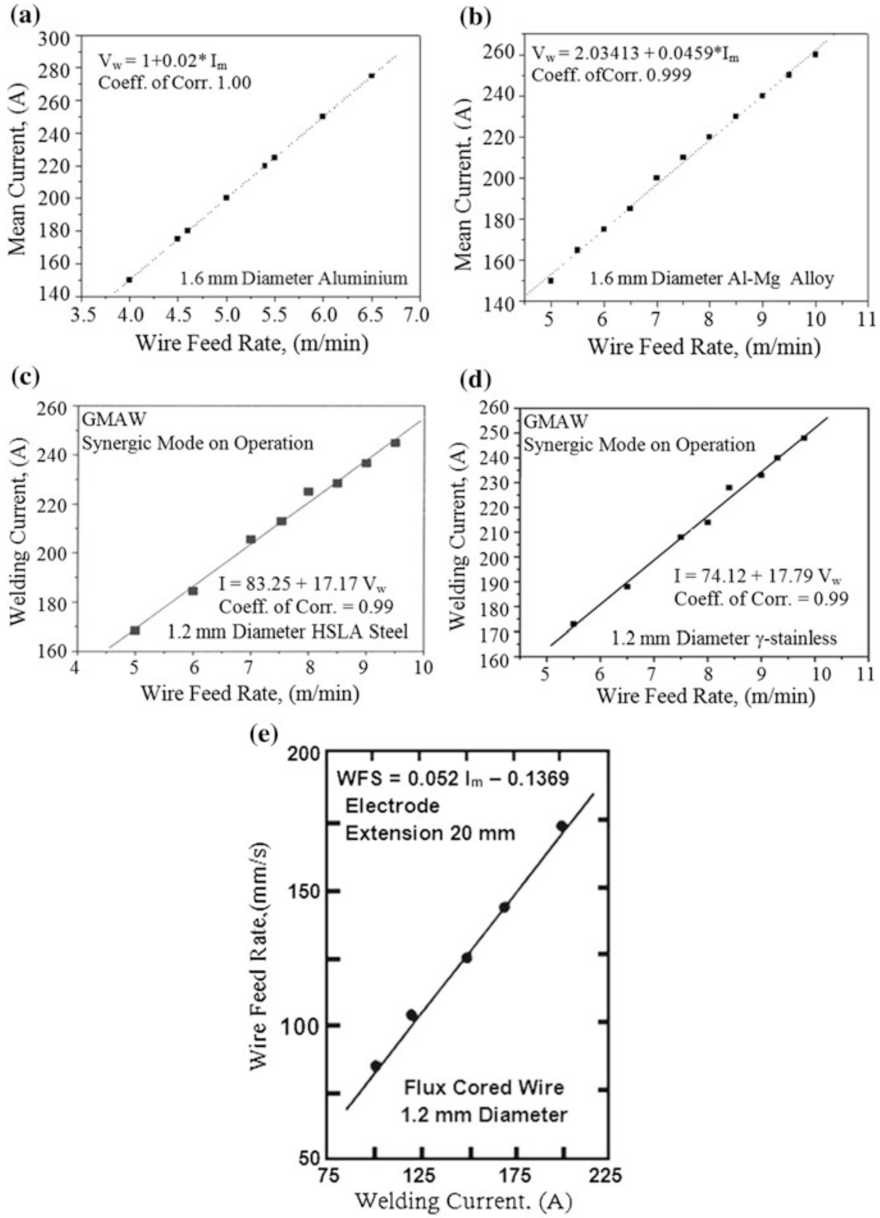

Fig. 2.2 Effect of wire feed rate on mean (P-GMAW) and welding (GMAW) current in case of **a** 1.6 mm diameter aluminium, **b** 1.6 mm diameter Al–Mg alloy and **c** 1.2 mm HSLA steel, **d** 1.2 mm γ-stainless steel and **e** 1.2 mm diameter FCW steel filler wires

pulse parameter simultaneously affects the other under the concept of energy balance [6] and hence influences the weld characteristics to a great extent [7–9]. The simultaneous influence of pulse parameters on each other in operation makes it difficult to select optimum combination of pulse parameters for any welding condition. Detailed relationships amongst the pulse parameters and their effect on metal transfer and weld bead characteristics are not yet well established [10–13]. Criticality noted in selection of pulse parameters possesses difficulties to operate this process in wide and versatile application of weld fabrication with ease and satisfaction. The limiting criteria for successful operation of P-GMAW primarily lies on the process control to avoid [3] arc extinction at too low base current, globular metal transfer at an insufficient peak current and arc burning back at too high peak current.

