Evolution of Advanced Process Control in GMAW: Innovations, Implications, and Application

Attempts to understand the original GMAW process, significant developments and trends in process control, and applications of intelligent GMAW are discussed

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Abstract

The first half of this paper reviews the significant body of work that has been devoted to understanding the fundamentals of the basic GMAW process and the use of this knowledge to develop and enhance process performance. Some of the important background studies devoted to metal transfer mechanisms are reviewed, and the tools developed to model the process and define the critical control variables for GMAW are discussed.

The limitations in process performance, such as unstable transfer in low current globular, spray, and short circuit transfer modes and the perceived risk of lack of fusion in short circuit transfer, are considered. These limitations have been mitigated to some extent by process optimization based on the process models developed as well as improvements in welding consumables. Despite the limitations, it is suggested that satisfactory operation could be achieved with simple equipment and a limited number of essential control variables. Early attempts to rectify the limitations are described, but it is argued that these early innovations were restricted by the limited operating envelopes and capabilities of the original power supplies.

The radical development of advanced electronic power control and its effect on extending the process operating modes is described, as are the developments in dynamic waveform control. The introduction of synergic control to enable the more complex control variables to be accommodated is also discussed. The effect of waveform control and synergic program constraints on welding procedure management is analyzed, and the advantages of improved process monitoring are reviewed.

Future developments in process monitoring and control based on artificial intelligence are introduced, and a possible development to improve synergic program flexibility is suggested. Finally, the type of applications that fully utilize this 'intelligent' GMAW are illustrated.

Keywords

- Gas Metal Arc Welding
- Metal Transfer
- Waveform Control
- Synergic Control
- Welding Procedures
- Process Monitoring
- Machine Learning

Introduction

This paper aims to support the AWS 2023 Comfort A. Adams lecture "Intelligent GMAW." The term "intelligent GMAW" has been used here based on the Oxford dictionary definition of "intelligent" as "having a high degree of understanding."

Comfort A. Adams was a preeminent engineer who recognized the potential and importance of welding. He was an innovator who understood the multidisciplinary nature of welding technology and the importance of a fundamental understanding of the underpinning science. In Adams' words: "The science and art of welding involved so many branches of technology that it had as yet a long way to go in the field of fundamental research" (Ref. 1).

GMAW was conceived more than 80 years ago and remains one of the most important industrial welding processes. The first half of this paper deals with the various attempts to

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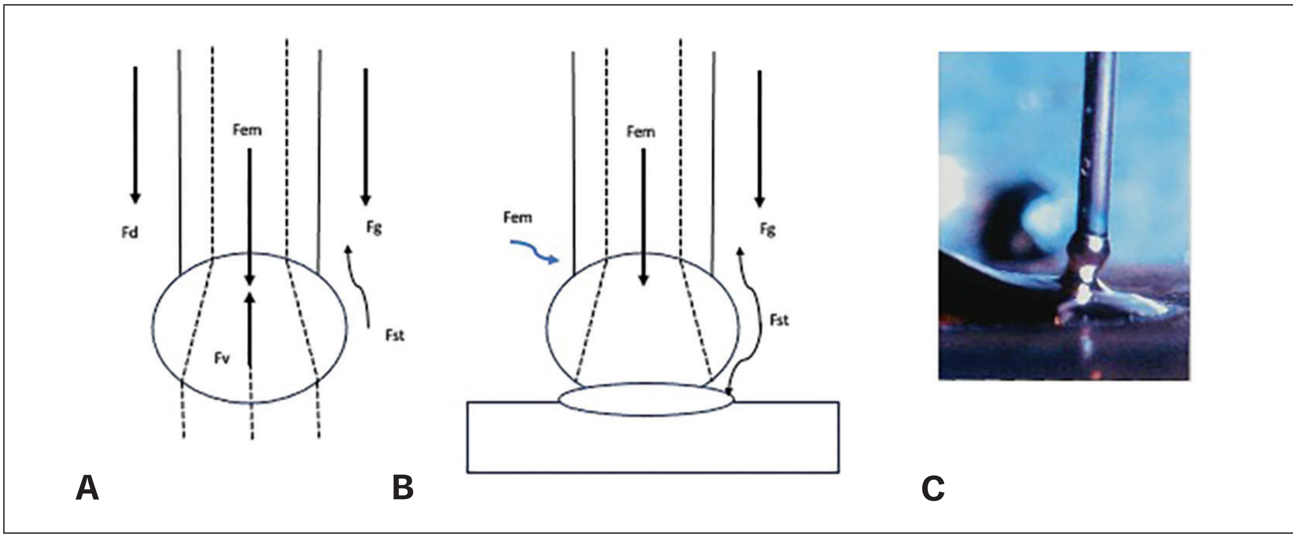


Fig. 1 — A — Static balance of forces free flight transfer. Fg gravitational force, Fd aerodynamic drag, Fe electromagnetic force, Fv vapor jet force, and Fst surface tension force. B — Short circuit situation where surface tension between droplet and pool, Fst, dominates, while electromagnetic pinch forces aid droplet separation; C — photograph of short circuit in progress.

understand the original GMAW process fundamentals. This underpins the recognition of the limitations of conventional GMAW and the potential for intelligent application of fundamental knowledge, together with major improvements in system technology.

The remainder of the paper deals with the most significant developments and the latest trends in process control as well as the potential consequences of these developments and outstanding challenges for the future.

Background

Metal Transfer Mechanisms

The mode of metal transfer defines the features, applications, and useability of the GMAW process. When it was first introduced, GMAW was operated in the free-flight transfer mode. The short arc process mode was introduced a few years later.

A phenomenological classification of metal transfer modes was produced for the International Institute of Welding (IIW) in 1969 (Ref. 2), using direct high-speed cine imaging. A large amount of work on understanding and modeling metal transfer has continued since this time. Early attempts were made to understand the basic mechanisms of metal transfer and the influence of process variables. In 1960, Needham et al. (Ref. 3) described the mechanism by which metal was transferred from the filler wire into the molten weld pool. More-sophisticated studies of metal transfer have been based on physical, numerical, finite element, and computational fluid flow techniques. Lancaster (Ref. 4) produced a comprehensive review of these approaches to quantifying metal transfer mechanisms. More recently, Kim and Eager (Ref. 5) produced an analysis of globular to spray transition based on force balance and pinch instability theories, and Haidar (Ref. 6) used numerical physics-based modeling to predict droplet formation and the globular-to-spray transition. The static force balance approach (Ref. 7) remains one of the most useful models when attempting to understand metal transfer mechanisms. This physical, semiquantitative model considers gravitational, aerodynamic drag, electromagnetic, vapor jet, and surface tension forces operating on the droplet, as shown in Fig. 1.

At detachment of a droplet in free flight transfer, in the gravity position, the detachment forces need to exceed the retention forces, or:

$$Fg + Fd + Fem > Fst + Fv \tag{1}$$

In general, gravitational, surface tension, and electromagnetic forces are dominant in globular and spray modes. The effect of the forces will, however, be affected by the welding position. The magnitude of the forces and, in particular, Fem and Fv are strongly influenced by current density, filler material composition, and shielding gas. The approximate magnitude of all these forces may be calculated and are useful indicators of metal transfer phenomena, both favorable and adverse. Using this model, it is possible to explain the basic behavior of the process and its enhancements. For example, free flight-spray transfer gives uniform, projected transfer of small droplets. However, it only occurs above a certain transition current when the electromagnetic forces are strong enough to overcome surface tension and pinch the droplet from the wire tip. The transition current varies depending on the wire diameter and composition of the wire and the shielding gas. For a typical 1.2 mm diameter carbon steel solid wire in an argon CO_2 shielding gas mixture, the transition current is around 220 amps. Above this current, the transfer is uniform, but the heat input is too high for thin materials and out-of-position welding. Below this current, the

