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RESEARCH PAPER

Recent gas metal arc welding (GMAW) process developments: the implications related to international fabrication standards

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Abstract In this paper, the current status of advanced gas metal arc welding (GMAW) process developments and recent research on heat input determination is presented. After a brief review of the basic requirements for welding procedure control, the way in which welding fabrication standards may accommodate these developments is discussed. This paper is specifically intended to address potential issues with fabrication standards where welding procedural control is used but should also provide guidance to researchers and welding engineers on the various process developments and their implications. The scope of the paper is restricted to GMAW and is focused on standards that relate to the fabrication of ferritic steels, although the principles discussed may be relevant to other arc processes and material groups.

Keywords (IIW Thesaurus) GMA welding · Waveform control · Process procedures · Synergic control · Energy input

1 Introduction

For many years, the standards relating to welding fabrication by arc welding have been based on the assumption that 'conventional' steady DC or sinusoidal AC current is used. The electrical parameters used to control weld quality have naturally been related to these types of power output. More advanced process waveforms, which were developed to control process performance, became commercially available more than 30 years ago, but these were based on variants of early equipment designs, which limited their capabilities. The introduction of electronic power control and, in particular, the application of primary rectifier-inverter welding power sources in the late 1980s enabled much more flexible control of output waveforms and resulted in the development of some novel metal transfer control techniques. The addition of microprocessor and digital signal processors to welding systems has extended these developments and has resulted in a large number of proprietary process control options being available. These developments have resulted in significant benefits for the user and an extended range of gas metal arc welding (GMAW) applications.

In addition to specifying the electrical parameters used to control welding processes, many existing fabrication standards use heat input or arc energy for determination of appropriate procedures and their ongoing control. Whilst the process developments mentioned earlier have evolved, attention has also been devoted to improved determination of welding arc energy, thermal efficiency and heat input. The determination of the appropriate value and the method of calculating arc energy can have a significant influence on fabrication standards as discussed in the following.

The implications of all of these developments and particularly the use of more complex transient waveforms on welding fabrication standards do, however, need to be re-considered. The paper attempts to highlight the dangers of inappropriate calculation of welding energy and incorrect heat input values.

2 Welding procedure control

In order to appreciate how the developments mentioned earlier affect fabrication codes and standards, it is necessary to briefly discuss how and why welding procedure control is applied:

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Welding is recognised as a 'special process' in the ISO 9000 quality system standards and ISO 3834 [1] on the basis that 'welds cannot be fully verified by subsequent inspection and testing of the product to ensure that the required quality standards have been met'. The primary means by which quality and long-term performance of a welded fabrication are maintained is by 'procedural controls' and specifically Welder and Welding Procedure Qualification. These rely on essential variables established during welding procedure qualification trials being faithfully duplicated in production.

Various international standards specify the means by which procedural control is applied, but the basic stages are as follows:

1. A preliminary welding procedure specification (pWPS) is established and documented based on the material being welded, the joint type, the welding process, welding consumables, etc. This pWPS specifies the parameters which need to be controlled to ensure that the appropriate weldment quality is achieved. These parameters may be defined in the standards as 'essential variables'. The preparation of the pWPS often involves calculation or modelling to determine the most appropriate conditions to avoid defects, such as heat-affected zone degradation or hydrogen-assisted cold cracking in steel.
2. Welding procedure tests are carried out using the parameters defined in the pWPS, and the completed weld is subjected to a defined set of mechanical and non-destructive tests. A procedure qualification record (PQR) describes the results of these tests, and if these meet the required quality, a final welding procedure specification (WPS) is approved and clearly documented.
3. The WPS defines the procedures and process variables used in production, and these 'input' parameters are monitored to ensure that the qualities of production welds match those of the welding procedure test piece.

In stage 1, both the advanced process developments and revised values of heat input will affect the estimation of welding procedure requirements and the prediction of parameters, which enable the specified joint quality to be achieved. Once these parameters have been established by a procedure qualification process in stage 2, the main objective is to reliably reproduce the approved procedural parameters during production. In stage 3, the implications of the advanced process characteristics and effective monitoring of key or 'essential' variables are most important.

A further aspect of procedural control is the skill of the welder. In order to reproduce the results of the welding procedure qualification in production, it may be required to ensure that the welder meets some generic standard skill requirement or, in some cases, the welder must be qualified and approved to complete a specific welding procedure.

3 Process developments—control of metal transfer

The naturally occurring modes of metal transfer in consumable electrode arc processes were described by Van Adrichem in 1969 [2]. Later, the ability to control metal transfer using dynamic control of the welding current waveform led to development of pulsed gas metal arc welding, but this approach has more recently been extended to controlled dip or short arc welding as well as modified spray arc. The underlying mechanisms and the main characteristics of the modified transfer modes remain the same as those defined by Van Adrichen, but improved process performance, stability and joint quality are obtained using these control techniques.

A simple summary of the metal transfer modes was prepared for IIW SG 212 in 2003 [3], and an updated version of this is shown in Table 1. Table 2 summarises the features of the common controlled transfer modes. The conventional modes are obtained by adjustment of predetermined parameters such as consumable type and diameter, current and voltage, electrical stick out and shielding gas. The controlled modes employ dynamic control of electrical parameters and, in some cases, transient wire feed control to achieve enhanced process performance. More details of these basic controlled metal transfer modes are provided in the following section.

