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Journal of Materials Processing Technology 164–165 (2005) 1113–1119
Journal of Materials Processing Technology
www.elsevier.com/locate/jmatprotec

Advancements in pulse gas metal arc welding

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Abstract

Environmental concerns have driven manufactures to look for alternative materials like aluminium that are lighter in weight and possess good thermal and electrical conductivity. However, fabrication of alternative materials presents a considerable challenge for fabrication in volume production. Welding is one of the most common fabrication processes. Good thermal and electrical conductivity act as a drawback for welding and generally results in excessive heating of base material. Pulse gas metal arc welding (GMAW-P) overcomes this drawback by producing spray transfer at lower mean currents. Modern welding has become complex due to need for setting up of combination of large number of welding parameters to achieve best quality of weld. Trial and error methods are impractical. In addition, there are many facets of disturbances and each has its own source and mitigation techniques. This need has resulted in several advancements in GMAW-P technology. This paper reviews progress in performance of GMAW-P technology.

Keywords: Synergic systems; Pulse gas metal arc welding; Microprocessor-based control

1. Introduction

Gas metal arc welding (GMAW) is widely used in industries for welding wide variety of ferrous and non-ferrous materials. GMAW achieves coalescence of metals by melting continuously fed current-carrying wire. However, attractive-looking GMAW needs consistent, high-quality welding procedures to achieve good quality. This need is due to continuous control metal transfer that is necessary in GMAW.

At relatively low currents, GMAW operates in the globular metal transfer mode. When current is increased, the process transits to spray mode. Globular mode is characterized by periodic formation of big droplets at the end of electrodes (which detach due to gravitational force in to the weld pool) and suffers from lack of control over molten droplets and arc instability due to formation of big droplets. Spray mode offers high deposition rate but minimum current for spray mode is too high for some materials, large heat input to workpiece, wide bead, and only downhand positional capability are some of its drawbacks. These modes of metal transfer are shown in Fig. 1(a) and (b).

During the mid-1960s, an alternative transfer technique of GMAW-P was invented. This mode of metal transfer overcomes the drawbacks of globular mode while achieving the benefits of spray transfer. This mode is characterized by pulsing of current between low-level background current and high-level peak current in such a way that mean current is always below the threshold level of spray transfer. The purpose of background current is to maintain arc where as peak currents are long enough to make sure detachment of the molten droplet.

Due to existence of number of metal transfer modes, the knowledge of the transition current zone between the globular and spray mode has great importance in the GMAW process, because it determines the working conditions of the process [14]. This region of operation for pulse is very narrow and is dependent upon number of changing welding conditions during welding operation [13]. Hence good process stability and quality of weld fillet can only be obtained by controlling the mode of metal transfer. With the advent of electronics, significant progress has been made in the development of high-performance arc welding equipment. This

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0924-0136/$ – see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.jmatprotec.2005.02.100

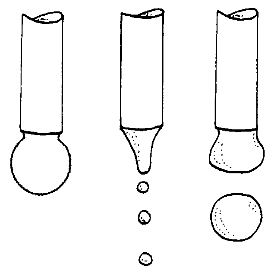

Fig. 1. Different modes of metal transfers in GMAW: (a) globular, (b) spray, and (c) pulse.

paper describes some of the recent developments in the area of control technology to enhance capability of GMAW-P.

2. Advancement in power source design

The basic function of a welding power source is to produce and control current and voltage required for arc welding. Market demands for reduction in size, cost, weight and improved reliability has seen many changes in the design of power sources. These advancements in the design have been possible because of advances in electronics industry and better understanding of welding arc phenomena.

2.1. Conventional transistorised power sources

Conventional transistorised power sources were in-phase regulator type utilising paralleled connected banks of small power transistors, which serves as variable load resistor. Welding machines of this design are simple and robust in nature. The drawbacks of this design are high cost, large size due to water-cooling units and lacks advanced control feature needed for GMAW-P.

2.2. Secondary transistor-controlled series regulators

The secondary transistor-controlled series regulators operate in two modes through secondary transistor: periodic on and off at a switching frequency or by adjusting the ratio of the make-time to the break-time (pulse width modulation). Higher output is attained by large switching frequency or by higher ratio of make-time to the break-time. Benefits from machines of this design is reduced power dissipation, air cooled comparatively smaller size, smooth output and are well suited for the pulsed GMAW due to improved response rate and better control. Popular variations like chopper control power sources are available, yet they are still inefficient, available in restricted ranges of control and operation, bulky and expensive to manufacture.

