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Correlation between pulse 300 series SS wire parameters

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R Saluja[1] **and K M Moeed**[2]
[1] Department of Mechanical Engineering, Integral University, Lucknow, India
[2] Principal, Integral Polytechnic, Integral University, Lucknow, India

E-mail: ratisaluja@gmail.com

Abstract. A centralized and extensive relationship linking arc characteristics is presented to explain the metal transfer phenomenon, electrode melting rate, metal transport and weld-solidification during the Pulse gas metal arc welding. The study details interpretation of numerous arc, heat and mass transfer correlations during molten stage of the electrode, initiation of droplet, growth, detachment, transfer and impingement into the weld-pool. An interactive coupling between pulse process parameters, temperature distribution and weld pool dynamics has been discussed. This review elucidates conditions of the pulse metal transfer in the arc column and into the weld pool on the basis of current waveform, magnitude of peak, base and pulse current for 300stainless steel wire.

Keywords: Droplet, filler-wire, metal transfer, pulse gas metal arc welding, wire feed rate

1. Introduction

A high-temperature plasma arc between a continuous, consumable filler wire and the weld pool is built up in pulse-gas metal arc welding (p-GMAW) and initiates periodical impingement of one droplet per pulse at the end of wire tip. P-GMAW is a welding technique, in which the high arc current is upheld in contrast to conventional GMAW to initiate pulse transfer [1].

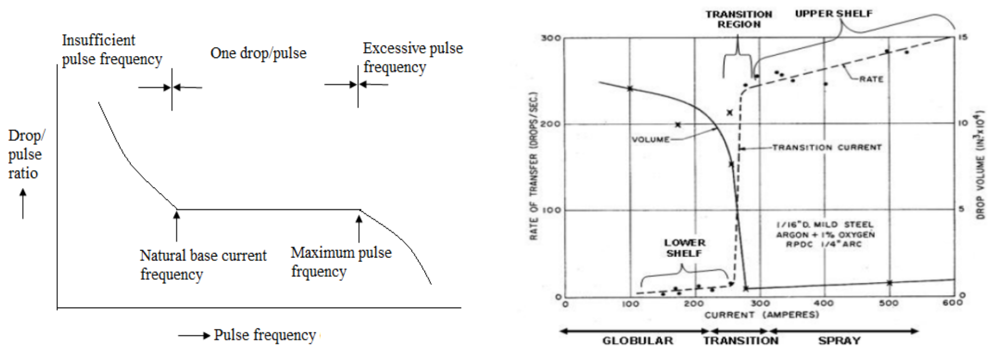

Figure 1(a). Illustration of pulsed wire current as a function of drop/pulse ratio and pulse frequency [3].
Figure 1(b). Influence of arc-current on drop transfer rate and droplet volume in an argon-rich shielding [4].

Where traditional GMAW uses continuous AC or DCEP/ DCRP current supply, unlikely p-GMAW requires intermittent DC. Thus current is giving 'cooling off' during the welding process in pursuance to meet precise and quality weld requirements. The droplet formation, growth and detachment in arc region, its transfer in weld pool, and its periodical impingement are governing by the equilibrium of forces and heat transfer in the arc plasma, within the droplet in conjunction to the weld pool [2]. Essential factors, in connection with static characteristics of the power supply, qualitative characteristics that affect the productivity of p-GMAW are arc stability, wire melting and feed rate [5].

The transition phenomenon of the filler wire is escorted by a chronological alteration in welding current during pulse welding as displayed in figure 1 (a). The transition is recognized with an increase in droplet detachment frequency and an inverse reduction in the droplet volume as shown in figure 1(b) [4]. The shortcoming of short circuit and globular metal transfer are prevailed opting pulse mode transfer for stainless steel. With solid SS wires, another advantage of pulsed power welding is that larger diameter wires upto 1.6mm can be used. In this research, we will pursue aspects and methodologies espoused for selection of pulse parameters, heat retained by the droplet, effect of the pulse waveform and resistance heating of the electrode together with index of the wire melting and feeding rate along with pulse transfer phenomenon.

2. Pulse Metal Transfer Phenomena

As arc force and deposition rate are exponentially dependent on current, the pulse welding process above the transition current crafts the arc forces irrepressible in the vertical and overhead positions. Decrease in the magnitude of average and pulse current, lessen the arc forces and deposition rates, therefore enhancing feasibility for all positions welding for 300 series stainless steel [7]. The metal transfer and the curved weld pool surface have significant effects on the transitory distributions of amperage, arc-region temperature and pressure [2].