The ability to manipulate the detailed transient waveforms to produce specific process benefits has resulted in the availability of more than 50 proprietary process options which are now known as waveform-controlled welding processes. A listing of the systems currently available is given in Appendix Table 4, with an indication of the related operating mode. The implications for the application of these systems will be discussed

Table 1 Summary of basic and controlled metal transfer modes

Main mode	Conventional sub-mode	Controlled mode
Short circuit (short arc, dip transfer)		Controlled short circuit
Globular	Globular drop	
	Globular repelled	
Spray	Drop spray	Pulsed drop spray transfer
	Conventional spray	Modified spray
		Pulsed Spray
	Steaming spray	
	Rotating spray	

Source: [3]

Table 2 Summary of generic features of controlled metal transfer modes

Controlled transfer mode	Features	Notes: classification numbers Appendix Table 4
Pulsed transfer	Allows spray type transfer to be used below spray transition current (in dip transfer range). Gives very stable operation and positional capability.	Suitable for Stainless steel, Aluminium and other non-ferrous materials. 5.6, 5.7
Controlled short circuit	Improved process stability. Reduced spatter. Improved tolerance to root gaps. Improved sidewall fusion.	Travel speed may be increased by transient wire feed modulation. 5.3, 5.3.1, 5.3.2, 5.3.3.3, 5.10
Modified spray	Allows stable operation at short arc length. Reduced fume and improved access to root.	5.5
Combined variants	Combination of several operating modes	5.9
AC variants	(Including controlled short circuit)	5.8

With reference to Appendix Table 4 classification

further, but one consequence of the use of more complex transient current and voltage waveforms is that it requires a different approach to the calculation of power, arc energy and heat input.

3.1 Waveform-controlled welding

ISO/TR 18491 [4], which was released in 2015, adopts the generic term ‘waveform-controlled welding’, which covers the developments referred to earlier; it is defined as ‘welding process modification of the voltage and current wave shape to control characteristics such as droplet shape, penetration, wetting, bead shape or transfer mode (s)’. This term relates to the welding process and not the welding equipment since systems which offer a waveform-controlled welding option are often ‘multi-process’ and may offer facilities for conventional DC welding. The ISO/TR addresses the methods of measurement and calculation of arc energy, which need to be applied in waveform-controlled processes.

3.2 Waveform-controlled process principles

3.2.1 Pulsed transfer

The earliest controlled transfer process development operated in the free flight mode by utilizing a current pulse to control droplet detachment. By using electronic-controlled power sources, it was possible to define the current waveform precisely and parameters which transfer one droplet of metal per pulse may be defined. By varying the pulse frequency stable, spatter-free transfer may be obtained at mean currents below the transition current, which would normally be required for natural spray transfer as explained by Allum [5]. The power source output is normally current controlled, and a series of simple algorithms may be used to relate pulse parameters to mean current and pulse frequency to wire feed speed [6]. The arc voltage or arc length is controlled by varying the relationship between the mean current and the wire feed rate. Whilst it has been shown that a simple rectangular pulse may be used to produce single drop per pulse transfer, modified waveforms have also been employed to enhance process performance.

3.2.2 Controlled short circuit transfer

Controlled short-circuit transfer techniques modify the current waveform and, in some cases, the instantaneous wire feed speed to improve process stability and reduce spatter. A detailed description of the approach and comparison with conventional short-circuit transfer is given elsewhere [7], but a brief description of the principles is included here.

In dip transfer, the short-circuit frequency cannot be independently imposed on the process and some form of feedback control is necessary. The basic principle of the controlled short-circuit process is shown diagrammatically in Fig. 1.

The current is reduced from the arcing level for a short period as soon as a short circuit is detected (by a voltage fall). This delay in the normal current rise ensures that the wire tip is in contact with the weld pool and avoids initial short-circuit instability. The current may then be increased to a predetermined level (usually lower than that which occurs during natural short-circuit transfer). Prior to rupture of the short circuit, the current is reduced to a low level to avoid explosive rupture of the thin molten metal filament, which joins the wire to the droplet. This technique virtually eliminates spatter. The droplet is transferred to the weld pool under the influence of surface tension. The preemptive short-circuit rupture detection may be achieved using voltage, rate of voltage rise or values calculated from instantaneous current and voltage. To ensure the re-establishment of a stable arc, the current decay may be controlled or a current pulse may be applied immediately after the arc is established. A further development of this technique involves the synchronous variation of the transient wire feed speed in conjunction with current waveform. This approach provides additional control and allows the operating current range to be extended. It is, however, important to note that regardless of the current waveform or transient wire feed oscillation, the transfer mode remains