2.3. Primary transistor switched inverter technology

Primary transistor switched inverter technology transform input signal to high operating frequency using high-speed transistor switches. Operations at high frequency give direct benefits in the form of portability, lesser weight, arc stability, faster response times, energy efficient and reduced running cost. Indirect benefits are in form of reduction in labour and transportation cost. A brief comparison between inverters and other forms of power source design is tabulate in Table 1.

Table 1
Comparison of various power source designs

Power sources	Traditional	Inverter
Power consumed	More	Less
Electrical efficiency	Poor	Good
Size	Large	Compact
Weight	More	Less
Areas of usage	Research only	Wide range
Frequency of operation	Low	High
Running cost	High	Low
Cost of production	High	Low
Labour cost	High	Low
Material cost	High	Low
Number of tapings in transformer	More	None
Design	Simpler	Complex
Repair	Possible	Replace mostly
Control of metal transfer mode	Poor	Better
Arc stability	Low	High

3. Advancement in pulse waveform

3.1. Principal factors and influences

GMAW-P offers significant benefits. However, in order to achieve these advantages, careful setting of large number of welding parameters is required. Complete explanation of influence of individual parameters is beyond the scope of this paper. The influence of various parameters has been summarized in Tables 2 and 3.

3.2. Pulse waveforms

Waveforms are response of welding power source to actions of electric arc. The area under the waveform determines the amount of energy transmitted by a single droplet to the workpiece. Waveform allows heat transfer to workpiece in a more effective manner and has the ability to manipulate travel speeds, heat input, fumes, spatter and appearance of weld.

Table 2
Influence of various system parameters

Parameters	Influences
Welding speed	Penetration Metal transfer mode
Wire size	Penetration
Wire-feed rate	Penetration Weld bead shape
Shielding gas	Arc stability Metal transfer mode Weld bead shape Molten droplet detachment

Table 3
Influence of various pulse parameters

Parameters	Influences
Peak current	Metal transfer mode Tapering of electrode Penetration Molten metal droplet detachment
Peak time	Number of droplets detached per pulse
Base current	Molten metal droplet detachment Temperature of transferred metal Fluidity Width of weld pool Wetting in weld bead Influences drop size
Mean current	Metal transfer mode
Frequency	Number of droplets detached per pulse Mean current
Pulse duration	Number of droplets detached per pulse Influences drop size
Duty cycle	Number of droplets detached per pulse
Response rate	Melting rate Diameter of molten droplet Fused plate and reinforcement area

In order to improve control of metal transfer, waveforms can now be tailor made to suit different welding conditions as the power sources respond to changes demanded by the software instantaneously.

New way of achieving better penetration is through use of two distinct series of welding pulses and pulsing wire-feed rate. Two of the pulse waveforms employing this technique have been shown in Fig. 2. In Alu-Plus, combinations of hot and cold series of pulses at a fixed frequency are employed [5]. Set of cold pulses maintains the arc length, preheats both the electrode wire and the material surface, stabilises weld pool and produces a weld ripple each time it is fired. Set of hot pulses improves control over weld pool and penetration. Pulsing of wire-feed rate produces acceleration and deceleration phases resulting in ripples on weld bead [2]. During acceleration phase, arc energy grows and achieves better weld penetration. In deceleration phase, arc energy reduces and stabilizes weld pool.

