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SYNERGIC CONTROL IN MIG WELDING
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PENETRATION CONTROL IN TIG WELDING

BY
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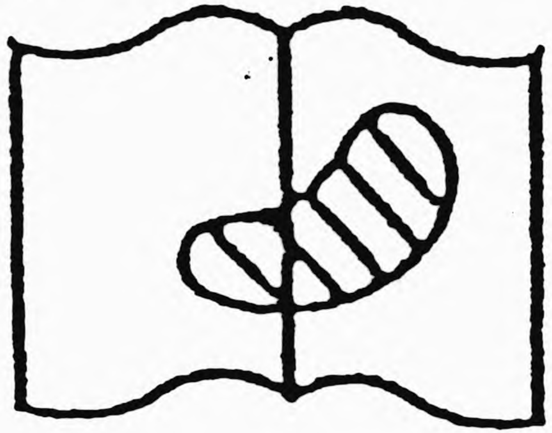

ABSTRACT

Part I: Synergic control in MIG welding

Synergic controls (i.e. real time control methods) for both steady DC open arc and short circuiting arc operations have been developed in this study. These have been based on the generalised quadratic and linear 'power–current' and linear 'voltage–current' equations which adequately describe the MIG welding operation. The controls are low cost electronic units which are added to a 'transistor' controlled power source. The units based on the 'power–current' concept can operate with the power source set in the constant current, constant voltage or any intermediate mode of output characteristics, and regulate only the steady DC open arc operation. The unit based on the 'voltage–current' concept operates with the power source set in nominally constant voltage mode, and regulates both steady DC open arc and short circuiting arc operations. These controls adjust the current, voltage or power automatically according to any operator–selected wire feed speed whether maintained constant at any level, varied gradually or modulated with any waveform to achieve 'thermal pulsing'.

In addition, two approaches have been used to adapt the synergic control units to a lower cost, thyristor controlled power source which is more widely used in industry. In one approach, the generalised control equation used previously for the transistor controlled power source has been extended to take account of the output characteristics of the thyristor controlled power source. As an alternative, the control units themselves have been modified to allow for the different power source characteristics.

The control systems have been successfully demonstrated for producing sound welds in a wide range of welding applications, for both mechanised and manual welding techniques.

Part II: Penetration control in TIG welding

A 'backface' penetration control system developed at Liverpool University, based on a 'video camera' instead of a 'photodiode' as a sensor, has been evaluated at The Welding Institute. Essentially, the system controls the size of the weld pool, instead

of an average level of radiation, by regulating pulse current period, by means of a fibre optics image guide/video camera/microcomputer based controller. The system has been found to be capable of controlling the weld bead penetration uniformly in stainless steel plates and joints, for constant as well as variable material thicknesses.

However, the system cannot be used with high frequency (HF) arc discharge, as required for automatic arc initiation, because the software and electronic components are corrupted.

A hard-wired control unit has therefore been developed at The Welding Institute to replace the microcomputer based controller. This unit can be operated reliably with automatic HF arc initiation. Furthermore, it has been shown to control weld bead penetration in stainless steel plates and joints, for constant as well as variable material thicknesses.

ACKNOWLEDGEMENTS

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PART I

SYNERGIC CONTROL IN MIG WELDING

CHAPTER 1
INTRODUCTION

1.1. STATEMENT OF THE PROBLEM

Direct current MIG (Metal Inert Gas) welding process[1] has three operational modes — steady DC open arc[2], short circuiting arc[3] and pulsed arc[4]. Each mode may be used to produce sound welds but, prior to welding, the equipment (power source and wire feeder) must be set up accurately to provide a stable welding condition.

To establish the correct welding conditions, the conventional method is to adjust each parameter by means of control knobs provided on the equipment, and then adjust and readjust while optimising the condition. This requires not only skill but time which could otherwise be utilised for productive welding. Furthermore, the method is impracticable for automated and robotic operations requiring a fast change in welding conditions to suit various joints.

To facilitate setting up a stable welding condition, power sources with constant voltage type output characteristics are commonly used, because these provide a degree of self-adjustment in arc length as a consequence of relatively large changes in the current. However, when the arc is prone to disturbance, for example, when welding joints with narrow angle preparations or those between rusty plates, the current can fluctuate erratically over a wide range, causing unstable arc operation. For such applications, constant current operation is preferable, because the current fluctuations are restricted within narrow limits and the arc operation remains stable.

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[1] MIG (or MAG) welding is Gas-shielded metal-arc welding process using a consumable bare wire electrode where the shielding of the arc and weld pool area is provided by the shroud of inert gas, active gas or mixture of gases.

[2] In steady DC open arc, the overall current remains steady at a level specified by the wire feed speed.

[3] Short circuiting arc operation comprises arcing and short circuiting alternating at approximately 50–200 Hz.

[4] In pulsed arc operation the current is switched between two levels at a predetermined frequency.

However it is not easy to set up a working welding condition without one-knob or feedback control, as the constant current mode does not provide any self-adjustment of the arc length; the current has to be accurately adjusted relative to a given wire feed speed to obtain a stable arc of the required length. Furthermore, even minor changes in wire feed speed, which can frequently occur with commercial equipment, lead to degeneration of the established welding condition, causing arc instability which can result in defective welds.

The difficulty in setting up welding conditions effectively has already been resolved for the pulsed arc operation by developing a real time control method called 'synergic' control[5]. This is based on a relationship between all the relevant parameters for pulsed arc operation. An electronic control unit or a microcomputer executes the relationship automatically and controls the power source output, so that the required pulse parameters for any given wire feed speed are supplied to the arc. All that is needed from the operator is to select the wire feed speed for the required application. With this control, manual, mechanised or fully automated welding operations can be accomplished easily, efficiently and economically, and welds of consistently high quality can be made even in difficult applications. As the synergic system simplifies pulsed arc operation, it has now become an essential feature of practically all modern pulsed MIG welding power sources.

1.2. OBJECTIVE

This project has been aimed at developing synergic control (i.e. real time control methods) for both steady DC open arc and short circuiting arc operations, comprising low cost electronic control units to be added to a power source. These controls would coordinate all the relevant parameters automatically to establish any required welding condition, by adjusting essentially the single knob controlling the power source output and wire feed. The expected benefits of these systems include simplicity, ease and reliability in welding operations, improved weld quality, extended application range and cost effective production.

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[5] Synergic is a 'one-knob' control system, executing a relationship, whereby the relevant operating parameters are adjusted automatically for any wire feed speed, whether constant, varied gradually or modulated with any waveform.

1.3. MAIN FEATURES OF THE PROCESS

1.3.1. Basic operation

In steady DC open arc operation a steady current, Fig. 1–1 (1), is used to operate an open arc which is established between a bare wire consumable electrode and a workpiece to be welded. A nominally inert gas is supplied to shield the arc zone from the atmospheric gases. The arc heat melts the workpiece to form a weld pool, and also melts the consumable wire so that the molten metal is transferred across the open arc, in a series of discrete droplets, into the weld pool to form the weld bead. The wire is continuously fed from a spool into the arc at a required speed to achieve the desired weld metal deposition rate. The wire feed speed is matched with the wire burnoff rate by adjusting the arc current (or voltage) so that a constant arc length (say between 3 and 10 mm) is maintained to provide stable arc operation.

In principle, short circuiting arc operation is similar to the steady DC open arc operation, except that the arc voltage (arc length) is reduced for a given wire feed speed, such that the arc operation comprises arcing and short circuiting intervals alternating at approximately 50–200 Hz. Consequently, both the arc voltage and current fluctuate consistently, Fig. 1–2 (2), and therefore these parameters in general are described by their mean values.

1.3.2. Essential requirements

For successful operation of both steady DC open and short circuiting MIG arcs, there are two essential requirements which must be fulfilled. Firstly, any given wire feed speed must be matched with the wire burnoff rate, so that a constant arc length is maintained. Otherwise, an excessive wire feed speed would cause stubbing of the wire into the weld pool, or an insufficient speed would cause burnback whereby the arc becomes excessively long and melts the contact tube supplying current to the wire. Secondly, metal transfer from the wire should be in the form of small droplets (of the order of the wire diameter), to allow the formation of a uniform weld bead. Otherwise, large droplet or globular type metal transfer would produce not only irregular welds but also cause lack of penetration defects.

With steady DC open arc operation, the first requirement can be fulfilled over the entire current (or wire feed speed) range, approximately 50–500 A. However, the

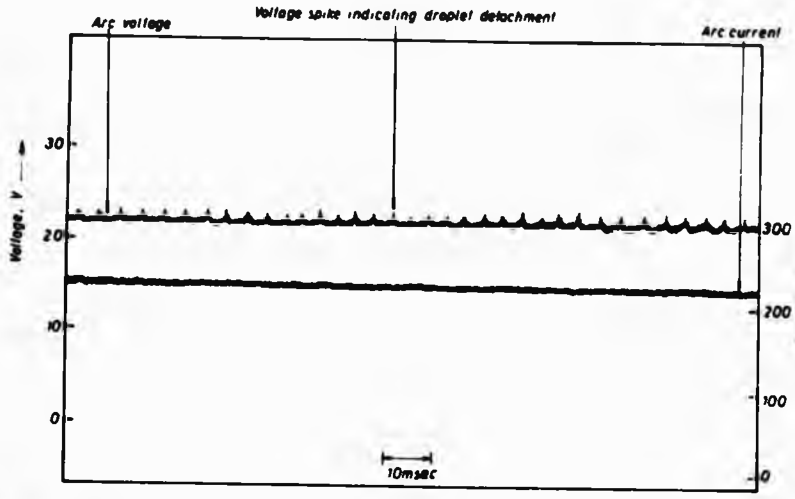


Fig. 1-1. Typical oscillogram of arc voltage and current for the steady DC arc operation, using 1.2 mm diameter Inconel wire at 225 A in argon shielding gas (1).

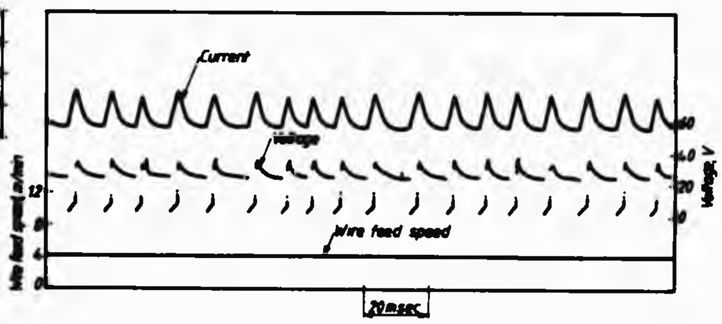


Fig. 1-2. Typical oscillogram of arc voltage and current for the short circuiting arc operation, using 1.0 mm diameter mild steel wire at 4.2 m/min wire feed speed in CO_2 shielding gas (2).

second requirement can be fulfilled only over a limited range, from a 'critical' current level upwards at which a transition occurs from the unsuitable globular to the desirable spray (small droplet) type metal transfer. Thus, applications requiring low currents, such as joining thin sheet or heat sensitive materials, positional welding root runs and weld surfacing, cannot be accomplished.