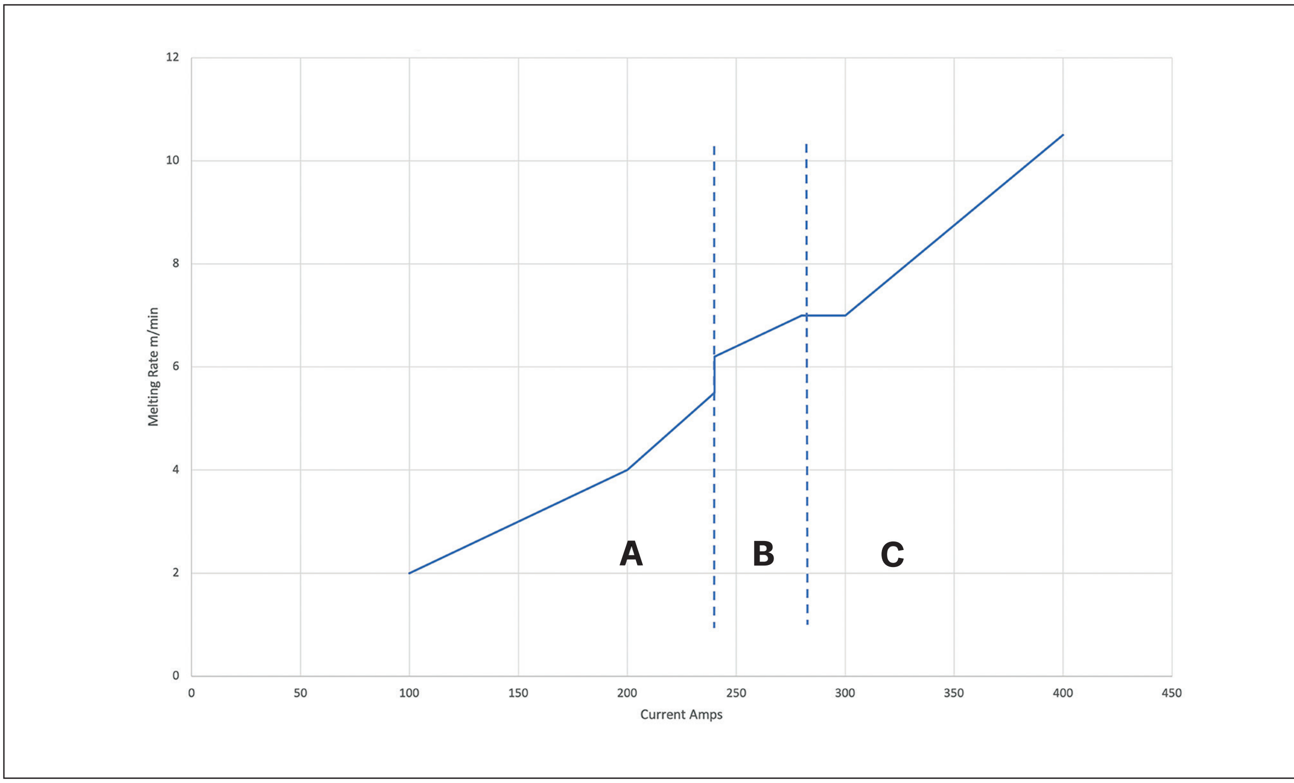


Fig. 2 — The drop spray burn-off characteristic identified by Ma (Ref. 11). Melting rate vs. current for 1.2 mm AWS A.5 70S6 wire, argon/5% CO_2, transistor series regulator power source. Melting rate range m/min (39.37 in./min). A — Globular region; B — drop spray; C — spray mode.

free flight transfer is globular. Vapor jet force Fv may play a role in destabilizing metal transfer, promoting globular or repelled transfer in high current CO_2 shielded welding of steel.

Short circuit transfer can operate below the transition current and provides a low heat input process mode applicable to thinner materials and out-of-position welding. However, a stable short-circuit transfer mode requires careful fine-tuning of the welding parameters. Using the force balance analysis above, the electromagnetic force can assist by reducing the cross-section of the neck of the material above the droplet, and the surface tension force acting between the weld pool and the wire tip must be sufficient to overcome the surface tension force retaining the droplet on the wire. Unfortunately, the short circuit current available from a conventional constant voltage or 'flat' characteristic power source is very high and the electromagnetic pinch force may be excessive. This may lead to very high electromagnetic pinch forces, explosive rupture of the neck of material above the droplet, and instability and spatter generation.

Improving Metal Transfer

The limitations of conventional transfer modes are indicated above. Before the introduction of electronic power control in welding systems, various attempts were made to address these limitations in both free-flight and short-circuit transfer modes. These solutions were electrical rather than electronic.

Fixed Frequency Pulsed Transfer

To enable spray-type transfer to be used at currents below the spray transition current, modulation of the current or voltage waveform at multiples of the mains frequency was introduced in the 1960s. The modulated high current cycle was interspersed with a low current background cycle, either from the same power supply or a second, parallel supply. Usually, the 'high current' phase operated for a period of one-half cycle of the mains frequency supply. Depending on the consumables used, the mains frequency, and peak current, this would represent around 5 to 10 droplets per pulse. The mean current could be reduced significantly by the low background current phase. This technique was used successfully for out-of-position welding of alloy steels and aluminum in critical applications, such as cryogenic tanks and armor steel. Variants of the process using simple phase-controlled silicon-controlled rectifier (SCR) solid-state devices were introduced for wave shaping, but these were relatively costly alternatives. Whilst successful welding conditions could be obtained, the operating range was restricted, and parameter selection remained relatively complex.

Short Circuit Transfer Modification

Conventional short-circuit transfer relies on the repetition of a constant succession of arcing and short-circuiting cycles. Arc heating and wire tip conditioning occur in the arcing phase, while droplet transfer takes place in the short-circuiting period, as discussed above. Transfer is very regular when the operating parameters are correctly adjusted and the joint conditions are unchanging. Unfortunately, small perturbations in conditions may cause instability. Low-frequency modulation, often using a two-level wire feed speed variation at around 1 to 5Hz, to produce a succession of overlapping 'spot' welds has been used to aid gap filling, but it does not change the underlying operating mode. Imposing fixed predetermined, fixed frequency, current pulses does not assist since it cannot accommodate the natural statistical variability of the process.

Decoupling Deposition from Effective Heat Input

The coupling of deposition rate to effective heat input is a limitation common to all conventional transfer modes. Attempts to decouple heating and deposition in conventional GMAW have been made. Smith (Ref. 8) used two power sources connected in parallel: a low current (constant current) power source for the arcing supply and a high current (constant voltage) supply for the short circuit. This allowed partially decoupled control and improved tolerance to fusion defects in pipeline girth welding. It was, however, complex and costly. Boughton et al. (Ref. 9) applied a similar technique by using a capacitor bank to supply the short circuit energy, and the result was a simple, cost-effective system for thin sheet metal welding using a low current single-phase supply. The early attempts at metal transfer control were, however, very restricted in operating range due to constraints on control and response rates of the electrical systems. These developments did, however, indicate the benefits of partial decoupling but also the need for increased operating range and improved control of metal transfer and energy input.

Advanced Electronic Power Control

The availability of high-power semiconductor devices in the 1970s enabled solid-state welding power supplies to be produced with less reliance on electromagnetic and switched control systems. The earliest commercial examples of these were secondary phase-controlled systems using silicon-controlled rectifiers. These provided continuous fine control of output and facilities, such as low power remote control, since the control signal operated at low voltage electronic circuit levels of a few milliamps. However, these designs still relied on costly primary transformers. For research applications, very high response rate programable welding power source designs were developed, based on transistor analog series regulators (Ref. 10). These systems provided a unique platform for GMAW metal transfer research.

Drop Spray Transfer

Ma (Ref. 11) used a transistor series regulator to investigate free flight transfer with a 1.2 mm-diameter steel consumable in an Argon-5%CO_2 shielding gas. He identified a unique transfer mode known as "drop spray," which occurred over a very narrow current band (Fig. 2).

The significant features of the drop spray mode are the slight increase in melting rate, the uniform drop size, minimum fume, and low spatter formation. The restricted operating current range and the requirement for very precise and stable current control did, however, limit this mode to very high-performance power supplies. It can, however, be exploited using pulsed waveform control with lower cost and more efficient primary rectifier inverter systems and computer control (Ref. 12). The concept of 'static voltage-current characteristics,' commonly used for conventional welding power supplies, is no longer appropriate when discussing electronic power control since the current-voltage relationship is dynamically controlled. Most systems are considered as current-controlled.