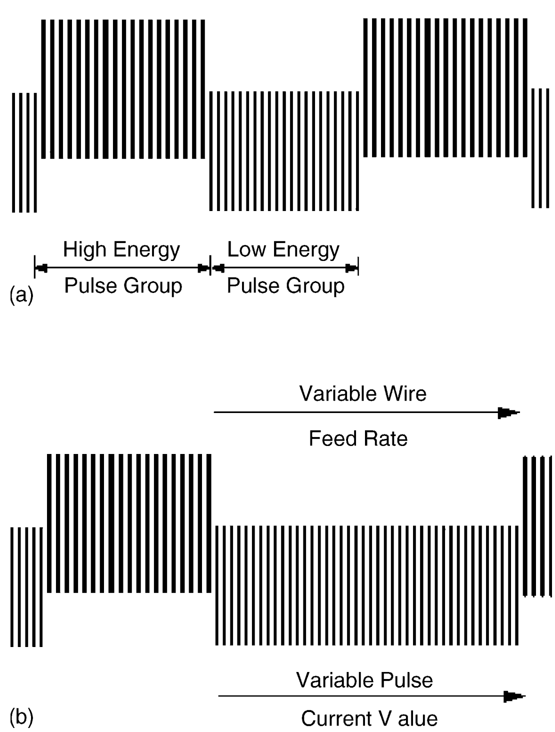

Fig. 2. Different pulse waveforms for GMAW-P: (a) Alu-Plus [5] and (b) Double Pulse [2].

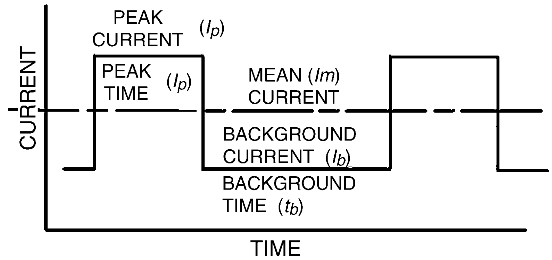

Fig. 3. Perfectly rectangular signal.

3.3. Physical equations for controlled transfer based upon output electrical signal format

(a) Perfectly rectangular [3] (see Fig. 3):

$$I_{\mathrm{m}} = \frac{I_{\mathrm{p}} t_{\mathrm{p}} + I_{\mathrm{b}} t_{\mathrm{b}}}{t_{\mathrm{p}} + t_{\mathrm{b}}}$$

$$W = \frac{\alpha I_{\mathrm{m}} + \beta L (I_{\mathrm{p}}^2 T_{\mathrm{p}} + I_{\mathrm{b}}^2 T_{\mathrm{b}})}{T_{\mathrm{p}} + T_{\mathrm{b}}}$$

(b) Trapezoidal [6] (see Fig. 4):

$$I_{\mathrm{m}} = \frac{\frac{t_1(I_{\mathrm{p}}-I_{\mathrm{b}})}{2} + t_2(I_{\mathrm{p}} - I_{\mathrm{b}}) + \frac{t_3(I_{\mathrm{p}}-I_{\mathrm{b}})}{2} + I_{\mathrm{b}}(t_{\mathrm{p}} + t_{\mathrm{b}})}{(t_{\mathrm{p}} + t_{\mathrm{b}})}$$

$$W = \alpha I_{\mathrm{m}} + \beta L I_{\mathrm{m}}^2 + \frac{(I_{\mathrm{p}} - I_{\mathrm{b}})^2 t_{\mathrm{p}} t_{\mathrm{b}}}{(t_{\mathrm{p}} + t_{\mathrm{b}})^2} - \frac{(I_{\mathrm{p}} - I_{\mathrm{b}})^3}{3(t_{\mathrm{p}} + t_{\mathrm{b}})\frac{\mathrm{d}I}{\mathrm{d}t}}$$

(c) Exponential [12] (see Fig. 5):

I_{m} (meant current) and W (wire-feeding rate) simplify to same as for trapezoidal waveform. α and β are constants associated with arc and resistance heating.

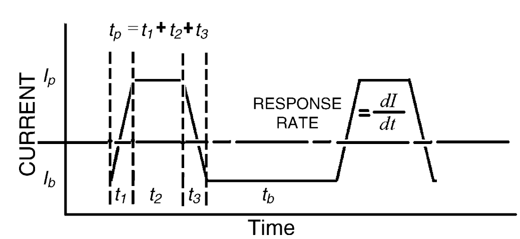

Fig. 4. Trapezoidal signal.

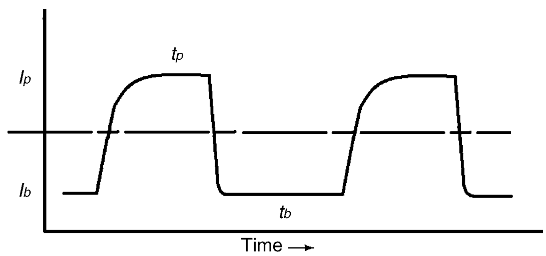

Fig. 5. Exponential signal.