The limitations of short circuit and spray mode of metal transfer of GMAW process are successfully overcome by using P-GMA welding with its excellent directional capabilities [14, 15]. The process has better and more precise control on metal transfer and is capable of welding at a comparatively low heat input and hence more useful as compared to GMAW [16]. The optimum region for pulse amplitude and duration are well defined [17]. However, a success of the process to produce sound weld is largely governed by the pulse parameters, which simultaneously interact among themselves during welding and dictate weld quality. The interaction of pulse parameters is largely independent of the type of power source commonly in use [18]. Thus, the selection of right pulse parameters is quite critical and needs knowledge of correlation amongst the pulse parameters, behaviour and thermal nature of metal transfer and weld characteristics [3, 10–13].

2.1 Basic Process Variables and Control

In P-GMAW process the mean current, I_m, for a square wave pulse is expressed [10, 19] as

$$I_m = \left(I_p\, t_p + I_b\, t_b\right) \cdot t_{pul}^{-1} \tag{2.1}$$

where, t_b is base current duration and t_{pul} is pulse cycle time expressed as

$$t_{pul} = t_p + t_b \tag{2.2}$$

So, the I_p can be resolved as

$$I_p = \left(\frac{t_{pul}}{t_p}\right) \cdot I_m - \left(\frac{t_{pul}}{t_p} - 1\right) \cdot I_b \tag{2.3}$$

At a given wire feed rate (V_w) and droplet volume (V_d), a stable parametric zone containing all feasible combinations of pulse parameters such as I_p, I_b, t_p and f can be obtained [10] by evaluating the Eq. 2.3 under the following constraints,

$$I_m = m\,V_w + C \tag{2.4}$$

where, m is the slope, and C is the intercept. The restriction of required droplet volume, V_d, estimated by considering transfer of one drop per pulse (Number of droplets transfer per second equal to the frequency of pulse current) can be expressed as

$$V_d = \frac{A_w \cdot V_w}{f} \tag{2.5}$$

In terms of pulse frequency, f, the t_{pul} as a function of the characteristics of filler wire and volume of drop transfer is expressed as

$$f = \frac{1}{t_{pul}} \tag{2.6}$$

$$t_{pul} = \frac{V_d}{A_w \cdot V_w} \tag{2.7}$$

The optimum condition of drop detachment parameter is necessary to maintain smooth, reproducible spray transfer at all operating conditions. Based on the experimental observations, optimum condition for a given filler wire diameter and material ensuring one or multi drop transfer per pulse can be achieved over a range of combinations of I_p and t_p defined as

$$I_p^2\, t_p = D_n \tag{2.8}$$

where, D_n is detachment parameter denoting number of drops detached in each duration of pulse. However, in every case the condition for minimum base current for stable arc, below which arc extinguishes is observed as

$$I_b \geq \beta \tag{2.9}$$

where, β is minimum base current limit for stable arc. The range of possible combinations of pulse parameters is quite restricted at low wire feed rate or I_m but, it extends with the increase in it [3]. At a specific arc length an approximately linear relationship exists between the peak and base currents for a given combination of wire feed rate, V_w, pulse frequency, f, and peak current duration, t_p, [3].

$$I_p \propto I_b \tag{2.10}$$

At a given peak current duration and a peak current in excess, I_e, over the base current, both the base current and pulse frequency vary in direct proportion to the wire feed rate.

$$I_e = I_p - I_b \tag{2.11}$$

$$I_b \text{ and } f \propto V_w \tag{2.12}$$

At a given pulse frequency and I_e, both the base current and peak current duration also vary directly with wire feed rate.