Waveform-Controlled Pulse Transfer

The possibility of variable frequency pulsed GMAW using a transistor power supply had already been demonstrated (Ref. 13), but the work of Ma allowed a very systematic way of defining single droplet pulsed transfer and enabled clear control rules to be developed. Single drop detachment per pulse may be produced by applying a specific pulse amplitude for a defined time. This requires the supply of precise current pulses. Although originally investigated with costly transistor series regulator systems, most commercial primary rectifier/inverter power supplies can achieve the desired level of control. The optimum parameters are defined by the following relationship:

$$\boldsymbol{I_p^n t_p = D} \tag{2}$$

where I_p is the current amplitude, n is a value normally between 1.1 to 2, tp is the pulse duration, and D is the detachment constant (Ref. 14).

The optimum parameters for single droplet detachment may be determined by direct observation of the drop transfer using high-speed video or by interpretation of high-speed current and voltage traces. Ideally, the droplet formed during the background and subsequent pulse period is detached immediately after the end of the pulse, during the following background period. This 'ideal' transfer time is indicated by a discernible peak in the high-speed transient current records.

The background current I_b can be maintained at a level that is just sufficient to maintain an arc, and its duration is inversely proportional to the pulse frequency. Since the droplet size is virtually constant, the amount of metal detached from the consumable is also predictable. As a result, the wire feed speed (WFS) has a simple relationship to pulse frequency, such that:

$$\boldsymbol{WFS = kf} \tag{3}$$

where k is a constant and f is the pulse frequency.

These assumptions are based on the use of a simple current-controlled, rectangular waveform power supply. The melting rate would be expected to follow the relationship shown in Equation 5 if the mean current of the waveform is used. In practice, the melting rate (MRp) can be significantly affected by changes in the excess current (Ip-Ib) and the rate of change of current during the pulse (dI/dt), as shown by Richardson (Ref. 15). The melting rate relationship can then be expressed as:

$$MR_p = \alpha I_m + \beta l\left(I_m^2 + \left(\frac{\left(I_p - I_b\right)^2 t_p t_b}{\left(t_p + t_b\right)^2}\right) - \frac{\left(I_p - I_b\right)^3}{3S\left(t_p + t_b\right)}\right) \quad (4)$$

where S is the 'slew' rate (the rate of change of current dI/dt), I_m is the mean current, I_b is the background current, I_p is the pulse current, t_p is the pulse duration, and t_b is the background duration and a is a constant. Richardson indicated melting rate changes of 10 to 30% when the excess current and slew rate were varied.

Waveform-Controlled Short Circuit Transfer

The limitations of conventional short circuit transfer are described above. Because the process is stochastically variable, it is not feasible to superimpose the sort of preprogrammed waveform control that is used for pulsed transfer. Boughton (Ref. 16) argued that if the onset of a short circuit could be predicted, the short circuit current could be clamped at a low level to prevent explosive electromagnetic pinch effects, and subsequent transfer of the droplet would result from the surface tension between the droplet and the weld pool. He demonstrated the effectiveness of this approach with a high performance, current controlled power source. Subsequently, a variety of approaches have been used to implement these requirements (Ref. 17).

Sophisticated commercial GMAW power sources commonly use primary rectifier-inverter technology and digital signal processor (DSP) or computer software control. These systems have high response rates, flexible dynamic output control, and the required programmability to exploit the transfer modes described above. In some versions of waveform-controlled short circuit transfer, the transient wire feed rate is also controlled during the short circuit (Ref. 18).

In 2017, a group of experts from IIW listed and categorized more than 40 commercial variants of waveform control, including modified spray, pulse, and short-circuit transfer modes (Ref. 19).

Process Parameter Control Approaches

Basic Process Control

With early GMAW systems, the adjustment of operating parameters to match the desired operating characteristic was achieved by selecting a voltage and adjusting the wire feed speed to obtain stable operation. Secondary circuit inductance could also be adjusted to provide fine adjustment of arc operation. These systems are well understood (Ref. 19) and have been used for many years. They provide good arc performance and even inherent self-adjustment of arc length. Their main limitations are the need for some skill in choosing the appropriate operating parameters and the lack of independent control of deposition rate and effective heat input. The basic equipment was simple and comprised a 'flat' characteristic, or nominally constant voltage DC power supply, and a constant speed wire feed unit. Control of the process requires the wire feed rate to be matched to the melting rate of the filler wire. Lesnewich (Ref. 21) used the following equation to express melting rate in terms of the key welding variables:

$$MR = \alpha I + \frac{\beta L I^2}{a} \quad (5)$$

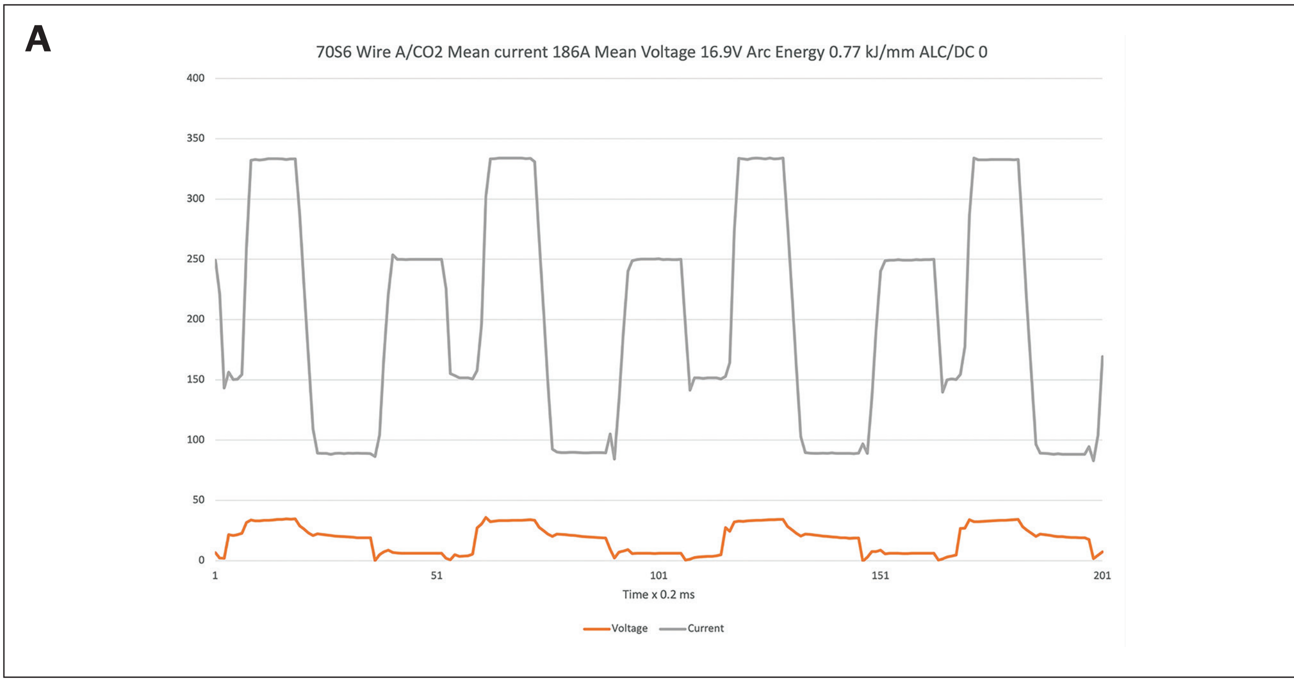
where MR is the wire melting rate, I is the mean arc current, L is the electrical extension of the wire from the contact tip, a is the cross sectional area of the wire, and α and β are constants. The first term in this equation represents the arc heating effect and the second term the resistive heating in the electrode extension.

One Knob and Synergic Control

As early as 1968, Manz (Ref. 22) developed a system that enabled wire feed speed and voltage to be varied over a wide operating range using a single control. This was used to maintain the voltage/current relationship within a predetermined operating range for conventional constant voltage power source. The term 'synergic control' was first used when more flexible parameter control was facilitated by electronic power supplies. The International Institute of Welding originally described Synergic control as "any system (open or closed loop) by which a significant pulse parameter (or corresponding wire feed speed) is amended such that an equilibrium condition is maintained over a range of wire feed speed, or average current levels."

Commercial systems use preprogrammed parameters to define the waveforms and the adaptive control functions as well as the optimum operating range. The algorithms that relate the parameters are often referred to as 'synergic lines.' It is important to note that 'synergic control' is not a GMAW process mode but a system control technique, applicable to all metal transfer modes.