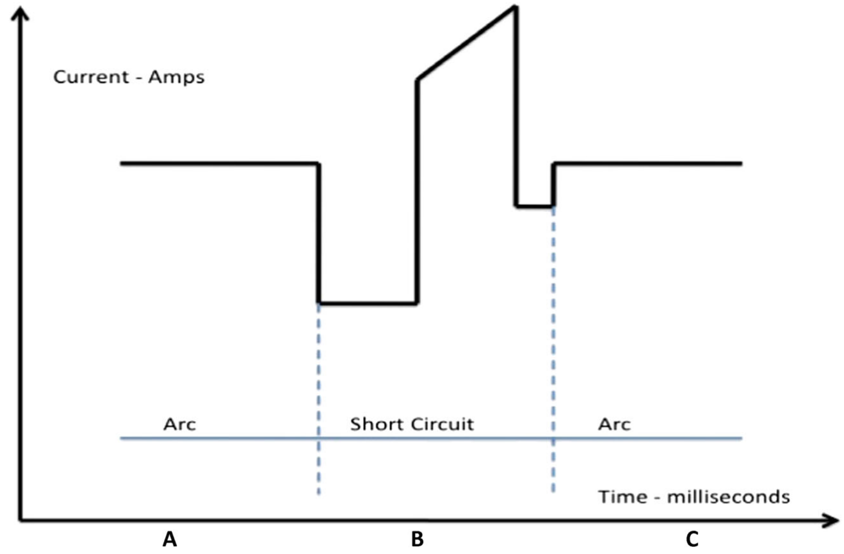

Fig. 1 Diagrammatic representation of a controlled dip transfer current waveform arcing period **A**, Short circuit period **B**, arcing period **C**

dip or short-circuit transfer with the general characteristics associated with this transfer mode.

3.2.3 Modified spray, combined variants and AC operation

Possibly, the first example of 'modified spray transfer' was the artificial stabilisation of the drop spray transfer by Ma et al. [8]; this relied on an extremely stable current supply. Later variants of modified spray transfer have relied on process parameter feedback to control the power supply output and, for example, enable spray transfer to be maintained at very short arc lengths. In addition to the modes described earlier, the power source manufacturers have combined the control technologies to offer 'enhanced' hybrid modes of operation in DC and AC processes.

3.2.4 Synergic control

Synergic control is not a process mode but a method of simplifying control of a number of process variables. Synergic control was originally [9] defined as 'Synergic control embraces any system (open or closed loop) by which a significant pulse current 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)'. As the definition implies, it was developed for use with pulsed transfer welding but has been adopted for other process modes to provide a system of 'pre-programmed' or 'one-knob' control. The initial aim was to match the wire feed speed with the burn of rate of the wire to provide stable operation over the maximum possible range of adjustment. With variable frequency pulsed gas metal arc welding, rectangular current pulses and one drop per pulse transfer, there is a simple linear relationship between between wire feed rate and pulse frequency [6]. This relationship between calculated burn off rate and wire feed speed may be pre-programmed into the equipment based on a knowledge of consumable type and size, shielding gas, etc. and has become known as the 'synergic line'. Over time, the inbuilt algorithms associated with this basic synergic line have been refined to compensate for factors such as changes in electrical stick out resistance and the non-linearity of the relationship between pulse frequency and droplet size. Individual manufacturers of waveform-controlled systems have tailored these synergic lines, pulse shape and supporting algorithms to further enhance process performance. Although the underlying principles are well established in practice, optimisation may involve the determination of many individual parameters and the details remain specific to individual equipment manufactures.

4 The effect of process mode on weld quality

4.1 Pulsed transfer

Pulsed transfer has been available for some time, and it offers an alternative to conventional short-circuit transfer in a similar mean current range for a wide range of materials. It is acknowledged that very low spatter levels, good positional capability and consistent weld integrity can be achieved with pulsed transfer. Although a wide range of adjustable pulse parameters are possible, these are normally pre-programmed according to material, wire size and shielding gas. In such cases, the mean current or the related wire feed speed may be used as the main control parameter. The original variable frequency, one drop per pulse systems, was based on simple rectangular current pulse waveforms, which lent themselves to relatively simple control algorithms which express wire melting rate and hence wire feed speed with pulse frequency [6]. It has, however, been shown that even with these simple waveforms, the burn off behaviour can be significantly affected by changes in the rate of current rise and the current difference between the background and peak current (sometimes referred to as the excess current). Stevenson [10] and Richardson et al. [11] reported that melting rate increased with both excess current and rate of current rise by between 10 and 30% for a 1.2-mm-diameter plain carbon steel wire. These researchers derived the following melting rate equation to accommodate these changes in excess current ($I_\mathrm{p} - I_\mathrm{b}$) and rate of current change or slew rate S (dI/dt).

$$\mathrm{MR}_p = \alpha I_m + \beta I\left(I_m^2 + \left(\frac{(I_\mathrm{p}-I_\mathrm{b})^2 t_\mathrm{p} t_\mathrm{b}}{(t_\mathrm{p}+t_\mathrm{b})^2}\right) - \frac{(I_\mathrm{p}-I_\mathrm{b})^3}{3S(t_\mathrm{p}+t_\mathrm{b})}\right) \quad \left[\mathrm{m}/\mathrm{s}\right] \qquad (1)$$

where MR_p is the pulsed transfer melting rate averaged over one pulse cycle, α is a constant related to arc heating, and β is a constant related to resistive heating in the wire; I_p and I_b are the pulse and background currents, respectively, and t_p and t_p are the related pulse and background times, respectively.

