An Abington Publishing Special Report

Pulsed Arc Welding

Eur Ing J A Street, BA, CEng, SenMWeldI

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Preface

This special report describes how the conventional continuous DC TIG and MIG welding processes of post-war years eventually became unable to meet the joining requirements of advanced materials and the increasingly demanding joint geometries of complex assemblies, such as those in nuclear power stations, thereby holding back progress in some vitally important areas of technology.

It identifies the limited performance of the available welding equipment which resulted in inadequate process control, and outlines the restricted knowledge of arc behaviour and metal transfer, all of which had to be systematically examined, quantified and understood before useful improvements could be made.

The importance of precisely controlled welding sets and accurate instrumentation is emphasised, as both were crucial not only in the development of the pulsed AC and DC arc welding processes to their present sophisticated states but also for the reproducible transfer of welding procedures from development laboratory to worksite for reliable quality assurance.

The main theme of the report is concerned with evaluation of the benefits of current pulsing in TIG and MIG welding. In this evaluation various forms of thermal pulsing in TIG and MIG welding, and droplet pulsing in the MIG process, are described in detail to show how the new techniques were introduced and developed to overcome the difficulties associated with the old. Some disadvantages of pulsing are also included to stress the importance of choosing an appropriate level of technology to fulfil a given requirement.

Although not a review, some comparisons between processes and techniques are inevitable when spanning almost 30 years of technological advancement, so a little relevant historical information has been included to provide a frame of reference for the benefit of the reader.

Finally, the report compares various types of welding sets and their modes of operation, and examines different degrees of complexity in programmable welding sets, to make a prediction of where trends are likely to lead in the future.

Between 1962-85 the author was personally involved in development and evaluation of all the pulsed welding processes described here, and of instrumentation techniques to quantify them. He was a Senior Research Engineer on Welding Institute research programmes which resulted in the origination and/or development of pulsed AC and DC TIG, pulsed wire feed spray MIG and AC MIG welding, and Project Leader for synergic pulsing. As a member of the small team working on transistor analog welding sets and fast response, positive drive, wire feeders he participated in development and, in particular, application of specialised instrumentation needed for evaluation of the new processes and equipment. He has also been responsible in the capacity of Principal Research Engineer for promotion of the Institute's advanced arc welding instrumentation in Europe, Scandinavia and the USA as well as the UK by demonstration of equipment and presentation of papers at workshops and seminars.

The author would like to thank numerous colleagues in different departments of The Welding Institute for their various contributions in the form of advice, help, discussions and co-operation over the last 28 years.

1 INTRODUCTION

Since about 1960 widespread use of advanced metals and complex joint configurations increasingly led to failure of conventional arc welding processes to produce satisfactory welds. This was particularly evident in some of the early TIG welding of joints for nuclear energy and aerospace applications where, because reliability is of great importance, good control of weld bead penetration and width is essential. Such control is now routinely achieved by periodically switching the welding current between preset low and high levels, or pulsing, to regulate heat input and therefore the behaviour of the molten pool and its subsequent solidification. At low frequencies (i.e. 1-10 Hz) this results in thermal pulsing which enables difficult joints to be made in thin materials and also between workpiece components with unequal thermal capacity, because of either dissimilar geometry (thick to thin) or different thermal conductivity (stainless steel to carbon steel), which were previously impossible with continuous DC. Pulsing at higher frequencies (1-10 kHz) in TIG welding gives control over arc stiffness and directionality, and also beneficially influences grain growth during solidification of the molten pool.

Modulation of welding current is used extensively in MIG welding for control of droplet detachment and transfer, and of arc behaviour. In droplet pulsing, metal transfer is made independent of gravity via strong electromagnetic detachment forces. All-positional welding is therefore possible at lower average currents than for natural spray transfer, without need for dip (short circuit) operation. Low heat input is maintained, resulting in a smaller, more controllable molten pool than for natural spray, but without the spatter and lack of fusion defects of dip transfer. Thermal pulsing in MIG welding is directly comparable with its TIG counterpart but requires precisely modulated wire feeding except when operated synergically.

Welding sets designed for continuous DC operation were used by the author for the early investigations into pulsing but their slow response, high ripple content and general lack of controllability seriously limited progress. Transistor welding sets based on series analog regulators were developed specifically for pulsed arc welding. They pulse from a fraction of a hertz to 10-15 kHz and have switching response of 10^5-10^6A s^{-1} with controllable volt-amp characteristics from constant voltage to constant current, or combinations of both.

Better welding sets demanded versatile and accurate instrumentation to quantify their performance. Meters alone, as fitted to standard DC welding equipment, are not able to indicate transient events such as pulses. Modern oscillography was used extensively by the author to monitor pulsed arc behaviour, combined with sensors capable of faithfully converting the welding conditions into readily measurable electrical signals and high speed cine photography to relate the signals to the physical occurrences which caused them. Meters were used where appropriate to indicate pulse parameters, after electronic processing of the signals.

2 PROBLEMS ASSOCIATED WITH CONTINUOUS DC WELDING

2.1 TIG welding

For all arc welding which starts at ambient workshop temperature there is a rise in workpiece temperature as welding progresses. If welding continues for sufficiently long a steady state is reached when heat input from the arc equals heat lost from the workpiece by convection, conduction and radiation*. This steady state temperature may easily be a

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* See appendix

few hundred degrees celsius, resulting in considerably greater depth of penetration and bead width at the end of a weld than at the start, even at constant welding current and arc energy. On a linear joint between components with high specific heat capacity* the rise in temperature is not normally large (it is sometimes possible to bear contact by hand with the parent material immediately after welding) and poses no serious problems. For circumferential joints, particularly in thin walled tubular sections and in materials with low specific heat capacity, weld bead geometry will almost certainly be adversely affected by undue rise in temperature caused by buildup of heat, and over penetration or burnthrough may eventually occur.

The author's principal objectives in TIG welding were to participate in development of the process to a sufficiently reliable state for precision work to be carried out with confidence.

2.2 Spray, globular and dip transfer MIG welding

Two common sources of difficulty in spray or open arc MIG welding are irregular droplet transfer and arc instability, particularly when current is near the transition threshold from spray to dip transfer and operating fluctuations (e.g. erratic wire feeding) cause intermittent crossing of this threshold. A related problem occurs at low current density in open arc operation when a molten drop of many times the electrode diameter forms on the tip. Gravity eventually detaches the globule when its weight overcomes surface tension forces, and transfer takes place, often with excessive spatter. Before transfer, the arc wanders and its cone covers a large area, dissipating energy. This is globular transfer,

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* See appendix

which can be used only in the flat position and is associated with lack of penetration, fusion defects and uneven weld beads.

In dip transfer, wire feed rate is deliberately made higher than burnoff rate. This results in a period of short circuiting, during which the melted electrode tip makes contact with the molten pool. Transfer occurs by surface tension effects before the wire is fused by resistive heating and arcing resumes. The cycle repeats at 50-200 Hz, depending mainly on wire composition, diameter, welding current and electrode extension. Because arcing is not continuous, dip transfer is a cold process suitable for all positional work and use on thin material. But it can often be too cold, causing lack of fusion defects and unacceptable reject rates.

For MIG welding, the author's main objectives were to raise deposition rates, obtain greater precision in fusion control and improve process stability.

3 HOW PULSING IS OF BENEFIT

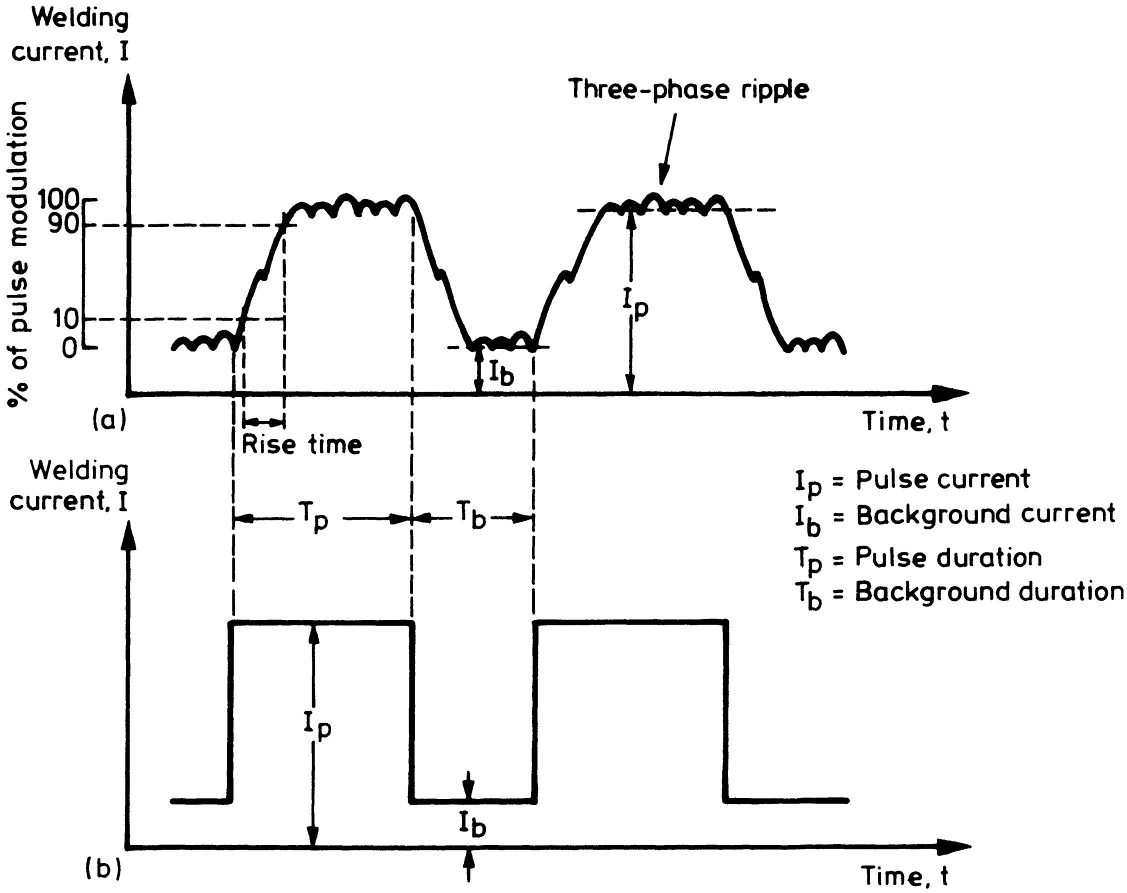
The two distinct types of pulsing in TIG welding are thermal and high frequency pulsing.

3.1 Pulsed TIG welding (thermal pulsing)

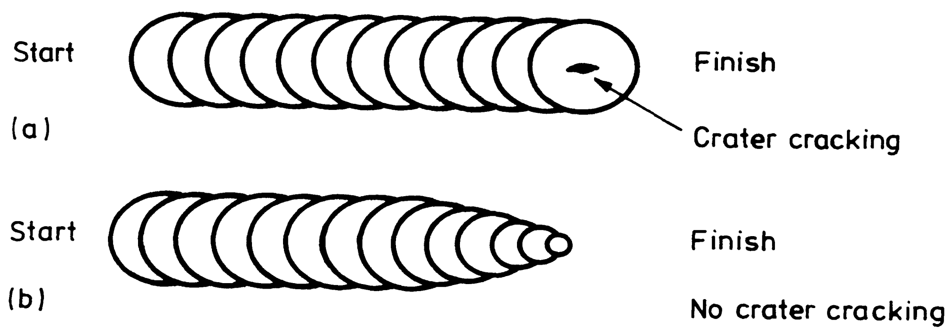
Before detailed consideration of thermal pulsing, an outline of conventional TIG welding's origins and limitations is appropriate. Steady DC TIG welding was introduced in 1942 by Meredith[1] and brought important improvements in weld quality to non-ferrous materials for aeroplane manufacture (significant in wartime), particularly to magnesium and its alloys which have relatively low melting points and burn in air. DC TIG was adopted for ferrous materials also but its application was limited to joining components with fairly well matched thermal capacities. It is not well suited to welding thick to thin joints because burnthrough of the thinner material occurs before adequate fusion of the thicker and, for tube welding, a steady rise in temperature is accompanied by increased depth of penetration and weld width as the joint progresses. Without programming welding current to compensate, which is difficult without complex closed loop feedback, variable weld properties result and quality is uncertain. Another problem is that a large, slowly cooling molten pool leads to formation of undesirable columnar grain growth (as-cast structure) on solidification which is associated with defects such as solidification cracking, mechanical anisotropy, porosity and low toughness.[2]

It was in 1962, whilst attempting to weld thin stainless steel sheet with uniform 100% penetration and negligible distortion, that the author first became directly involved in pulsed TIG welding.

Thermal pulsing consists of melting a single spot until complete penetration results, reducing heat input to allow solidification to occur, then repeating this cycle while the heat source is traversed relative to the workpiece so that a series of overlapping, full penetration spot welds of uniform size is produced. In pulsed TIG welding, alternate fusion and solidification are obtained by switching between high and low currents, respectively (Fig. 1). The high current (5-200 A) is normally higher than for continuous DC TIG welding to ensure rapid full penetration, after which switching to a low current (1-15 A) allows the molten pool to solidify but maintains a pilot arc for application of the next pulse. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time (0.05 to about 1-2 s) instead of being more slowly wasted by conduction into adjacent parent material as in continuous DC operation. Speed of growth of the weld nugget determines HAZ width, and also sensitivity to irregularity in heat sink caused by local variation in material thickness or uneven jigging. Fast growth or high temperature



1 Pulsed TIG welding current waveforms representative of: a) Commercial equipment with harmonic distortion; b) Transistor welding set, approximating to ideal waveshape.