For steel wires, the limitation imposed by globular metal transfer may be removed by using short circuiting arc operation. In this process, not only can the balance between the wire feed speed and burnoff rate be maintained, but also small droplet type metal transfer is achieved by means of the short circuits.

Another essential requirement, relevant only to short circuiting arc operation, is that the rate of rise of current during a short circuit must be restricted between two limits, Fig. 1–3 (3), by means of an inductance (or some other device) contained in the arc circuit. Otherwise, an excessive rate would cause spatter, or an insufficient rate a sluggish arc performance. Between these limits, the rate of rise of current can be adjusted further to provide optimum arc performance.

1.3.3. Parametric relationships

1.3.3.1. *Steady DC open arc operation*

a). Constant current mode

In general, with steady DC arc operation, a welding condition is established with the power source set in either constant current or constant voltage mode. For the constant current mode, whereby the current supplied to the arc, in principle, remains fixed at any selected value, the operating variables include wire feed speed and current, for a given arc length (or voltage) and wire extension. Over a range of welding conditions, for a required wire material/ wire diameter/ shielding gas combination, these variables provide a relationship between the wire feed speed and current (called burnoff), which is used as a basis for the arc operation. The relationship specifies a unique current for any required wire feed speed, which must be supplied to the arc to match the feed speed with the burnoff rate, so that a constant arc length is maintained. The relationship is substantially linear over the operating range, relevant to the desirable spray type metal transfer, Fig. 1–4 (4,5,6), such that the current increases with the wire feed speed. In addition it makes an intercept on the current

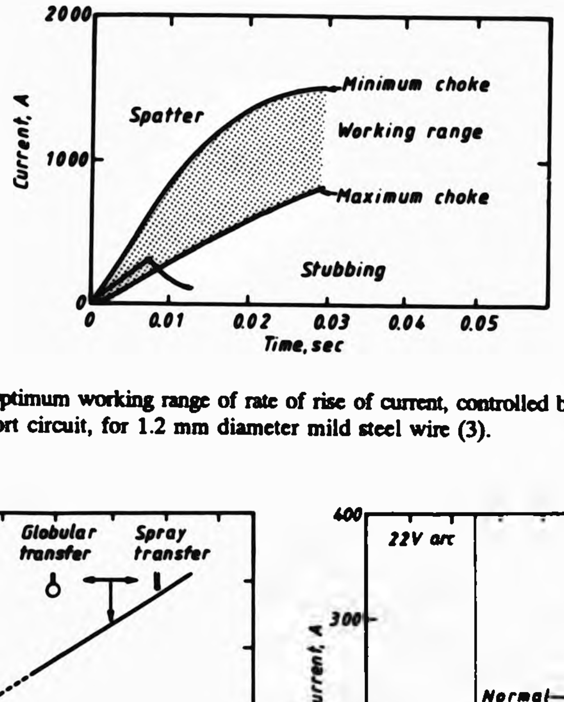


Fig. 1–3. Optimum working range of rate of rise of current, controlled by inductance during a short circuit, for 1.2 mm diameter mild steel wire (3).

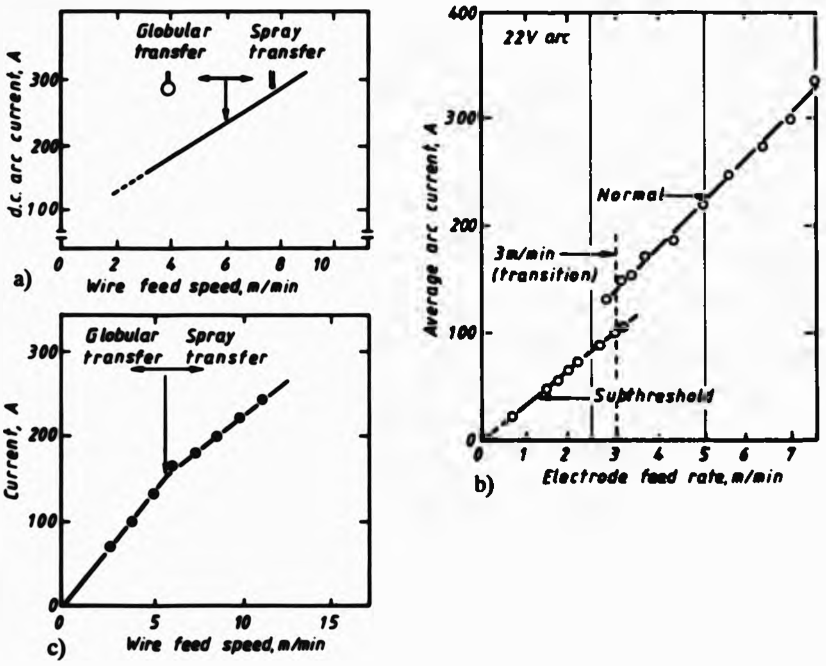


Fig. 1–4. Typical burnoff characteristics:
a) mild steel wire/1.2 mm diameter/Ar+5%CO_2 (4),
b) aluminium wire/1.6 mm diameter/Ar (5),
c) zirconium alloy wire/1.2 mm diameter/Ar (6).

axis when extrapolated to zero feed speed. Although both the slope and intercept are unique for a given wire material/wire diameter/shielding gas combination, these parameters in general are different for each combination. That is, the relationship is specified by a given combination.

b). Constant voltage mode

For the constant voltage mode, whereby the voltage supplied to the arc, in principle, remains constant at a selected value, the operating variables include the arc voltage and wire feed speed (or current). For a range of welding conditions, using a fixed wire extension and arc length, the two variables provide a relationship between the arc voltage and current, which forms a basis for the arc operation. The relationship specifies a unique voltage for any required current. Over the usable range, relevant to spray type metal transfer, the relationship is substantially linear such that the voltage increases gradually with the current, and it makes an intercept on the voltage axis when extrapolated to the current at zero value. For example, four relationships are shown in Fig. 1-5 (7), relevant to four wire composition/wire diameter/shielding gas combinations. Although both the slope and intercept are unique for a given combination, these parameters in general are different for different combinations.

The effect of a change in the arc length on an arc voltage v. current relationship is that, while the slope remains practically constant, the intercept or the voltage level increases with the arc length. For the allowable arc length range, from say zero to the distance between the workpiece and contact tip, the voltage level is increased producing a family of parallel relationships, whereby the lowest curve corresponds to stubbing arc operation, and the highest curve corresponds to the arc operation giving burnbacks, Fig. 1-6 (8). For a given arc current, the correlation between the arc voltage and arc length is shown in Fig. 1-7 (7). This correlation is also linear over the usable arc length range, from about 3-10 mm.

1.3.3.2. *Short circuiting arc operation*

For the short circuiting arc, the power source is normally operated in the constant voltage mode. This operation includes mean voltage and mean current (or wire feed speed) as variables which need to be coordinated to establish a stable welding

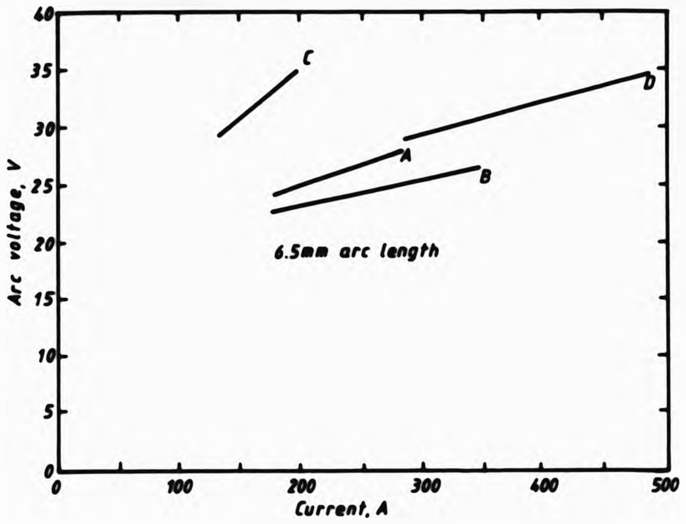


Fig. 1-5. Typical arc voltage v. current relationships at constant arc length (7):
A) aluminium bronze wire/1.6 mm diameter/argon,
B) aluminium wire/1.6 mm diameter/argon,
C) aluminium wire/1.0 mm diameter/helium,
D) nickel wire/1.6 mm diameter/argon.

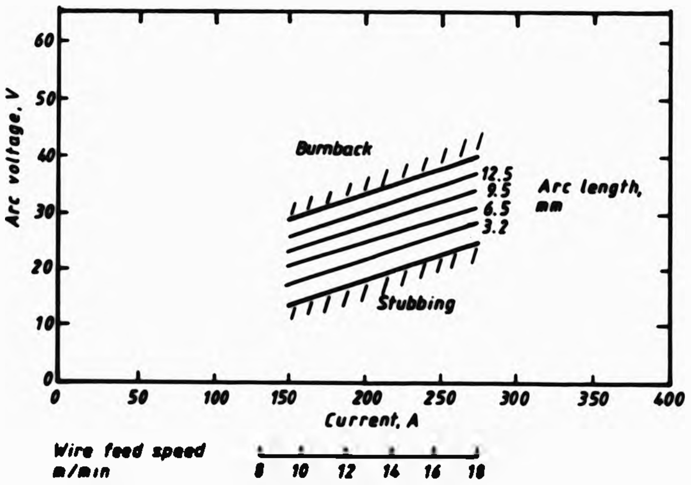


Fig. 1-6. Effect of arc length on arc voltage v. current relationship, for 1.0 mm diameter aluminium wire in argon shielding gas (8).

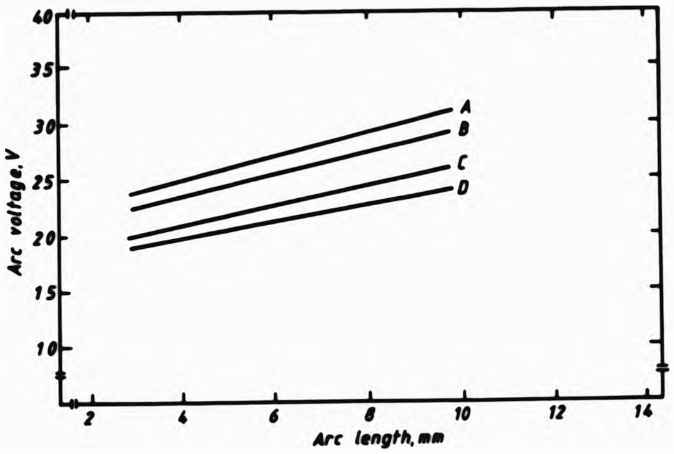


Fig. 1-7. Correlation between arc voltage and arc length at constant current levels for 0.8 mm diameter aluminium wire in argon shielding gas (7):
A) 16.5 m/min, 160 A, B) 12.7 m/min, 135 A,
C) 10.2 m/min, 105 A, D) 7.6 m/min, 80 A.