3.4. *Characteristics of pulse zone [8]*

(a) *Burn off criterion*: Maintain constant arc length by balancing wire-feed rate and wire burn off rate.
(b) *Metal transfer criterion*:
- Spray transfer must be produced at low wire-feed speeds;
- Pulse amplitude must exceed minimum limit to produce spray transfer;

(c) *Arc stability criterion*:
- Background current must exceed minimum limit;
- Background current and pulse amplitude should not be too high;

(d) *Capacity criterion*: Limitation to peak current by power source capacity at excessively very high pulse amplitude setting.
(e) *Droplet detachment criterion*:

$$I_{\mathrm{p}}^{\mathrm{n}} t_{\mathrm{p}} \geq c$$

where n is the slope, c a constant, and both are dependent on chemical composition and diameter of filler wire (see Fig. 6).

4. Advancement in control features

With increasing use of automation in welding systems, need for automatic control system for achieving better quality and improved control has grown. In a welding system, principal sources of disturbances, which need constant control and adjustments, are welding parameters.

For achieving controlled transfer during pulse welding, it is essential that wire-feed rate is balanced by burn rate [8]. This means achieving one drop per pulse condition all the time, which involves constant control of all the pulse parameters. Synergic control [4] is defined as – 'any system (open or closed loop) by which a significant pulse parameter (or the corresponding wire-feed speed) is amended such that an equilibrium condition is maintained over a range of wire-feed speeds (or average current levels)'. Synergic has been practically implemented into modern welding machine in two forms: one-knob control and microcomputer control.

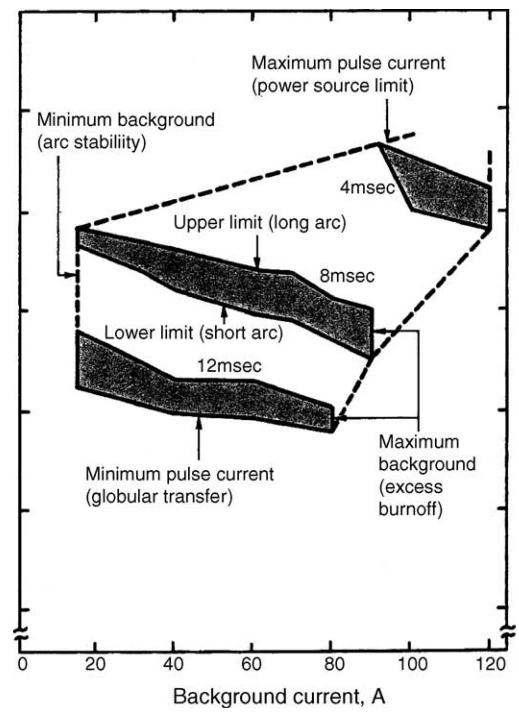

Fig. 6. Pulse parametric zone [7].

4.1. *One-knob control*

One-knob control achieves manipulation of all pulse variables by using a single control or knob. This type of control eases the jobs of welder, allowing him to manipulate all welding parameters over wide range of wire-feed rate and current. This system uses tacho generator reading as input to hardwired electrical unit, which generates appropriate square waveform based on input. Logic of one-knob control is implemented in two ways.

4.1.1. *Synergic control*

This mode can also be regarded as wire-feed speed control of mean current [12]. Power supply and wire-feeder are directly linked in such a way that means current is determined by wire-feed rate to ensure stable arc. The circuit arrangement for this system is shown in Fig. 7.

The pulse waveform (see Fig. 8) produced by this type of control has constant peak duration and excess current. Variable pulse parameters are peak current, base current and base current duration. This control can only be operated in the fixed ranges of mean current as large mean current might produce multiple droplets detachments per pulse.

4.1.2. *Self-regulating control*

This mode can also be regarded as voltage control of mean current or error voltage system [12]. The welding voltage varies according to the arc length in GMAW. This system always tries to restore arc length to set reference voltage by automatically modifying the burn off rate. The circuit arrangement for this system is shown in Fig. 9.