Conversely, droplets-impingement significantly influences the surface contour and the convective heat transfer in the weld-pool [8]. The buckled weld pool controls the current distribution within the arc-region. These circumstances instantly affect the transport of heat and momentum flux from the arc plasma to the molten weld-puddle [9].

3. Governing equations for pulse parameters

Suitable combinations of pulse parameters provide steady and controlled metal transfer [10]. Typical degree and amount, fairly accurate properties of welding parameters for steel, can be quantified by detailed relations described in this study [9].

3.1 Formulation of pulse, average and base current

Peak current duration (T_p) is the time span between commencements of increase of current to the beginning of decrease of current during a pulse and base current duration (T_b) is the time duration spent at lesser current as mentioned in figure 2[11]. The primary parameters of pulsed GMAW pulse cycle time (T_{pul}) is expressed as

$$T_{\mathrm{pul}} = (T_{\mathrm{p}} + T_{\mathrm{b}}) \quad (1)$$

Load duty cycle (D) is ratio of the pulse width to the cycle time, can be expressed by the following equation

$$D = T_{\mathrm{p}}/(T_{\mathrm{p}} + T_{\mathrm{b}})\mathrm{X}100\% \quad (2)$$

Although above parameters are entailed to quantify magnitude of average current in pulse waveform, still attention has to be paid to simplify operating conditions by keeping the average current below the transition current [12,13]. Average and peak current for a square wave p-GMAW can be resolved as

$$(I_{\mathrm{avg}}) = \frac{(I_{\mathrm{p}}T_{\mathrm{p}} + I_{\mathrm{b}}T_{\mathrm{b}})}{(T_{\mathrm{pul}})} \quad (3)$$

$$I_{\mathrm{p}} = \left(\frac{T_{\mathrm{pul}}}{T_{\mathrm{p}}}\right).I_{\mathrm{avg}} - \left(\frac{T_{\mathrm{pul}}}{T_{\mathrm{p}}} - 1\right).I_{\mathrm{b}} \quad (4)$$

For a known wire feed rate (V_w), droplet volume (V_d), slope (m) and intercept (C) a stable parametric region over a range of possible combinations of pulse parameters could be evaluated under the following constraints.

$$I_{\mathrm{avg}} = \mathrm{mV_w} + \mathrm{C} \quad (5)$$

The theoretical condition of entailed droplet volume (V_d), can be approximated as

$$V_d = \frac{A_w . V_w}{f} \quad (6)$$

Pulse frequency (f) is number of droplets transfer per second. Assuming one drop per pulse is triggered in p-GMAW [9].

$$f = 1/(T_p + T_b) \quad (7)$$

During the p-GMAW, deviation in the temperature field and melting of the electrode wire speed influence size of droplet. The transition type is an important factor that dominates the arc stability, depending on the current waveform. Therefore, consider the effect of pulse waveform along with the assumption that wire-tip melts continuously. The role of pulse frequency is to command overall heat input, wire melting rate and arc characteristics [14]. Thus frequency (*f*) can also be quantified as a function filler wire rate (V_w), weld-area (A_w) and volume of drop transfer (V_d)

$$f = \frac{A_w . V_w}{V_d} \quad (8)$$

The optimum condition of drop detachment parameter (D_n) symbolizing frequency of droplets can be achieved for all possible combinations of I_p and T_p, and can be symbolized as

$$I_p^2 \, T_p = D_n \quad (9)$$

Various researches have been proposed using this power law relationship for evaluation of I_p and T_p by assuming 'n=2' and $I_p^2 T_p$= constant, presuming other process parameters fixed. The condition for minimum base current (I_b) below which arc extinguishes and minimum base current limit (β) for stable arc, is stated as

$$I_b \geq \beta \quad (10)$$

Investigators have opted minimum base current, for minimizing overall heat input. If base current is not maintained up to a level large contoured bead and lack of fusion results as a consequence. Its level can diverge significantly, however, for Grade 304 SS its range will be 50A. A linear association subsists between the peak (I_p) and base currents (I_b) for known combinations of variables as wire feed rate (V_w) pulse frequency(*f*) and peak current duration (T_p) for a fixed arc length[14]. Relation between a known peak current excess over the base current (I_e), variation in wire feed rate (V_w) will be

$$I_p \propto I_b \quad (11)$$

$$I_e = I_p - I_b \quad (12)$$

$$(I_b, f) \propto V_w \quad (13)$$

From above equations, 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.