It is important to note that the significant changes in melting rate can occur at the same arc energy value for this relatively simple rectangular waveform. Such changes in melting rate may cause weld bead profile changes and affect fusion behaviour.

As the approaches to waveform control have evolved, dynamic control of pulse wave shape has been adopted to extent the process tolerance and compensate for contact tip to workpiece distance (CTWD) or arc length changes. These pulse wave shapes are often proprietary but have the potential to change the arc energy to melting rate behaviour as discussed earlier.

4.2 Controlled short arc welding

Some independent studies comparing the features of the controlled short-circuit process modes have been undertaken, and in general, it has been concluded that the controlled short-circuit process improves process stability, reduces spatter levels, improves penetration control (particularly of root beads) and may reduce the risk of lack of sidewall fusion; for many of these reasons, it offers the welder increased process tolerance. Dean [12] found that in controlled short-circuit welding; the fusion behaviour was correlated with arc energy calculated using instantaneous measurements of arc voltage and current, but these studies were based on ‘bead-on-plate’ trials. The number of these independent studies is limited; they do not cover the wide range of controlled short-circuit options now available and are insufficient to provide a general objective assessment of the relationship between arc energy, bead profile and fusion behaviour.

5 Measurement of power and arc energy in waveform-controlled welding

In conventional GMAW using essentially steady DC current, the arc current and arc voltage may be measured using equipment meters or common external instruments. These measurements and Eq. (4) will not, however, give an accurate value of arc energy when the waveform is subject to transient variations. For waveform-controlled welding, it is clear that some form of instantaneous measurement of the electrical parameters is necessary to obtain a true value of power and energy. This is even true for conventional short arc or dip transfer where mean current and voltage have been used erroneously to calculate power and energy for many years. In fact, as will be shown later, the use of these equations for conventional dip transfer overestimates the true arc energy; this will introduce inaccuracies in the estimation of parameters during the pWPS stage although the procedure qualification process should ensure that the required properties are maintained if the essential variables approved in the PQR are reproduced in production.

To cater for processes such as pulsed transfer GMAW, Bosworth [13] and Joseph et al. [14] suggested that the most appropriate method to calculate arc power should be based on instantaneous measurement of current and voltage to calculate ‘average instantaneous power’. According to Joseph, the average instantaneous power, P_AI, is then given by

$$P_\mathrm{AI} = \sum_{n=1}^{n} \frac{I_i V_i}{n} \quad [\mathrm{W}]\ \ \mathrm{Joseph}\ \ (2003) \qquad (2)$$

where I_i is the instantaneous current, V_i is the instantaneous voltage[1], and i is equal to 1 to n where n is the number of samples.[2]

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[1] V is often used as a symbol for voltage, but U is preferred to avoid confusion with travel speed (v).

[2] The integral format of this expression is mathematically correct, but in practice, when using digital data acquisition of an unknown waveform, the summation approach shown in Eq. (2) is preferred and is used to calculate energy displays in many power sources.

More recently, Pehle et al. [15] have proposed a similar approach to define 'real welding power' *Ps* defined by the following integral:

$$P_{\mathrm{s}} = \frac{1}{t_{\mathrm{s}}} \times \int_0^{t_1} U_{(t)} \times I_{(t)} dt \quad [\mathrm{W}] \quad \text{Pehle} \quad (2015). \tag{3}$$

It is important to note that Joseph used a data acquisition system capable of capturing voltage and current samples at 4500 Hz whilst Pehle used a high-resolution measuring system with a sample rate of 80 kHz. Such systems are commonly used for accurate estimation of power and energy in waveform-controlled welding. Dedicated welding data loggers and high-quality power meters are also available to carry out these measurements on existing systems, but many of the more recent digital welding power sources incorporate these functions within the equipment. ISO/TR 18491 recommends a 'sample rate of at least 10 times the frequency of the waveform': In the case of energy or power supplies with inbuilt power or energy displays, the manufacture is able to determine and apply the appropriate sampling frequency but where external systems are used it is important that the sample rate is set to a high enough value to accurately capture the true waveform. In practice, most commercial welding data acquisition systems can provide sample rates above 5 kHz.

These measurement principles have been adopted by ISO/TR 18491[3], which introduces the following terms to allow accurate evaluation of arc energy:

Conventional arc energy (*E*) is 'the product of welding voltage and current divided by the travel speed of welding' or

$$E = \frac{U \times I}{v} \times 10^{-3} \quad [\mathrm{kJ/mm}] \qquad \text{ISO/TR 18491} \tag{4}$$

By convention, the units of arc energy are kilojoules per millimetre if travel speed is expressed in millimetres per second.

Two new terms are required in order to accurately evaluate the welding power ($U \times I$ in Eq. 4) to cater for waveform-controlled processes which experience rapid fluctuations in arc voltage and current. These are the following:

Instantaneous power, which is defined in ISO/TR 18491 as follows:

'welding power determined by averaging the product of current and voltage made at rapid intervals which capture brief changes in the welding waveform'.