$$I_b \text{ and } t_p \propto V_w \tag{2.13}$$

From the Eqs. 2.12 and 2.13 it may be understood that at a given I_e, both the base current and either pulse frequency or peak current duration vary directly with wire feed rate. This relationship remains valid for the entire operating range of wire feed rate from 0.5 to about 10 m/min under shielding of Ar + 5% CO_2 with high degree of arc stability and stable mode of metal transfer, as confirmed in case of using 1.2 mm diameter mild steel filler wire. Thus, the Eq. [2.6] can also be expressed as,

$$I_m = I_b + I_e\, t_p\, f \tag{2.14}$$

A solution of the Eqs. 2.4 and 2.14, as given below implies that for a synergic operation both the base current and the product of peak current in excess over the base current, peak current duration and pulse frequency must vary directly with wire feed rate [20].

$$m \cdot V_w + C = I_b + I_e\, t_p\, f \tag{2.15}$$

2.2 Phenomena of Metal Transfer

It is reported [17] that under identical conditions of welding, transition current for P-GMAW is comparatively higher than that of GMAW. It may often happen due to presence of stationary pendant droplet at the tip of the electrode during base current, which requires additional current to overcome inertia of droplet. The transition current for 1.2 mm diameter steel electrode under the shielding of Ar + 20% CO_2 has been found 380 A in P-GMAW process as compared to 275 A observed in GMAW process [17, 21]. However, in spite of this it is possible to achieve spray mode of metal transfer in P-GMAW at a mean current that is much lower than the required welding current of conventional GMAW process for this purpose. It offers greater ease of operation for welding in all positions, for root passes without backing, as well as for joining thinner plates with consistent quality.

2.2.1 Mechanism of Drop Detachment

The duration of entire mechanism of detachment of a droplet from electrode tip in P-GMAW process primarily combines four stages as time required for heating and melting, formation and growth of drop, necking at the root of growing drop and detachment of droplet, while the current amplitude varies during each stage [22] of action. Under the influence of peak current, a continuous spray of drops may transfer if the pulse duration is prolonged. Time required to form and detach a droplet is inversely proportional to the amplitude of peak current but independent of its duration. Once necking starts, the process requires certain period to detach the droplet, which primarily depends upon peak current and wire diameter, irrespective of the current level at the time of its detachment. Necking as a plastic deformation of heated electrode happens due to the Lorentz force and melting of filler wire occurs under the neck. The detachment of the drop is induced by vaporisation of molten metal at the neck due to resistance heating. The speed of droplet detachment is determined by the rate at which the fused metal is compressed into droplet [4]. It is well known that in P-GMAW, the metal transfer characteristics and thermal behaviour of weld deposit are governed by the pulse parameters, which interact amongst themselves during welding and dictate the characteristics of weld deposit [7, 8, 23, 24].

2.2.2 Nature of Metal Transfer

A steady state of metal transfer at a low level of mean current of P-GMAW creates a high Lorentz force for short duration by superimposition of the pulses of high current resulting into drop detachment and its accelerated movement in axial direction [25]. Each pulse detaches one or more droplets depending on its amplitude and duration. The behaviour of metal transfer in pulsed current gas metal arc welding is better understood by dynamic analysis [26]. The metal transfer in gas metal arc welding under modified pulsed current condition is also studied by numerical analysis [27].

At a given duration of a peak current the mean current as well as base current along with its duration has insignificant influence on droplet transfer. The droplet detachment takes place within a range of combination of I_p and t_p [10, 12, 14, 28, 29] according to $I_p^2 t_p$ = Const., where the constant depends up on properties of filler wire. Although metal transfer primarily depends on peak current and its duration, the volume of metal detached per pulse is generally governed by the ratio of wire feed rate and pulse frequency. Thus, the nature of metal transfer such as the diameter, velocity and number of droplets transferred per pulse is largely governed by the combined influence of pulse parameters. Type of metal transfer in P-GMAW is broadly classified into two categories as one drop transfer per pulse and multi drop transfer per pulse. The one drop transfer per pulse is popularly used in thin sheet welding with relatively low heat input. But the multi drop transfer per pulse is gaining wide application in welding of various kinds of engineering components due to use of relatively high current giving rise to higher deposition rate at controlled heat build-up in weld.