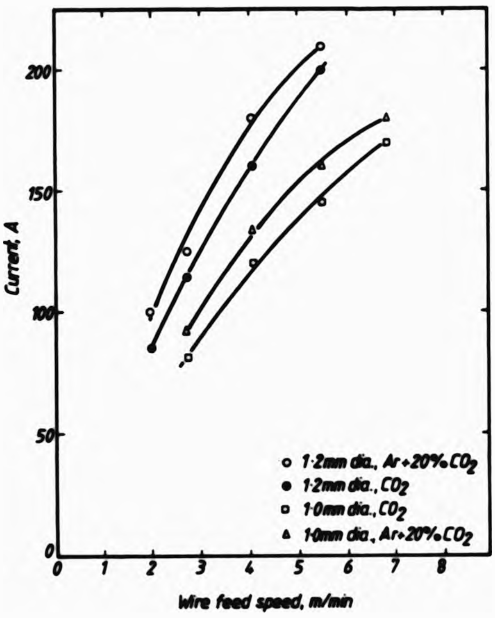


Fig. 1-8. Burnoff relationships for short circuiting arc operation, using 1.0 and 1.2 mm diameter mild steel wires and CO_2 and Ar+20%CO_2 shielding gases, with 12 mm wire extension (2).

condition. The inductance must also be adjusted to control the rate of rise of current during a short circuit, but this parameter, once set, should remain constant for any welding condition. Over the operating range, for a given wire extension, the variables provide a relationship between the mean arc voltage and mean current which defines the basis of the operation. For any given wire composition/wire diameter/shielding gas combination, the relationship specifies a unique mean voltage for any required mean current (or wire feed speed as specified by the burnoff relationships shown in Fig. 1-8 (2) for various combinations). For a given combination, the mean voltage v. mean current relationship is practically linear such that the voltage increases gradually with the current, and it makes an intercept on the voltage axis when extrapolated to the current at zero value, as shown in Fig. 1-9 (2). Although both the slope and intercept are unique for a given combination, these parameters in general are different for each combination.

The effect of changing the arc length on the mean voltage v. mean current relationship is that the slope remains practically constant, but the intercept or the voltage level is increased with the arc length. For the allowable arc length range, from stubbing to the onset of open arc operation, which is very limited, a family of approximately parallel relationships is produced, whereby the lowest curve corresponds to inadequate heat input during an arcing period, and the highest curve represents the welding conditions with inadequate short circuiting frequency, Fig. 1-10 (2).

1.4. APPROACH FOR THE DEVELOPMENT OF SYNERGIC CONTROLS

Both steady DC open arc and short circuiting arc MIG welding operations have been characterised by empirical relationships between the wire feed speed, arc current and voltage for mild steel wires using various wire diameter/shielding gas/wire extension combinations, and described by generalised equations. These relationships were used to derive control (synergic) equations. Furthermore, to implement the synergic equations automatically, three types of hard-wired electronic control units have been designed and constructed and interfaced with a 'transistor' controlled power source. These systems have been evaluated and found to be capable of performing the

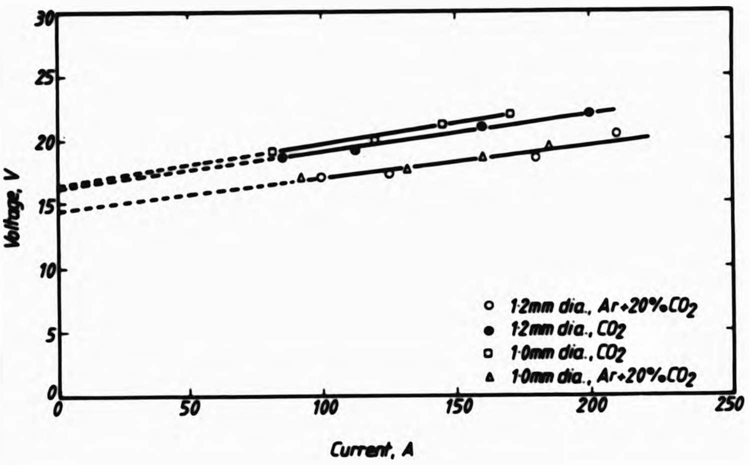


Fig. 1–9. Voltage–current relationships for short circuiting arc operation, using 1.0 and 1.2 mm diameter mild steel wires and CO_2 and Ar+20%CO_2 shielding gases, with 12 mm wire extension (2).

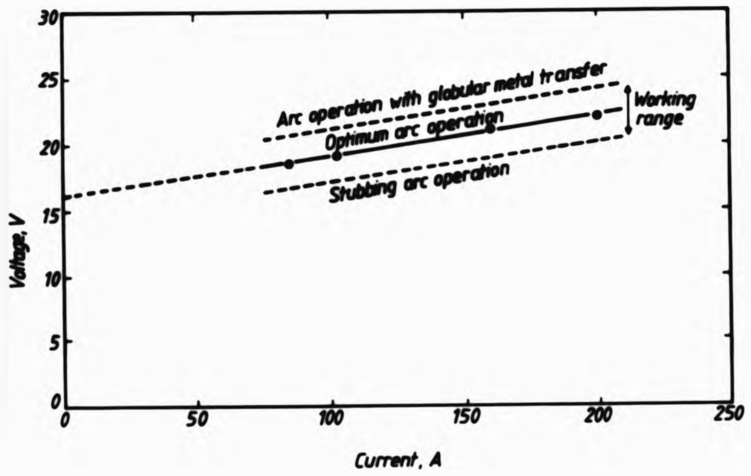


Fig. 1–10. Voltage range for the short circuiting arc operation, using 1.2 mm diameter mild steel wire and CO_2 shielding gas (2).

synergic operations, whereby suitable current and voltage are adjusted automatically giving stable arc operation for any selected wire feed speed whether maintained constant, varied gradually or modulated automatically to achieve thermal pulsing. Further evaluation using modulated wire feed speed has shown that sound welds can be made even for 'narrow angle' butt joints.

The success of the synergic controls for both the steady DC open arc and short circuiting arc operation, described above, relied on the capability of a versatile laboratory type 'transistor' controlled power source. To transfer the newly developed synergic controls into industry, the control units were then adapted to operate with a commercially available 'thyristor' controlled power source.

The adaptation comprised derivation of the synergic control equations to include variables relevant to the thyristor controlled power source. Based on these equations, the control circuits were modified and interface circuits constructed to link the control units with the power source.

The performance of these control systems has been tested comprehensively for arc initiation and stability of arc operation using wire feed speed maintained constant, varied gradually or modulated automatically. Further tests have been carried out to find how the control systems would respond to a change in the process parameters, such as wire extension, wire diameter and shielding gas composition. Finally, the control systems were tested for the welding of the typical joints.

CHAPTER 2
A CRITICAL REVIEW OF ONE-KNOB CONTROLLED MIG WELDING POWER SOURCES

2.1. SUMMARY

Several 'one-knob' controlled power sources have been developed previously to simplify the setting up of parameters for a steady DC open arc and short circuiting MIG welding operations; these developments have been described in reference 9. Briefly, the control is achieved by means of electrical and electronic circuits which execute the basic parametric relationships. The control is based on the 'arc voltage control' concept (10) whereby a required voltage is maintained automatically whilst regulating the wire feed speed. This system would not maintain a constant arc length, which is essential for producing sound welds, over the operating wire feed speed range. The arc voltage must be increased progressively with the feed speed according to the relevant arc voltage-wire feed speed (or current) relationship, for a constant arc length.

Alternatively, the control has been based on the 'arc length control' concept whereby a required arc length is maintained automatically for any wire feed speed whilst regulating the arc voltage according to the operating relationship. The arc length control is either stepwise, which retrieves any one of only a limited number of the preprogrammed welding conditions (11,12,13,14,15), or continuously variable, which sets up any welding condition over the operating wire feed speed range (8,17,18,19,20,21,22,23). The continuously variable control, achieved by using the 'flat' output characteristics of the power supply unit, is considered to provide more stable welding conditions compared with that using the 'rising' output characteristic. Nevertheless, in either mode, any wire slipping over the wire feed rolls or any wire restriction in the conduit would still cause an unstable arc operation.

2.2. INTRODUCTION

To facilitate the steady DC open arc and short circuiting arc operation, many attempts have previously been made to develop control methods which would coordinate all the relevant parameters automatically, to establish a required welding condition, by adjusting only one-knob controlling the power source output and wire feeder. These systems, which have achieved varying degrees of success, are called 'self-adjusted', 'self-regulated', 'programmed' or 'one-knob' controlled power sources.

In general two approaches have been tried out to design a one-knob controlled power source, and each implemented using various control methods. One approach has been based on the 'arc voltage control' concept whereby a required voltage is maintained automatically while regulating the wire feed speed. The other approach has been based on the 'arc length control' concept whereby a required arc length is maintained automatically, for any wire feed speed over the operating range, while regulating the arc voltage.

2.3. ARC VOLTAGE CONTROL

The method for implementing the arc voltage control concept has been that the 'one-knob' control is used to set up a reference value representative of the required arc voltage. This value is compared with the actual arc voltage and the difference between the two values, called the error signal, is then used to regulate the wire feed speed such that the error is minimised. Thus the required arc voltage is maintained automatically.

Only one example of a practical 'arc voltage control' system, Fig. 2-1a as original (10) and Fig. 2-1b as functional, has been identified. This includes a 'current control generator' with its armature connected in series with the armature of the wire feeder motor. Both the armatures together are connected across the welding arc, such that the current control generator operates in the parallel relationship with the transformer-rectifier power supply unit supplying the arc. With this arrangement, the output voltage of the generator provides the reference voltage, which is compared with the operating arc voltage due to the parallel operation, and the difference between the two values determines the current supplied from the generator to the armature of the wire feeder motor. That is, the error voltage regulates the wire feed speed, such that the required arc voltage is maintained automatically.

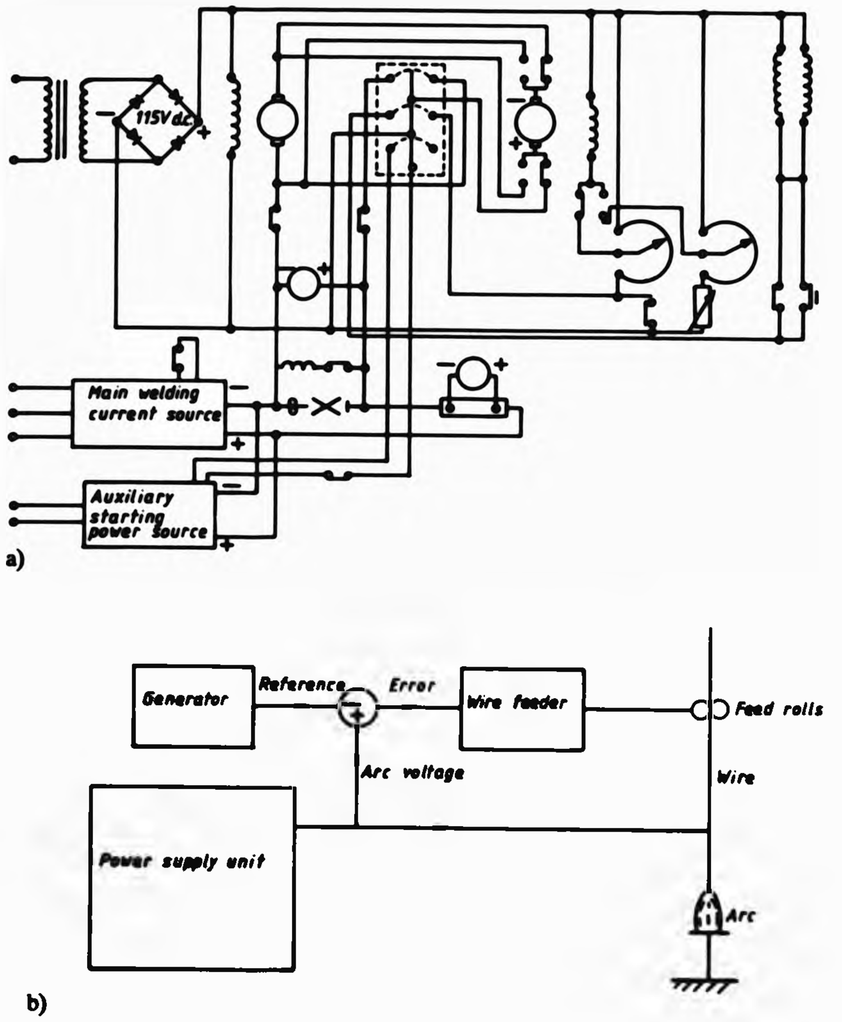


Fig. 2-1. Arc voltage control system:
a) original diagram (10),
b) functional diagram.