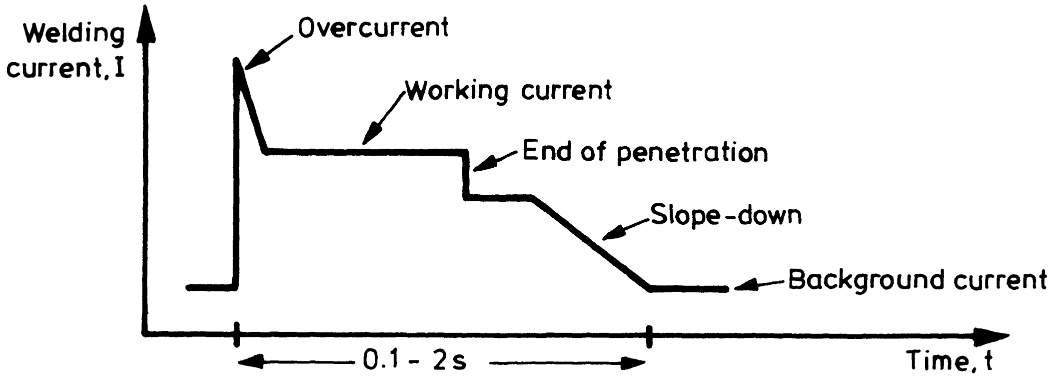
2 Pulsed TIG weld surface appearance: a) Overlapping spots of equal size with crater cracking in final spot; b) Detail of tapered out spots to prevent crater cracking.

gradients result in a small HAZ and greater tolerance to changes in heat sink. High gradients produce compressed isotherms ahead of the weld nugget and maintain a small HAZ whilst effectively preventing the heat source from 'seeing' the bottom of the joint until full penetration occurs. A short rise time (about 1% of pulse duration) is required to achieve this effect which is believed to be the reason for pulsed TIG welding's tolerance to variable heat sink conditions. Successive weld spots are deliberately overlapped, as in resistance seam welding, by about 60-70% , i.e. just beyond the centre of each previous spot to remove solidification craters by remelting. Programmed reduction of current (tapering out) is used at the end of a run to give smaller and smaller spots which eventually have no craters (Fig. 2). In theory a wide range of pulse current amplitudes and durations can be used provided that the coulomb product of current x duration (Q = IT) remains within usable limits, but in practice there is a preferred range of currents for a particular material, therefore pulse duration becomes the only variable needed for different joint geometries and material thicknesses.[3]

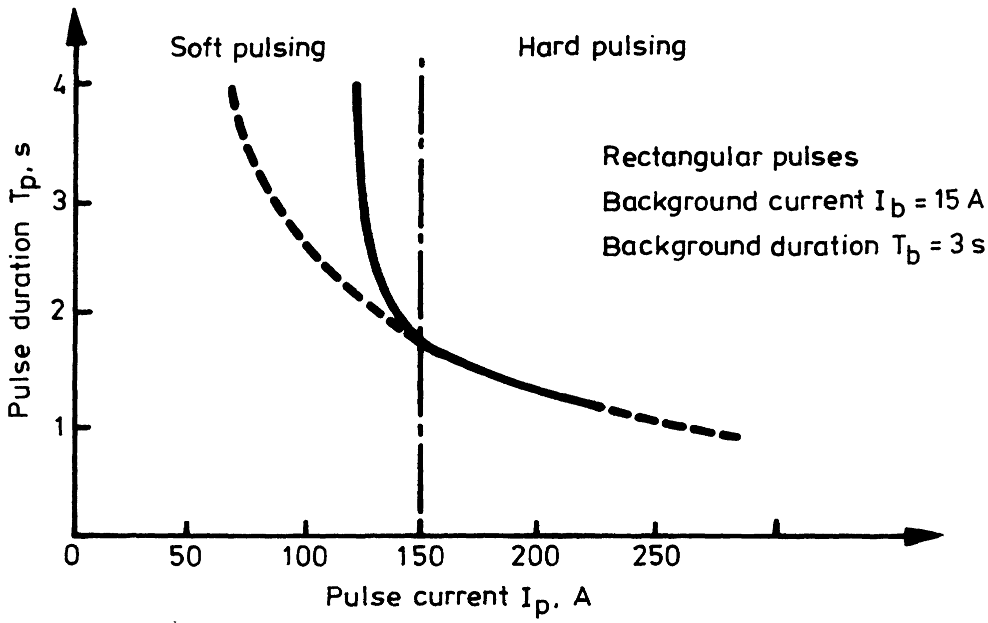
Pulsed TIG welding is also tolerant to a wide variety of materials and thicknesses when operated at constant coulomb value.[4] For example, based on analysis of heat flow, research at The Welding Institute and elsewhere showed that optimum pulse current is determined mainly by material properties, principally by average thermal diffusivity but not significantly by thickness. Preferred currents were around 400 A for copper, 150 A for austenitic stainless steel and 50 A for lead, irrespective of thickness. In contrast, for continuous DC welding it is necessary to vary current in proportion to thickness. The analysis showed also that pulse duration varies as thickness squared, so that material of 1 mm thickness requires only one tenth of the pulse duration of the same material 3 mm in thickness.

For most applications a simple rectangular current pulse is sufficient for control of penetration in materials up to about 3 mm thickness but more complex waveforms have been used (Fig. 3) for root passes in thick walled pipe, and were investigated and used successfully by the author to butt weld Cu-Ni-Fe tubing, a good thermal conductor. Using continuous DC TIG welding on this alloy it was impossible to melt a small enough molten pool to produce a satisfactory weld profile, even with helium shielding, because of excessive thermal conduction to adjacent parent material and resulting temperature rise. An intentional overcurrent at the start ensures that the molten pool is rapidly formed directly beneath the tungsten electrode tip. Relatively high current gives a 'stiff' arc with good directional stability as well as contributing to rapid penetration which is further developed under control at a second preset current. The amplitude of this second current determines whether a pulse is 'hard' or 'soft' (Fig. 4). The low current region of the curve gives soft pulses which result in slow advance of the fusion boundary with respect to thermal time constant of the material (reciprocal of thermal diffusivity). The high current region relates to hard pulses where the rate of advance of the fusion boundary is rapid, and approximates to constant coulomb operation. Soft pulsing has its uses where depth of penetration is greater than about 4 mm to obtain heat transfer by convection of liquid metal, and where surface oxides on the parent material cause discontinuous (or stepped) fusion and expansion of the molten pool. In all other applications hard pulsing is used to deliver minimal heat input for the amount of fusion required.

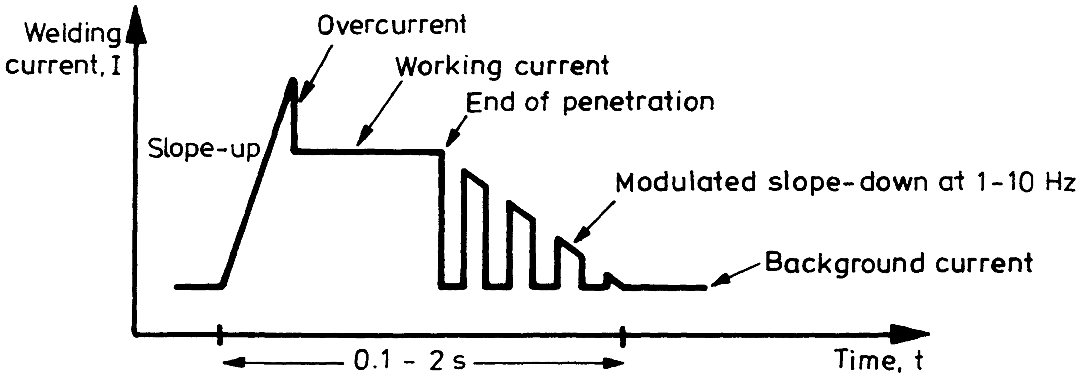
When sufficient penetration has occurred, current is rapidly reduced to the background level. For materials sensitive to crater cracking under constraint, solidification cracking or porosity, current is more gradually reduced. Modulated slope-down at 1-10 Hz (Fig. 5) has been used to give a sequence of rapid remelting and resolidification to control crater cracking. It also induces equiaxed grain growth by imparting at the solid to liquid



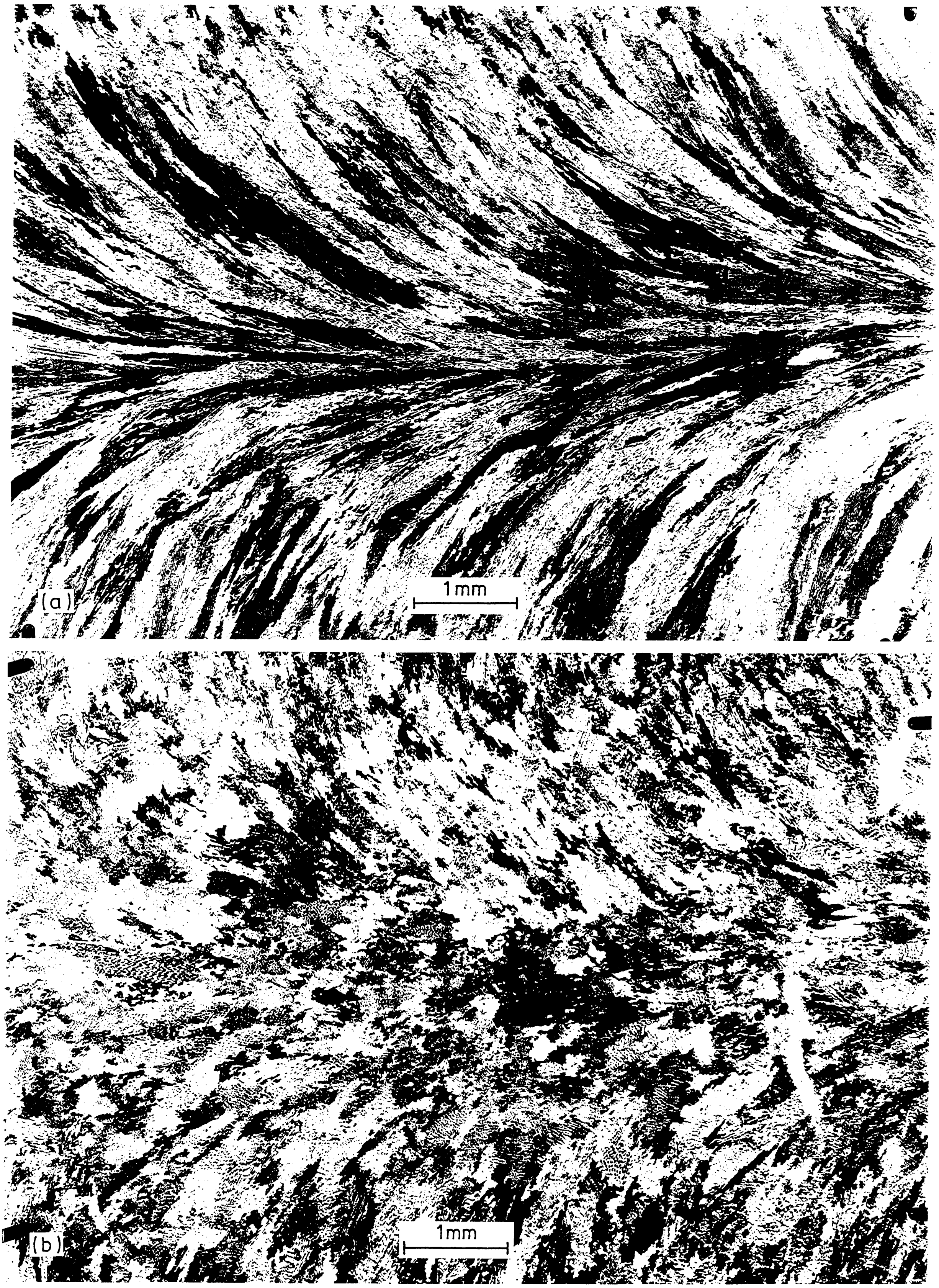
3 Complex pulsed current TIG welding waveform with rapid rate of rise to preset overcurrent for penetration control.



4 Experimental relationship between pulse current and duration for full penetration in TIG welded 3.5 mm AISI type 316 stainless steel.



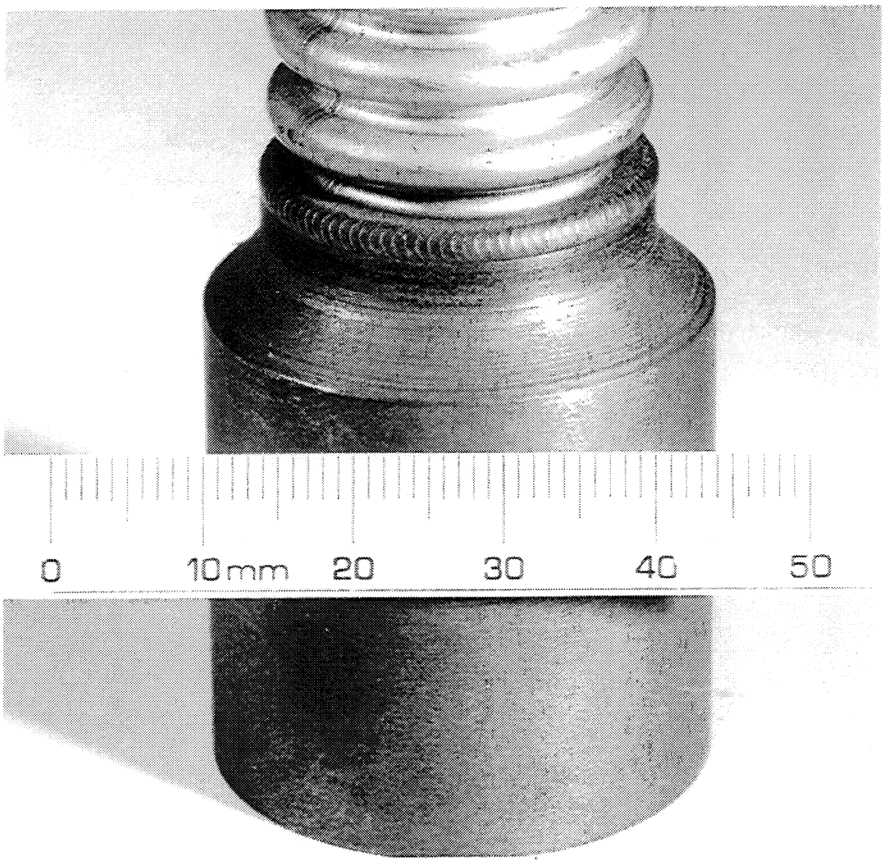
5 Modulated slope-down for solidification control of molten pool in TIG welding.



6 Grain growth in TIG welded AISI 321 stainless steel with modulated slope-out: a) Natural columnar formation without modulation; b) Modulation at 10 Hz.

interface thermal (and hence mechanical) shock at the growth front, preventing long columnar formations from developing (Fig. 6).

Agitation of the molten pool can be induced by pulsing at or near its resonant frequency (e.g. 1-10 Hz) to enhance circulation and improve control of segregation.[5] In non-ferrous materials such as aluminium and magnesium and their alloys, tenacious refractory surface oxide films are disrupted by such motion, assisting in coalescence of the melted edges at the joint line. Figure 7 is an example of the precision achieved using pulsed TIG welding on a difficult joint. A convoluted austenitic stainless steel tube 35 mm diameter, 0.1 mm wall thickness was welded to a 1.0 mm wall thickness low carbon steel end piece.