The emergence of waveform-controlled transfer meant several waveform characteristics — waveform shape, time functions, and dynamic characteristics — need to be chosen. This flexibility is ideal if welding conditions need to be optimized, but it could complicate parameter selection for the equipment operator. Fortunately, the basic process rules for waveform control are well-defined. For pulsed transfer, the optimum pulse parameters may be preprogrammed for a specific consumable combination using Equation 2 and the wire feed/pulse frequency relationship may be adjusted using Equation 3.



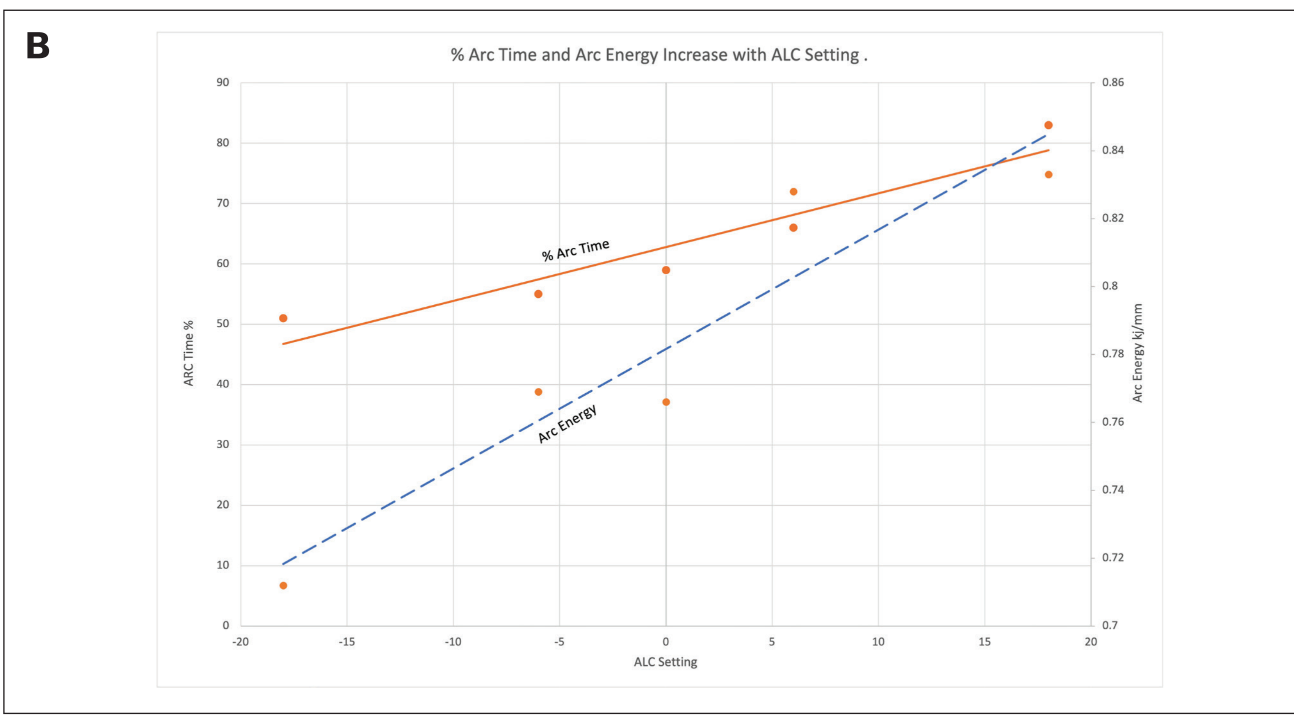


Fig. 3 — A — Controlled short circuit waveform used in these trials; B — effect of user adjustments to arc length control (ALC) on the percentage of arcing time and arc energy.

Multiple parameters may be fine-tuned as the wire feed speed/current is changed. For example, in pulsed transfer, the background current and time may be related by a term such as:

$$Ibtb = BH \qquad (6)$$

where BH is the 'background heating' constant.

This relationship maintains a similar background heating effect when pulse frequency is altered. The practical effect is to extend the stable range of synergic control. Similarly, adjustment of other parameters of waveform, such as the current slew rate and the dynamic voltage/current relationship, may be incorporated in the synergic relationship to optimize metal transfer.

Implications of Waveform-Controlled Metal Transfer and Synergic Process Control

Pre-programming of welding parameters using 'one knob' and synergic control are examples of intelligent control. They were originally designed to simplify parameter selection for normal workshop applications. The current generation of GMAW systems provides the benefits of improved waveform-controlled process capabilities and intelligent process selection for a wide range of applications. There are, however, some considerations which need to be addressed regarding their use.

Waveform Control Variables

In waveform-controlled pulsed metal transfer, the single droplet detachment parameters, pulse amplitude, and pulse duration need to be defined as described above. For waveform-controlled short circuit transfer, control of short circuit sensing, short circuit current limits, wetting in time, and droplet forming current peaks during the arc period can be controlled in a synergic manner over a range of currents. Most of the parametric optimization techniques limit adjustment of the key variables for process optimization in waveform-controlled pulse and short circuit transfer to the equipment manufacturer's laboratory or research facilities. Limited 'user' adjustment of some parameters is usually provided to fine-tune the predetermined synergic program. Typical adjustments are:

- Arc Length or Arc Length Correction (ALC). Commonly based on altering the wire feed rate to mean current relationship (e.g., the value of k in Equation 3, for pulsed transfer).
- Peak current. The droplet-forming current pulse amplitude is applied after the short circuit when the arc is reestablished.
- Simulated inductance or rate of change of current (slew rate in Equation 4). Sometimes referred to as 'pinch,' which is the inverse of inductance.
- Tail out. The current decay profile after the peak current.
- Dynamic Correction and Pulse Correction.

These adjustments are usually limited, and, unfortunately, there is little commonality between the manufacturers on the terminology used for these adjustment features. The influence of the adjustments may influence process performance. For example, recent investigations of arc length control on a proprietary controlled short circuit system indicated that unanticipated changes in arc energy can occur. The waveform of the associated waveform is shown in Fig. 3A, and the changes in arc energy associated with a range of adjustments of ALC are shown in Fig. 3B.

Whilst the changes are relatively small, their importance will depend on the intended application. In this case, the potential thermal damage to a quenched and tempered steel substrate was of interest since retention of mechanical properties was critical.

Synergic Program Constraints

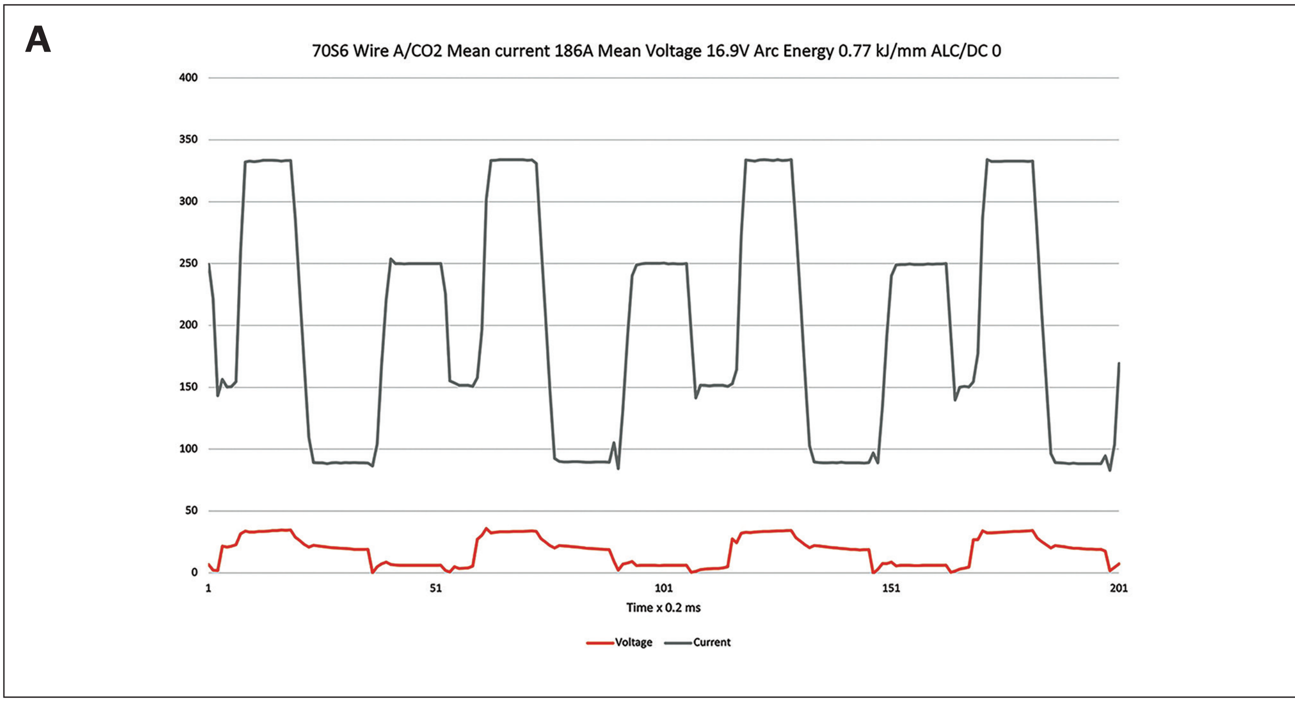
In synergic systems, common melting rate algorithms may be based on Equations 3 and 5 above, but how the waveform is modified with increasing wire feed speed may also be modified. For example, in pulsed transfer, the frequency of pulses increases with wire feed speed, but if the background current is maintained at a fixed level, the arc heating and droplet preheating during the background period will decrease. As a result, process stability may deteriorate, and the control range may be limited. One way of combating this is to include a fixed relationship between the background current and background time in the synergic relationship, as shown in Equation 6. In addition, synergic algorithms may also include waveform shape factors, as well as transient current-voltage relationships and the user adjustments listed above. These preprogrammed relationships are usually incorporated in fixed user-selected programs that are provided for specified consumables. If the consumable system required is not listed in the system program, it may be necessary to use the nearest similar program or request a modified program from the manufacturer. The danger of arbitrarily selecting the 'nearest' consumable program from the selection offered is that process performance may be poor. A recent example, where a user selected a controlled short circuit program for a gas-shielded flux-cored wire when using a self-shielded, flux-cored, hard-facing consumable, illustrates this point. This resulted in unacceptable welding performance (see Fig. 4).