2.4. ARC LENGTH CONTROL

An arc length control system has been based essentially on the parametric relationship between the arc voltage and current (or wire feed speed), such as shown in Fig. 1-9, for a constant arc length, relevant to any given wire composition/wire diameter/shielding gas combination. The method used for executing the relationship has been either stepwise or continuously variable.

2.4.1. Stepwise control

The stepwise control is that whereby the specific parametric combinations, constituting the welding conditions, are preprogrammed and any one condition can be retrieved automatically using one-knob control. To program the system, the required combinations of the operating parameters, mainly wire feed speed (or current) and voltage, are predetermined from the relevant burnoff and voltage-current relationships. Then, for each combination, a specific electrical and electronic circuit is constructed to control together the power supply output and the speed of the wire feeder, such that the specified wire feed speed (current) and voltage are adjusted simultaneously. All circuits, relevant to the required number of the parametric combinations, are connected to a multi-position switch, i.e. one-knob, whereby each position operates a specific circuit to set up the required welding condition automatically.

Practical systems

Based on the stepwise approach, a number of 'one-knob' controlled power sources have previously been developed (11,12,13,14,15). An early development was a specialised power source (11) designed to set up a steady DC arc condition automatically (excluding two other conditions relevant to pulsed arc operation) for any one of the seven wire composition/wire diameter/shielding gas combinations. For each combination, an electronic program card was designed which contained information on the specific values of open circuit voltage and wire feed speed comprising the welding condition. In operation, the insertion of a wire reel operated a rotary switch which selected the relevant card. This card then provided signals to various relays to adjust the relevant taps on the tapped transformer for setting-up the required voltage and, in addition, adjusted taps on the electrical circuit supplying the wire feeder for setting-up the corresponding wire feed speed. Thus, the welding condition could be set up automatically.

The power source, described above led to the development of another more flexible 'Migmatic' power source (12). In this system, which has remained only of laboratory interest, the power supply was based on a transformer-thyristor unit, so that the output could be adjusted electronically instead of changing taps on the transformer. In addition, the thyristors were feedback controlled and, therefore, the output voltage was stabilised against any changes in the mains voltage or ambient temperature. Furthermore, programming of the required welding conditions was not fixed but very flexible, and could be carried out via a pinboard. This board had 300 sockets for programming altogether ten welding conditions. A set of thirty sockets was allocated for programming each condition; twelve for voltage, eleven for wire feed speed, five for inductor selection, and the remaining two for choice of shielding gas. Each welding condition was completely programmed by inserting eight pins altogether, whereby three pins selected a coarse, a medium and a fine voltage setting, such that the sum adjusted the required voltage. Similarly, three pins set up the wire feed speed, one pin adjusted the inductor and one pin selected the shielding gas. Once the pinboard was programmed, then any required welding condition could be retrieved automatically by means of a ten-position switch, provided on the gun for convenience.

The control concepts used for developing the two power sources described above, have been utilised in the construction of a number of commercial power sources. For example, these included Autolynx (13), Migomat-160 (14) and Autoweld (14). Autolynx provided 'one-knob' adjustment at three positions for setting-up any one of the three welding conditions automatically. These conditions were considered to be suitable for welding workpiece thickness ranges of 0.5-0.7 mm, 0.9-1.2 mm and 1.6 mm using 0.6 mm diameter mild steel wire.

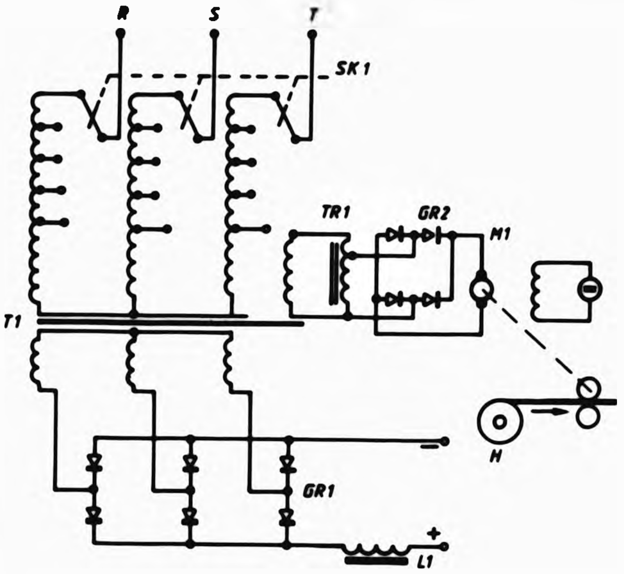
Migomat-160 provided a five-position switch, whereby the first four positions were relevant to the short circuiting arc operation, but the fifth position enabled MIG spot welding. The first four positions could select four welding conditions (combinations of open circuit voltage and wire feed speed) automatically, corresponding to 60, 80, 120 and 160 A arc current, using 0.8 mm diameter wire.

Autoweld provided a six-position control knob whereby the first five positions could set one of five predetermined welding conditions for the short circuiting arc operation, corresponding to 40, 50, 65, 80 and 100 A, using 0.6 and 0.8 mm diameter wires. Each knob position selected a tap on a transformer together with a suitable voltage to be supplied to the wire feeder motor, so that a matching combination of open circuit voltage and wire feed speed was adjusted automatically.

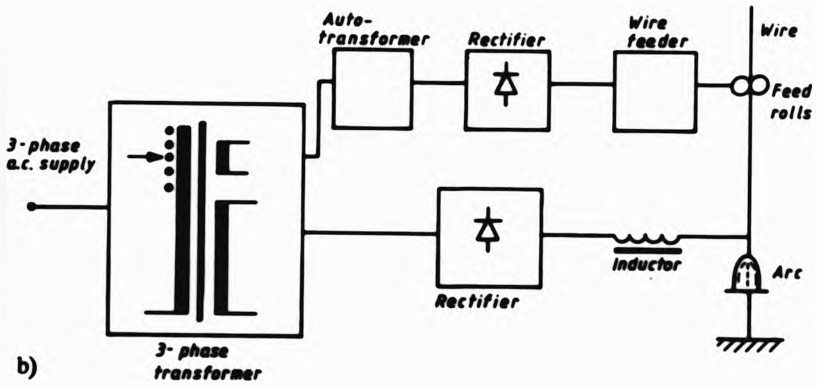
A later development by Philips Electronic and Associated Industries Ltd (15) had its electrical circuit designed in three versions. The first version, Fig. 2-2a as original (15) and Fig. 2-2b as functional diagram, comprised a 3-phase transformer-rectifier unit with each of three primary windings having five taps. The identical taps on each phase could be connected to the mains supply by means of a five-position switch, and thus enabled the open circuit voltage to be adjusted in five steps. The circuit also supplied the wire feeder from an additional single-phase secondary winding connected to a rectifier via an autotransformer. By adjusting this device the wire feed speed could be coordinated with the open circuit voltage such that, for any position of the switch adjusting the taps, a stable welding condition would be obtained automatically.

The second version, Fig. 2-3a as original (15) and Fig. 2-3b as functional diagram, was essentially similar to the first, except that an autotransformer with five taps and an inductor with three taps were incorporated in each of the primary windings of the welding transformer. The function of these inductors was to provide a required 'droop' in the output characteristic of the power source, to generate large variations in the output voltage relative to the current. These variations were required to increase the response of the wire feeder relative to the welding current, so that stability of the welding conditions would be enhanced.

The third version, Fig. 2-4a as original (15) and Fig. 2-4b as functional diagram, was also similar to the first one, except that the circuit supplying the wire feeder was modified. The autotransformer had been removed, and the single-phase secondary winding supplying the wire feeder was provided with five taps. These taps were selected together with the corresponding taps provided on the 3-phase primary windings of the welding transformer, via a single five-position switch. For different



a)



b)

Fig. 2–2. Stepwise controlled power source (first version):
a) original diagram (15),
b) functional diagram.

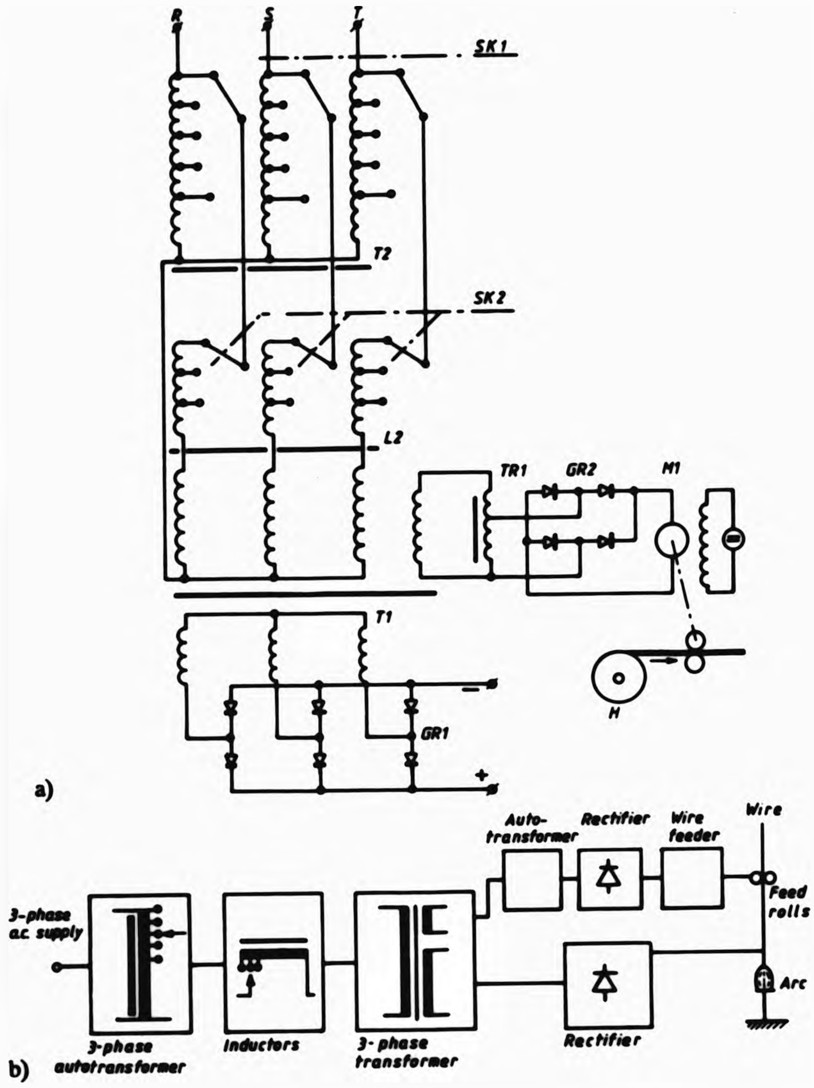


Fig. 2-3. Stepwise controlled power source (second version):
a) original diagram (15),
b) functional diagram.