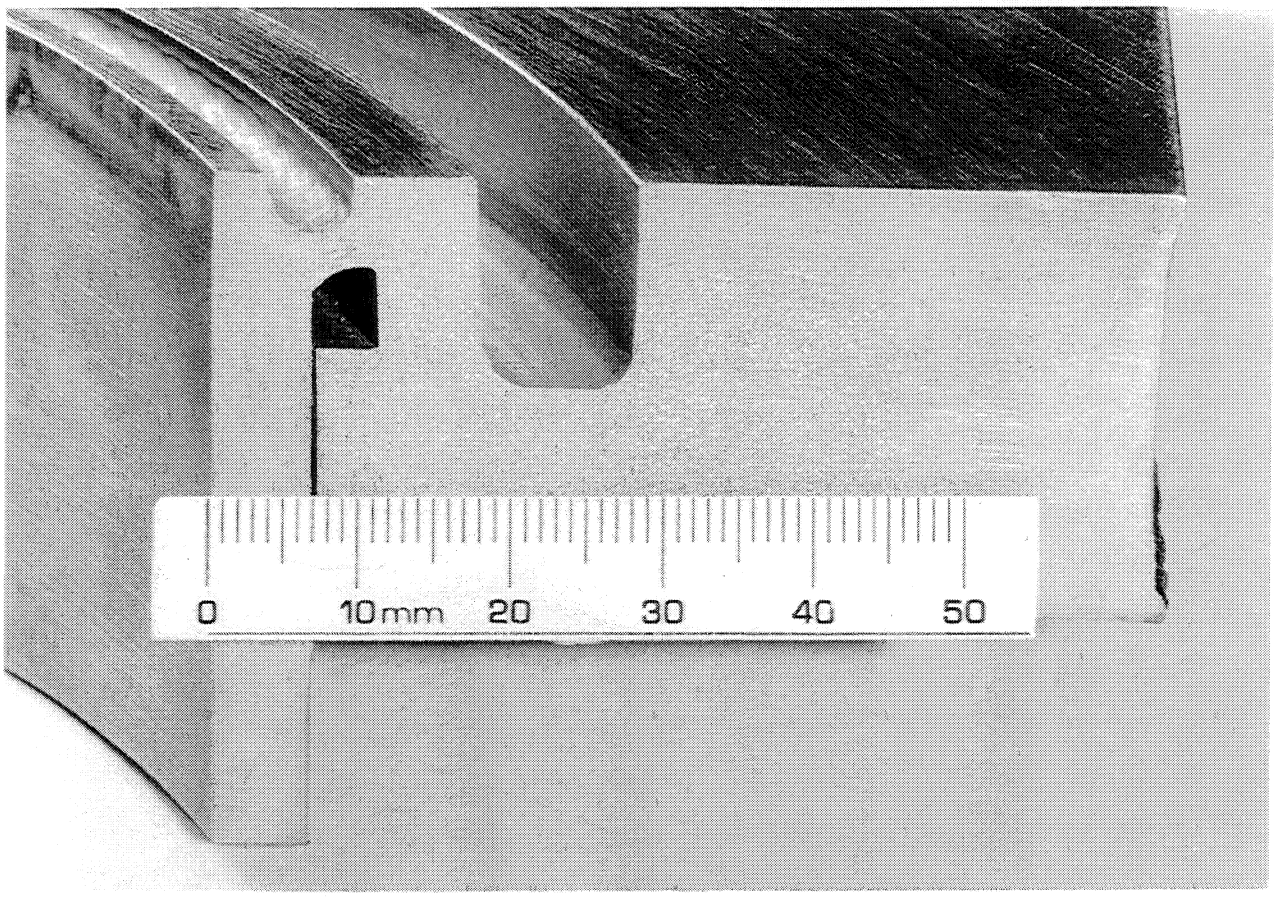
7 Low carbon steel end piece joined to convoluted austenitic stainless steel tube by pulsed TIG welding. Rectangular pulses of 75 A, 70 ms peak; 15 A, 140 ms background were used.

Squarewave pulsing at 75 A, 70 ms with background 15 A, 140 ms and rise and decay times of less than 50 μs were used successfully. Longer pulse and slope-up/slope-down times resulted in excessive melting and burnthrough of the already thin stainless steel. High quality and reproducibility were essential in this application because the joints were for flexible domestic gas couplings and five million were to be made.

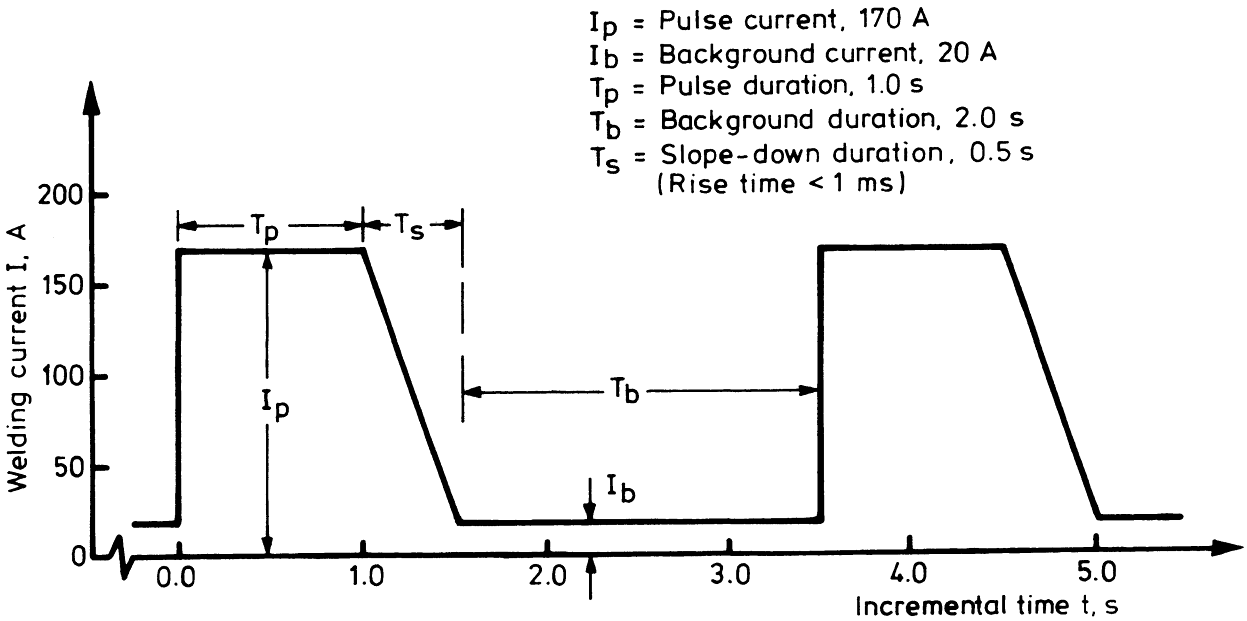
Another demanding application, but in thicker material is shown in Fig. 8. This is the root pass in a tube to tubeplate joint in AISI 304 stainless steel, welded using a trapezoidal waveform (Fig. 9) at 170 A, 1.0 s pulse and 20 A, 2.0 s background with slope-down 0.5 s. The tube is 200 mm diameter into tubeplate of 10 mm wall thickness. The unusual joint configuration was designed to minimise thermal distortion and provide integral filler material for the otherwise autogenous process but it prevented visual inspection of the weld back face, so that accuracy and reproducibility of fusion were essential to ensure full penetration for this nuclear power station component. As already stated, pulsed TIG is more tolerant to variations in fitup than steady DC and this joint successfully accommodated up to 2 mm mismatch between tube and tube plate. Figure 10 shows some examples of other difficult to weld joint configurations where dissimilar thermal capacity of components prohibits use of continuous DC and Fig. 11 represents the uniformity obtained in penetration profile when using correct pulse conditions.

3.2 High frequency pulsed TIG welding

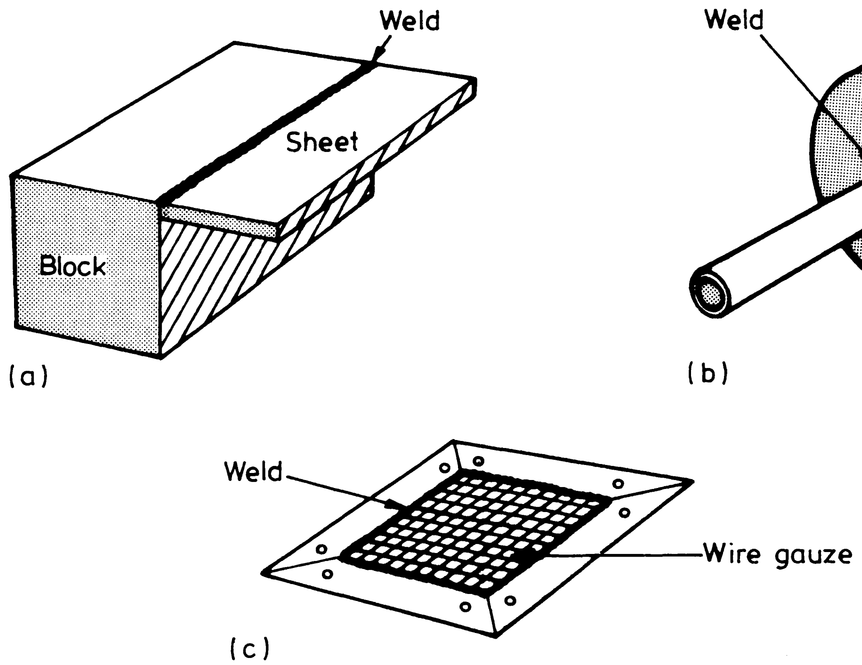
Less is known about this than thermal pulsing but reported work[6] indicates useful potential, and the author was involved in exploratory investigations using austenitic stainless steels. Frequencies of 5-15 kHz superimposed on the welding current generate forces which agitate the molten pool, disturbing nucleation sites and delaying freezing.



8 Tube to tubeplate root pass in AISI type 304 stainless steel using trapezoidally pulsed TIG welding. Pulse conditions 170 A, 1.0 s with 0.5 s slope-down; background 20 A, 2.0 s (courtesy Whessoe Heavy Engineering).

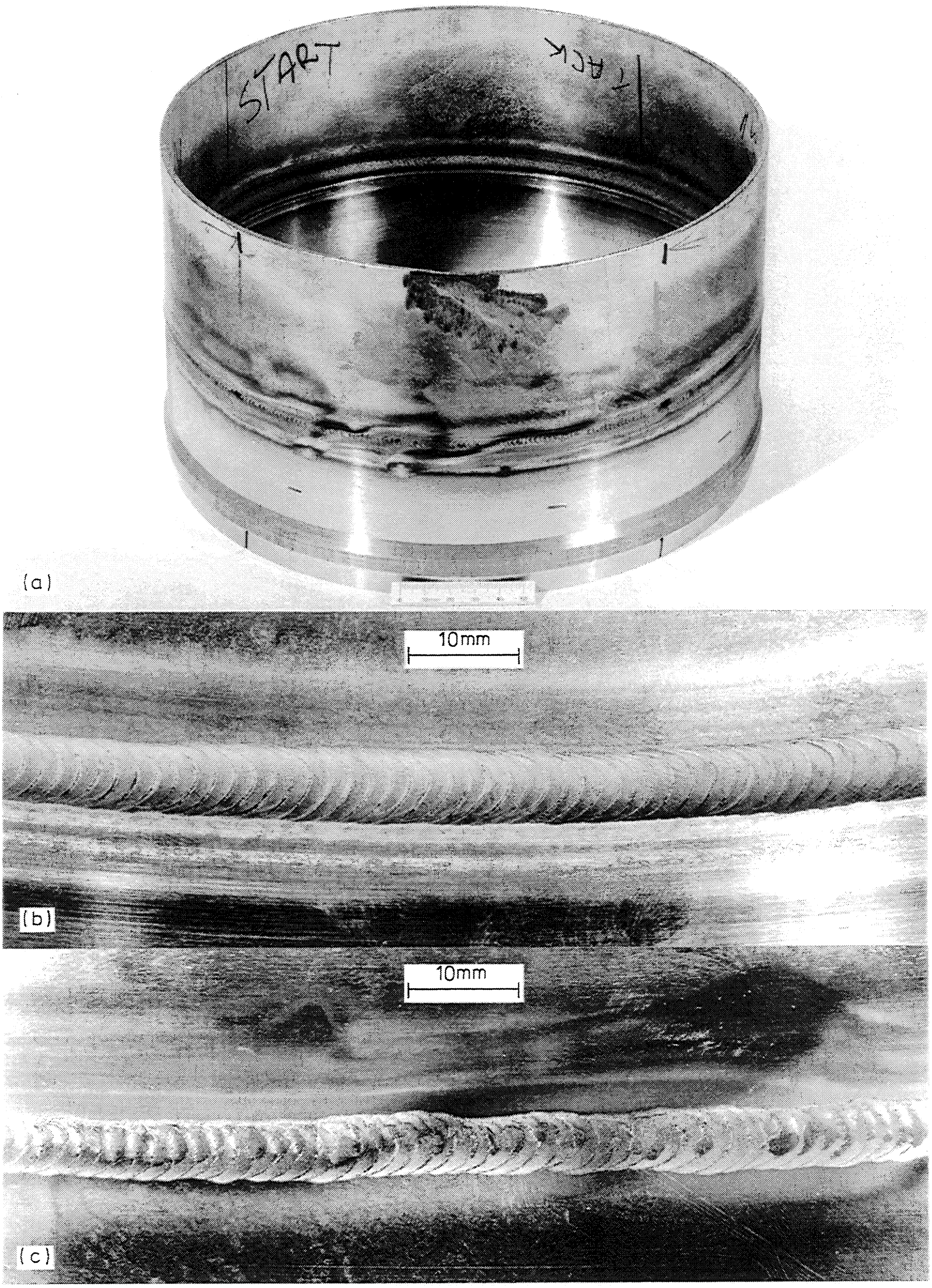


9 Two complete cycles of actual current waveform used for tube to tubeplate TIG weld of Fig. 8.



10 Difficult to weld joint configurations: a) Thick to thin section, ratio 10:1; b) Tube to flange; c) Wire gauze to retaining frame for filter element.

Higher welding speeds can consequently be used but control of solidification microstructure is of more interest. At these audio frequencies it is unlikely that fluctuations in solidification are caused by changes in heat flow, but there is evidence of grain refinement in ferrous and non-ferrous materials.[7] A possible explanation is that sonic disturbances propagating through the molten pool mechanically affect nucleation and its distribution. Another is that molten pool turbulence breaks tips off dendritic grains which become sites for heterogeneous nucleation and block further columnar growth. Repeated interruption of columnar growth then leads to formation of a region of equiaxed grains. An improvement in hot cracking resistance and centreline cracking is claimed. High frequency pulsing also gives improved arc stiffness which is useful in preventing wandering in root preparations and on thin sheet.

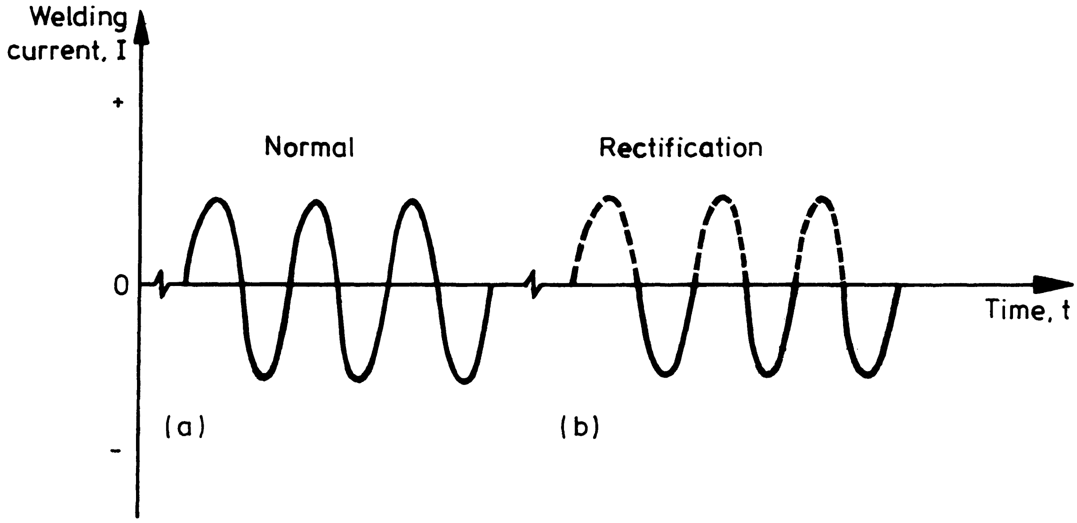


11 Nuclear fuel standpipe extension for an AGR in AISI type 321 stainless steel 250 mm diameter, 3 mm wall thickness: a) Section of TIG welded standpipe; b) Upper weld surface; c) Weld backface (courtesy Darchem Engineering).