The problem here probably resulted from the incorrect program selection by the user and the inherently unstable globular transfer characteristic of the chosen consumable.

Welding Procedure Management

Welding Procedure Qualification

Welding procedure qualification is the primary quality assurance measure for welded fabrication and is embodied in many international codes and standards. It relies on pre-qualification of the essential variables used for a representative sample of the target weld and the duplication of these essential variables in production. For conventional GMAW, the essential process variables, including the process mode, the arc voltage the arc current, wire feed speed, travel speed, and heat input, are clearly defined. Since the parameters are predetermined for a synergic waveform-controlled GMAW process, it might be assumed that the only equivalent essential variables might be arc current, travel speed, and heat input. The transferability of welding procedures is addressed in ISO TR 18491 (Ref. 23), *Welding and allied processes – Guidelines for measurement of welding energies*, and summarized in relation to ASME IX *Boiler and Pressure Vessel Code* by Melfi (Ref. 24). This relates to the need to measure heat input or arc energy using instantaneous current and voltage measurements for waveform-controlled GMAW, as opposed to the use of mean values for conventional GMAW. This is an important difference between conventional and waveform-controlled parameter measurement, but it is also necessary to consider operational and welding system-specific differences between different commercial



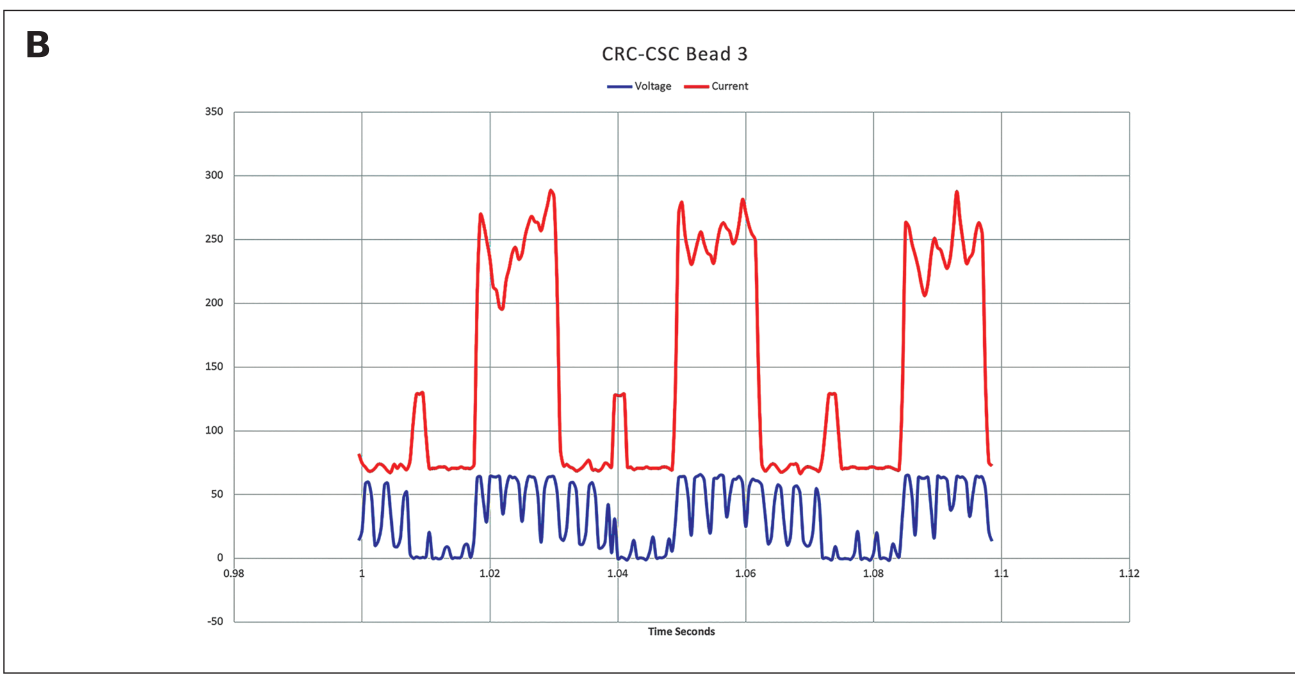
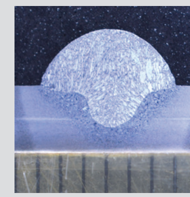
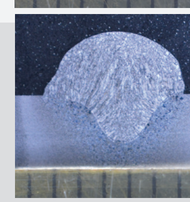


Fig. 4 — A — Acceptable controlled short circuit waveform, indicating rapid short circuit clearance and uniform arcing period; B — unacceptable controlled short-circuiting control, using the same welding system, with ineffective short circuit clearance and transient globular-short circuiting.

systems. For example, conventional short circuit transfer is often used for closed root or a gap of around 1.6 mm for V butt joints in relatively thick steel, but the short circuit controlled transfer can operate satisfactorily with gaps of 1.6 mm to 2.5 mm. This is advantageous because it allows the operator to ensure excellent fusion and penetration bead profile, but it does require a slightly different technique. In addition, the difference in proprietary preset programs and synergic algorithms, the terminology, and provision of different user adjustments means that it may be difficult to transfer procedures from one manufacturer's system to another machine. This is discussed further below.

Table 1 — Waveform Controlled Short Circuit Transfer Tests. Three Systems from Different Manufacturers. Bead on Plate, AWS A.5 70S6 1.2 mm (0.047 in.) Wire, Argon/2.75% O_2/16% CO_2 Shielding Gas, Travel Speed 305 mm/min (120 in./min), Weld Length 130 mm (5.12 in.), 3 mm (0.32 in.) Plain Carbon Steel Plate.

System	Wire Feed Speed m/min (in./min)	CTWD mm (in.)	Current A	Voltage V	Arc Energy kJ/mm* (kj/in.)	Bead Area mm^2 ($in.^2$)	Fusion Area mm^2 ($in.^2$)	Ratio Bead/ Fusion	Macro
A	3.0 (118)	15 (0.59)	117	16.8	0.39 (9.9)	12.5 (0.0193)	5.1 (0.008)	2.5	
B	3.0 (118)	15 (0.78)	118	13.2	0.40 (10.2)	10.76 (0.0166)	3.42 (0.0053)	3.1	
C	3.0 (118)	15 (0.59)	127	14.6	0.39 (9.9)	11.4 (0.0177)	4.9 (0.007)	2.3	

Note: 1.2-mm-diameter wire is often referred to as 0.045 diameter in the United States. *Calculated in accordance with ISO TR 18491.