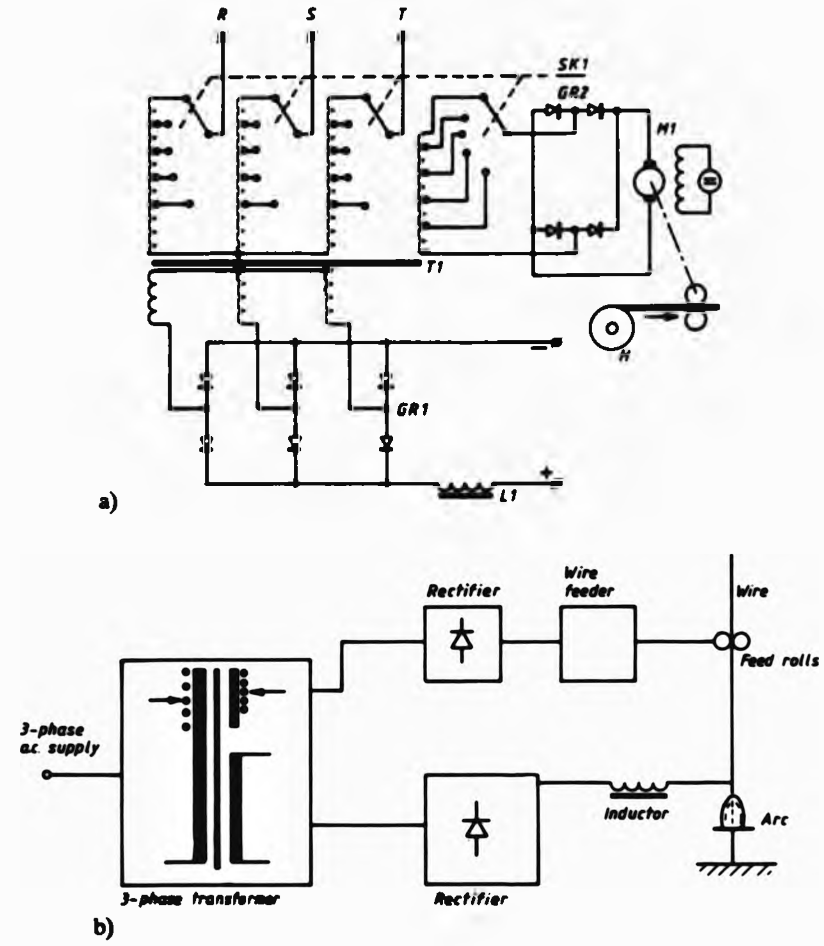


Fig. 2–4. Stepwise controlled power source (third version):
a) original diagram (15),
b) functional diagram.

positions of the switch, the output open circuit voltage was altered in steps, but the wire feed speed remained unchanged for all the positions. This feature enabled 'one-knob' welding operation with different diameter wires.

2.4.2. Continuous control

Continuous control is that whereby a specific parametric relationship, representing a continuous range of welding conditions, is preprogrammed, and any welding condition within the range is retrieved automatically using one-knob control. To program the system, the required relationship, whether voltage v. current, voltage v. wire feed speed or current v. wire feed speed is predetermined. Then an electrical and electronic circuit is constructed to control together the power supply output and the speed of the wire feeder, such that the specified relationship is maintained automatically. Based on this concept, mainly two techniques have been identified to accomplish the control operation. In one technique, the 'one-knob' controls the power supply unit such that the output is a 'rising' type voltage-current characteristic. In the other technique, the 'one-knob' controls the level of the conventional 'flat' type output characteristic, corresponding to the required current or wire feed speed.

a). Control with 'rising' output characteristic

Essentially the power supply unit is designed to provide a 'rising' voltage-current static output characteristic, similar to an arc voltage v. current relationship, relevant to a specific wire composition/wire diameter/shielding gas combination. To match the characteristic with a relationship for any required combination, and for any operating arc length, means are provided for adjusting both the intercept (i.e. open circuit voltage) and slope of the characteristic. Once the characteristic is made identical with the operating relationship, then the power source is expected to provide a suitable arc voltage for any required wire feed speed (or current) automatically.

Practical systems

The concept of 'rising output characteristic' was implemented to design the 'Fillerarc' power-source (8), comprising a motor-generator power supply unit. To enable the output characteristic to be programmed, by adjusting its intercept and slope, relevant to any required wire composition/wire diameter/shielding gas combination, the power source was provided with two controls. One control, operating a field rheostat, varied the open circuit voltage (that is the intercept on the voltage axis) continuously from 10–30 V. The other, a four–position switch selecting a suitable tap on the series field, could adjust the slope at any one of the four values. Thus, both the controls together enable the output characteristic to be matched, as nearly as possible, with a required arc voltage v. current operating relationship. Once the characteristic was programmed, then the power source was ready to set up a welding condition automatically, for any wire feed speed selected by the operator.

b). Control with 'flat' output characteristic

The 'flat' static output characteristic of a power supply unit is that whereby the voltage decreases gradually (less than about 5 V per 100 A) as the current increase. Any point on the characteristic, coordinating voltage and current, does not necessarily represent a feasible operating point. This is because, the slope of the characteristic is negative, whereas that of a voltage v. current relationship for arc operation is positive. Therefore, their intersection, which gives the stable arc operation, occurs only at one point. That is, an output characteristic with a specified voltage level provides only one operating point. This point is shown in Fig. 2–5 for a constant wire feed speed and variable arc length (16), and in Fig. 2–6 for a variable wire feed speed and constant arc length.

To achieve stable arc operation over the entire current (or wire feed speed) range, a control mechanism (current control) is designed which enables the voltage level of the output characteristic to be varied. This variation moves the operating point along the specified voltage v. current parametric relationship, corresponding to any required current (or wire feed speed). For example, the operating points for 'low', 'medium' and 'high' currents are shown as solid symbols on the set of three characteristics, Fig. 2–7.

Furthermore, if the arc length is required to be increased or decreased over its operating range, for any given current, then the control mechanism is designed to raise or lower further the level of the output characteristic (by means of 'fine voltage' or 'fine arc length' or 'trim' control). This variation produces a voltage/current

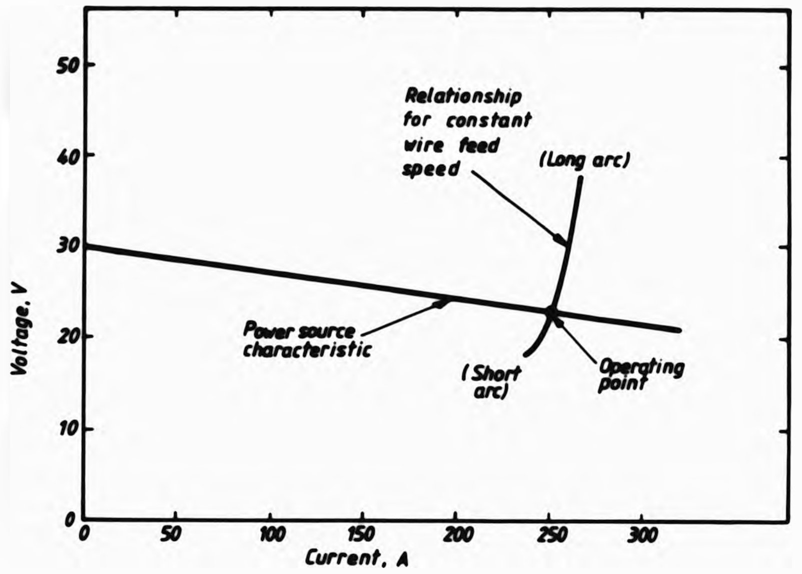


Fig. 2–5. Operating point defined by the power source output characteristic and voltage v. current relationship for constant wire feed speed but variable arc length operation (16).

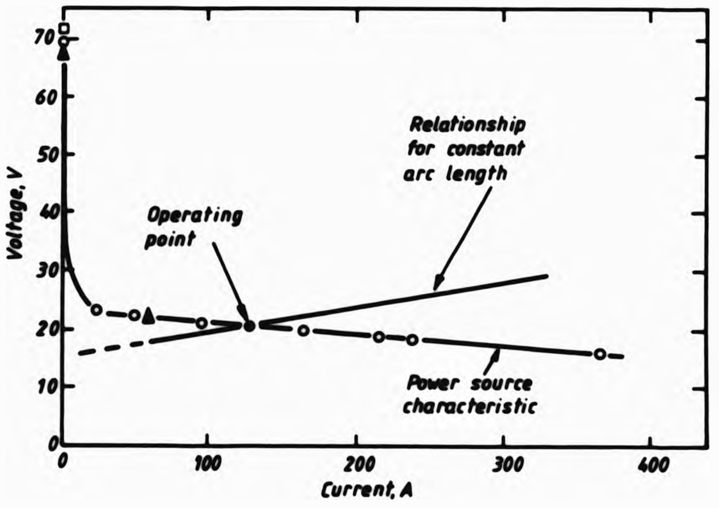


Fig. 2–6. Operating point defined by the power source output characteristic and voltage v. current relationship for constant arc length but variable wire feed speed operation.

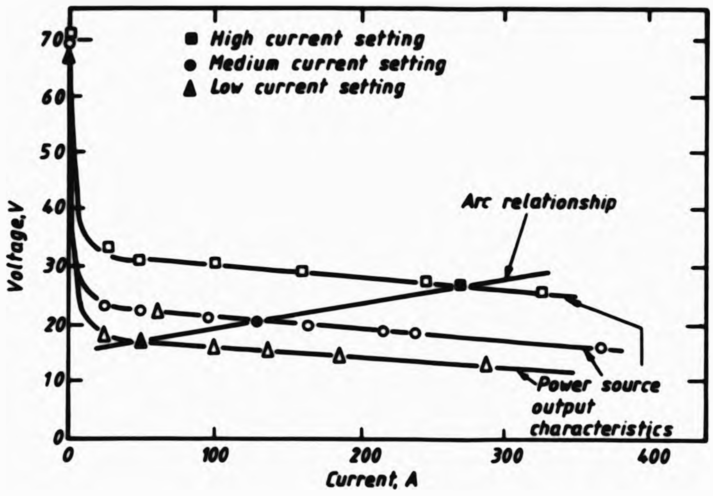


Fig. 2–7. Static output characteristics of the power supply unit with 'low', 'medium' and 'high' current settings, together with voltage v. current relationship for arc operation.