A fast response transistor welding set was used to generate the 5-10 kHz modulated welding current for high frequency pulsing. Special instrumentation techniques were applied because squarewave pulsing at, for example, 100 A and 5 kHz is a rate of change of current of 5×10^5A s^{-1}. At this frequency, stray circuit inductance distorts the modulated waveform, and further distortion is introduced by the inherent inductance of the conventional current shunt used to produce oscillograms. The problem was minimised by keeping welding cables short, straight and bound together to prevent coils being formed. A low inductance shunt was made at first from a 250 mm long, 75 mm wide nichrome strip, bent transversely to a V shape at mid-length and folded flat on itself with a thin foil of mylar insulation between. With minimum enclosed area for the current path, inductance was low enough for distortion to be negligible. Overheating degraded the insulation and prevented this air cooled shunt from being used continuously because, in an effort to maintain a high resistance to inductance ratio as well as about 1V 100 A^{-1} signal output, its resistance (R) was 10 mΩ compared with a normal 0.5 mΩ. At 150 A welding current (I) power dissipation ($W = I^2R$) was 225 W, so a coaxial, tubular water cooled replacement was developed and used successfully. Current change (dI/dt) in an inductor (L) generates reverse voltage (-E) according to $-E = L\ dI/dt$. A volt or so of spurious signal is therefore produced at $dI/dt = 5 \times 10^5$A s^{-1} by an inductor of only 2×10^{-6}H, not uncommon among normal meter shunts. Signal to noise ratio is therefore undesirably low, sometimes less than unity.

3.3 Pulsed AC TIG welding

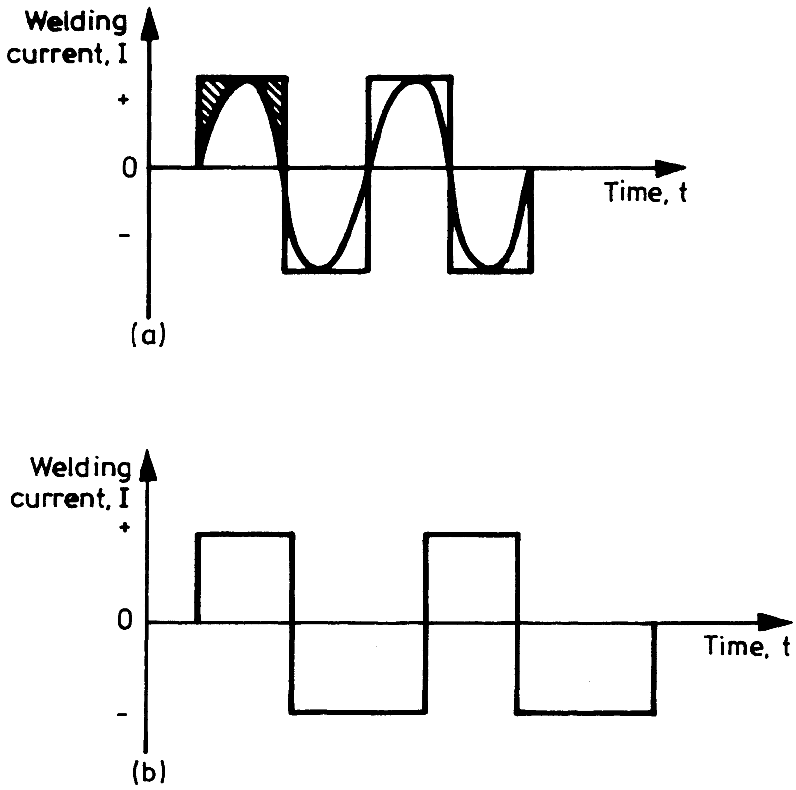
Until 1972 no pulsing in AC TIG had been reported but work by the author on thin walled aluminium brass tube for desalination plant demanded a combination of AC with low heat input and led to development of pulsed sinusoidal operation.[8] Zinc is an important alloying element in aluminium brass and other brasses. Its melting temperature (693 K) is low



12 Sinusoidal AC TIG welding waveforms: a) Normal; b) Electrode positive half cycles removed by complete rectification.

compared with those of the other constituents (1356 K for copper) so that not only is it lost to excess by evaporation when molten, adversely changing weld metal composition, but its vapour in the arc causes complete rectification (Fig. 12), defeating the purpose of using AC for disruption of tenacious refractory surface oxides during the workpiece negative half cycle. Reliable pulsing between high and low currents was made impossible by intermittent reignition failure following cyclic zero crossing. The problem was solved by connecting a high open circuit voltage (400 V OCV) reignition and background current supply in parallel with the main welding transformer and commutating the pulse current with independently fired inverse-parallel connected thyristors. The author was able to run stable arcs as low as 0.25 A with this circuitry.

Individual control of each polarity permitted correction of inherent rectification caused by asymmetry between positive and negative half cycles of current, and the high OCV ensured consistent reignition for successful pulsing. Since then, commercial squarewave welding



13 Rectangular AC TIG welding waveforms: a) Shaded area represents extra energy compared with sinusoid of equal amplitude and duration; b) Asymmetrical waveform with longer duration electrode negative half cycles to increase heat input to workpiece.

sets have become available. The rapid current reversal (10-50 μs) through zero obtainable with squarewave operation makes reignition after cyclic arc extinction much easier than with sinusoidal operation, allowing OCVs of 50-80 V to be used. The short reversal time does not allow tungsten or workpiece to cool significantly and thermionic emission of charge carriers is sustained into the next opposite polarity half cycle. Furthermore, greater arc energy is available from a squarewave than a sinusoidal half cycle of equal amplitude and duration, giving more concentrated pulsing. Individual control of positive and negative polarities (Fig. 13) allows a welder to choose the optimum combination of heat input versus cathodic cleaning for a wider variety of non-ferrous materials than normal AC and allows compensation for inherent rectification without need for a large, expensive series capacitor to block the DC component. These improvements have been of considerable benefit in welding thin (0.1-1.5 mm) aluminium sheet.

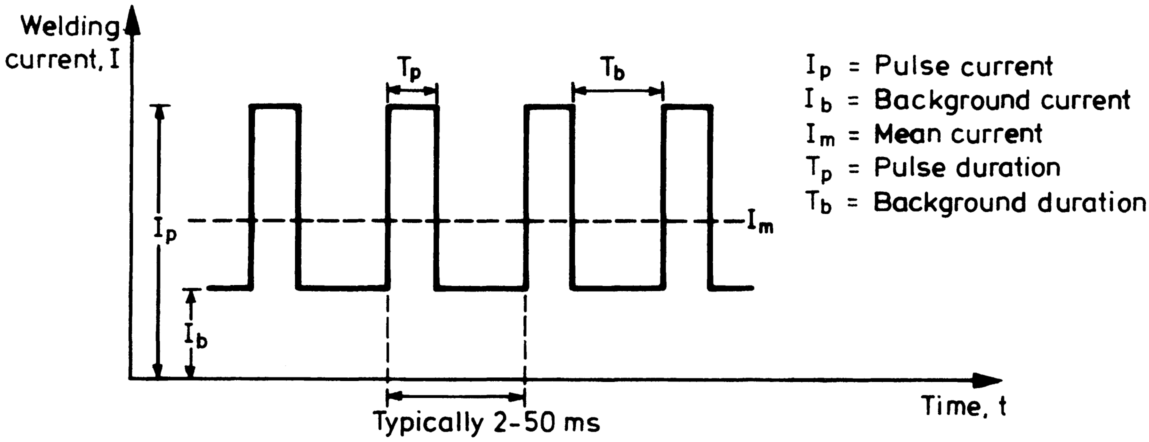
3.4 Pulsing in MIG welding

The main type of modulation in MIG welding is pulsing at 20-500 Hz for control of droplet detachment and arc behaviour but, with synchronised wire feed, low frequency (1-10 Hz) thermal pulsing has also been achieved by the author,[9] which is directly comparable with pulsed TIG welding.

3.4.1 Conventional pulsed MIG welding

Pulsed current for control of metal transfer and arc stability was described by Needham[10] in 1962, and in 1963 the author's involvement in pulsed MIG welding for aluminium began when he transferred to the Needham and Carter team. Pulses at that time were sinusoidal only, because they were derived directly from mains supplies, and had frequencies which, through rectification and commutation techniques, were fixed multiples or sub-multiples of supply frequency (50 Hz in the UK) but over a relatively limited range, e.g. 16⅔, 25, 33⅓, 50, 100, 150 and 300 Hz.

Pulsing was introduced originally for control of metal transfer by imposing artificial cyclic operation on the arc system. The cycle consists of alternately applied high and low currents (Fig. 14), the high level causing rapid melting and enforced detachment of the melted electrode wire tip, the low acting as a background level to sustain a pilot arc, keep the tip molten, give stable anode and cathode roots and maintain the average current during a complete cycle at a level similar to that for non-pulsed welding.

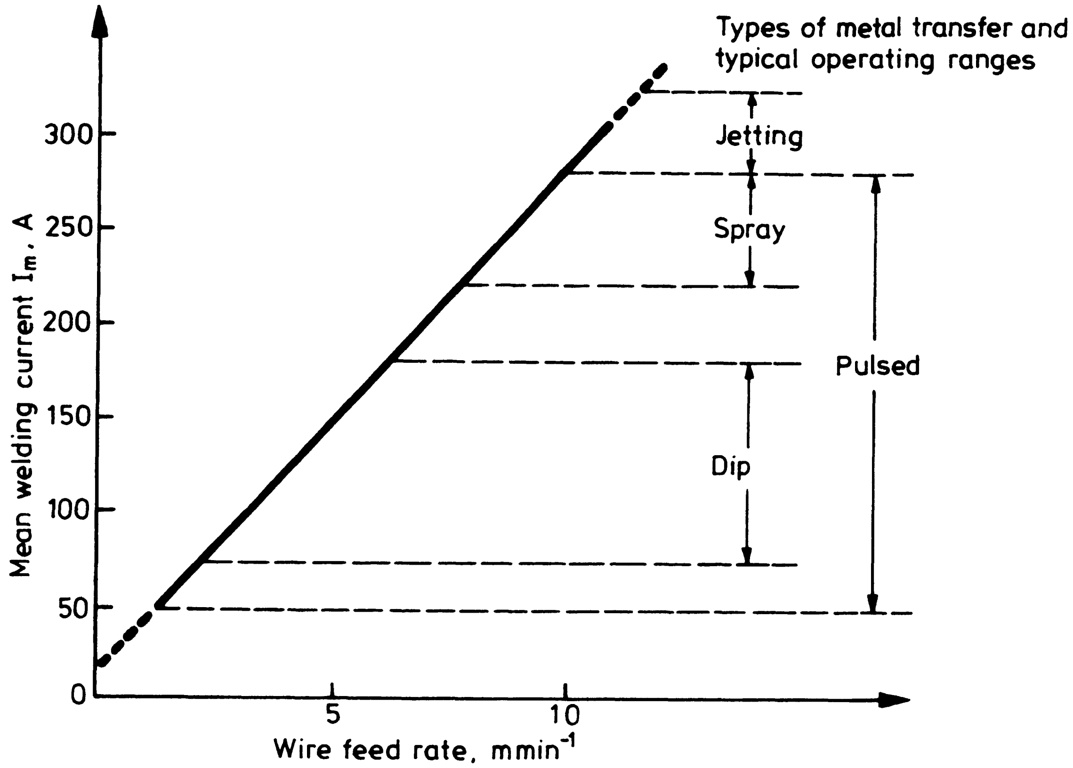


14 Ideal pulsed MIG welding current waveform - frequency range typically 20-500 Hz.

Modern semiconductor controlled welding sets permit use of a wide range of pulse amplitudes, durations and waveforms at frequencies from a few hertz to kilohertz. With such versatility, pulse conditions can be chosen for a variety of effects. Pulse current and current density must be sufficiently high to ensure that spray transfer (not globular) always occurs so that all-positional welding can be used. Pulse amplitude and duration are best combined to melt and detach a single droplet of the same diameter as the electrode wire. Pulse duration must be long enough for electromagnetic Lorentz forces in the arc to detach and propel the droplet across the arc gap with sufficient speed to make transfer independent of gravity and position. Droplets consequently have inherently higher kinetic energies, thereby enhancing agitation and circulation of the molten pool provided that pulse duration is not so long that multiple transfers occur and that droplets do not reach the molten pool before a pulse ends, otherwise spatter may be generated. The background current need only provide a pilot arc stiff enough to be immune to wandering until the next pulse arrives.

3.4.2 Benefits of pulsed MIG welding

Current pulsing in MIG extends spray operation to well below the natural transition (about 180-220 A for 1.0-1.2 mm mild steel wire) from dip to spray transfer (Fig. 15), allowing use



15 Burnoff characteristics of 1 mm diameter mild steel electrode wire (Si-Mn deoxidised, BS 2901:Part 1:1970:A18) in Ar/5%CO_2 shielding gas.

of smooth, spatter free welding at average currents e.g. 50-150 A which would otherwise be too low for all except dip transfer with its irregular transfer and accompanying spatter. Correctly adjusted dip transfer is useful in ferrous welding of thin (0.6-2.0 mm) materials such as car bodies but is not used for non-ferrous welding.

Pulsing with rectilinear waveforms became possible with the advent of high current semiconductor welding sets. A rectangular pulse raises current from background to peak in only 10-50 μs, giving a stiffer arc and more rapid and controllable melting and detachment of the electrode tip than with a sinusoid. Combined with equally rapid return from peak to background, arc energy is efficiently utilised for the intended purposes of droplet and arc control, not dissipated in unproductive electrode or workpiece heating. For a given heat input per unit length of weld the pulsed arc gives a narrower and deeper fusion zone compared with conventional DC operation, and the HAZ is smaller.[5] Control of bead shape and more continuous heat input are also achieved.

3.4.3 'One knob' control

Although current pulsing allows all-positional droplet transfer, MIG welding in the vertical position was traditionally carried out by dip transfer because of difficulties in establishing and maintaining the required pulse parameters. A disadvantage of dip transfer is that its low heat input results in lack of sidewall fusion defects. Weaving across and washing up the sides of the joint preparation help prevent such defects but impose more demands on manual and mechanised techniques.

One knob control welding sets are now commercially available which generate pulses over a wide range of useful frequencies, with pulse amplitudes, widths and waveforms to meet the requirements of all positional welding.[11] Their advantages are many:

1 Melting and detachment of droplets (hence droplet size) are made independent of average welding current, as is arc stability. Electronic pre-programming of these and other parameters eliminates setting up by the welder;

2 Heat input can be varied to give the optimum value for any task without operator participation in individual parameter selection;

3 Weld bead size can be varied during welding by one knob adjustment because electronic co-ordination of related parameters, i.e. current and wire feed rate, is automatic;

4 The electronics circuitry of the welding set can be interfaced with robots, manipulators or other elements of mechanised welding systems;

5 Uniformity of control of welding parameters means that welding procedures set up in one place are capable of being transferred accurately to another, e.g. from development workshop to factory site anywhere in the world.