Instantaneous power (IP) is equivalent to the average instantaneous power suggested by Joseph, and its units are watts. ISO/TR 18491 does not express the term mathematically, but the previous definition would translate to the following:

$$\mathrm{IP} = \frac{1}{n} \sum_{n=1}^{n} (I_i \times U_i) \qquad [\mathrm{W}] \tag{5}$$

Instantaneous energy, which is defined in ISO/TR 18491 as follows:

'welding energy determined by summing the product of current and voltage measurements made at rapid intervals which capture brief changes in the welding waveform'.

This definition is intended to represent the *total* welding energy for a given weld but can be misinterpreted. In addition, the units of energy are joules (W s) and the definition should be revised to incorporate sample time and may more accurately be written as follows:

'welding energy determined by summing the product of current, voltage and the time interval between instantaneous measurements, made at rapid intervals which capture brief changes in the welding waveform'.

The 'instantaneous energy' (IE) or more accurately total IE would then be expressed as follows:

$$\mathrm{IE} = \sum_{n=1}^{n} (I_i \times U_i \times t_i) \quad [\mathrm{J}] \tag{6}$$

where t_i is the time interval between the instantaneous measurements or the reciprocal of the sample frequency.

Using IP or IE Eqs. (5) and (6), the true arc energy *E* in kilojoules per millimetre for waveform-controlled processes may be calculated using either of the two equations provided in ISO/TR 18491

$$E = \frac{\mathrm{IP}}{v} \times 10^{-3} \quad [\mathrm{kJ/mm}] \tag{7}$$

or

$$E = \frac{\mathrm{IE}}{L} \times 10^{-3} \quad [\mathrm{kJ/mm}] \tag{8}$$

where *v* is the weld travel speed in millimetre per second and *L* is the weld length in millimetre.

5.1 Implications of revised arc energy measurements for waveform-controlled processes

For steady DC welding, Eqs. (4), (7) and (8) are expected to give similar results. but as reported by Joseph [14] and Pehle [15] et al., the true arc energy for waveform-controlled processes calculated using Eqs. (2), (3), (5) and (6) will give significantly different results from that suggested by Eq. (4). For pulsed gas metal arc welding, Joseph [14] reported an increase in

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[3] The discussion refers to the current version of ISO/TR 18491, and the authors' comments are incorporated in the conclusions at the end of this paper.

Table 3 Results of spot checks of arc energy using typical workshop systems

Process mode	Mean current amps	'Mean' arc energy. Eq. (4) (kJ/mm)	True arc energy. Eqs. (7) and (8) (kJ/mm)	Error (± %)
Spray transfer	255	0.79	0.79	0
Conventional dip transfer	106	0.41	0.38	−8.3
Waveform-controlled dip	54	0.27	0.25	−4.7
Pulsed transfer	140	0.22	0.29	+23

the value of arc energy of 18% using Eq. (2) rather than Eq. (4), whereas using Eq. (3), Pehle [15] reported increases of 50%.

The author of this paper conducted random spot checks on several typical workshop systems, and the results are shown in Table 3.

All of the measurements were made with a proprietary welding data logger (AMV 4000) at a sample rate of 5 kHz. The values shown were calculated from the raw instantaneous current and voltage measurements. It should be stressed that this was a random check of existing welding systems rather than a methodical study over a range of currents. It simply confirms that for pulsed arc welding, the true arc energy is significantly higher than that which suggested by the conventional product of mean values; in the case of conventional and controlled dip transfer, the conventional measurement overestimates the true arc energy. The different behaviour of dip and pulsed transfer was observed by Joseph et al. [14] and is the result of the normal phase relationship of instantaneous voltage and current.

The measurement errors have implications for the arc energy used to predict the avoidance of defects at the pWPS stage: For example, taking the true arc energy values for pulsed transfer from Table 3, the calculated t8/5 time based on EN 1011 [16] gives a 46% longer cooling time than that which would be suggested by Eq. (4). Pehle [15] calculated a similar result (50% longer cooling time) and confirmed cooling times consistent with the true arc energy using thermocouple measurements.

6 Heat input and arc energy

In parallel with the process developments referred to earlier, there has been considerable effort to determine the relationship between arc energy and the heat input to the workpiece. Hurtig et al. [17] illustrate the relationship between arc energy and the various thermal losses in a welding system. Unfortunately, the only direct way to measure the effective thermal cycle is by implanting thermocouples in the heat-affected zone or plunging thermocouples into the molten weld pool. Even under laboratory conditions, it usually requires many attempts to obtain reliable results using these techniques. It is obviously impossible to apply such a technique in production and impractical to apply it during procedure qualification tests. Arc energy may be measured directly using the methods discussed earlier. As stated in ISO/TR 18491, the term 'heat input' is more correctly arc energy modified by an arc efficiency factor. The thermal efficiency factor normally designated 'k' or 'η' in fabrication standards is an attempt to relate arc energy to the thermal effects, which change the material properties in the weld zone and contribute to metallurgical damage and the risk of post weld defects. Some fabrication standards (for example EN 1011 and ISO/TR 17671-1) tabulate thermal efficiency factors; for the standards mentioned, the value given in both is 0.8 for a range of GMAW/MIG/MAG/FCAW processes. Dupont et al. [18] used calorimetry to measure the thermal efficiency and obtained a value of 0.8 ± 0.04, but the source of the values tabulated in the standards is unknown. Scotti et al. [19] have used a liquid nitrogen calorimeter to explore the relationship between arc energy and the absorbed energy in a welded plate and have pointed out the range of intrinsic errors associated with this approach.