Welding Procedure Transferability

The transferability of welding procedures between conventional and waveform-controlled synergic systems, or synergic systems from different manufacturers, also needs some consideration. A very useful pragmatic approach has been proposed by Melfi (Ref. 24) to address this issue for the ASME IX standard. In this case, the transferability of procedures is based on the comparative method of measuring heat input, either using conventional meters and average current and voltage or the instantaneous power or energy measurements required for waveform-controlled processes as defined by ISO TR 18491 (Ref. 23). It provides a relatively straightforward and practical solution for welding procedure transferability. Unfortunately, the transferability of procedures between different waveform-controlled systems may not be as straightforward. Although the principles of waveform-controlled metal transfer may be similar for systems that provide controlled short circuit or pulsed transfer, there may be subtle differences in the control technology provided by different equipment suppliers. These differences may result in process performance differences. For example, the melting rate may be affected by the slew rate and excess current in pulsed transfer, as demonstrated by Equation 4. If the welding procedure is established based on wire feed speed, both the current and arc energy may be affected by these variations.

Whilst equivalent arc energy may be a guide for comparing welding procedures, it may be necessary to conduct simple verification trials, at the same arc energy, to ensure that the basic welding performance (weld bead profile, penetration, fusion profile, and heat-affected zone properties) are equivalent to those originally qualified. A recent trial by the author compared three common commercial waveform-controlled short circuit mode systems. The welding parameters were adjusted to achieve the same instantaneous (ISO/TR 18491*) arc energy. The results are summarized in Table 1.

All of the resultant weld beads were of excellent appearance, process stability was good, and spatter levels were extremely low. It can be seen, however, that the parameters needed to be adjusted to achieve the equivalent arc energy, and the mean current and voltage, as well as the consequent 'conventional' arc energy, were all different. This trial was part of an ongoing investigation that will be reported in due course. It should also be noted that the rate of change of current, voltage, and wave shape may also be affected by the secondary inductance of the welding circuit, and most manufacturers recommend a fixed secondary cable length when using waveform-controlled processes. Alternatively, parameter compensation for cable length changes may be used.

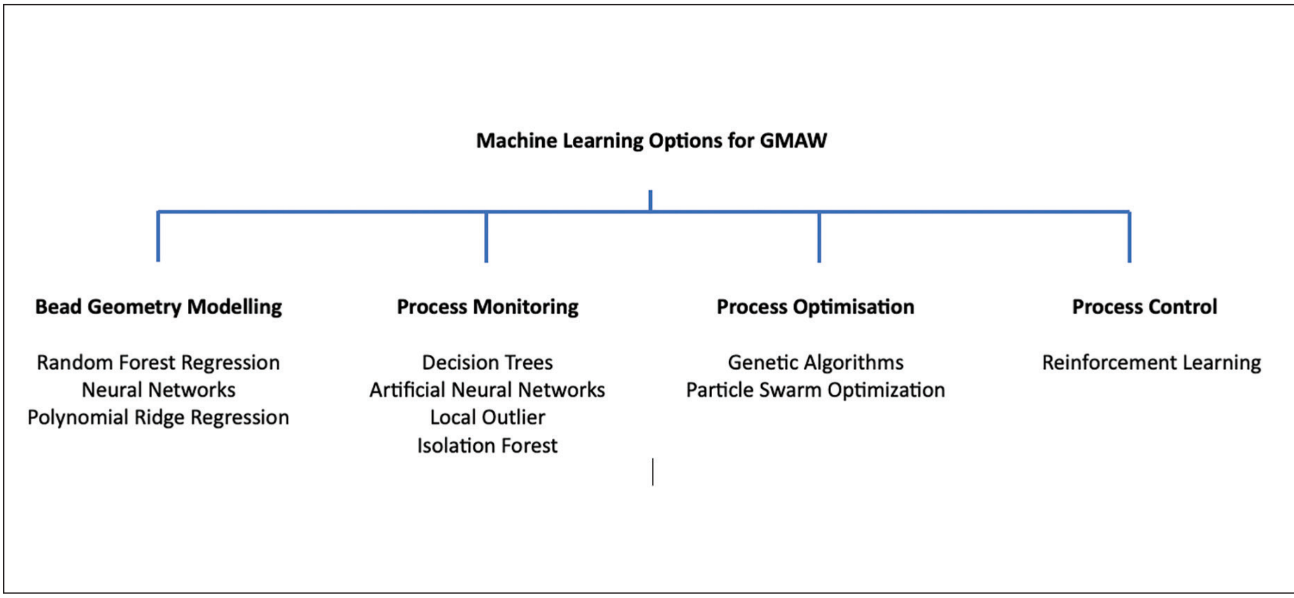


Fig. 5 — Schematic view of machine learning algorithms options for gas metal arc welding and applications (after Ref. 34).

Benefits of Intelligent Process Control

The improvements in metal transfer control described above can provide process operational benefits, such as greater process tolerance and reduction of spatter and fume. They also provide some measure of decoupling of metal transfer and arc heating. Dean (Ref. 25) showed that controlled short-circuiting waveforms can be tuned to improve fusion by considering the ratio of arc time to total cycle time. In addition to these process advantages, the controlled metal transfer approaches also lend themselves to 'one knob' or synergic control. This parameter control system simplifies the operator interface with the process and potentially offers greater consistency.

Limitations and Challenges

The programs provided by the manufacturer are usually adequate for a wide range of material and consumable combinations. As mentioned above, problems may arise if the appropriate consumables are not available or are incorrectly selected. Diagnosing these issues may be difficult if the user is reliant on the 'synergic' capability of the system and has no knowledge of the process fundamentals.

Process Monitoring

Process monitoring remains an essential element of welding procedure control. In the past, this meant manual supervision of individual production cells, but the advent of intelligent, computer-based, digital monitoring systems has meant that supervision may be achieved more accurately and reliably. These systems were initially supplied as standalone welding data loggers but are increasingly incorporated into advanced welding systems. In addition to the reliable collection of accurate data, the information can be used to automatically detect deviations from the procedural variables and provide preemptive input to quality assurance systems.

To faithfully reproduce the time-dependent variations of welding waveforms, the sample rate of the data logging system must be relatively high (typically 2 to 5kHz), especially for waveform-controlled GMAW. This results in the collection of very large amounts of data, and it is necessary to automate the data analysis task to produce meaningful quality information. Some of the options for data analysis and reporting include simple event alarms, signature analysis, probability density distribution, and frequency domain analysis. To simplify analysis, it is quite common to use a 'windowing technique' (Ref. 26) to separate the data into smaller blocks (typically 1000 samples). Individual windows may be analyzed to provide a 'snapshot' of process stability. Data from several windows may also be analyzed to produce a general assessment of process consistency over a longer period. This may indicate the number of weld segments that have fallen outside the expected parameters. Event analysis produces reports of the deviation of an essential variable from its intended value based on preset alarm levels. If the expected performance is represented by a normal distribution, the variability may be expressed in terms of standard deviation, and the results may be then presented in the form of control charts, which indicate deviations outside the acceptable parameter envelope as well as trends indicating loss of process control (Ref. 27). Simpson (Ref. 28) developed a signature analysis technique to train and subsequently monitor the GMAW process to identify potential defects. Arc voltage signals were captured at 8kHz, and a two-dimensional statistical distribution was calculated in a 30 × 30 array. The distribution was filtered, remapped, and scaled. Vector space operations were used to compare the signature images. A 'quality' index was derived based on the signature of the initial stable part of the weld, or a known stable condition. The system has been validated using con-