2.2.2.1 One Drop Transfer Per Pulse

The detachment parameter, D_n, (Eq. 2.8) for one drop transfer per pulse is primarily determined by selection of proper combination of peak current and its duration. The same value of detachment parameter may be obtained using different combinations of peak current and its duration such as higher I_p with shorter duration or lower I_p with relatively longer duration. For one drop per pulse the droplet volume, V_d, can be obtained [10, 14] by Eq. 2.5 when the wire feed rate (burn off rate), V_w, is expressed as

$$V_w = m\, I_m \tag{2.16}$$

where, the slope m depends up on type of filler wire. Using the Eqs. 2.1 and 2.16 the Eq. 2.5 can be resolved as

$$V_d = A_w\, m\, (I_p\, t_p + I_b\, t_b) \tag{2.17}$$

The control of droplet transfer can also be made through estimation of pulse frequency, f′, [30] by using the following expression.

$$f' = \frac{A_w\, V'_w}{V'_d} \tag{2.18}$$

where, V'_w is estimated wire melting rate obtained from the sum of molten mass at I_p and I_b, and V'_d is estimated volume of a droplet obtained from the predicted droplet diameter using static balance theory at the peak current. When the ratio of applied pulse frequency to the theoretical pulse frequency is equal to unity, each pulse tends to produce one drop [31].

2.2.2.2 Multi Drop Transfer Per Pulse

The metal transfer undergoes through a instability condition that can be analysed on the basis of the pinch instability theory [32–34] to estimate a critical wavelength

(λ_c) of a cylindrical current conductor liquid column, which tends to grow and cause the column to break up into droplets. This theory postulates that the pinch force being most active at I_P, the liquid column breaks up due to self-induced electromagnetic force. Electrode tip may develop a tapering depending on its chemical composition and welding current, which reduces the effective fluid cylinder diameter by a factor δ. The diameter of droplet, D, may be estimated by considering the electrode tapering coefficient, δ, and using the concept of energy balanceEnergy balance concept in detachment dynamics of liquid metal droplets as follows.

$$D = [4r/(1 + 3\theta_t)/16] \tag{2.19}$$

where,

$$r = R_w\,\delta \tag{2.20}$$

$$\theta_t = \mu_o\, I_p^2/(\gamma\pi^2\, r) \tag{2.21}$$

μ_o and γ are the permeability of free space and coefficient of surface tension of liquid filler metal respectively and R_w is radius of filler wire. Number of droplets transferred per pulse, N_D, may be estimated by mass transfer per pulse divided by mass of each droplet as follows.

$$N_D = \left[\frac{(A_w\, V_w\, \rho_w)}{f}\right] \bigg/ \left[\frac{\pi\, D^3\, \rho_d}{6}\right] \tag{2.22}$$

where, ρ_w is the density of filler wire and ρ_d is the density of molten filler metal [35]. The Eq. 2.22 implies that at a given I_b and I_m, number of droplets transfer per pulse decreases with increase of pulse frequency [36]. At the ratio of applied pulse frequency to the theoretical optimum pulse frequency less than unity, it tends to promote a situation of multi drop transfer per pulse [31]. In case of multi drop transfer the detachment parameter, D_n, is significantly higher than that of one drop transfer per pulse [14].

2.2.3 Role of Pulse Parameters

Influence of pulse parameters on nature of metal transfer is in principle similar in case of both the one or multiple drop transfer per pulse with respect to energy input and phenomena of wire melting. But it differs significantly in reference to the mechanism of drop detachment and its characteristics of transfer to weld pool. The role of pulse parameters in controlling one drop transfer per pulse is well known from the inception of the P-GMAW process in practice. But, effect of pulse parameters on multi drop transfer per pulse is yet to be fully understood primarily with respect to its thermal nature and transfer behaviour affecting the weld characteristics. Various aspects of this process have been discussed in latter chapters more in detail. However, some basic issues of the influence of pulse parameters on nature of metal transfer in reference to one drop transfer per pulse may be realized now.