Pulse parameters - influence on process behaviour

Modern transistor welding sets produce the rectangular waveform, ripple free pulses needed for reproducible control of metal transfer and arc behaviour. These pulses approximate closely enough to ideal waveshapes (Fig. 16) for useful calculations to be made concerning process parameters, impossible with magnetic amplifier (transductor/saturable reactor) controlled equipment. Pulse and background currents are not significantly affected by voltage change, therefore pulse current and duration (I_p, T_p) and background current and duration (I_b, T_b), together with wire feed rate (W) and voltage required to regulate arc length, can be used to define the process.[11] In contrast, continuous DC operation requires a welding set with constant voltage characteristics (2-6 V 100 A^{-1}) to obtain arc length control. This dictates that the process is defined by wire feed rate and OCV but not by welding current, which is a disadvantage as current is the most important parameter.

In squarewave pulsing, droplet detachment is governed by I_p and T_p, droplet volume by wire feed rate divided by pulse repeat frequency (W/f), and arc stability by I_b and T_b. Given the accurate control of these fundamental parameters* which is possible with transistor welding sets, process flexibility is considerably improved in comparison with conventional DC MIG operation.

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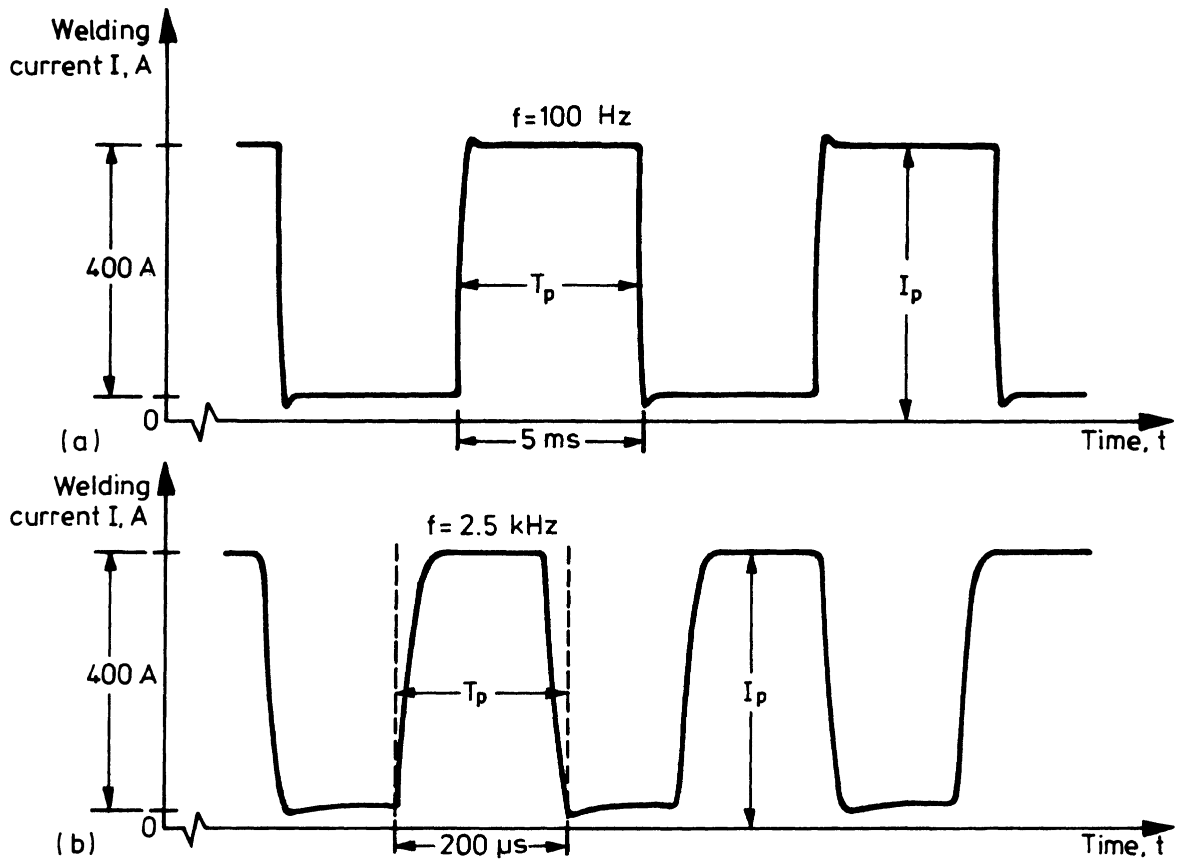
* See appendix



16 Squarewave current response of 500 A linear transistor regulator welding set operating at 400 A with pulse repeat frequency of: a) 100 Hz and virtually no distortion; b) 2.5 kHz and some harmonic distortion.

3.4.4 Synergic pulsing

Synergic* (from the Greek syn, together and ergon, work) pulsing was the outcome of research at The Welding Institute, in which the author participated, to investigate in detail the fundamental requirements for operating pulsed MIG welding, but has become a term with different meanings through uninformed use. True synergic pulsing provides unit current pulses to detach identical molten droplets of predetermined volume from the electrode wire, combined with the other parametric relationships necessary for stable wire

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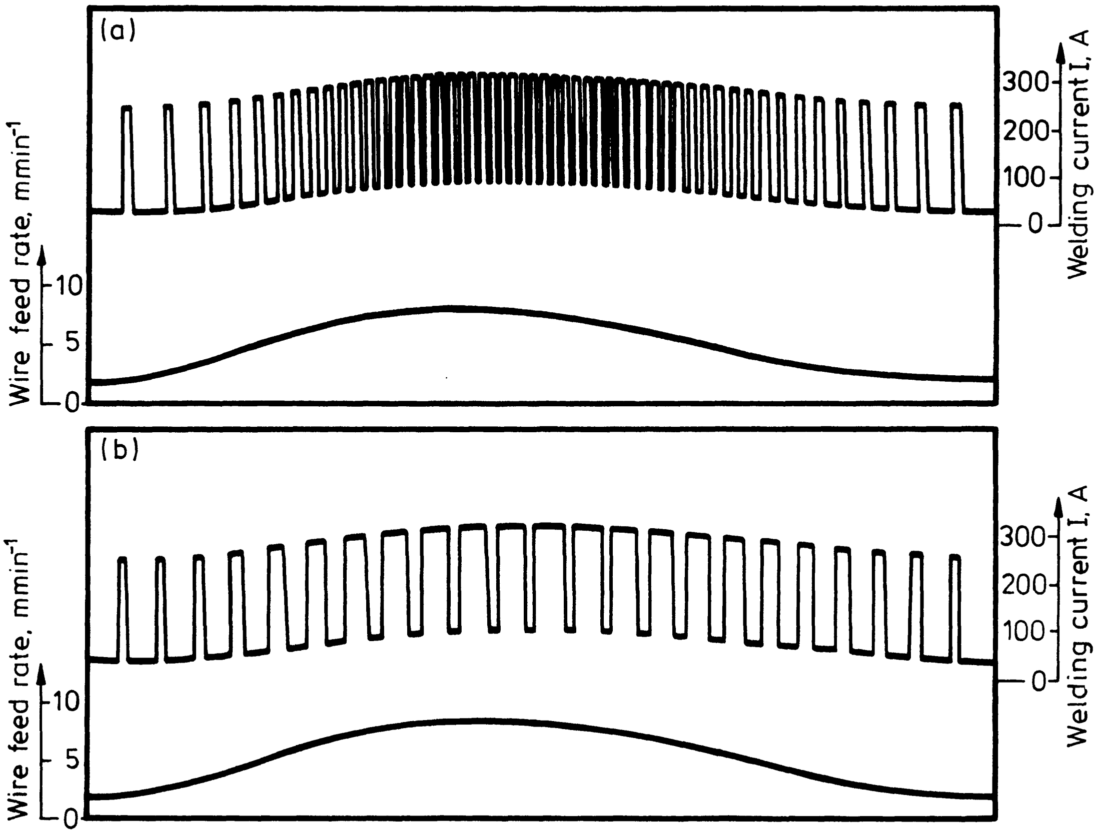
* See appendix



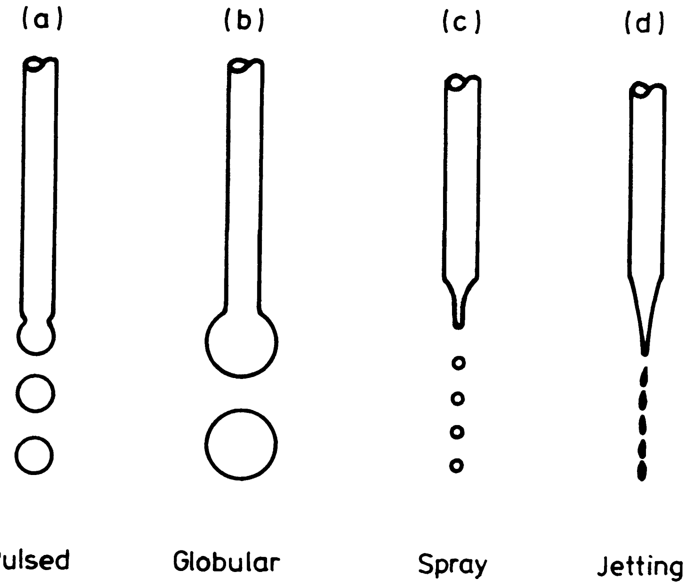
17 Main types of synergic pulsing: a) Variable pulse repeat frequency at constant pulse duration; b) Variable pulse duration at constant pulse repeat frequency.

burnoff. There are two main types of synergic pulsing,[12] covering burnoff rates of about 0.5-10 m min^{-1}:

1 Variable pulse repeat frequency at constant pulse duration;

2 Variable pulse duration at constant pulse repeat frequency (Fig. 17). Because it is easier to maintain unit droplet characteristics at constant pulse amplitude and duration, this form of synergic pulsing is preferred in practice. The three essential characteristics of this type of synergic operation are:

i Pulse parameters are selected automatically;



18 Types of metal transfer in open arc MIG welding. Electrode wire diameter D, droplet diameter d:

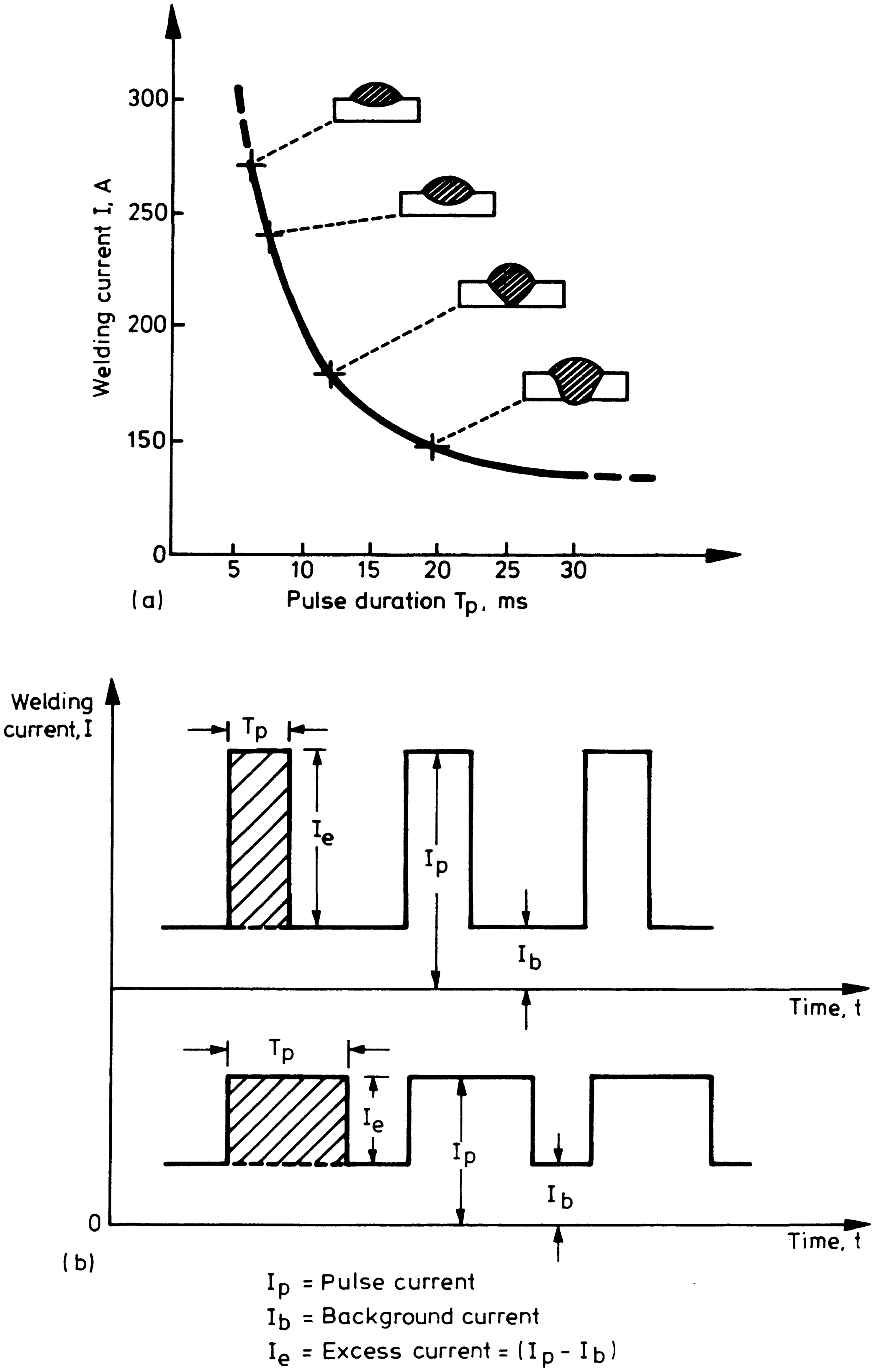
a) Pulsed, $d \approx D$; b) Globular, $d \geq 2D$; c) Spray, $d \leq \frac{D}{2}$; d) Jetting, $d \leq \frac{D}{4}$.

ii Pulse frequency is directly related to wire feed rate;

iii Electronic control of parameters ensures uniform penetration and weld bead profile.

Pulse amplitude and width are chosen to melt and detach a unit droplet the same diameter as the parent electrode wire (Fig. 18). Pulse repetition frequency is dictated by wire feed rate, e.g. as wire feed is increased, pulse frequency is automatically increased in direct proportion under open loop control.

Unit pulses are unique to a given material and wire diameter and their details are programmed into the welding set. An operator has only to preselect material and diameter once for any welding operation, then adjust the one knob which governs wire feed rate.



19 Effect of pulse duration (T_p) on weld penetration profile: a) For 1.6 mm diameter aluminium wire on 6 mm thickness plate (after Needham); b) Stylised constant current x time product squarewave pulses at same repeat frequency. In practice, background current (I_b) is varied with wire feed rate and pulse frequency (after Amin).