$$I_{avg} = I_b + I_e I_b f \quad (14)$$

Substituting the value of average current from equation 14 in equation 5, a combined result for a synergic p-GMAW can be obtained. It signifies that deviation in base current, peak current excess over the base current, the peak current duration and pulse frequency varies with WFR for synergy p-GMAW [10].

$$m.V_w + C = I_b + I_e T_p f \quad (15)$$

3.2 Computation of peak current time and droplet detachment time

Considerations are also given to the heating time span (t_1) required for droplet necking preparation, necking and droplet growth time (t_2), and duration during which part of the neck reaches to the melting point is known as detachment time (t_3) [15]. Accordingly, droplet detachment time (t_d), can be calculated by

$$t_d = t_1 + t_2 + t_3 \quad (16)$$

T_p should be greater than t_1, otherwise no droplet will be formed, and as droplet necking would not be triggered. Consequently, initiation of pulse spray transfer occurs, if magnitude of peak current (T_p) is lesser than sum of heating time and drop growth time. A. Thus condition for current duration (T_p) can be expressed as:

$$t_1 < T_p < t_1 + t_2 \tag{17}$$

Equation 18 correlates the peak and background conditions by a combination of exponential and Lorentzian function for calculating correct value of peak current. This equation can be applied to characterize the minimum time essential for droplet detachment at a preferred peak current value [16].

$$Tp = \left[496.1\, X\, (1 - e^{-0.003 I_b T_b})) + \frac{270.1}{(\frac{(I_b T_b - 188.2)2}{8423.5})}\right] / I_p \tag{18}$$

3.3 Quantification of temperature distribution of the electrode wire

Steady motion of the solid wire dependent variables are enthalpy (H) and specific internal thermal energy (I) of system. If radial velocity (v) for steady wire disappears while keeping axial velocity (u) uniform than the volumetric thermal energy generation rate is a consequence of resistive/Joulean heating (qG'''). The thermal energy equation for the electrode-wire and droplet can also be stated in cylindrical coordinates in equation 19.

$$\frac{\partial \rho l}{\partial t} + \rho u \frac{\partial H}{\partial x} + \rho v \frac{\partial H}{\partial r} = \frac{\partial}{\partial x}\left(kr\frac{\partial t}{\partial x}\right) + \frac{\partial}{r \partial x}\left(kr\frac{\partial T}{\partial x}\right) + qG''' \tag{19}$$

If T (x, t) is the temperature of the electrode stick-out, and dependent variable wire feeding speed (V_w) is kept constant, the next one dimensional thermal transmission can be expressed by governing equation 20 [17].

$$\partial T/\partial t + V_w\, \partial T/\partial x = (K/c\rho)\, \partial^2 T/\partial x^2 + (j^2/4.2c\rho)R(T) \tag{20}$$

Where ρ is filler wire density, j is current density ($j = 4I_w/\pi W d_e{}^2$), K is thermal conductivity, C is Bulk specific heat, d_e is wire diameter and R (T) is specific resistance at temperature T. If φ is the equivalent voltage of molten-wire due to heat generation at arc region, H_o is the equivalent voltage of molten droplet temperature holding per unit mass, T_m is melting point of wire. At stable GMAW arc with constant wire extension (E_x) with respect to time ($dE_x / dt = 0$), the temperature distribution of wires can also be expressed as

$$dE_x/dt = -(\emptyset j - 4.2K\, \partial T/dx|_{x=Bx})/4.2(\rho H_0 - \rho c T_m) + V_w \tag{21}$$

Arc stability in p-GMAW is mainly due to variation in arc length, means the extent of the temporal change of the arc length or the wire extension length E_x. Ignoring the influence of heat conduction in the filler wire, the temperature distribution of the wire gradually varies with time, the wire melting rate can be expressed by the formula. Therefore, the temporal change of E_x is

$$\frac{dE_x}{dt} = V_w - v(t) = V_w - \{\emptyset j(t) + a\, E_x j(t)^2)\}/4.2\rho\, (H_0 + b) \tag{22}$$

As shown in figure 2(a), the melting speed of the wire is proportional to E_x, the effect of anti-heat generation is large for stainless steel at high current value and high wire melting rate. It gets worse during pulse welding, as the current flows intermittently. Assume the case of steady state, under the completely constant current value, the temperature of the electrode wire ($\partial T / \partial t = 0$) is constant. It is also assumed that the resistivity of the drop does not depend on the temperature ($R(T) = R_o$). To determine $T_{m,}$ solution of equation (20) becomes as follows.