At a given base and peak currents along with their duration the pulse frequency directly varies the mean current [1]. Thus, there is an optimum frequency for any welding condition and around that critical pulse frequency the metal transfer takes place as one drop per pulse. At a given mean current increase of peak current shifts critical frequency range towards higher side for one drop transfer per pulse. But, at a lower value of pulse frequency the spray mode of metal transfer occurs during the period of peak current [36]. Consideration of the rate of ascent and descent of pulse or peak current is important because a sharp rise and fall of current helps in restricting the width of arc plasma and produces a relatively stiffer arc [11]. A high but narrow pulse tends to produce a more constricted arc than a lower one. Thus, even a wide pulse can be used with high pulse for tight joints. The dynamic effects developed during peak current duration are responsible for metal transfer. However, the time for formation and detachment of a droplet is inversely proportional to peak current, but it is independent of its duration [22]. At a given peak current some critical level of its duration is always necessary to transfer a droplet within the pulse peak [14]. At a given mean and peak currents, a too short duration of peak current does not allow the drop detachment to take place within t_p rather it may be pushed to occur at the half way along the down slope of the pulse. At this situation the drop detachment occurs under a comparatively smaller Lorentz force with lower drop velocity, which reduces the depth of penetration. However, at a relatively higher peak current duration the main drop may be detached just at the end of the pulse followed by a detachment of second drop during base current period without proper direction causing deposition out of the weld pool [25].

In P-GMAW the role of base current is to retain the welding arc between the pulses [37–39]. An appropriate base current significantly facilitates the control over weld pool and consequently on weld bead shape. To keep the overall heat input at low level the base current is often set to a minimum, which may result a high crowned weld bead with poor side wall fusion. The drop detachment is hardly influenced by wire melting phenomenon during base current duration. The volume of droplet detached from filler wire can be significantly influenced by the base current and its duration, although an appropriate value of peak current and its duration set a condition for certain form of drop detachment [14]. During variation in mean current with the change of pulse frequency at a given peak current and its duration, the droplet volume may be fixed by maintaining constant electrode heating at base current duration. It can be made constant with enhancement of base current as its duration decreases with increase of pulse frequency [21]. At a given peak current and its duration, increase of base current duration increases the detachment time of droplet, whereas magnitude of base current is having an insignificant effect on detachment time. Effect of base current duration on drop detachment time is comparatively more pronounced at low peak current, where by employing a higher value of peak current the influence of base current on droplet detachment may be reduced [29]. At an appropriate drop detachment parameter, D_n, the detachment of one drop during base current can also be achieved with smooth weld metal transfer giving good bead appearance [29].

2.3 Thermal Characteristics of the Process

The understanding of thermal characteristics of P-GMAW process basically starts from the wire melting or burn off rate of filler wire as a function of pulse parameters. During transfer of molten filler metal in a size of relatively big drops or being fragmented into a stream of tiny droplets based on the pulse parameters, their thermal behaviour at the time of detachment followed by deposition in weld pool largely governs the thermal characteristics of the process. From the time of its inception in practice the fundamentals of thermal characteristics of P-GMAW process is largely understood with respect to one drop transfer per pulse as described below. However, considerable variation in metal transfer by multiple drop modes in entire pulse system affecting the thermal characteristics of the process has also been studied in advanced applications of P-GMAW process, which is discussed latter.