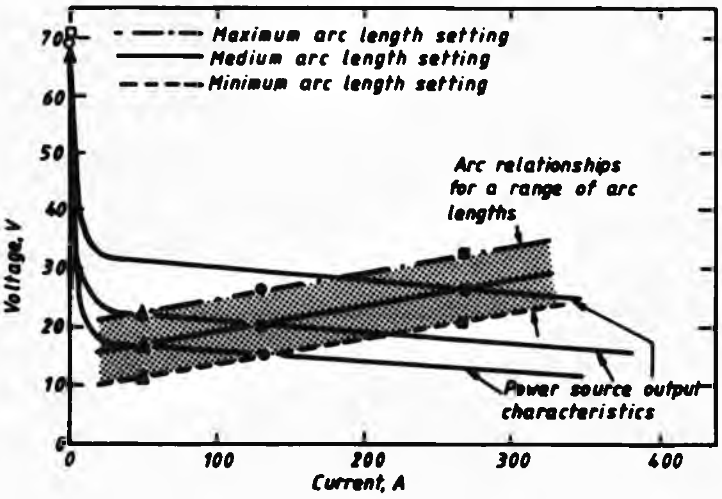


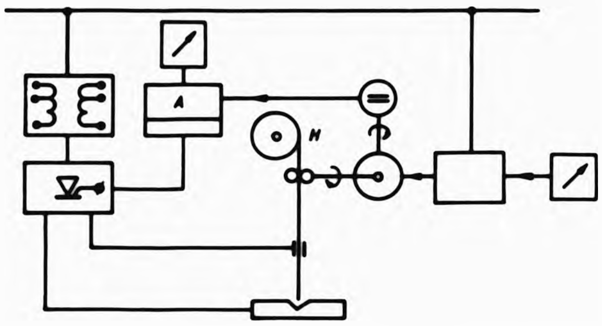
Fig. 2–8. Voltage–current operating zone, shown dotted, derived for the combined variation of the current and voltage settings.

operating zone, Fig. 2-8. Any voltage/current coordination in the zone represents a feasible operating point which can be established by the combined variation of the 'current' and 'voltage' controls. This control concept has been implemented by various control techniques to construct 'one-knob' controlled power sources.

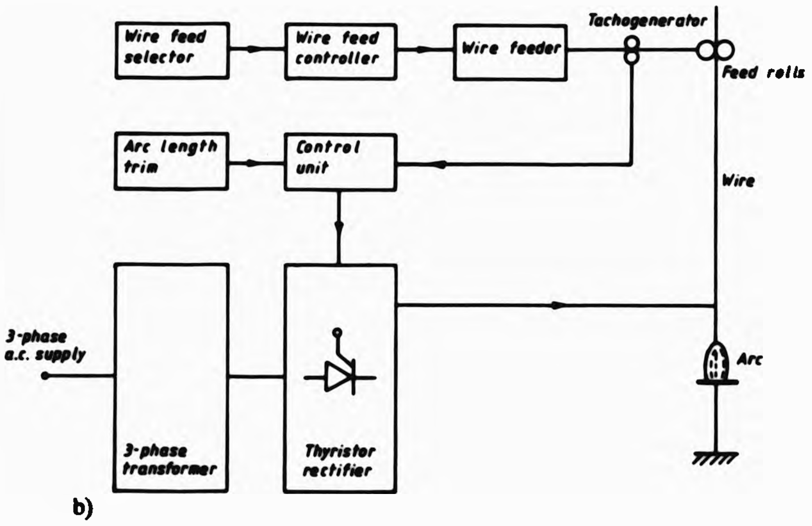
Practical systems

The one-knob control provided on the 'one-knob welder' (17), developed in 1968, was coupled mechanically, by means of gears, to both an autotransformer and a potentiometer. The autotransformer controlled the input voltage to the power supply unit, such that the open circuit voltage could be varied from 18 to 35 V, while the potentiometer controlled the speed of the wire feeder. Thus, the one-knob correlated both the wire feed speed and the output voltage, such that a stable welding condition could be set up automatically for any wire feed speed. The mechanical coupling was designed mainly to operate for 0.9 mm (0.035 in.) diameter wire. To alter the arc length, the coupling design provided some flexibility such that it could be released to readjust the autotransformer relative to the potentiometer. This enabled the voltage level of the output characteristic to be increased or decreased, changing the arc length as required over the wire feed speed range.

Another power source (18) developed in 1974, Fig. 2-9a as original and Fig. 2-9b as functional diagram, incorporated electronic controls for programming the output characteristics. The control unit was designed to receive a signal representative of the required wire feed speed from a feedback controlled wire feeder, and to provide an output signal representative of the open circuit voltage relative to the feed speed. This signal was then used to control the output of the transformer-thyristor power supply unit, such that the required open circuit voltage was maintained automatically, establishing a stable welding condition. The control unit was made flexible in that it provided two controls, which were continuously variable, for adjusting the output characteristic as required. One control varied the intercept, that is the open circuit voltage, while the other varied the slope. Thus the output characteristic could be matched with the arc voltage v. wire feed speed (or current) relationship relevant to any given wire composition/wire diameter/shielding gas combination. Another important function of the control varying the open circuit



a)



b)

Fig. 2-9. One-knob controlled power source regulating arc voltage v. wire feed speed relationship electronically:
a) original diagram (18),
b) functional diagram.

voltage was that, for a given combination, the arc length could be adjusted easily by the operator even during the welding operation. Thus, the control system simplified setting-up welding conditions for any required combination, wire feed speed and arc length.

An electronic control system (19), Fig. 2-10a as original and Fig. 2-10b as functional diagram, reported in 1975, comprised a memory bank which was preprogrammed with 20 programs (voltage v. wire feed speed relationships) relevant to various wire composition/wire diameter/shielding gas/process variant combinations. The system enabled any required program to be selected by means of a number of push buttons provided on the front panel of the power source. The program coupled the wire feed speed with the output characteristic of the transformer-thyristor power supply unit electronically such that a suitable voltage level was adjusted automatically for any required wire feed speed. In this system three inductance terminals were provided on the front panel, and a lamp was lit up automatically to indicate which terminal must be connected in the welding circuit, relevant to the selected program.

A new range of MIG welding power sources has recently been developed in Japan, including for example the OTC Transistarc MM350, National Pana Auto Memory 350 and Hitachi Micom Auto 350MA. Their design approach is based on transformer-thyristor or transistor combinations, together with low cost electronic control circuits. These circuits are preprogrammed (excepting any pulsed operation) to execute voltage v. wire feed speed relationships relevant to various wire composition/wire diameter/shielding gas combinations. The power sources enable any required combination to be selected by means of switches provided on the front panel. Then the power sources become ready to operate from one-knob 'current' control, with a further 'trim' control which enables arc length to be varied as required. The current control sets any required wire feed speed and, in addition, adjusts the level of the output characteristic corresponding to any required current, for a given voltage control (or arc length) setting. This determines a unique operating voltage for the required current (and wire feed speed). Furthermore, a range of output voltage for any given current can be obtained by varying the voltage control. That is, any arc length can be selected over the operating range.

Another 'one-knob' power source developed and improved in the late 1970s and

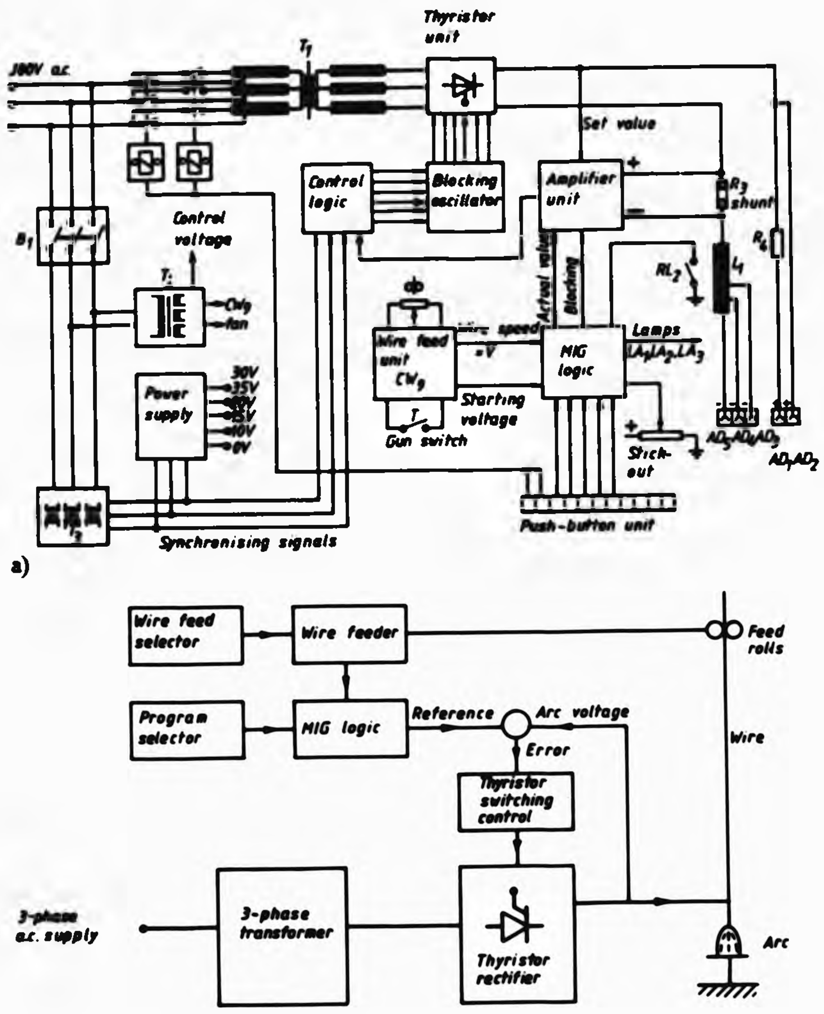


Fig. 2-10. AGA MIG 400 electronic welding power supply:
a) original diagram (19),
b) functional diagram.

early 1980s (20,21,22,23), called SAM (Servo Adjusted MIG), includes a transistor controlled power supply unit and a feedback controlled wire feeder which are controlled together by an electronic control unit, Fig. 2-11a as original and Fig. 2-11b as functional diagram. The 'one-knob' control enables a welding condition to be set up automatically relevant to any required wire feed speed. In operation, the 'one-knob' supplies a signal to the wire feeder to set up any required wire feed speed and, in addition, provides the relevant information to the control unit. This unit then determines a 'reference' signal representative of the suitable current level, which should be maintained specifically during the arcing intervals of the short circuiting arc operation, to achieve optimum arc performance. In addition, the control unit uses the arc voltage and current signals to identify the arcing periods and determines a signal representative of the actual arc power exclusively during the arcing periods. This signal is compared with the 'reference' signal to determine an 'error' which is then used either to readjust the wire feed speed while the power supply output remains preset according to the 'reference', or to readjust the output while the feed speed remains preset. Thus, the system is designed not only to set up a welding condition automatically, but also to maintain a constant arc power at the optimum value during the arcing periods.