After that, all other parameters are called up automatically under electronic management. Because pre-programmed open loop control is used, no further tuning of parameters is needed. Synergic pulsing is flexible enough to accommodate intentional changes in pulse 'signature', imposed for control of penetration profile. For example, provided that the current x duration (coulomb) product is kept constant, I_p and T_p may be varied in inverse proportion (Fig. 19) to extract the full control potential from the process.

The effect of pulse duration on penetration is significant. Short pulses produce shallow penetration, and much deeper bowl shaped weld bead profiles result from longer pulses.

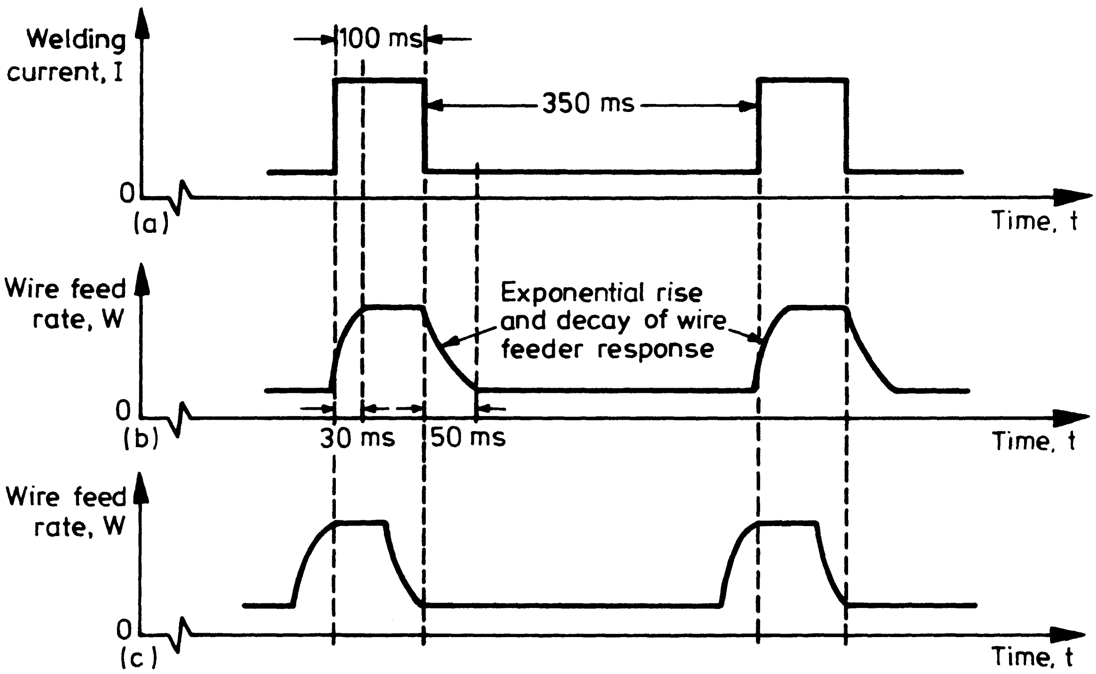
3.4.5 Advantages of synergic pulsing

In operation the synergic system provides high arc stability even when wire feed rate fluctuates because of slipping drive rolls, variations in mains supply voltage or poor motor speed regulation. Almost instantaneous readjustment of the pulse parameters ensures that no arc instabilities result and consequently no defects occur in the weld. Because the synergic system accommodates fluctuations in wire feed rate, it is possible to modulate wire delivery intentionally for weld profile control. At the end of a run wire feed rate can be progressively reduced from the normal welding level for crater filling. At the start, wire feed rate can be progressively increased to avoid build up which normally occurs in MIG welding.

This feature is useful in pipework where normal circumferential seams with cold starts are subsequently overlapped. A tapered start is a more satisfactory profile for overlapping, readily obtainable with synergic pulsing. If changing parameters are required for joint filling, for example, to accommodate a changing gap in a root run, average current can be reduced to avoid burnthrough by reducing current alone. Similarly, in subsequent and capping passes, wire feed rate may be adjusted to maintain the required joint geometry. Fume evolution is lower for single droplet transfer compared with identical volume multiple transfer because surface area from which evaporated metal ultimately becomes particulate is also lower.

3.4.6 Thermal pulsing in MIG welding

Droplet pulsing is not the only type possible in MIG welding. Thermal pulsing via modulated wire feed rate[9] has been developed by the author and this has many useful characteristics. It is obtained by switching between low and high currents as for pulsed TIG, but wire feed rate also must be switched synchronously in MIG (Fig. 20). Early work

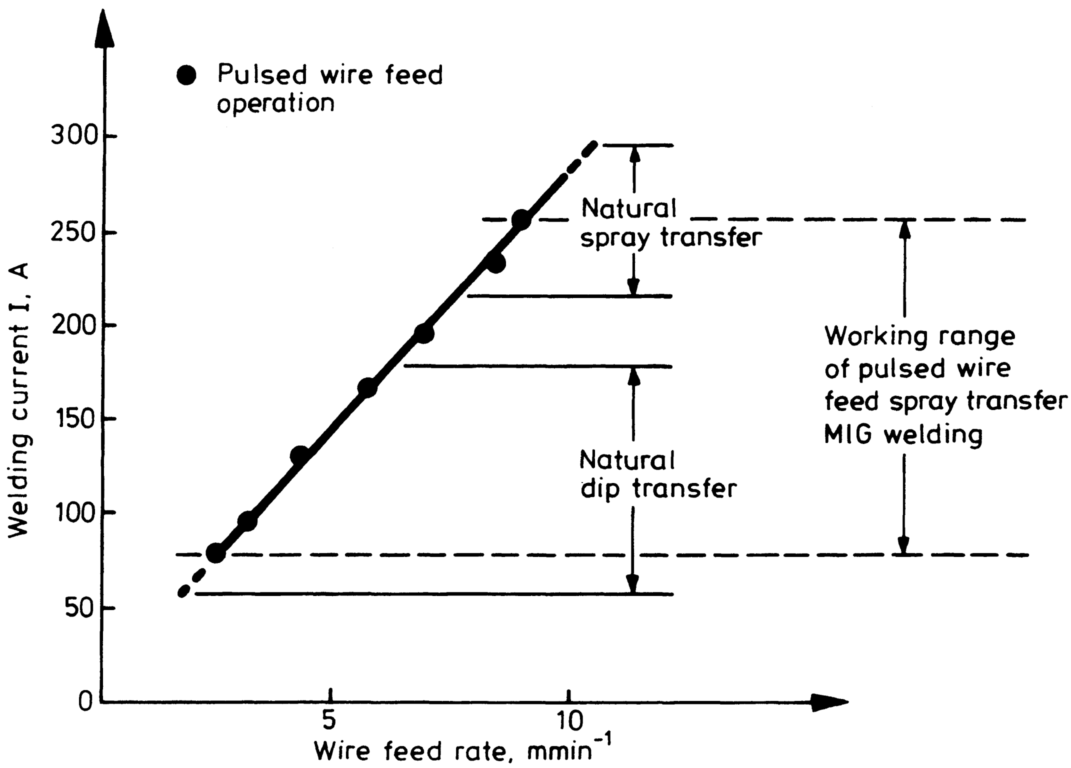


20 Fast response wire feeder pulsed synchronously with transistor welding set at nominal 2.2 Hz: a) Virtual squarewave welding current; b) Natural response of wire feeder with inertial lag; c) Wire feeder response advanced with respect to welding current to compensate for lag.

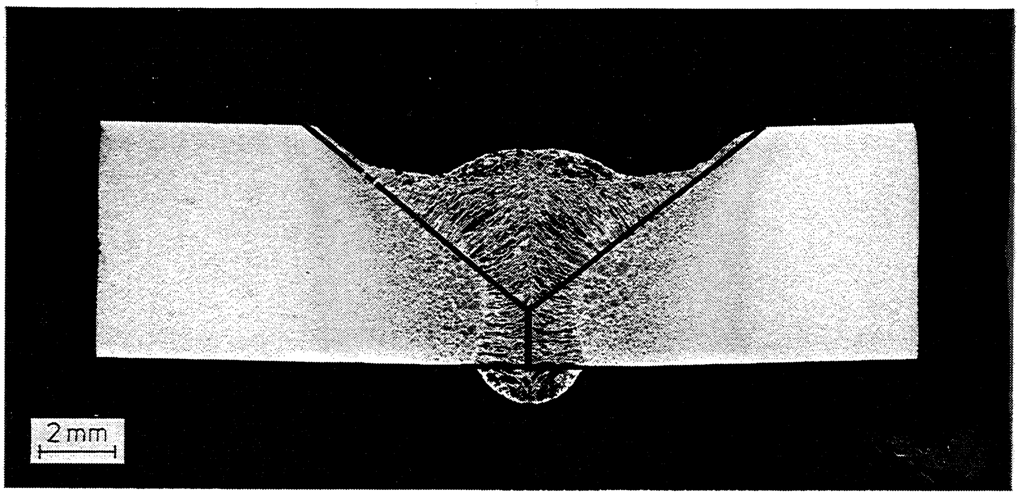
was conducted with a commercial wire feeder which had an inertial time constant of about 0.2-0.3 s. Synchronous switching of welding current and wire drive motor caused problems because current reached its pulse level almost instantaneously but the selected wire feed rate was reached about 0.2 s later. This usually resulted in burnback near the start of a pulse or if not, stubbing in occurred near the end. Advancing the motor drive command with respect to welding current by the 0.2 s difference in response corrected the out of phase relationship, and pulsing at 2 Hz was achieved without a special wire feeder. An incidental advantage of such pulsing also became evident via high speed cine photography which was taken to study arc behaviour and metal transfer. Deliberate over advancement of the wire drive so that the electrode wire tip was 0.5-1.0 mm from the workpiece at the onset of each current pulse produced a short, intensely directional arc and excellent weld penetration. Removing the motor drive command before the end of a current pulse allowed the arc to lengthen to 10-15 mm while the wire feeder lost speed, allowing good sidewall fusion to take place. This pulsed wire feed process gave conventional thermal pulsing comparable with pulsed TIG welding, combined with arc length control for regulation of fusion behaviour. Faster response motors with low inertia printed armatures later became available, permitting up to 8 Hz squarewave pulsing. It was necessary to use controlled excess armature current to accelerate to peak wire feed rate sufficiently quickly, and to apply reverse polarity current for electrodynamic braking, to obtain the required squarewave pulsed response. This placed severe mechanical, electrical and thermal demands on motor, drive system and controller; demands which were removed by the advent of synergic pulsing. Wire feed motors could be cyclically driven more gently from background to peak wire feed rate and back again because a high output (45 V 1 000 rpm^{-1}) DC precision tachogenerator in slipless contact with the moving wire was used to provide the analog voltage signal to drive the welding current pulse frequency generator. Pulse frequency would therefore always be correctly matched to wire feed rate, even accommodating slip between wire and drive rolls.

3.4.7 Benefits of pulsed wire feed MIG welding

Control of fusion and weld bead profile is possible by thermal pulsing, directly comparable with pulsed TIG welding. Other benefits are a downward extension of the working range of the spray transfer MIG process (Fig. 21) to obtain a good penetration profile at low mean currents which otherwise would dictate use of dip transfer; and the ability to penetrate with precision a joint preparation with 1.5 mm root face , no root gap and no backing, eliminating the need to use TIG welding (Fig. 22).



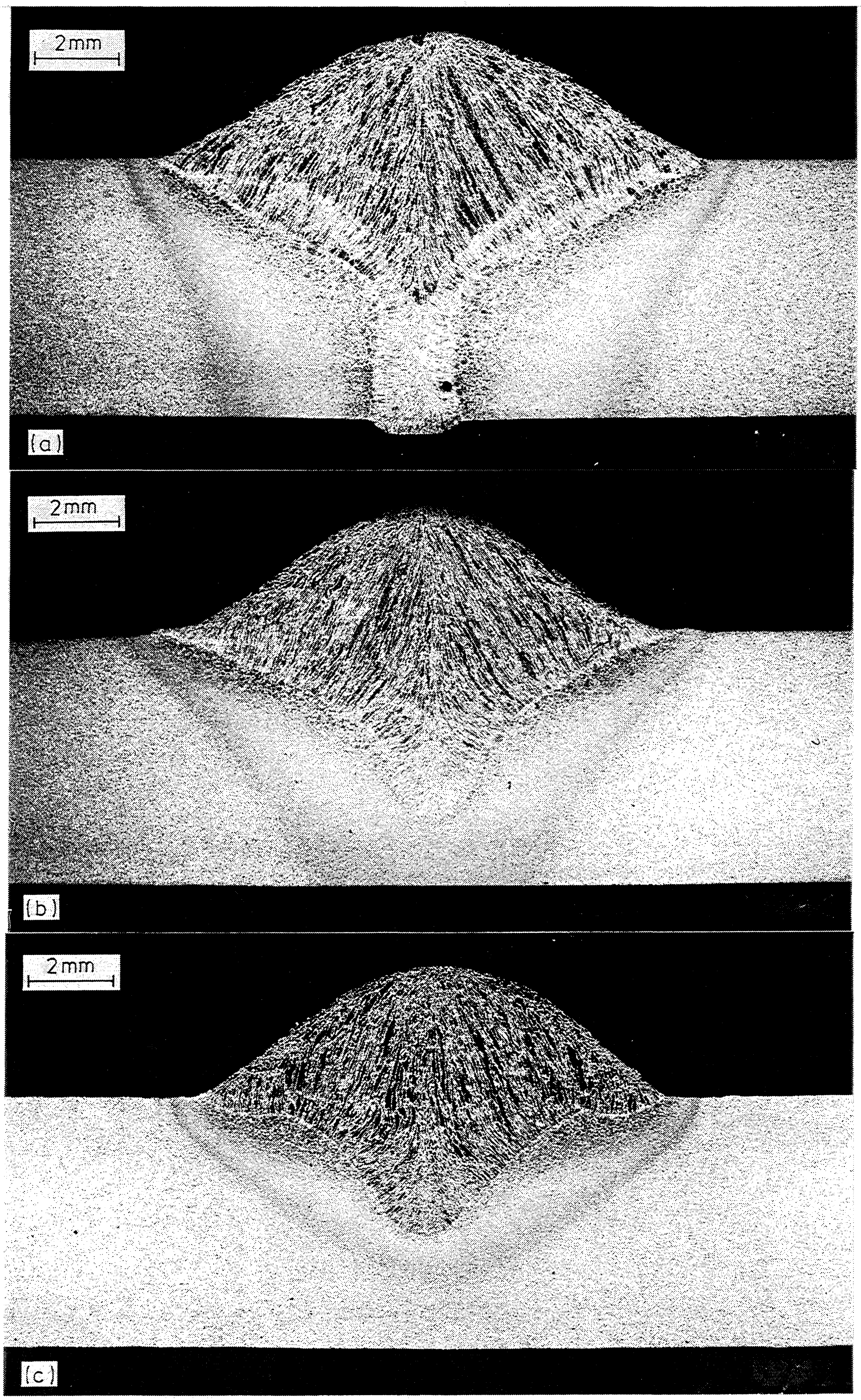
21 Burnoff characteristics for 1 mm diameter mild steel wire (Si-Mn deoxidised, BS 2901: Part 1:1970:A18) in Ar/5%CO_2 shielding gas, using pulsed wire feed (1-5 Hz) MIG welding. Note that average wire feed rates and current amplitudes are given for pulsed operation.