For several years, researchers have used a range of calorimetric techniques to more accurately determine thermal efficiency in welding. In particular, Haelsig [20] and co-workers have developed a novel water calorimetric technique, which has been used to measure the efficiency of a large number of welding processes [20–22]. In the most recent work from this group [23], it has been shown that thermal efficiency is related to process mode, joint configuration, welding position and layer sequence of multi-pass welds. In the case of process mode, the efficiency varied from 0.85 for dip transfer to 0.70 for spray whilst a particular waveform-controlled process (pulsed transfer) gave a value of

0.77. The efficiency of the GMAW process is also sensitive to the operating voltage and current, shielding gas and contact tip to work distance (CTWD).

7 Implications of process developments for fabrication standards

The implications of the preceding sections are discussed in the following.

7.1 Preliminary welding procedure specification

When formulating a pWPS for a waveform-controlled process, the appropriate method of specifying the process parameters must be considered. With the possible exception of wire feed speed, the control parameters may differ from system to system. The arc energy must be calculated according to Eqs. (9) or (10) from values of IP and IE [Eqs. (5) and (7) or (8)], which are displayed on the power source, measured using a suitable welding data acquisition system or high-quality power meter. If these calculations are not used, the arc energy and, consequently, the cooling time t8/5 may be in error by around 20 and 50%, respectively. In the case of fabrication standards such as EN 1011 and ISO/TR 17671 which use a thermal efficiency factor to calculate heat input and subsequently t8/5 time, the research reported earlier also suggests that the standard tabulated values of efficiency are incorrect. In addition, the variability of the reported values should be taken into account. For example, in the case of avoidance of hydrogen-assisted cold cracking (HACC), the lower values of thermal efficiency may need to be considered since this will reduce the effective heat input, increase cooling rate and may lead to increased preheat requirements. In other standards [23, 24] which use ‘arc energy’ rather than heat input to estimate safe welding conditions (usually based on graphical techniques), thermal efficiency has no direct influence on pWPS calculations, but the sensitivity of heat input to the various factors identified by Haelsig [23] should be noted as these may restrict the ‘safe’ operating envelope.

Errors in preparing a preliminary welding specification may lead to failure of the welding procedure qualification test or the specification of sub-optimal procedures. The welding procedure test is a costly and time-consuming process, and failure and retesting are very undesirable. The pWPS stage is also an opportunity to ensure that the resultant welding procedure is not on the borderline of the operating envelope, provides adequate productivity and is not too conservative. In addition, the range of qualification can be determined at this stage. Once the proposed procedure test is successfully completed, there is little scope for further optimisation.

Perhaps, the main lesson from the heat input research is the potential sensitivity of weld quality to a large range of process variables. This underlines the importance of the procedural control measures specified in the standards.

7.2 Welding procedure qualification—transferability

The main issue facing the use of the extensive list of waveform-controlled processes (Appendix Table 4) is the transferability of pre-qualified welding procedures previously tested and approved using conventional steady DC GMAW or using different waveform-controlled processes. In order to transfer qualified welding procedures, the ‘source’ and ‘target’ WPS must produce equivalent weld quality. The weld quality may be evaluated as follows:

1. The metallurgy and mechanical properties of the weld metal and heat-affected zone which result from the thermal cycle of the welding process: These properties are assessed in the welding procedure test, but in general, they are almost impossible to detect in the finished fabrication. The thermal cycle may also influence defects such as cracking, and the initial welding procedure is designed to reduce the risk of these defects. Whilst some of these defects may be detected by post weld inspection and non-destructive examination, the operating envelope may be affected by the change of process mode.
2. Geometrical features of the weld such as bead profile and fusion behaviour: Defects such as lack of penetration and excessive reinforcement may be obvious during post weld inspection, but lack of sidewall fusion is often difficult to detect.

The transferability of welding procedures which have been approved by procedure qualification tests using different arc energy measurements is addressed fully in ISO/TR 18491 by a comprehensive table and flowchart. This approach has been adopted in the US standard ASME IX as described by Melfi [25]. This avoids the need for requalification based on arc energy and addresses the quality issues referred to in (1). These provisions, however, only cover the arc energy transferability based on (1) and do not necessarily cover the issues mentioned in (2) unless other variables such as metal transfer mode are identical. In terms of welding procedure transferability, there are also possible procedural differences and the different operating parameters used by commercial equipment suppliers. For example, a conventional short-circuit procedure may specify a closed root gap or a maximum gap of around 1.6 mm whereas the controlled short-circuit process may use a root gap of between 1.6 and 2.5 mm.

The transfer mode should also be common to the two alternative options; for example, short arc or dip transfer has quite different operating characteristics to pulsed transfer even at the same mean current. The transfer mode differences may not be clear from the commercial name given to the process, but Appendix Table 4 gives some assistance in this respect. In addition, the waveform-controlled processes may have different fusion characteristics and deposition rates even if the transfer mode and the arc energy are the same.