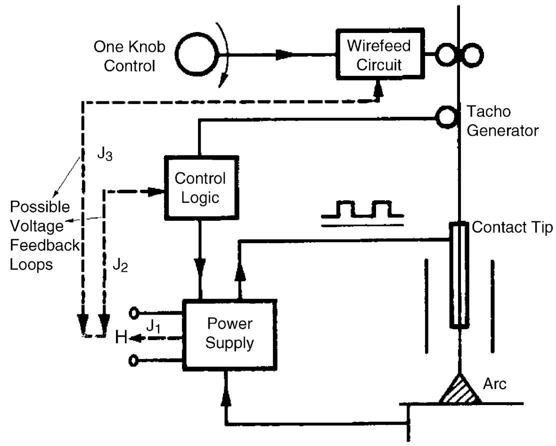

Fig. 7. Synergic control [12].

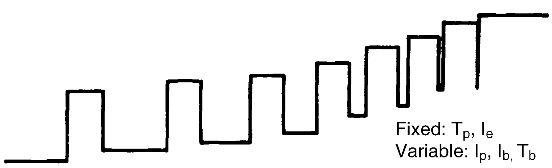

Fig. 8. Pulse waveform of synergic control [1].

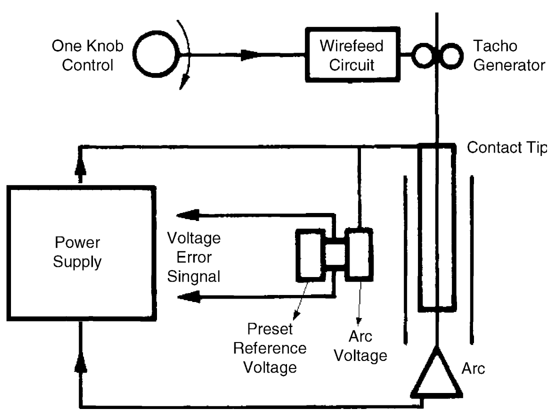

Fig. 9. Self-regulating control [12].

The pulse waveform (see Fig. 10) produced by this type of control has constant peak duration, peak current and base current. Only variable pulse parameter is base current duration. This control logic is poorly defined as base current influences droplet size [1] and requires constant adjustment to electrical stick out (or arc length).

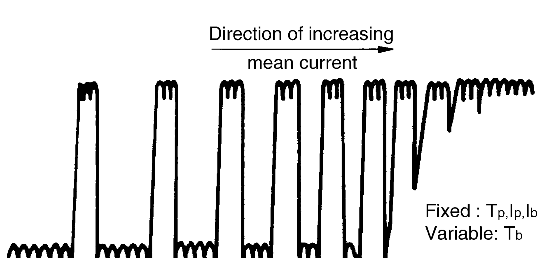

Fig. 10. Pulse waveform of self-regulating control [1].

One-knob control also suffers from need for calibration at the start that requires considerable operator skills, cannot incorporate other system variables such as shielding flow gas rate control, seam tracking, etc., and simpler design gives poor flexibility as it restricts search.

4.2. Microcomputer control

Latest generation of advanced electronic power sources are controlled by microprocessor or microcontroller. They have replaced traditional hard-wired systems for controlling, sequencing and timing of operations to achieve optimum output. The microprocessors increase flexibility by quick retrieval of predetermined process parameters and storing algorithms, which can compute relationship between various pulsing parameters. Synergic relationships between pulse parameters can be stored in some form of memory system, e.g., EPROM, EEPROM (electrical erasable programmable read only memory) or FLASH ROM, etc. [10].

Fig. 11 shows microcomputer control for synergic systems. This system first takes wire material and diameter as input to compute molten metal droplet volume. Based on droplet volume, pulsing parameters, wire-feed rate and arc length are automatically selected from memory. The possible disturbances in the system can be extinguishment of arc and change in wire-feed rate or arc length. Former is overcome by initiating the arc again by supplying a high level DC current. Latter is automatically corrected by resetting freshly calculated values of pulsing parameters from synergic relationships defined in the memory.

Various types of controls developed with help of digital technology by using microprocessor are as follows.

4.2.1. Arc length regulation control

Arc regulation in modern welding power source is achieved through control of arc voltage. Any change in arc length will possibly result in longer arc length or short-circuiting, which can be detected by monitoring arc voltage. The possible scenario for voltage change is shown in Table 4.

Voltage drop below predetermined threshold arc voltage causes short circuit to occur. To clear short circuit, short pulse of high current is applied as in "dip pulse" shown in Fig. 12. Pulse then returns to its normal form.