22 Transverse section of root pass in 6.4 mm thickness mild steel plate using pulsed wire feed MIG welding. Pulse current 300 A, 0.1 s duration and background current 25 A, 0.1 s duration.

3.4.8 Pulsing in AC MIG welding

AC MIG welding[13] was developed by the author et al in 1974-75, following work by Amin on electrode negative operation. The objective was to explore the possibility of exploitation of the best properties of conventional electrode positive welding, combined with the almost double deposition rate of electrode negative polarity. After extensive work to develop circuitry for arc reignition after cyclic current reversal, stable operation was achieved which showed that AC MIG welding does indeed combine the desirable bowl shaped penetration profiles of DC electrode positive with the high deposition rates of electrode negative operation (Fig. 23). Metal transfer occurs during the electrode positive half cycle only, resulting in a form of pulsing inherent in the process at a rate governed by the mains supply frequency. The background current is of equal amplitude but opposite polarity. Consequently, arc behaviour and metal transfer at low wire feed rates exhibit the advantages of DC pulsed MIG with projected spray transfer, without the need to adjust pulse and background currents to stabilise the arc and metal transfer. Another advantage of AC MIG welding is its resistance to magnetic deflection (arc blow). Work by the author



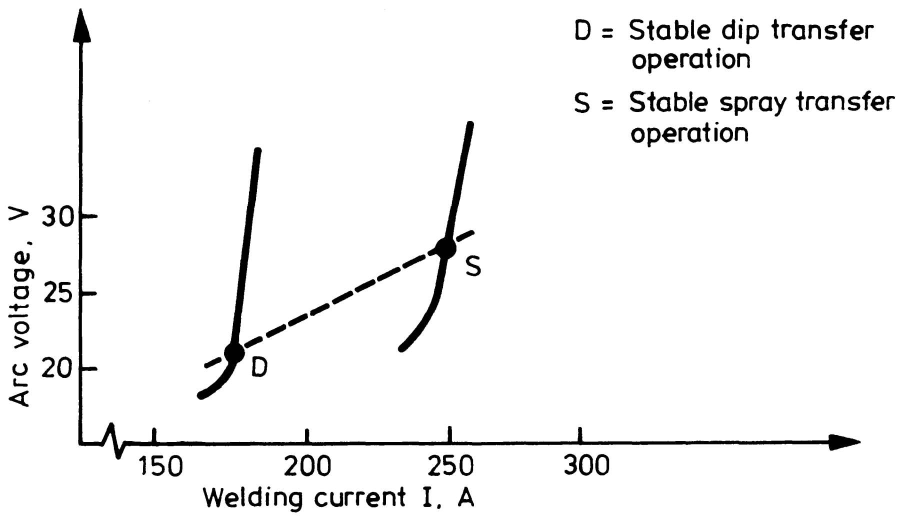
23 MIG weld bead profiles at high deposition rate using 1.2 mm mild steel electrode wire (Si-Mn deoxidised, BS 2901:Part 1:1970:A18 in Ar/5%O_2 shielding gas. Wire feed rate 15 m min^{-1}, traverse speed 0.5 m min^{-1}: a) DC electrode positive; b) AC; c) DC electrode negative.

showed that the process tolerated an arc zone flux density of 9-10 mT (90-100 gauss) from a transverse electromagnetic field before instability occurred. DC MIG welding, however, had a threshold of only 3-4 mT (30-40 gauss) for otherwise identical operating conditions. Preliminary investigations were conducted at 50 Hz using a mains transformer supply for welding current. Later tests, run at 400 Hz from a standard portable welding alternator, showed that better resistance to magnetic deflection could be obtained at higher frequency. Some ferromagnetic materials,such as 9% nickel steel, cause problems with arc deflection which AC MIG welding could solve. Similar problems exist with structural and other ferritic steels which have been moved using electromagnetic handling. For these, demagnetisation is often required before welding, but is expensive, time consuming and not always uniformly achieved.

3.4.9 Pulsed arc voltage

Complementary to current pulsing is pulsed voltage in MIG welding, which causes controlled changes in arc length or transfer mode at otherwise constant wire feed rate and mean current, and was explored by the author for use in narrow V groove weld preparations. For example, a transition from dip to spray transfer is imposed when voltage is pulsed in the range 18-24 V. Cyclic repetition at a suitable frequency of 1-2 Hz enables the benefits of low heat input during the dip transfer mode to be combined alternately with the better fusion and reduced spatter of the spray mode, for work on 1-3 mm thickness steel sheet. Pulsing between 24-30 V or so at constant current and wire feed rate results in periodic instantaneous lengthening and shortening of the arc, maintaining spray transfer throughout. In V preparations the shorter arc melts weld material immediately beneath the electrode wire, but the longer arc fuses the sidewalls and washes in molten metal at the joint. This combination gives good penetration and reduces lack of sidewall fusion defects.

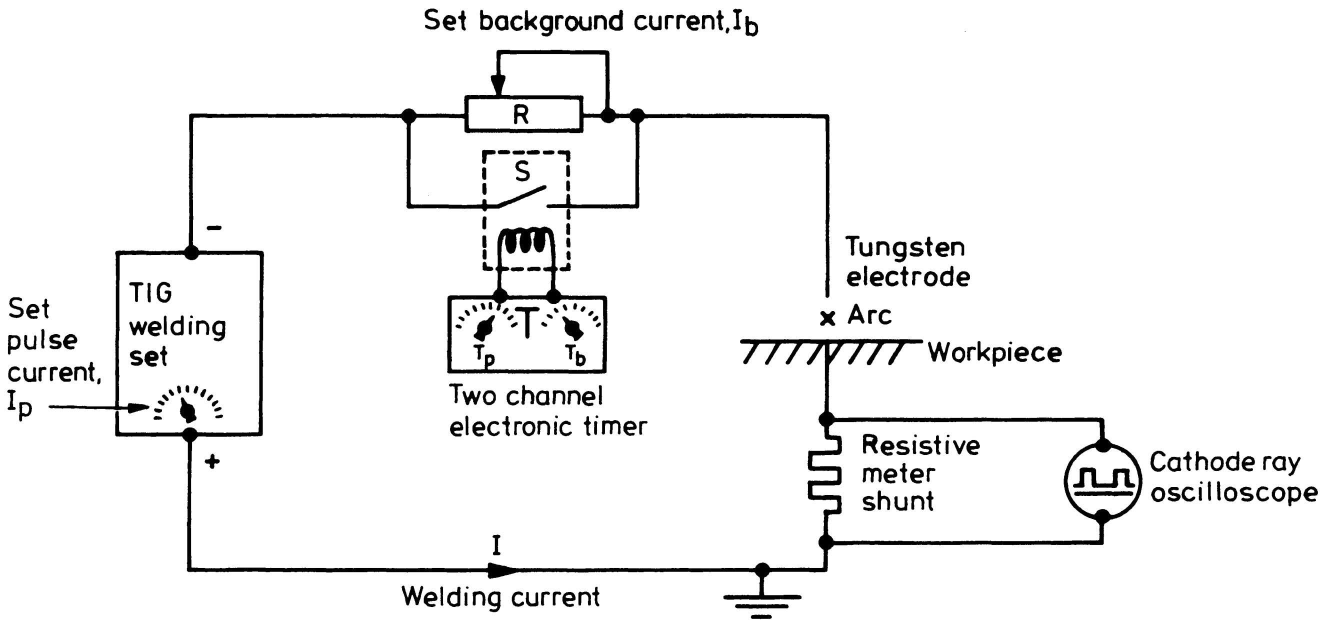
In practice, pulsed voltage arcing is obtained by operating the welding set between two constant voltage (flat characteristic) output levels at rates considerably faster (switching at 0.1 ms) than for modulated wire feed. A limitation is that there is usually a preferred arc voltage for a particular welding condition. Combining pulsed arc length and modulated wire feed[10] overcomes this limitation, by operating alternately at independently stable sets of arc voltage, welding current and wire feed rate parameters (Fig. 24).



24 Two sets of independently stable welding parameters. Pulsing from one to the other at a few hertz provides control of heat input for all-positional operation (after Needham).

3.4.10 How pulsing is achieved

It is relevant to describe in outline how pulsed welding is achieved, because the equipment required has direct bearing on the economics of a welding process and, if complex and expensive, may be unsuitable for low volume production despite technical benefits.



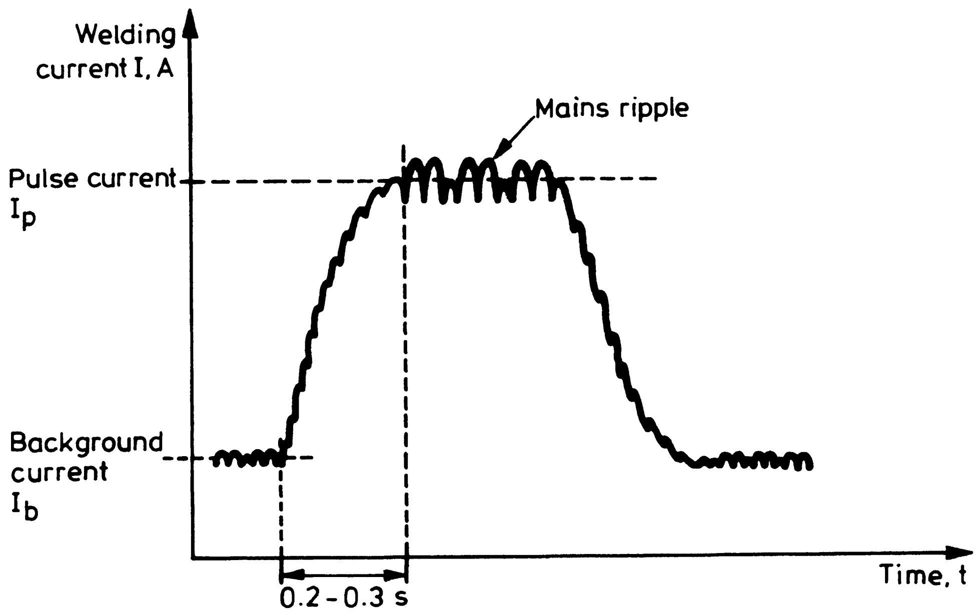
R = 50Ω 250W wirewound variable resistor

S = 150A fast response contactor with magnetic blowout

T = Timer to set pulse and background duration (T_p and T_b)

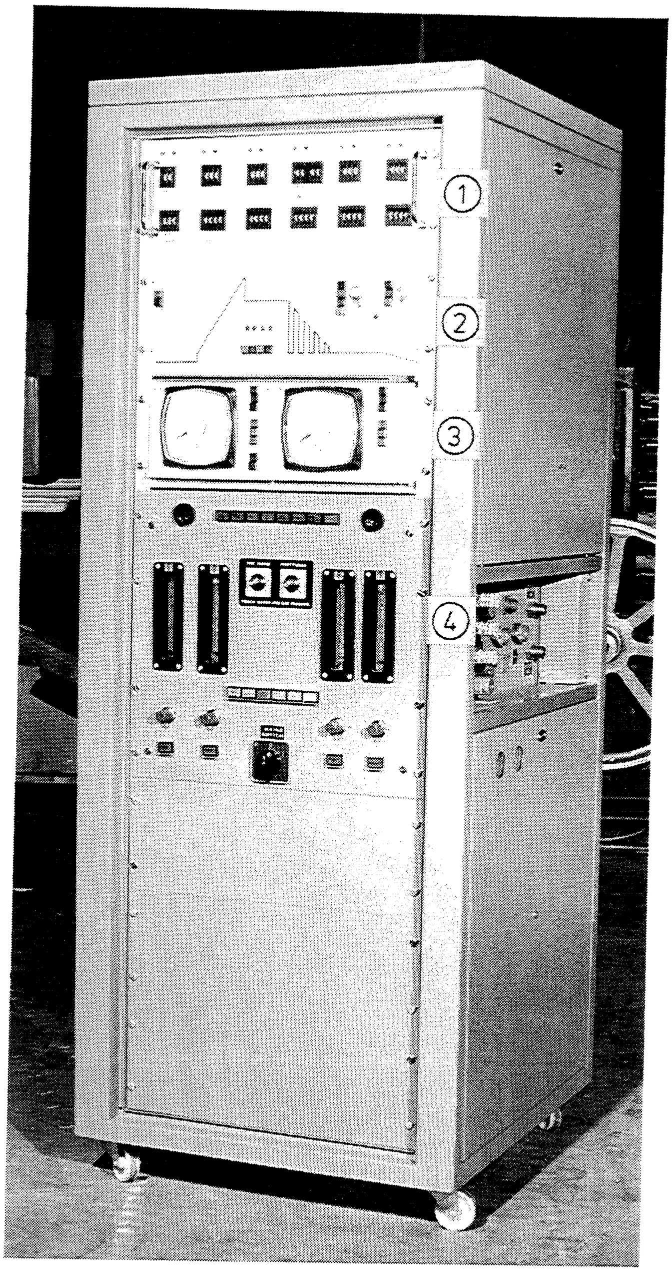
25 Circuit used by the author in 1962 for pulsed TIG welding 0.25-0.64 mm thickness stainless steel sheet.

The author carried out what may have been the earliest pulsed TIG welding in 1962 with primitive but functional equipment. A normal drooping volt-amp characteristic (40 V 100 A^{-1}) TIG welding set was used with a high power wirewound variable resistor, series connected in the welding circuit to provide background current of 1-5 A (Fig. 25). A 150 A electromechanical contactor, driven by an electronic timer, was used to short circuit the resistor cyclically at about 0.5-2 Hz for pulse current of 5-100 A which was preselected on the welding set's variable output control. This arrangement was eventually used successfully for welding square edge close butt joints in 0.25-0.64 mm (0.010-0.025 in) FV520S stainless steel sheet for wing skins of the UK's politically ill fated TSR2 fighter aeroplane. It was obvious then that more sophisticated welding equipment would be



26 Typical step response of commercial TIG welding set with magnetic amplifier current control.

necessary if reproducible, high quality work was to be made possible on a commercially useful scale. With the arrangement described it was not possible to set pulse and background currents independently. Interaction had to be compensated for by judicious adjustment of the transductor control and variable resistor. Adjustment of pulse and background durations was also interactive using the available timer, leading to more problems. The worst obstacles to consistent welding were only revealed oscillographically as the welding set's integral meters were unsuitable for pulsed work; they were the slow response of the welding set and ripple modulation of its current output. Slow response resulted in exponentially rounded leading and trailing edges on pulse waveforms (Fig. 26). Ripple made it impossible to quantify current amplitude accurately with respect to penetration, and both varied from one welding set to another, prohibiting satisfactory transfer of welding procedures. So, although the advantages of pulsing were recognised, equipment design was inadequate for practical benefits to be gained.