Although the performance benefits of the waveform-controlled processes have been documented, there has been limited direct comparison of the weld quality produced by different options. Three studies have been identified to date [26–28], but these were restricted to a limited number of waveform-controlled processes and are difficult to correlate with the more than 50 options now available.

Unlike conventional process modes, the transferability of a WPS from one waveform-controlled welding system to another may also be difficult due to the way in which the process mode is set up, whilst conventional process control parameters are usually limited to wire feed speed (current), voltage and, in some cases, secondary inductance, the waveform-controlled processes use a variety of settings such as ‘peak current’ and ‘arc length’ and the only common set parameter is usually wire feed speed.

The situation is further complicated by the fact that the control variables for the waveform-controlled processes differ from manufacturer to manufacturer. Most systems employ synergic control, and synergic lines are pre-programmed based mainly on user selection of wire type and size, shielding gas and, in some cases, joint type.

As discussed earlier, the synergic algorithms may be very complex and are usually inaccessible to the end user. The only common adjustable variable available to the user seems to be wire feed speed whilst some systems provide arc length adjustment; others, for example, provide peak current and ‘tail-out’ control of the waveform. It may be possible to develop a factor such as the ratio of arc energy to wire feed speed, which would provide a basis for comparison between processes, but this would still need to be qualified by reference to transfer mode and is unlikely to capture subtle but important differences in fusion behaviour. In the absence of any clear correlation between systems, it is suggested that where a welding procedure is qualified using a waveform-controlled power process, it is necessary to use the same waveform-controlled welding process for production welding (this includes the same power source manufacturer, model, program and synergic lines).

7.3 Procedural control—production monitoring

For effective procedural control, it is essential that the parameters used for the procedure qualification test are reproduced in production. In most international fabrication standards, the essential and non-essential variables used in the WPS are clearly defined as is the range of qualification. For waveform-controlled processes, variables such as mean current and voltage may be inappropriate, and as indicated earlier, it may be necessary to use the same power source manufacturer, model, program and synergic lines. The arc energy calculated in accordance with Eqs. (9) or (10) should be used for welding procedure tests, and for production monitoring, the values need to be provided on suitable displays inbuilt into the equipment or by means of suitable external data logging systems. As suggested in ISO/DIS 15614–1.2 2015 [29], heat input may be replaced by arc energy in the WPS, since the only requirement after welding procedure qualification is to ensure that production faithfully reproduces the WPS and arc energy offers a non-ambiguous and measurable quantity which is not influenced by the thermal efficiency issues related to heat input.

7.4 Welder qualification

If a generic skill qualification is accepted (welders qualified and certified to a national or internationally approved standard), it is suggested that a welder qualified on a conventional welding process may be accepted as qualified to use an equivalent waveform-controlled process provided that sufficient instruction on the operation of the system is given. The reverse is not true; welders qualified on a waveform-controlled process may not be automatically qualified for conventional processes where higher levels of skill are generally required. For example, a welder qualified using controlled short-circuit transfer may not be able to achieve the same results with the conventional process whereas a welder who has the skills necessary to carry out welding with the conventional process may be considered to be qualified for welding using the controlled process mode. Given that the welder is provided with adequate instruction on the equipment set-up, this is purely a skill issue. In the case of welder qualification to a specific procedure, the same considerations as those applied to the welding procedure qualification should apply.

8 Conclusion

In the previous sections of this paper, the effects of the recent developments in GMAW welding processes and research associated with heat input determination have been discussed in an attempt to inform an assessment of the implications for international fabrication standards.

When waveform-controlled processes are used, the fabricator should understand which underlying process mode is being adopted, since there are clear differences between the features and performance of the various systems and the equivalent conventional process.

It has also been established that when waveform-controlled processes are used, an alternative measure of arc power and arc energy to that used for conventional process operation is necessary. Guidance on these measurements is provided in ISO/TR 18491.

Inappropriate use of mean power and energy calculations for waveform-controlled processes will lead to significant errors in the true arc energy calculations.

Recent research indicates that the thermal efficiency values quoted in some standards are subject to a wide range of variation. There are differences in the treatment of heat input in European, USA and some Australasian standards, and this will probably require a varied approach: Where thermal efficiency is used to calculate heat input or cooling time, the sensitivity of the estimates to recently published efficiency values must be considered. This is particularly relevant at the pWPS stage, but following procedure qualification, arc energy should be sufficient to maintain reproducible production welds.

ISO/TR 18491 and ASME IX handle the transferability of welding procedures by using arc energy and a simple bead-on-plate test to ensure equivalence, but this approach is mainly concerned with producing equivalent thermal cycles in the weldment. As discussed earlier, there are possible differences in fusion and bead geometry when different modes of operation are employed, and these are not necessarily captured by comparing arc energy.