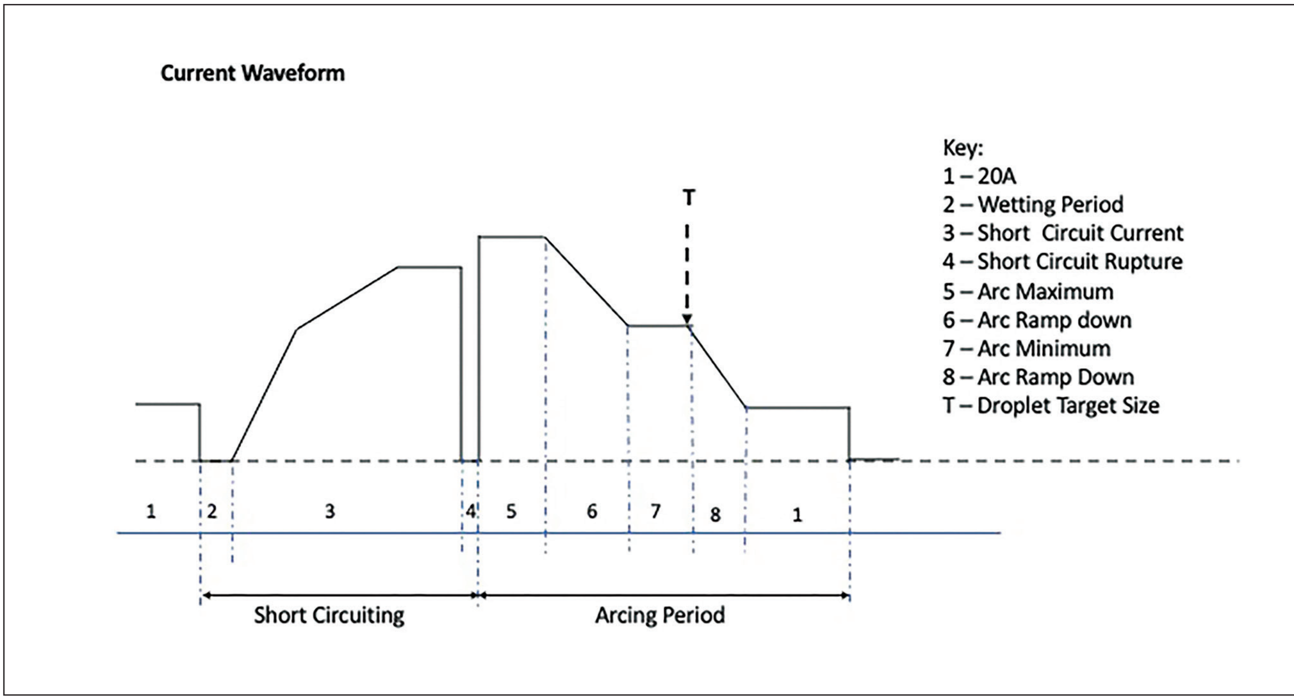


Fig. 6 — Closed loop control waveform (after Ref. 40).

ventional short circuit, pulse, and spray transfer welding of plain carbon steel and three common artificial 'faults,' namely seam tracking faults, gas contamination, and process stability. Ogunbyi (Ref. 29) used the windowing technique to analyze transient voltage and current data, which was collected at a sample rate of 5kHz. The maximum Imax, minimum Imin, and arithmetic mean Imean values of the transient current signals in each window were calculated automatically, as was the mean of the voltage signal V mean and the arithmetic average of all the voltage values below or equal to Vmean. To simplify the interpretation of the waveform and metal transfer, several ratios, or 'indices,' were used as follows.

The Transfer Index:

$$TI = 1 - \frac{I_{min}}{I_{mean}} \quad (7)$$

Transfer Stability Index:

$$TSI = \frac{I_{max}}{I_{mean}} \quad (8)$$

Dip Consistency Index:

$$DCI = 1 - \frac{V_{bk}}{V_{mean}} \quad (9)$$

Power Ratio:

$$PR = \frac{I_{bk}V_{bk}}{I_{mean}V_{mean}} \quad (10)$$

The indices were determined experimentally for many welding conditions. Using these simple indices, high-speed video recordings of the arc performance, and logical arguments, the performance of the process may be classified for individual windows of data. The transfer mode and its stability may be determined. For example, IF (TI < 0.1) AND (DCI < 0.1) AND (TSI < 1.1) THEN Transfer is SPRAY and STABLE. One of the benefits of the simple indices approach is that the calculations can be rapidly executed online.

These approaches may be used for monitoring manual GMAW but are becoming increasingly important in robotic welding applications where high production rates can lead to even higher wastage if the process is not adequately controlled. This is particularly the case when GMAW is used for wire arc additive manufacturing, where high-value components may be produced and online NDE is often impractical. In these cases, simple statistical process monitoring to ensure compliance with welding procedures is the first line of defense, but more-sophisticated approaches may be used for defect detection, as discussed below.

Future Developments

Artificial Intelligence

Artificial Intelligence covers a wide range of technologies applicable to GMAW. Most of the 'intelligent' systems

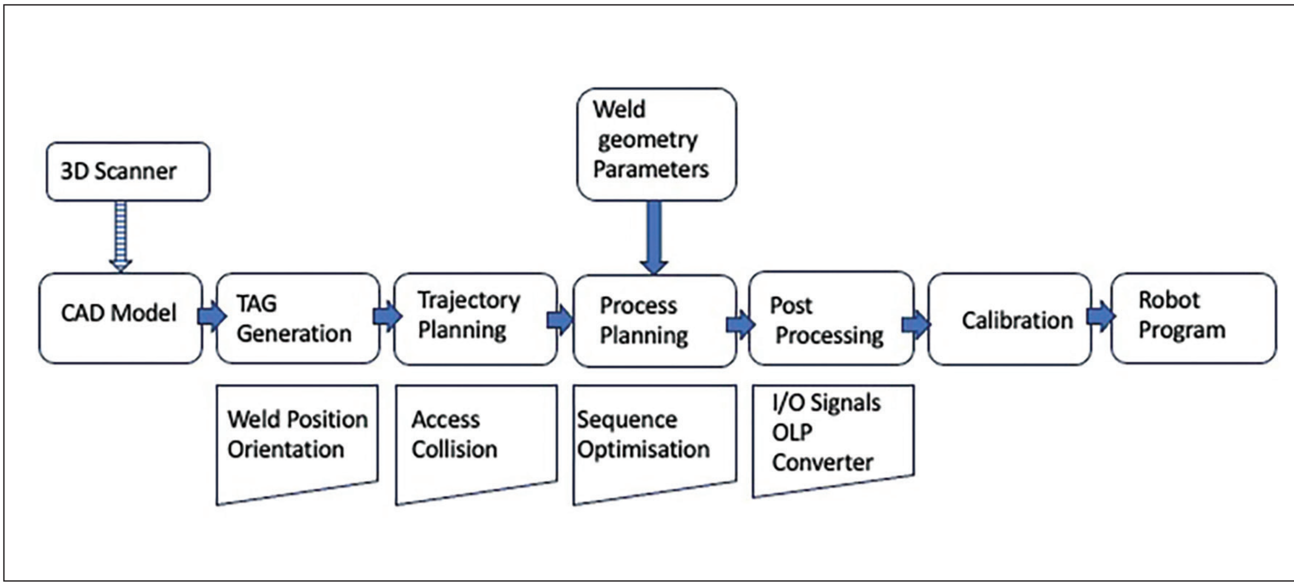


Fig. 7 — Schematic diagram of automatic offline programming (AOLP) software components (after Ref. 42).

for monitoring and control mentioned above are based on process physics and mathematical models or algorithms.

Knowledge-based expert systems represent early attempts to apply AI approaches to GMAW welding procedure generation and defect risk assessment (Refs. 23, 31). Some of these types of expert systems have already been integrated into proprietary welding system software and welding procedure database packages.

Artificial neural networks (ANN) have been used for some time to relate welding parameters, as inputs, to bead geometry as outputs (Ref. 32). Some work has also been reported on the use of ANNs for the prediction of the mechanical properties of welds (Ref. 33). In most cases, these predictive models were used as alternatives to purely empirical statistical approaches, and their performance was comparable. Some automated robot programming (AOLP) and integrated GMAW-DED software systems also embed ANN models in their structure, mainly for bead geometry prediction.

Machine Learning

More-sophisticated AI techniques have recently been reviewed by Mattera et al. (Ref. 34) for GMA-DED monitoring and control. They found that most of the research related to bead geometry and penetration prediction (Ref. 35). Process monitoring and defect detection (Ref. 36) also formed a significant area of study. Direct control of the process was less common, but online correction of weld geometry using weld pool imaging has been demonstrated. Increased interest has been shown in using advanced AI approaches in GMAW due to the increased computational capabilities of AI-enabled computers and the availability of stable libraries that allow for simple prototyping and deploying of applications. Figure 5 summarizes the range of options reported in application studies devoted to GMAW machine learning.