27 Transistor welding set rated at 300 A: 1 - Digital thumbwheel switches to preset current and duration; 2 - Waveform generator for current modulation; 3 - Current and voltage monitor panel; 4 - Mains input switch, shielding gas and cooling water controls.

Towards the end of the 1960s the transistor welding set (Fig. 27) was developed by a team of investigators, including the author, at The Welding Institute.[14] Its performance and flexibility accommodated the demands of precision welding. It had stable, ripple free output which could be precisely set from 1-500 A in 0.1 A increments, current pulsing over a wide frequency range (less than one hertz to about 10 kHz) and sequencing controls which could be linked with welding heads, traverse assemblies, positioners, etc, for comprehensive programming. Such welding sets were not cheap (about £ 20k in 1975) because they were produced on a one off basis, but were justified by the nuclear, aerospace and other advanced applications to which they were put. The operating principle is simple. A three phase transformer converts the mains supply voltage to about 60 V rms which is full wave rectified by a bridge of diodes and smoothed by a 0.1 F electrolytic capacitor. A bank of power transistors, matched electrically and connected to act as a single 500 A device regulates the welding current. Inbuilt reference commands are compared with current and/or voltage feedback from the welding circuit to regulate output as required. With closed loop feedback control, output stability is held to better than ±0.5% of maximum welding current, even when mains voltage varies by ±20%. Controllable performance from such transistor welding sets enables procedures to be transferred and permits complex waveforms as described earlier to be generated easily. Recently, commercial production of transistor, thyristor and inverter welding sets has led to considerably reduced prices.

4 DISCUSSION

Since its introduction about 30 years ago, pulsing has been continuously developed in TIG and MIG welding and extensively used for a growing number of high technology applications where reliable and reproducible joints are required. The wide range of pulse welding equipment commercially available today strongly indicates that the technical benefits of pulsing considerably outweigh the disadvantages. At the time of writing there are about 30 commercial types of synergic welding sets available in the UK alone and the number is steadily growing. One of the most difficult decisions that a user now has to make is how to match the specification of pulse welding equipment with the requirements of the joint (and allow a sufficient margin for contingency). Over specification of equipment leads to excess cost and is an indirect disadvantage of the welding process. An example is where synergic pulsing has been advocated as being necessary in MIG welding, and claimed by some manufacturers to be an essential facility in commercial equipment. Rationalisation of non-synergic pulse parameters would, however, have been sufficient for many applications without involving extra complexity, the related increased risk of breakdown, or expense. In general, modern pulse welding sets have become reliable, versatile and relatively cheap through improved components and design, compared with their predecessors.

Pulsing has some technical disadvantages also. Most noticeable is that pulsing is slower than continuous welding for the same run length, dependent on pulse to background (mark to space) ratio, but the extra time taken can be repaid many times over by consequent reduction in reject rates. Another potential disadvantage of using incorrectly set pulse conditions is hot cracking. In some materials, e.g. copper alloys, hot cracking can be avoided by using pulsed TIG. In others, solidification cracking may be aggravated by pulsing unless waveforms are chosen to give slope-out on each pulse and prevent crater cracking from developing.

Ozone, which is extremely poisonous (occupational exposure level 0.1 part per million - even chlorine is ten times 'safer') and chemically destructive, is generated during MIG and TIG welding by the action of ultraviolet radiation from the arc on surrounding atmospheric oxygen. Welding fume considerably attenuates ultraviolet emission from an arc but, in pulsed mode, total fume evolution is generally lower than for continuous welding, particularly for the TIG process. This is because fume is generated more rapidly after several seconds of arcing, as temperatures of workpiece and electrode rise, than at the start. TIG pulse durations are not long enough for significant fume to be evolved, and the process may be regarded as a succession of fresh weld starts. Consequently, a higher proportion of ultraviolet is transmitted from the arc region than for a continuous DC operation, with proportionally higher ozone production. Furthermore, ozone can be formed not only close to the arc but also up to 1.2 m distant, escaping local fume extraction precautions. Ozone formation is also proportional to peak current, hence it is greater in pulsed than continuous operation at the same average current. A small amount (typically 300 ppm) of nitric oxide mixed with the shielding gas reacts with ozone to neutralise it, and has been used commercially with some success. But nitric oxide is also poisonous (OEL 25 ppm), so effective fume extraction is normally used for complete operator protection if manual pulsed welding is being performed for long periods. An incidental gain is that other toxic substances[15] vaporised from weld metal, such as hexavalent chromium, lead, cobalt, zinc, etc, are also removed from the breathing region, partly offsetting the primary inconvenience of ozone extraction.

Summary of the benefits of current pulsing in TIG welding compared with continuous DC

1 Rapid, controlled melting of parent material gives uniform depth of penetration and weld bead width;

2 Thermal energy is used more efficiently because rapid heat input, i.e. faster than the heat sink of the work can accept, results in quicker melting at the joint and therefore proportionally smaller loss by conduction into parent material;

3 Components with widely different thermal capacity because of dissimilar material properties or geometry can be welded consistently and reliably;

4 Alloys with volatile constituents (e.g. zinc) can be welded with short, sharp AC pulses whereas continuous DC operation causes intolerable evaporation;

5 Heat is transferred rapidly through the molten pool by weld metal circulation, preventing large thermal gradients from occurring. Boiling and consequent change in weld metal composition are therefore avoided, and porosity, spatter, fume and tungsten electrode contamination are minimised;

6 The higher current during a pulse produces a stiff arc with good directional stability which reduces wander. For root passes in narrow V preparations this is particularly beneficial in preventing preferential arcing from joint line to sidewalls.

7 Some control over grain growth during molten pool solidification is possible using high frequency pulsing;

8 In AC pulsing, individual control of electrode positive and negative half cycles enables optimum balance between workpiece cleaning and heating, respectively, to be obtained.

Summary of the benefits of current pulsing in MIG welding compared with continuous DC

1 Droplet detachment, metal transfer and arc behaviour are under complete control for a wider range of average welding currents than natural transfer permits;

2 Stable spray transfer can be used at average currents well below the natural thresholds at which globular and dip transfer occur;

3 By linking pulse frequency in direct proportion to wire feed rate at 'unit' droplet operation, synergic pulsing is obtained. This is tolerant to accidental or inherent wire feed variation and also accommodates deliberate modulation for thermally pulsed MIG welding;

4 Thermal pulsing is achieved in MIG welding by switching welding current and wire feed rate in unison or with controlled phase difference, permitting root, filler and capping passes all to be made with the one process;

5 Pulsed MIG is suitable for positional welding because droplet transfer is independent of gravity, and low average currents prevent formation of an uncontrollably large molten pool by keeping heat input low;

6 In AC pulsed MIG welding there is much better resistance to magnetic arc blow and up to 50% higher deposition rates are possible than for conventional DC electrode positive operation.

4.1 Future developments

There are various areas in which pulsed MIG and TIG welding may be improved. Welding sets and auxiliary equipment have already become more dependable and versatile through better circuit design and reliability of components. Modern semiconductors have led to high current transistor, thyristor and inverter based power sources which are lighter and smaller per amp than before (e.g. 500 A capability from a 90-100 kg combined MIG/TIG/MMA inverter welding set). Transistor welding sets driven in analog mode permit accurate control of welding parameters but are inefficient and require water cooling. They will continue to be used for high precision low volume production, but switched mode operation is likely to increase in future as it permits a considerable improvement in efficiency with only a small sacrifice in accuracy and response. Advanced transistor or thyristor inverter welding sets are forecast to dominate future developments,[16] and already one major Scandinavian manufacturer is planning to change to 100% inverter production. For pulsed operation using an inverter, response rate is determined by switching frequency and inherent circuit inductance. To a first approximation, welding set response is about ten times lower than switching frequency. Therefore a modern inverter welding set operating at constant 20-25 kHz switching frequency has a pulsing response of 2-2.5 kHz, ample for all pulsed MIG and TIG welding requirements. Apart from good response, inverters are smaller, lighter, more efficient and have higher power capability than non-switched mode equivalents. Such welding sets now contain programs for a wide range of welding conditions and materials, and a limit to present developments has not yet been reached. Programs exist at four main levels of complexity. The simplest is determined by the preset values of hardware components such as capacitors, resistors, inductors and mechanical or semiconductor switches. This is a cheap way of storing a limited number of fixed commands but to change instructions means substituting different electronic components. For example, a length of time (T) for pulse or background duration can be predetermined in capacitance (C) and resistance (R) using the relationship $T = CR$. A switched CR network gives a range of durations, but only a small range, say 10-20 values, before undue complexity and unreliability occur. The second type of program is contained on punched paper tape or magnetic tape or disk. This is normally used for multiple repetitive tasks such as contour machining, paint spraying, etc, not for arc welding. Next comes the microcomputer based program which is increasingly used in commercial welding sets and is probably the most important. The welder has to choose a program (and wire feed rate for MIG welding), all other operating parameters are automatically called up from software memory. Welding operation is monitored by the microcomputer which detects variations via integral transducers in the welding circuitry and makes appropriate running corrections. In addition, for MIG welding new sets of parameters are calculated and applied to match changes in wire feed rate as they occur. This method of programming is versatile and is most likely to influence future development because changes are easily made in software or by substituting different memories, normally by using EPROM chips. The fourth type of program uses a personal computer, e.g. an IBM PC, which replaces the internal microcomputer and communicates with the welding set via an electronic interface, e.g. an RS 232 C. This system is powerful enough for real time programming of complex operations such as robotic pulsed MIG welding with welding set, manipulator and robot under its control. Although extremely flexible, it requires specialist knowledge to operate and is expensive, but will influence future development of pulsed welding where justified.

It is expected that higher power semiconductors will be developed along with improved ferromagnetic materials for transformer cores to increase the specific power per unit weight of welding set still further.

Control of penetration in TIG welding remains a persistent problem. Various penetration sensing techniques are available, including arc voltage monitoring, infrared detection at the weld backface and thermography, but none is totally satisfactory. Closed loop feedback control is necessary to compensate for cast to cast variations where great variability in welding is often experienced even when using constant welding conditions.

Open loop control, achieved by presetting welding parameters, fails to produce consistently good results with variable casts of nominally the same material.

In pulsed MIG welding, manufacturers are continuing to develop a truly 'single knob' welding set to cover all fabrication requirements. It is believed that preferential effort will be concentrated on equipment advances in both TIG and MIG welding, rather than further process development, so that the welder can preselect material composition, thickness, joint type, etc, and a relevant program in the welding set's memory will deliver correct operating parameters. A better understanding of the effects of, for example, ripple modulation and rise time of the welding current is required before the ultimate objective of matching the welding set to the arc and process can be achieved for complete system control.

Despite technological advances, a welder's skill remains an important element in manual operation and continued emphasis must be placed on correct training to establish an adequate knowledge of process limitations and appropriate welding techniques to overcome them.[17] Emphasis must also be placed on long term production of 'well rounded' welding engineers with specialist knowledge of their own subjects and a working awareness of those in related disciplines. Integrated conscientious effort by all concerned should result in choice of optimum manufacturing, fabrication or repair methods for the ultimate benefit of society as a whole.

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APPENDIX

1 Heat loss

Total heat lost from an object being welded equals total heat input, provided that starting and finishing temperatures are identical. The proportions of thermal energy transferred by convection, conduction and radiation change with temperature, hence are difficult to quantify. Heat loss is mainly by convection and conduction at lower temperatures but, with increase in temperature, radiation losses become dominant for incandescent objects such as the molten pool. Convection cells are established in the air surrounding a hot object and also within the circulating molten pool. Thermal conduction in a solid body is given by

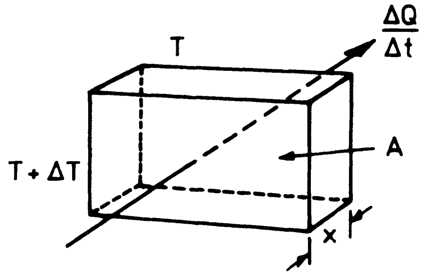
$$\frac{\Delta Q}{\Delta t} = -KA\frac{\Delta T}{\Delta x} \text{ J s}^{-1}$$

where $\frac{\Delta Q}{\Delta t}$ = thermal energy conducted per unit time, J s^{-1}

K = thermal conductivity, W $m^{-1}K^{-1}$

$\frac{\Delta T}{\Delta x}$ = thermal gradient, K m^{-1}

A = cross sectional area of object, m^2



Radiation losses are given by $\frac{\Delta Q}{\Delta t} = A\sigma(T^4 - T_0^4)$ J s^{-1}

where ΔQ = thermal energy radiated in time Δt, J s^{-1}

A = area of radiating surface, m^2

T = temperature of body, K

T_0 = temperature of surroundings, K

σ = Stefan-Boltzmann constant, 5.67×10^{-8} W $m^{-2}K^{-4}$

for a black body emitter ('full' radiator).

2 Specific heat capacity, C

$$\Delta Q = MC\Delta T \quad J$$

where ΔQ = thermal energy transferred to body, J

M = mass of body, kg

C = specific heat capacity, J $kg^{-1}K^{-1}$

ΔT = temperature change, K

Therefore $C = \frac{\Delta Q}{M\Delta T}$ J $kg^{-1}K^{-1}$

and is a measure of an object's ability to contain thermal energy.

3 Fundamental droplet parameters

— Droplet detachment is governed by $I_p{}^2T_p$ = constant, where the constant is determined by wire material and diameter, and I_p = pulse current, T_p = pulse duration.

— Droplet volume (v) is dependent on W/f assuming one droplet per pulse.

$$v = \frac{WA}{f} \quad m^3$$

where A = cross sectional area of wire, m^2

W = wire feed rate, m s^{-1} (converted from m min^{-1})

f = pulse repeat frequency, Hz

– Mean current (I_m) for squarewave pulsing is given by

$$I_m = \frac{I_p T_p + I_b T_b}{T_p + T_b} \quad A$$

4 Non-pulsed synergic welding

Synergic control has been extended to the spray and dip transfer MIG/MAG welding processes since its original development for open arc pulsed MIG operation. A 1990 definition by Amin is: 'Synergic MIG/MAG operation is achieved using a one knob control system that executes a relationship in which the relevant welding conditions are adjusted automatically, in real time, for any wire feed rate. Wire feed may be maintained constant, varied gradually or modulated with any waveform, i.e. synergic control is dynamic as opposed to static.'

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Pulsed Arc Welding

During the last 30 years widespread use of advanced metals and complex joint configurations increasingly led to failure of conventional arc welding processes to produce satisfactory welds. Control of weld bead penetration and width is now routinely achieved by pulsing the welding current between preset low and high levels to regulate heat input and therefore the behaviour of the molten pool and its solidification. At low frequencies this results in thermal pulsing which enables difficult joints to be made in thin materials and also between workpiece components with unequal thermal capacity, because of either dissimilar geometry or different thermal conductivity. Pulsing at higher frequencies in TIG welding gives control over arc stiffness and directionality and also beneficially influences grain growth during solidification of the molten pool.

In this evaluation of the benefits of current pulsing in MIG and TIG welding various forms of thermal and droplet pulsing are described in detail to show how the new techniques were introduced and developed to overcome the difficulties associated with the old.

The author, John Street, was involved in development and evaluation of pulsed welding processes, and instrumentation techniques to quantify them, at The Welding Institute.

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