2.5. DISCUSSION AND CONCLUDING REMARKS

One-knob controlled power sources set up the welding conditions efficiently because the relevant welding parameters are coordinated automatically. Otherwise, the parameters have to be adjusted individually by the conventional method of trial and error, by means of the relevant controls provided on the power source. Incorrect adjustment could cause the arc/metal transfer to become unstable resulting in defective welds.

Various approaches have been conceived and implemented to develop one-knob controlled systems. In general these control approaches either seek to maintain a constant arc voltage while the wire feed speed is regulated automatically (arc voltage control), or seek to maintain a constant arc length while the arc voltage is adjusted automatically for any given wire feed speed (arc length control). The 'arc voltage control' compares the required and actual voltages, and uses the 'error' to regulate the

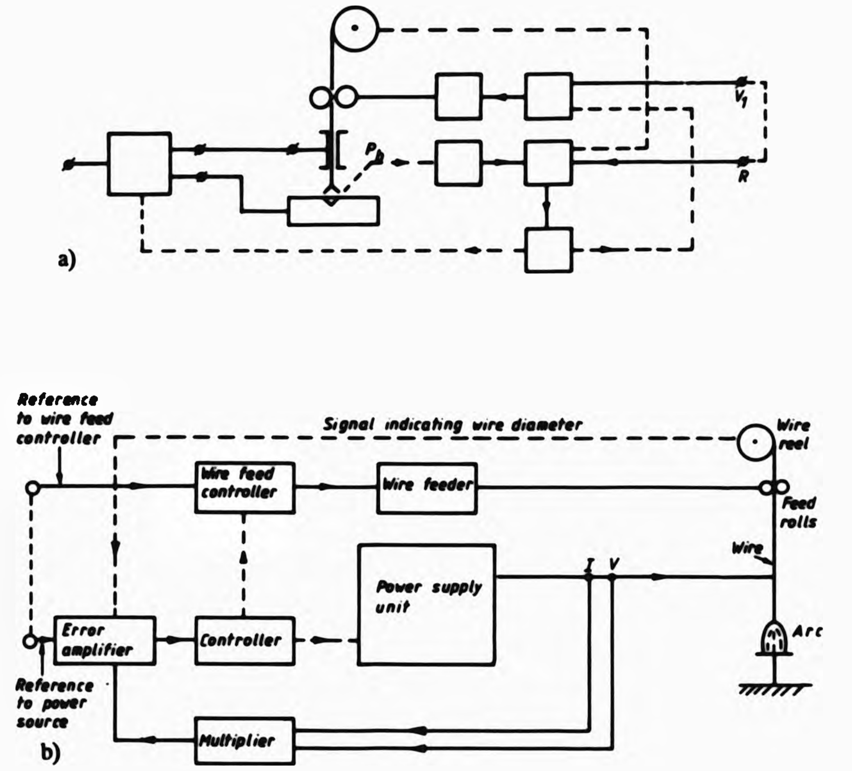


Fig. 2-11. Servo adjusted MIG (SAM) power source:
a) original diagram (20),
b) functional diagram.

wire feed speed maintaining the required voltage. A practical system based on this concept, includes the current control generator/motor/wire feeder combination. These are not only expensive and bulky, but also have high inertia and provide inadequate response to the fast voltage fluctuations which normally occur when welding.

The 'arc length control' executes a specific voltage v. wire feed speed (or current) relationship for a required arc length in either stepwise or continuous mode. In practice, the stepwise control approach is limited to only a few welding conditions. Otherwise, the design and construction of the power source become complex and require special devices to be used. As a result, the power source becomes expensive and therefore unacceptable commercially. In addition, the approach is inflexible because the parameters constituting the welding conditions are all fixed. Therefore, any 'trimming' of a welding condition to optimise the arc performance for a specific application cannot be carried out by the operator. This inflexibility could easily outweigh the efficiency and convenience provided by the one-knob control operation. Furthermore, for a welding condition to be reproducible, the stepwise approach requires the power supply output and wire feed speed to be stabilised against any changes, for example in the mains voltage and temperature (the latter can rise in the circuits during operation or through changes in the ambient temperature). Using modern electronic devices (such as thyristors and transistors) together with feedback control circuits, the power supply output and speed of the wire feeder motor can be stabilised, but still wire slippage over the feed rolls or wire restriction in the conduit would cause inconsistent welding performance.

The continuous control is accomplished using either a 'rising' output characteristic of the power supply unit, or a 'flat' characteristic. The first method requires the rising characteristic to be perfectly matched with the specific voltage v. current (or wire feed speed) relationship, to obtain a constant arc length for any wire feed speed. However, in practice, the perfect match would not be accomplished easily. Even if a perfect match could be achieved, the arc operation would still be unstable because the operating point, coordinating the required voltage and current, would be free to move along the characteristic. That is , if the arc length is extended due to a disturbance, the current would be increased extending the arc length further, to cause burnback. Conversely, a decrease in the arc length would be augmented due to reduction in current and result in stubbing. In other words, the system provides a welding condition which would become unstable due to arc disturbances. To eliminate such instability, the slope of the output characteristic should, in principle, be less than that for the operating relationship (24). However, if the slope difference is large, the arc length would not remain constant as required over the wire feed speed range. Whereas, with a small difference, the output characteristic and the relationship could intersect at various points, Fig. 2-12 (24). Therefore, the arc would be unstable because of shifting from one operating point to another.

The problem of arc instability, which would occur with the control method using the 'rising' output characteristic, can be eliminated with the control technique based on the 'flat' characteristic. But, with this technique, the output voltage and the wire feed speed are required to remain stable against any changes, for example, in the mains voltage, temperature of the circuits during operation and ambient temperature; and there should be no wire slippage on the feed rolls or wire restriction in the conduit. Otherwise the operating point, coordinating wire feed speed and voltage, would deviate and cause arc instability. To avoid such instability, various one-knob control systems based on the flat output characteristic include power supply and wire feed units which are stabilised by means of feedback control circuits. However, these systems would still not prevent arc instability caused by any wire slippage over the feed rolls or any wire restriction in the conduit. Therefore, the development of improved one-knob controlled systems should be continued.

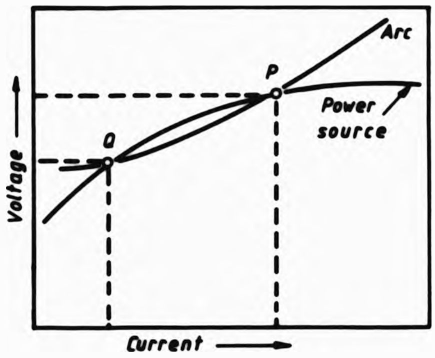


Fig. 2–12. Pair of working points produced by multi–intersections of voltage v. current relationship for arc operation and power source output characteristic (24).

CHAPTER 3
EXPERIMENTAL EQUIPMENT AND TEST PROGRAMME

3.1. EQUIPMENT

To study basic parametric relationships for both the steady DC open arc and short circuiting arc operations, the equipment comprised a welding rig and transistor power source. To accomplish synergic control using the transistor controlled power source, the equipment also included three types of control units for the steady DC open arc operation, and one of the control units could also be adapted for the short circuiting arc operation. In addition, to transfer the synergic controls into industry, the control units were adapted to operate with a commercial thyristor controlled power source, included in the equipment. While the development of the control units is described in Section 5.3., and their adaptation in Section 6.3., the features of the welding rig and power sources are described below.

3.1.1. Welding rig

The tests were carried out on a mechanised rig, Fig. 3–1, in which the workpiece was traversed uniformly under a stationary welding head, which was mounted vertically such that contact tip to workpiece distance could be adjusted as desired. The wire electrode was driven through the head by means of a Welding Institute multigrip wire feeder (25). This was driven from a reference signal, on the basis that 0–5 V reference input gave 0–15 m/min feed speed output. The calibrated reference signal of the desired waveform was provided by a reference control unit.

3.1.2. Transistor controlled power source

The transistor power source, designed and developed at The Welding Institute (26), comprised a 3–phase transformer–rectifier unit with the addition of a linear feedback controlled transistor series regulator. The transformer–rectifier provided steady DC which was then controlled by the regulator to supply the arc with any desired current waveform (e.g. smooth DC or modulated waveform). The range of current extended from 0–500 A. As the frequency response of the transistor regulator extended from

Wire feeder

Welding gun

Traverse

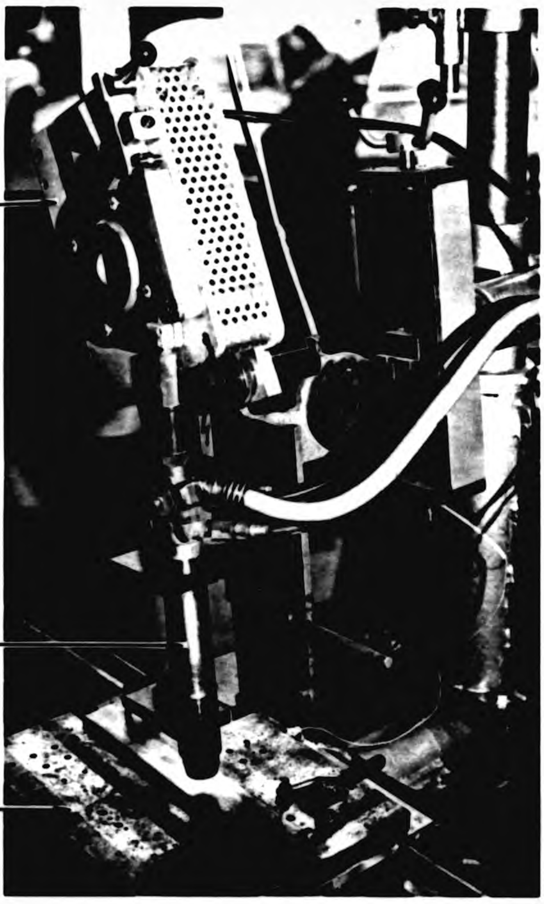


Fig. 3–1. The welding rig.

DC to about 10 kHz, the power source could provide a modulated current with a range of frequencies up to 1 kHz.

The regulator could be operated in either constant current or constant voltage mode. The regulator was driven from an instruction or reference signal, on the basis that 0–5 V reference input gave 0–500 A regulator output to the arc for the constant current mode, and 0–50 V output for the constant voltage mode. The calibrated reference signal of the desired level was provided by the associated electronic control unit for studying the parametric relationships, and, later, by the relevant synergic control units while testing the performance of the synergic controls.

While obtaining data for the parametric relationships for steady DC arc operation, the transistor regulator was operated in the constant current mode to maintain accurate control of the current level. As this condition does not provide any self-adjustment due to the power supply, the current had to be carefully adjusted so that the burnoff rate matched the wire feed speed for any required arc length.

3.1.3. Thyristor controlled power source

The selected power source is a commercial 3-phase transformer-thyristor controlled rectifier unit. For a given input reference signal, the power source provides a nominally constant voltage static output characteristic, with a droop of about 3 V/100 A.

To adapt the control units to this power source, information was required about the input/output relationships of the power source. This information has been obtained experimentally as described in Chapter 6.