To develop machine learning applications for GMAW, several sensors may be used, including current and voltage sensors, cameras, profilometers, acoustic emission, and pyrometers or thermal cameras. As with the other process monitoring techniques discussed above, current and voltage sensors combined with high sample rate data acquisition systems offer the most robust and simple means of data collection. Unlike the statistical approaches previously discussed, machine learning enables self-learning of complex patterns in data and offers new possibilities for data analysis of more-complex welding waveforms. By using statistical feature extraction techniques and frequency domain analysis, combined with the data window approach, it has been shown that anomalies of waveform process, such as waveform-controlled short circuit transfer, can be detected with high accuracy using a simple machine learning algorithmm such as the Local Outlier Factor (Ref. 37). Most of the applications developed using machine learning for process monitoring can identify anomalous process performance, which may indicate weld defects. The output is, however, 'advisory' and inherently low risk since it requires human intervention to determine follow-up actions.

Some interesting studies have also proposed the possibility of using data-driven optimization techniques for process parameter optimization and control. Mezaache (Ref. 38) demonstrated that a machine learning approach using the Particle Swarm Optimization technique was able to identify and predict the operating parameters that minimize heat affected zone (HAZ) depth in conventional constant voltage GMAW of plain carbon steel. The system produced results that indicate a linear relationship between voltage, wire feed speed, contact tip-to-workpiece distance (CTWD), welding speed, and HAZ depth. The results validated the technique against conventional empirical results. It is claimed that the approach 'saves time and improves efficiency,' but it is not clear whether it offers any improvement over conventional modeling methods. A recent 'hybrid' AI system development (Ref. 39) used a machine learning approach to expand the GMAW knowledge base for an expert system that generated welding procedures. It was claimed that the application of the welding procedure generated by the system produced defect-free joints.

To use machine learning for process control tasks, a more-robust approach must be used to avoid process instability. For this purpose, it is suggested that a data-driven decision-making framework should be used. For GMAW, data-driven control techniques via a decision-making framework have been employed to generate optimal references for the welding machine-level control systems. The aim has been to solve tasks, such as geometry control, weld bead profile, and penetration depth control. It is suggested that reinforcement learning is the most promising of the possible data-driven decision-making frameworks for multidimensional, nonlinear continuous control tasks, particularly for robotic GMAW. Current research concerning the application of data-driven techniques, such as Reinforcement Learning to Gas Metal Arc Welding, is mostly based on the development of adaptive PID control. In this case, the system adjusts input parameters, such as current, voltage, and welding speed references, during the simple constant voltage process (Ref. 40).

Potential future developments of AI technologies include the possibility of self-learning of optimum process parameters for consumables or materials that are not currently available in preprogrammed welding systems. Another fruitful area of AI research might be on remote process diagnostics when troubleshooting adverse process performance in the absence of skilled technical personnel. This is analogous to the medical applications of AI and may reduce the dependence of users on input from system manufacturers.

Adaptive Waveform Control

In variable frequency pulse transfer, the effective current peak current is significantly higher than the steady DC spray transition current (1.5 to 2.0 times). If a set of predetermined pulse parameters for a given material is not available, a first approximation to the optimum pulse parameters for single drop detachment may be obtained by multiplying the transition current by 1.5–2.0 and incrementing the pulse duration until a droplet detachment signal is observed immediately after the pulse terminates. This will require a high-speed data logger or digital oscilloscope and may be assisted by one of the spray transition current calculation methods, a data analysis technique such as the monitoring indices mentioned above, or machine learning.

It has also been shown (Ref. 40) that if a critical droplet size can be established, a simplified method of waveform control (Fig. 6) may be applied.

An estimated droplet size may be calculated or derived by monitoring of the process during the initial stage of arcing. The length of the electrode melted which corresponds to the droplet size is estimated by integrating the following expression during the arcing time ta:

$$\Delta L = K \int_0^{t_a} i(t)\,dt \qquad (11)$$

To find the value of the proportionality constant K, the target can be adjusted incrementally in subsequent arc cycles to attain the desired critical droplet size. The target threshold is exceeded when the short circuit occurs just before the current minimum is reached and the target level is incremented back to a safe level. Unlike many of the commercial waveform-controlled short circuit systems described above, this approach does not rely on premonition of the short circuit rupture but, instead, calculated or estimated optimum droplet size and its controlling parameters. The system also recognizes the potential variations in the short circuit cycle and incorporates a measure of adaptive response. This approach may be more forgiving for material variations and enhanced in the future by applying machine learning techniques.

Zang et al. (Ref. 42) also developed an adaptive control system for pulsed gas metal arc welding that employed a novel high frame rate vision system to monitor droplet oscillation and actively control the detachment current. This approach compensates for variations in the one-drop-per-pulse detachment parameters (Equation 2) and improves process robustness. It does require a more complex vision monitoring system, but recent advances in this area may improve its feasibility.

Applications of Intelligent GMAW

Robotic Automation of GMAW

Robotic automation is an effective way of improving the productivity and control of GMAW. The process control systems discussed above are increasingly employed in robotic welding applications. One of the impediments to the application of robots has been the difficulty of programming the systems, particularly for small-batch production. This problem can be resolved by the introduction of Automated Offline Programming (AOLP) (Ref. 43) and integration with synergic welding systems. AOLP Is a computer-based system that takes data from a computer-aided design (CAD) package and takes all the steps necessary to develop a robot program without manual intervention, as shown in Fig. 7.

The software utilizes mathematical modeling to optimize robot paths and avoid collisions as well as artificial neural network techniques for weld geometry planning. Integration of synergic GMAW control allows optimum welding parameters to be utilized. The system above was developed on behalf of the Defence Materials Technology Centre (DMTC) of Australia for a complex GMAW fabrication involving two linked robots each with 13 degrees of freedom but is now available as a standalone software package. Collaborative robots (COBOTS) are also emerging as a useful tool for small-batch GMAW welding tasks. Although these are usually programmed using a simple ‘lead through’ approach, they can also be used with the AOLP systems described above.

GMAW Wire Arc Additive Manufacturing

Robotic wire arc additive manufacturing (GMA-DED) is a growing application area for GMAW. When robotic GMA-DED was introduced in the early 1990s (Ref. 44), conventional short arc GMAW was used to successfully deposit plain carbon steel and nickel superalloys. The research in this process has grown exponentially in the last decade. Real applications are emerging in a range of materials. The default GMAW process mode now is waveform-controlled short circuit or pulsed transfer. Often, synergic controlled systems, integrated with an industrial robot, are employed. One of the issues with both ongoing research and industrial applications is that the systems may be treated as 'machine tools' rather than welding processes. The lessons learned from fundamental welding studies (Ref. 45) and accepted welding quality control practices may be ignored, and analysis of potential welding problems may be difficult. There is evidence that the approval processes for GMA-DED recognize the basic welding requirements and the need to apply welding procedure control approaches to product quality (Refs. 46, 47). It is possible that a 'two-tier' approach to quality could be adopted for GMA DED, with; 1) welding procedure development monitored by statistical process control, followed by 2) online process monitoring, using the techniques mentioned above, to identify process anomalies, possibly enhanced by knowledge base systems for defect identification to target post deposition NDE.

Conclusions

The GMAW process has undergone significant development since its introduction 80 years ago. Early work focussed on defining the metal transfer modes. This was followed by a period of quantifying the process mechanisms and the establishment of control rules for conventional operation. The advent of high response rate electronic power sources in the 1970s led to the possibility of radical improvements in metal transfer, and the inclusion of digital signal processors led to new methods of process parameter control. These innovations provided the opportunity to pre-program GMAW systems with optimum characteristics for specific user requirements. The same technology has been applied to process monitoring to enable adherence to qualified welding procedures. More recently, these GMAW process benefits have been exploited in automated welding, and the rapid growth of GMAW-DED, or wire arc additive manufacturing. Future developments will almost certainly utilize the new technologies of AI in both process monitoring and process control as suggested above.

Overall, the end-user benefits of these advances are improved GMAW useability, productivity, and compliance with quality standards. The use of pre-programmed welding systems is effective when routine applications are involved, but there are possibly some unintended consequences of these advances, which are discussed in the implications and challenges set out above.

Considerable progress has been made in the field of fundamental research related to GMAW, and the intelligent use of this knowledge will be essential for ongoing process development, as Adams predicted (Ref. 47).

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