Wire-feed arc voltage control achieves the control by modifying wire-feed rate. If arc length is increased, wire-feed rate is increased to main constant arc length. This method is currently not popular due to poor stability and comparatively slower response rate of wire-feeders.

Frequency arc voltage control achieves the control by modifying pulse frequency, which in turn modifies mean current. This mode basically restores the arc length by decreasing the number of drops transferred to the workpiece.

CC/CV arc voltage control depends upon dynamic characteristics of the welding power source. CV mode is characterized by large change in current for small voltage change (see Fig. 13).

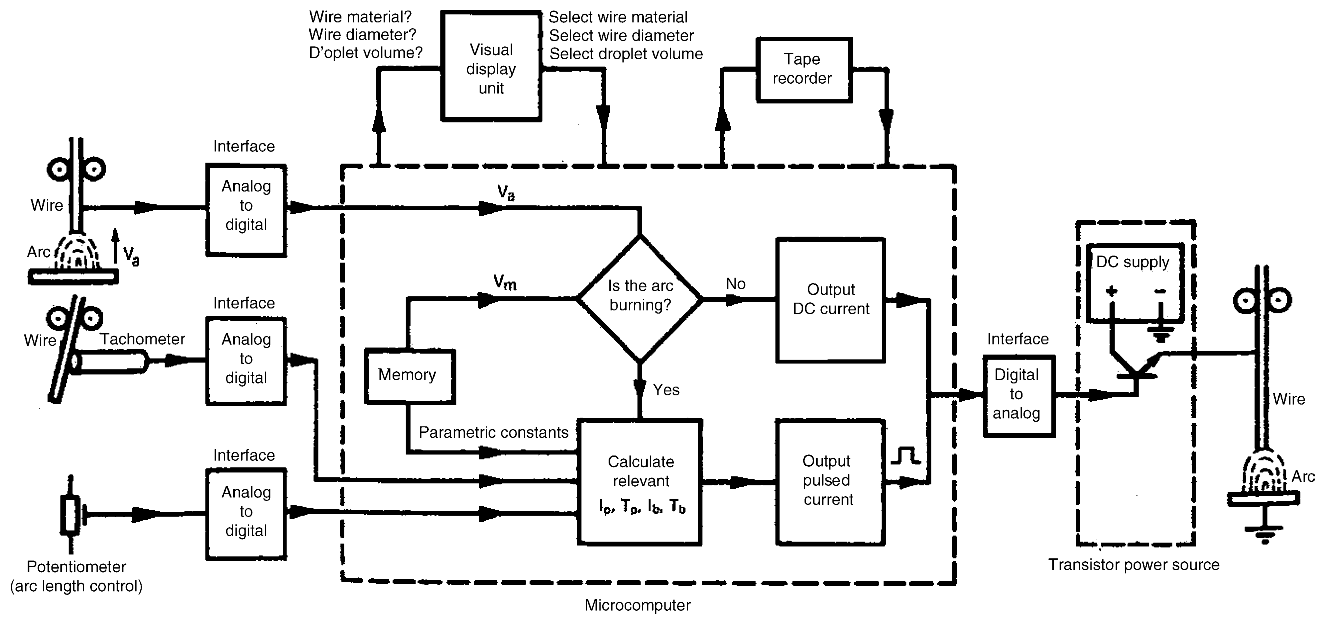

Fig. 11. Microcomputer-controlled pulsed synergic system [9].

Table 4
Different voltage changes in system

Scenario	Control method
Voltage drop below threshold	Short-circuit control
Voltage fluctuation	Wire-feed arc voltage control Frequency arc voltage control Constant voltage/current (CC/CV) arc voltage control

CV/CC pulsed MIG power source using both modes, assumes CC mode during pulse peak duration and CV mode during background duration.

CC mode during peak tries to control and self-regulate the arc length, while CV mode in background stabilizes arc length.

4.2.2. Arc ignition and start-up control

Traditionally welding is started by moving the welding wire towards workpiece and the short-circuited wire melts and ignites. Such a start is accompanied by some spatters.

The development in electronics has made welding power sources more intelligent. The welding power source can now be started without spatter and eliminates poor fusion defects generally observed for high conductivity materials such as aluminium. The start feature usually employs slow run in start techniques to eliminate start-up defects.