2.3.1 Wire Melting

The burn off rate or melting rate of filler wire in P-GMAW process is expressed [4, 12] as

$$V_{w(pc)} = \int_0^{t_{pul}} V_w \, t_{pul} \, dt_{pul} \tag{2.23}$$

For a square pulsed current waveform it is stated as

$$V_{w(pc)} = (V_{wp}\, t_p + V_{wb}\, t_b)\, t_{pul}^{-1} \tag{2.24}$$

where, $V_{w(pc)}$ is the overall wire burn off rate and V_{wp} and V_{wb} are the wire burn off rates during t_p and t_b respectively. In consideration of the expressions for the V_{wp} and V_{wb} the $V_{w(pc)}$ may be expressed as follows.

$$V_{wp} = A\, I_p + B\, E_w\, I_p^2 \tag{2.25}$$

$$V_{wb} = A\,I_b + B\,E_w\,I_b^2 \tag{2.26}$$

$$V_{w(pc)} = [A(I_p\,t_p + I_b\,t_b) + B\,E_w(I_p^2\,t_p + I_b^2\,t_b)]t_{pul}^{-1} \tag{2.27}$$

Considering the Eqs. 2.6 and 2.8 and by neglecting the ohmic heating during base current period in the context of $I_p^2 t_p \gg I_b^2 t_b$ the overall wire burn off rate $V_{w(pc)}$ as a function of men current and pulse frequency can be expressed as

$$V_{w(pc)} = A\,I_m + B\,E_w\,D_n\,f \tag{2.28}$$

In the light of the Eq. 2.5 considering the wire feed rate V_w in place of equivalent linear function of wire burn off rate $V_{w(pc)}$ the Eq. 2.28 can be expressed [5] as a function of the droplet volume V_d as follows,

$$V_d = A\,A_w\left(\frac{I_m}{f}\right) + A_w\,E_w\,B\,D \tag{2.29}$$

The Eq. 2.29 shows that for any wire feed rate, by fixing the ratio of mean current (I_m) to pulse frequency (f) the droplet size, especially for one drop transfer per pulse, can be held constant for a given wire diameter, electrode extension and detachment parameter. A value of 2 for the ratio of the mean current to pulse frequency gives satisfactory droplet transfer in case of using 1.2 mm diameter steel filler wire [40] when the volume of droplet remains insensitive to I_m. By following the same logic as stated earlier and by considering ohmic heating during base current duration the Eq. 2.27 reduces to

$$V_{w(pc)} = A\,I_m + E_w\,B\,I_{eff}^2 \tag{2.30}$$

where,

$$I_{eff} = \left\{k_p\,I_p^2 + \left(1 - k_p\right)I_b^2\right\}^{1/2} \tag{2.31}$$

and k_p is pulse duty cycle defined as the ratio of t_p to t_{pul}. The effective current I_{eff} may also be expressed as

$$I_{eff}^2 = I_m^2 + k_p.(1 - k_p).I_e^2 \tag{2.32}$$

Solving the Eqs. 2.30 and 2.32 and considering it further as a function of wire feed rate $V_{w(cc)}$ for conventional GMA welding (Eq. 1.4) the matter may be resolved as follows.

$$V_{w(pc)} = V_{w(cc)equiv.} + E_w\,B\,k_p(1 - k_p)I_e^2 \tag{2.33}$$

The expression given in Eq. 2.33 reveals [14] that the burn off rate of pulse current gas metal arc welding is comparatively higher than that of the continuous current welding under the welding current equivalent to mean current of the pulse process. The pulsed structure influences the burn off rate for a given mean or effective current and maximum burn off rate can be achieved when $k_p = 1/2$. Thus, it happens at equal peak and base current time and at largest peak current in excess over the base current.

2.3.2 *Thermal Behaviour of Droplet*

The P-GMAW has been employed in number of potential applications exploring its unique features of low heating of weld pool along with highly directional ability of metal transfer [41]. A relatively low temperature [42] of metal transfer in droplets favours better control of weld pool. In this welding process characteristics of metal transfer and thermal behaviour of weld deposit are largely governed by pulse parameters [9, 43] such as, I_m, I_p, I_b, t_p and f, which simultaneously interact among themselves during welding and governs the weld characteristics. At a given mean current and pulse duration, heat content of droplet at the time of detachment enhances significantly with the increase in pulse frequency [43]. The heat content and temperature of the droplets at the time of deposition in weld pool reduces with increase of I_m significantly [43]. The thermal or process efficiency of GMA welding becomes slightly lower with the use of rapid arc and pulsed current [44, 45].