$$T(x) = T_m - \left(\frac{I^2 R_0}{4.2c\rho} \cdot \frac{E_x}{v_w}\right) \cdot \frac{e^{\left(V_w \frac{x}{k}\right)-1}}{e^{\left(V_w \frac{Ex}{k}\right)-1}} + \frac{j^2 R_0}{4.2c\rho} \cdot \frac{x}{V_w} \tag{23}$$

However, $k = K / c\rho$, use small diameter wire MIG. Since it can be thought that $\left(V_w \frac{Ex}{k}\right) - 1$ in welding, and formula of wire melting rate is obtained from heat input state of the wire stick out and resistance of the wire extension, and it is understood that it receives the amount of heat retained by the droplet.

$$V_w = (\emptyset j + R_0\, E_x j^2)/4.2\rho R_0 \tag{24}$$

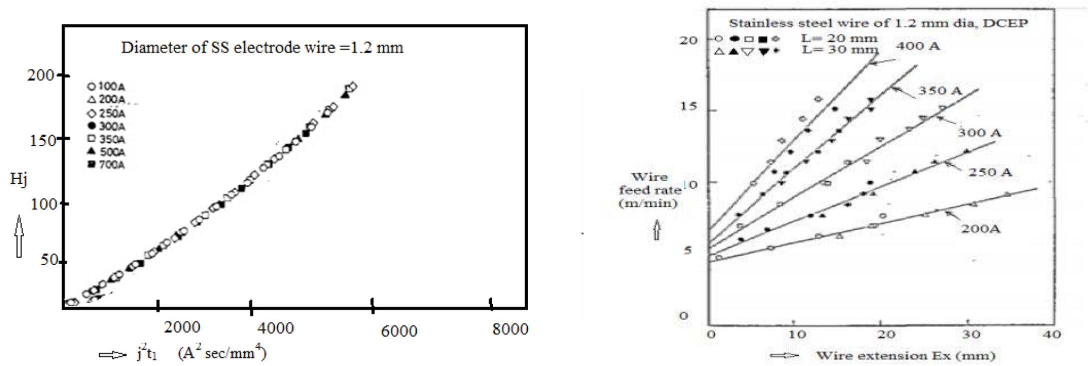

Figure 2 (a) Heat content per unit mass of GMA electrode wire by joule's heating [17]
Figure 2 (b) Alliance between WFS and electrode stick out for a 1.6 mm diameter steel wire with argon as shielding gas [5].

3.4 Calculation of heat retained by droplets

There are various theoretical and empirical techniques for calculation of wire melting rate in p-GMAW [5]. For wire melting coefficient (α_m), wire density (ρ), welding current (I_w), wire cross-sectional area ($F = \pi r {d_e}^2/4$), where d_e is diameter of filler wire, WMR can be expressed as

$$V_w = \alpha_m I_w / 3600\rho F \tag{25}$$

The amount of heat retained by the droplet (H_o) is heat quantity given from arc (H_A) and resistance obtained by heat generation (H_J). For stable MIG arc, the heat holding amount H_o of the droplet is

$$H_o = H_A + H_j \tag{26}$$

$$H_A = \emptyset j / 4.2\rho v_w \tag{27}$$

$$H_J = R_o E_x j^2 / 4.2\rho v_w \tag{28}$$

Resistance calorific value (H_J) can be derived from the direct energization of the wire without generating it. During the energization time t_1, the wire reaches the arc generation point. During initiation of the current flow, t_1 is time (t_1=E_x/V_w) for second pass than the amount of heat held per unit mass of wire at the time point. However, V (t) is the voltage between the gauge points and l_o is the gauge distance at room temperature. H_j can also be calculated as

$$H_J = j \int_0^{t1} V(t)dt / 4.2\rho l_0 \tag{29}$$

However, V (t) is the voltage between the gauge points and l_o is the gauge distance at room temperature.

$$V_w = (\emptyset j + a\, E_x j^2)/4.2\rho\,(H_0 + b) \tag{30}$$

H_o is obtained by using the resistance characteristic values 'a' and 'b' of the wire from figure 2(a) with maximum error 5%. The values of a' is 1.16 X 10^{-3} Ω.mm and 'b' is 29 cal/g for Grade 304 SS 1.2 diameter filler wire. Results conclude that experiment is prominent to measure long E_x to dissolve, hence it is practicable in the current range where droplets migrate with relatively small diameter. If, V_A = anode drop, V_{WA} is anode work function, V_T is an equivalent voltage of the plasma temperature in the case of steel. The equivalent voltage (φ) required for melting of wire can be estimated as