4.2.3. Weld termination control

Significant improvements have been made to achieve better control over weld termination. Burn back control sheds the accumulated molten metal at the end of the electrode and leaves a sharp end electrode ready for next weld. Crater fill control feature eliminates the crater, which is formed at the end of weld by gradually decreasing the welding current over a certain period or reversing the direction of welding at end.

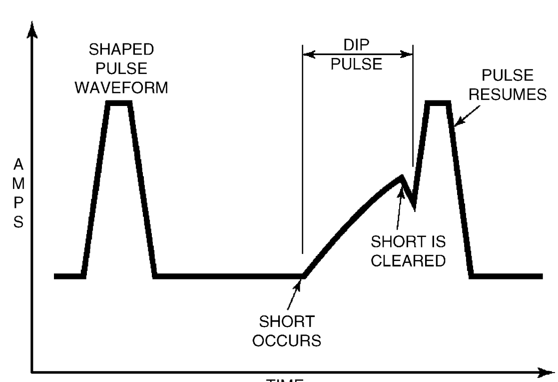

Fig. 12. Short-circuit control through dip pulse [11].

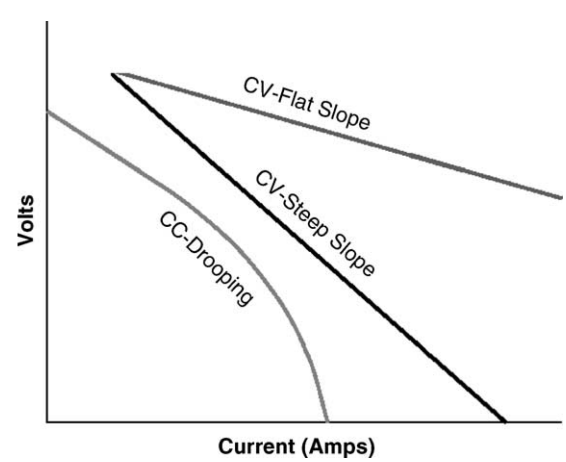

Fig. 13. CC/CV curves.

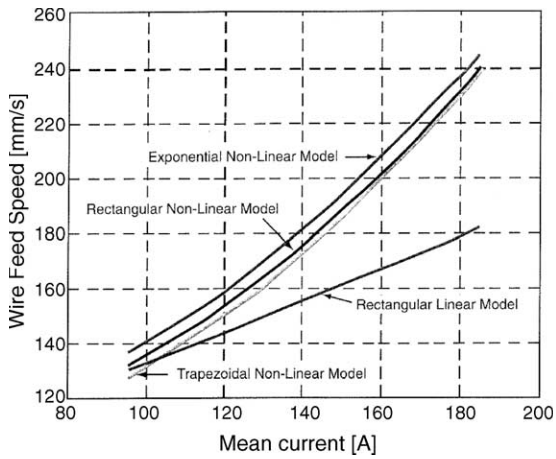

Fig. 14. Nonlinear models between mean current and wire-feed rate [6].

5. Discussion

In spite of several controls and methods described above, the welding arc in GMAW-P changes irregularly even under similar welding conditions. The two possible reasons for this behaviour are disturbance due to external and internal factors. The disturbance in the welding system causes deviation to occur from predetermined parameters settings.

Internal disturbances in the welding system may be attributed to influence of dynamic response of power source [3]. These deviations are due to nonlinear relationship between average current and resistance melting of wire and generally results in poor quality of weld. Fig. 14 shows some of the nonlinear relationships between average current and wire-feed speed. Improved external control is obtained by implementation of nonlinear relationships between welding parameters taking into account power source dynamics.

Stabilising the arc in real time due to disturbances means regularising the waveforms of the welding current and welding voltage. The nonlinear form of disturbances is difficult to model using conventional methods like PID controllers. Robust methods using artificial intelligence like neural networks, fuzzy logic and genetic algorithms must be implemented to refine control strategies. Such a system can self-diagnose the system and can easily respond to the changes. This feature also improves process consistency by elimination of need for trim control to counter deviations from predetermined parameters.

6. Conclusion

Recent developments in the controlled transfer have achieved better control of GMAW-P and offer benefits in both production and quality. The use of intelligent microprocessor control in conjunction with automatic feedback control systems can provide implementation of quality systems at affordable price. With advent of technology and increase in the knowledge base about welding processes, future trend of GMAW-P machines is likely to be improved performance at affordable price.

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