References

1. Collard, J.E.: Adaptive pulsed GMAW control: The digipulse system. Weld. J. **67**(11), 35–38 (1988)
2. Craig, E.: A unique mode of GMAW transfer. Weld. J. **66**(9), 51–55 (1987)
3. Amin, M.: Synergic pulsed MIG welding. Met. Constr. **13**(6), 349–353 (1981)
4. Cornu, Jean: Advanced welding system. IFS Publication Ltd. UK **2**, 127–165 (1988)
5. Lambentt, J.A.: Assessment of the pulsed GMA technique for tube attachment welding. Weld. J. **68**(2), 35–43 (1989)
6. Ghosh, P.K.: Decide pulse parameters for desired properties of pulsed current GMAW weld. In: International Welding Conference (IWC 99) on Welding and Allied Technology—Challenges in 21st century, New Delhi, pp. 18–28. 15–17 Feb 1999
7. Ghosh, P.K., Rai, B.K.: Characteristics of pulsed current bead on plate deposit in flux cored GMAW process. ISIJ Int. **36**(8), 1036–1045 (1996)
8. Ghosh, P.K.: An analysis of weld characteristics as a function of pulse current MIG welding parameters. Int. J. Joining Mater. **8**(4), 157–161 (1996)
9. Randhawa, H.S., Ghosh, P.K., Gupta, S.R.: Geometric characteristics of pulsed current positional GMA weld. ISIJ Int. **38**(4), 276–284 (1998)
10. Amin, M.: Pulse current parameters for arc stability and controlled metal transfer in arc welding. Met. Constr. **15**(5), 272–287 (1983)

11. Pan, J.L., Zhang, R.H., Ou, Z.M., Wu, Z.Q., Chen, Q.: Adaptive control GMA welding—a new technique for quality control. Weld. J. **68**(3), 73–76 (1989)
12. Smati, Z.: Automatic pulsed MIG welding. Weld. J. **65**(1), 38s–44s (1986)
13. Amin, M., Ahmed, N.: Synergic control in MIG welding. Met. Constr. **19**(1), 22–28 (1987)
14. Alum, C.J.: MIG welding—time for a reassessment. Met. Constr. **15**, 6, 347–353 (1983)
15. Craig, E.F.: Pulse spray welding—a mode of weld metal transfer that should revolutionize the GMAW process. Weld. J. **62**, 11, 79 (1983)
16. Weber, Jeff: Pulsed GMAW- a plus for mid western metalworker. Weld. J. **61**(11), 51–52 (1982)
17. Ueguri, S., Hara, K., Komura, H.: Study of metal transfer in pulsed GMA welding. Weld. J. **64**(8), 242–250s (1985)
18. Ghosh, P.K., Dorn, L., Goecke, S.F.: Universality of correlationships among pulse parameters for different MIG welding power sources. Int. J. Joining Mater. **13**(2), 40–47 (2001)
19. Choi, S.K., Ko, S.H., Yoo, C.D., Kim, Y.S.: Dynamic simulation of metal transfer. Part II: Short circuit transfer modes. Weld. J. **77**(1), 45s–51s (1998)
20. Amin, M.: Microcomputer control of synergic pulsed MIG welding. Met. Constr. **18**(4), 216–221 (1986)
21. Norrish, J., Richardson, I.F.: Metal transfer mechanisms. Weld. Met. Fab. **20**(1), 17–22 (1988)
22. Jilong, Ma., Apps, R.L.: MIG transfer discovery of importance to industry. Weld. Met. Fab. **14**(9), 307–316 (1982)
23. Ghosh, P.K., Gupta, P.C.: Use of pulse current MIG welding improves the weld characteristics of Al-Zn-Mg alloy. Indian Weld. J. **29**(2), 24–32 (1996)
24. Ghosh, P.K., Gupta, P.C., Somani, R.: Influence of pulse parameters on bead geometry and HAZ during bead on plate deposition by MIG welding process. Z. Metallkde **82**(10), 756–762 (1991)
25. Essers, W.G., Van Gompal, M.R.M.: Arc control with pulsed GMA welding. Weld. J. **63**(6), 26–32 (1984)
26. Choi, S.K., Yoo, C.D., Kim, Y.S.: The dynamic analysis of metal transfer in pulsed current gas metal arc welding. J. Phys. D Appl. Phys. **31**, 207–215 (1998)
27. Wang, G., Huang, P.G., Zhang, Y.M.: Numerical analysis of metal transfer in gas metal arc welding under modified pulsed current conditions. Met. Mater. Trans. B **35B**(10), 857–866 (2004)
28. Jacobsen, N.: Monopulse investigation of drop detachment in pulsed gas metal arc welding. Phys. D Appl. Phys. **25**, 783–797 (1992)
29. Trindade, F.M., Allum, C.J.: Characteristics in steady and pulsed current GMAW. Weld. Met. Fab. **16**(9), 264–271 (1984)
30. Easterling, K.E.: Mathematical modelling of weld phenomena (Cerjak, H., Easterling, K.E., eds.), p. 163.The Materials Society, London, (1992)
31. Kim, Y.S., Eagar, T.W.: Metal transfer in pulsed current gas metal arc welding. Weld. J. **72** (7), 279s–287s (1993)
32. Choi, S.K., Yoo, C.D., Kim, Y.S.: Dynamic simulation of metal transfer. Part I: Globular and spray transfer modes. Weld. J. **77**(1), 38s–44s (1998)
33. Kim, Y.S., Eagar, T.W.: Analysis of metal transfer on gas metal arc welding. Weld. J. **72**(7), 269s–278s (1993)
34. Lancaster, J.F.: The Physics of Welding, 1st edn, pp. 134–230. IIW, Pergamon Press, New York (1984)
35. Jeong, S.K., Cho, H.S.: An analytical solution to predict the transient temperature distribution in fillet arc welds. Weld. J. **76**, 223s–232s (1997)
36. Metals Handbook: Properties and selection: Nonferrous alloys and pure metals, vol. 2, 10th edn, p. 1099. ASM International, Metal Park, Ohio (1979)
37. Allum, C.J., Quintino, L.: Control of fusion characteristics in pulsed current MIG welding—part I. Dependence of fusion characteristics of process parameters. Met. Constr. **17**(4), 242R–245R (1985)