$$\emptyset = V_A + V_{WA} + V_T \tag{31}$$

3.5 Quantification of Wire melting rate

Wire melting or burn off rate of pulse GMAW is kept comparatively high, intended for droplet formation and transition of metal transfer mode. If overall wire melting rate is V_{wo} and V_{wp} and V_{wb} are the wire burn off rates for the period of peak current duration (T_p) and base current duration (T_b) respectively [18,19]. In consideration V_{wo} may be expressed as

$$V_{wo} = \int_0^{t_{pul}} V_w T_{pul} dt_{pul} \tag{32}$$

For a square pulse-GMAW equation 32 can be determined by

$$V_{\rm wo} = (V_{\rm wp}T_p + V_{wp}T_b){T_{pul}}^{-1} \quad (33)$$

Here V_{wp} and V_{wb} can be evaluated by the following formula

$$V_{\rm wp} = {\rm A}I_p + BE_w{I_p}^2 \quad (34)$$

$$V_{\rm wb} = {\rm A}I_b + BE_w{I_b}^2 \quad (35)$$

Here first term (AI_b) represents the contribution from arc melting, and the second term of ($BE_wI_b^2$) represents the contribution from electrode extension resistance heating as displayed in figure 2 (b). The arc melting term is dependent on the polarity, electrode type and size. For DCEP constant voltage pulse transfer magnitude of coefficient 'A' is approximated as 0.28 and value of 'B' lies within 0.9–1.0 [1].Therefore equation can be rewritten as

$$V_{\rm wo} = \left[{\rm A}(I_pT_p + I_bT_b) + {\rm B}E_w({\rm I}_p{}^2T_p + {\rm I}_b{}^2T_b){T_{pul}}^{-1} \quad (36)$$

Overall wire melting rate (V_{wo}) can be articulated as function of as a function of average current (I_{avg}) and pulse frequency (*f*) assuming ${\rm I}_p{}^2T_p \gg {\rm I}_b{}^2T_b$ and ignoring the ohmic heating droplet detachment. Thus equation 37 will provide constant wire feed rate (V_w) for given wire parameters by fixing the fraction of average current (I_{avg}) to pulse frequency (*f*) [1, 20].

$$V_{\rm wo} = {\rm A}I_{avg} + {\rm B\,E}_w\,{\rm D}_n\,f \quad (37)$$

Assuming wire feed rate (V_w) as equivalent linear function of overall wire melting rate (V_{wo}), equation 36 can be stated in terms of the droplet volume (v_d).

$$v_{\rm d} = {\rm AA_w}\frac{I_{avg}}{f} + {\rm A_w\,E}_w\,{\rm B\,D}_n \quad (38)$$

If droplet volume (v_d) is not influenced with average current by previous assumptions, and equation 36 can modified as.

$$V_{\rm wp} = {\rm A}I_m + BE_w(I_{\rm eff})^2 \quad (39)$$

Where

$${I_{\rm eff}}^2=\{D{I_p}^2 + (1\text{-D})\,{I_b}^2\} \text{ or} \quad (40)$$

$${I_{\rm eff}}^2=\{{I_{avg}}^2 + {\rm D}\,(1\text{-D})\,{I_e}^2\} \quad (41)$$

Pulse wire feed rate V_p can also mention in terms of wire feed rate of conventional GMAW V_{gmaw}.

$$V_{\rm wp} = V_{\rm gmaw} + BE_w{\rm D}\,(1-{\rm D})\,{I_e}^2 \quad (42)$$

Expression states that wire melting rate of p-GMAW is relatively higher than of conventional GMAW.

4. Conclusion

Various researchers investigated the intricate association of SS pulse parameters and detailed a critical and selective application using multiple techniques. Though, there is a squabble between researchers to consider base current for the formulation of practicable parameters for 300 SS series or not. It is mandatory to control arc current as is directly proportional to wire feed rate for steady GMAW process. The exact match between wire feed rate and wire melting rate is essential, as lesser wire feed rate grounds melt back the filler wire, whether higher feed rate extinguishes the arc. It is found that for a fixed peak current, its average value is also invariable at a particular pulse frequency. It is invariably influenced by the wire feed rate, even if the average current is constant, still.

The summarized review state that the wire melting rate of MIG welding is determined by arc melting equivalent voltage of fusion, length, and the resistance value of projecting part, heat retained by droplet, the magnitude of arc current and its types. In pulse welding, in addition to the pulse current waveform, the average current and the effective current are the determining factors of the wire melting rate. It is anticipated that quantification of wire and its governing parameters, investigational interpretations and numerical analysis for the p-GMAW process have directed towards innovative results enterprising the modeling and simulation feasibility of the process for welding of 300 series stainless steel.

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