ISO/TR 18491 should be used in conjunction with the relevant fabrication codes when waveform-controlled processes are employed. The following suggestions are made to clarify the terminology in the current version of ISO/TR 18491

1. The definition of waveform-controlled welding provided in ISO/TR 18491 could be extended to include those processes which use parameters other than current and voltage (e.g. transient wire feed variation) to define the process. A possible amendment could be ‘welding process modification of the current wave shape *or dynamic control of other parameters* to control characteristics such as droplet shape, penetration, wetting, bead shape or transfer mode(s)’
2. The term instantaneous power (IP) is defined in ISO/TR 18491; although the definition is correct, the term really describes ‘average’ instantaneous power in watts.
3. The definition of instantaneous energy (IE) in ISO/TR 18491 describes ‘total’ IE and requires some amendment (as indicated earlier) to ensure that it expresses energy in the appropriate units (J).
4. Whilst mathematical equations are not favoured in ISO/TR 18491, it is felt that the simple expressions provided earlier would provide some clarity to the definitions of IP and IE. These expressions could also provide clarity for researchers and suppliers of external welding data logging systems. The expressions could possibly be provided as an ‘informative annex’ to ISO/TR 18491.

Based on these conclusions, the following recommendations are made for further research:

8.1 Recommendations for future work

To ensure more reliable transfer of welding procedures between conventional and waveform-controlled processes, as well as transfer between waveform-controlled options, a single-objective criterion should be sought. This could be a simple expression such as the ratio of arc energy and wire feed speed, but it needs to accommodate the possible differences in bead profile and fusion characteristics. It is possible that this criterion could be derived by modelling, but some form of practical validation is also required.

The classification of waveform-controlled processes similar to that shown in Table 1, Appendix Table 4 needs to be extended, maintained and made available to fabricators to allow informed use of the processes in welding procedures.

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Appendix

Table 4 Based on DVS, 2014, Leaflet 0973 'Moderne Prozessvarianten'

Process name	Supplier	5.3 Controlled short arc	5.3.1 Low Spatter Short arc	5.3.2 Low energy short arc	5.3.3 Power controlled short arc	5.5 Modified spray arc	5.6 Conventional pulsed arc	5.7 Modified pulsed arc	5.8 AC process	5.9 Combined process variant	5.10 Cyclic wire movement
CMT	Fronius	x	x	x							x
CMT Advanced	Fronius	x	x	x					x	x	x
ColdArc	EWM	x	x	x							
ColdMIG	Merke	x									
ColdWeld	Cloos	x		x					x		
ControlWeld	Cloos	x	x								
ForceArc	EWM					x					
ForceArcPuls	EWM							x			
DeepArc	Merke					x					
FocusArc	Rehm					x					
NewArc	Kjellberg					x					
RapidWeld	Cloos					x					
RootArc	EWM	x	x	x							
SpeedArc	Lorch	x			x	x					
SpeedCold	Lorch	x		x							
SpeedPulse	Lorch						x	x			
SpeedRoot	Lorch	x	x								
SpeedShort Arc	SAF Oerlikon	x			x						
SpeedUp	Lorch	x					x	x		x	x
SteelDynamic	Fronius	x					x				
SteelRoot	Fronius	x	x								
WiseRoot	Kemppi	x	x								
WiseThin	Kemppi	x		x							
STT	Lincoln	x	x								
Rapid X	Lincoln							x			
AC Alu Pulse	Lincoln								x		
Process Z	Lincoln								x		
RMD	Miller	x									
Pulsed-MIG	Miller						x				
Pulse	Oerlikon						x				
Soft Silent Puls	Oerlikon							x			
Spray Modal	Oerlikon					x					
HPS	Oerlikon					x					
Advanced SeQuencer	Oerlikon	x									x
Easy Short Arc	Oerlikon	x	x								
Focus Puls	Rehm						x	x			
Power Puls	Rehm						x	x			
Pulse	Daihen Varstroj						x				
	Fronius						x				

Table 4 (continued)

Process name	Supplier	5.3 Controlled short arc	5.3.1 Low Spatter Short arc	5.3.2 Low energy short arc	5.3.3 Power controlled short arc	5.5 Modified spray arc	5.6 Conventional pulsed arc	5.7 Modified pulsed arc	5.8 AC process	5.9 Combined process variant	5.10 Cyclic wire movement
FRONIUS Synchropulse											
Pulse Multi Control (PMC)	Fronius						x				
PMC Mix	Fronius	x						x		x	
PMC Mix Drive	Fronius	x						x		x	x
PMC Synchropulse	Fronius						x				
Pulse Control Spray (PCS)	Fronius					x	x			x	
Low Spatter Control (LSC)	Fronius	x									
LSC Advanced	Fronius	x									
CCC	IMC	x	x	x							
SOFTMIG	IMC	x±	x	x							
MIGAC	IMC							x	x		
PulsadoTermico	IMC							x			x
AVS	IMC							x			
Pulsed-MIG	Miller						x				
Pulse	Oerlikon						x				
Soft Silent Puls	Oerlikon							x			
Spray Modal	Oerlikon					x					
HPS	Oerlikon					x					
Avanced SeQuencer	Oerlikon	x									x
Easy Short Arc	Oerlikon	x	x								
IAC (Intelligent Arc Control)	Migatronic	x	x	x							
Power Arc	Migatronic					x					
Duo Plus	Migatronic									x	x
Sequence Repeat	Migatronic									x	x
		5.3	5.3.1	5.3.2	5.3.3	5.5	5.6	5.7	5.8	5.9	5.10

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