38. Needham, J.C., Carter, A.W.: Material transfer characteristics with pulsed current. Br. Weld. J. **12**(5), 229–240 (1965)
39. Needham, J.C.: Pulse controlled consumable electrode welding arcs. Br. Weld. J. **12**(4), 191–197 (1965)
40. Quintino, L., Allum, C.J.: Pulsed GMAW: Interactions between process parameters. Part I Weld. Met. Fab. **16**(4), 126–129 (1984)
41. Ghosh, P.K., Dorn, L.: Thermal behaviour of pulsed MIG Al-Zn-Mg weld—an analytical model analysis. Int. J. Joining Mater. **5**(4), 143–150 (1993)
42. Waszink, J.H., Piena, M.J.: Experimental investigation of drop detachment and drop velocity in GMAW. Weld. J. **65**(11), 289s–298s (1986)
43. Ghosh, P.K., Goyal, V.K., Dhiman, H.K., Kumar, M.: Thermal and metal transfer behaviours in pulsed current GMA weld deposition of Al-Mg alloy. Sci. Technol. Weld. Joining **11**(2), 232–242 (2006)
44. Pépe, Nuno, Egerland, Stephan, Colegrove, Paul A., Yapp, David, Leonhartsberger, Andreas, Scotti, Americo: Measuring the process efficiency of controlled gas metal arc welding processes. Sci. Technol. Weld. Joining **16**(5), 412–417 (2011)
45. Bosworth, M.R.: Effective heat input in pulsed current gas metal arc welding with solid wire electrodes. AWS, Weld. J. **70**(5), 111s–117s (1991)

Springer

http://www.springer.com/978-981-10-3556-2

Pulse Current Gas Metal Arc Welding
Characteristics, Control and Applications
Ghosh, P.K.
2017, XXV, 322 p. 294 illus., Hardcover
ISBN: 978-981-10-3556-2