3.2. TEST PROGRAMME

3.2.1. Parametric relationships

For steady DC open arc operation, the parametric relationships were established for 1.2 mm diameter mild steel wire (BS 2901: Part 1: 1970: A18) in Ar+5%CO_2 and Ar+20%CO_2 shielding gases. For a given wire material/wire diameter/shielding gas combination, the operating range of wire feed speed and the corresponding ranges of arc current and arc voltage were determined for 10, 15 and 20 mm wire extensions, using 5 and 10 mm arc lengths for each extension. In addition, the parametric relationships were established for 1.0 mm diameter mild steel wire (BS 2901: Part 1: 1970: A18) in Ar+5%CO_2 using 10 mm wire extension and 5 mm arc length, to determine the effect of wire diameter. These tests provided data to establish the basic relationships of current v. wire feed speed, and arc voltage v. current. In addition, the data were used to determine the effect of wire extension, arc length, shielding gas and wire diameter on the relationships.

For short circuiting arc operation, parametric relationships were studied for the 1.2 and 1.0 mm diameter mild steel wires in Ar+20%CO_2 and CO_2 shielding gases. For a given wire material/diameter/shielding gas combination, data were obtained on arc current and arc voltage for the optimum arc performance over the operating wire feed speed range, so that the current v. wire feed speed and arc voltage v. current relationships could be established.

3.2.2. Evaluation of synergic control systems

For the steady DC open arc operation, control performance has been evaluated in bead-on-plate runs for wire feed speed maintained constant, varied gradually or modulated, using 1.2 mm diameter mild steel wire in Ar+5%CO_2. In addition, 1.0 mm diameter mild steel wire was used to determine the effect of wire diameter.

To test how the control system would respond to a gradually varying wire extension, bead-on-plate runs were made on a wedge-shaped workpiece which had its thickness reduced from 25 to 10 mm over a length of 250 mm. In addition, the control response to a sudden increase in the electrode extension was tested on a workpiece which had its thickness reduced in three steps, from 25 to 10 mm, each step being 5 mm.

Welding performance has been evaluated for butt and fillet joints, using both mechanised and manual techniques. Shielding gases used were Ar+5%CO_2, Ar+20%CO_2 and Ar+15%CO_2. The shielding gas Ar+15%CO_2 compared to Ar+20%CO_2 was found to give reduced spatter and, compared to Ar+5%CO_2, reduced the risk of lack-of-fusion defects and porosity.

For short circuiting arc operation, control and welding performance has been evaluated in bead-on-plate runs and joints using 1.0 mm and 1.2 mm diameter mild steel wire in CO_2 and Ar+20%CO_2. Furthermore, the effect of gradually varying the wire extension was tested on a workpiece similar to that used for open arc operation. The effect of sudden changes in wire extension was tested on a workpiece which was machined with a series of square grooves, 3 mm deep, 5 mm wide and 5 mm spaced apart.

CHAPTER 4
PARAMETRIC RELATIONSHIPS

4.1. STEADY DC OPEN ARC OPERATION

4.1.1. Specific basic relationships

For steady DC open arc MIG operation, with a required wire material/wire diameter/shielding gas combination, the operating variables included wire feed speed, current level and arc voltage, for a given arc length and wire extension. These variables provided two relationships which could specify the operation entirely; the first, current v. wire feed speed (called burnoff), and the second, voltage v. current relationship. These relationships, as obtained from the experimental data, are described below.

For the mild steel/1.2 mm diameter/Ar+5%CO_2 combination, using 5 mm arc length and 10 mm wire extension (15 mm contact tube to workpiece distance), the basic relationships are plotted in Fig. 4-1. The burnoff relationship, Fig. 4-1a, was the basis for the open arc operation, whereby the required wire feed speed specified a unique current. The relationship is linear such that the current increases with the feed speed, and it makes an intercept on the current axis when extrapolated to the feed speed at zero value. The relationship can be expressed by the following equation:

$$I = 26.4\,W + 80 \qquad [4\text{-}1a]$$

Where

I is the arc current, A;

W is the wire feed speed, m/min.

The voltage-current relationship, Fig. 4-1b, specified a unique voltage for the required current. Over the operating current range, the relationship is linear such that the voltage increases gradually with the current, and makes an intercept on the

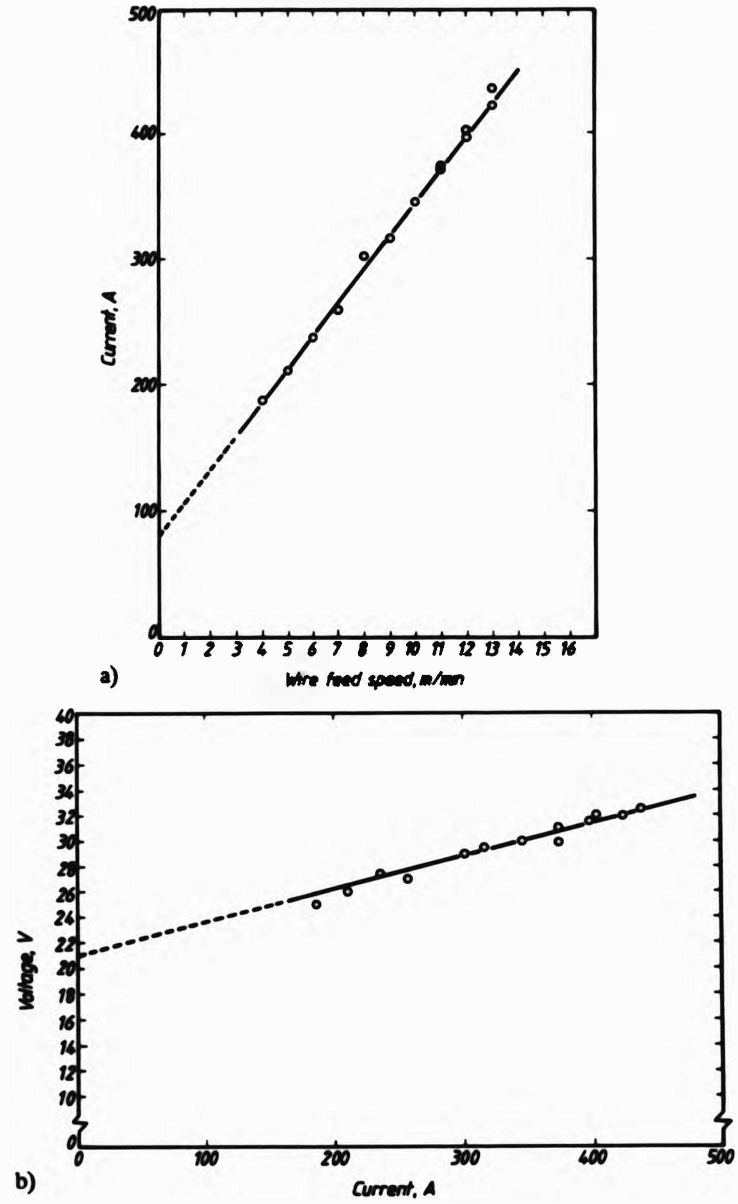


Fig. 4–1. Basic relationships for a mild steel wire, 1.2 mm diameter and Ar+5% CO_2 shielding gas, at fixed 5 mm visible arc length and 10 mm wire extension:
a) burnoff relationship, b) voltage–current relationship.

voltage axis when extrapolated to the current at zero value. The relationship can be expressed by the following equation:

$$V = 0.028\ I + 21 \qquad [4\text{-}1b]$$

Where
V   is the arc voltage, V.

4.1.2. Effect of process parameters on the basic relationships

a). Arc length

For the same welding conditions as above; mild steel/1.2 mm diameter/Ar+5%CO_2 combination, and a 15 mm contact tube to workpiece distance but with a 10 mm arc length (5 mm wire extension), the basic relationships are linear and can be expressed by the following equations:

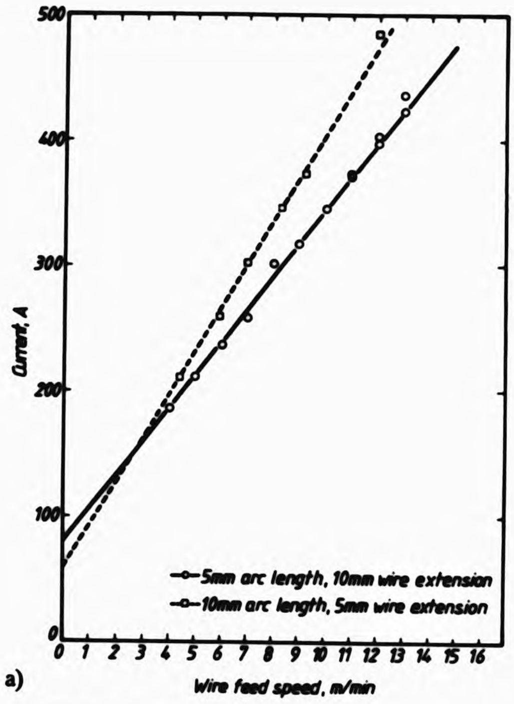
$$I = 34.3\ W + 60 \qquad [4\text{-}2a]$$

$$V = 0.029\ I + 23 \qquad [4\text{-}2b]$$

The equations are similar to the corresponding equations [4-1a] and [4-1b] for 5 mm arc length except that, for the burnoff relationship, the slope is increased from 26.4 to 34.3 A/m/min while the intercept is decreased from 80 to 60 A. Whereas, for the voltage-current relationship, the slope is slightly increased from 0.028 to 0.029 V/A, and the intercept is increased from 21 to 23 V. These effects are shown in Fig. 4-2. However, the change in the arc length, from 5 to 10 mm, had no effect on the linearity of either relationship.

b). Wire extension

The effect of wire extension from 10 to 15 to 20 mm on the basic relationships, at 5 mm arc length, is shown in Fig. 4-3. The two pairs relevant to 15 and 20 mm wire extensions can be expressed by the following equations.



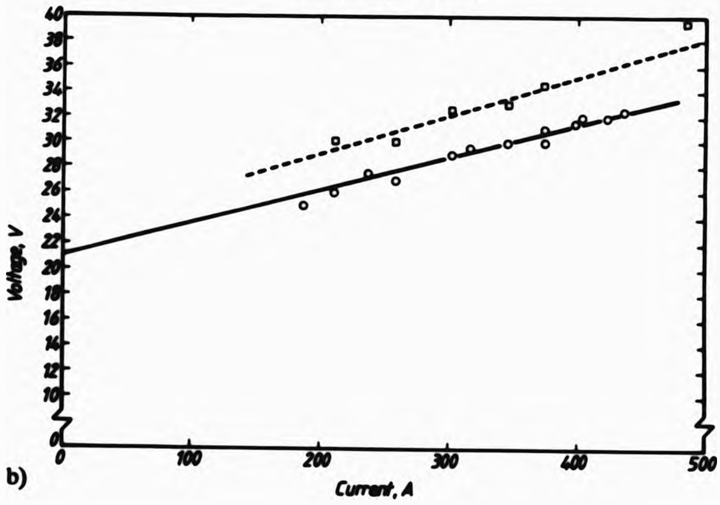


Fig. 4–2. Effect of arc length on the basic relationships using a mild steel wire/1.2 mm diameter/Ar+5%CO_2 combination:
a) burnoff relationships, b) voltage–current relationships.

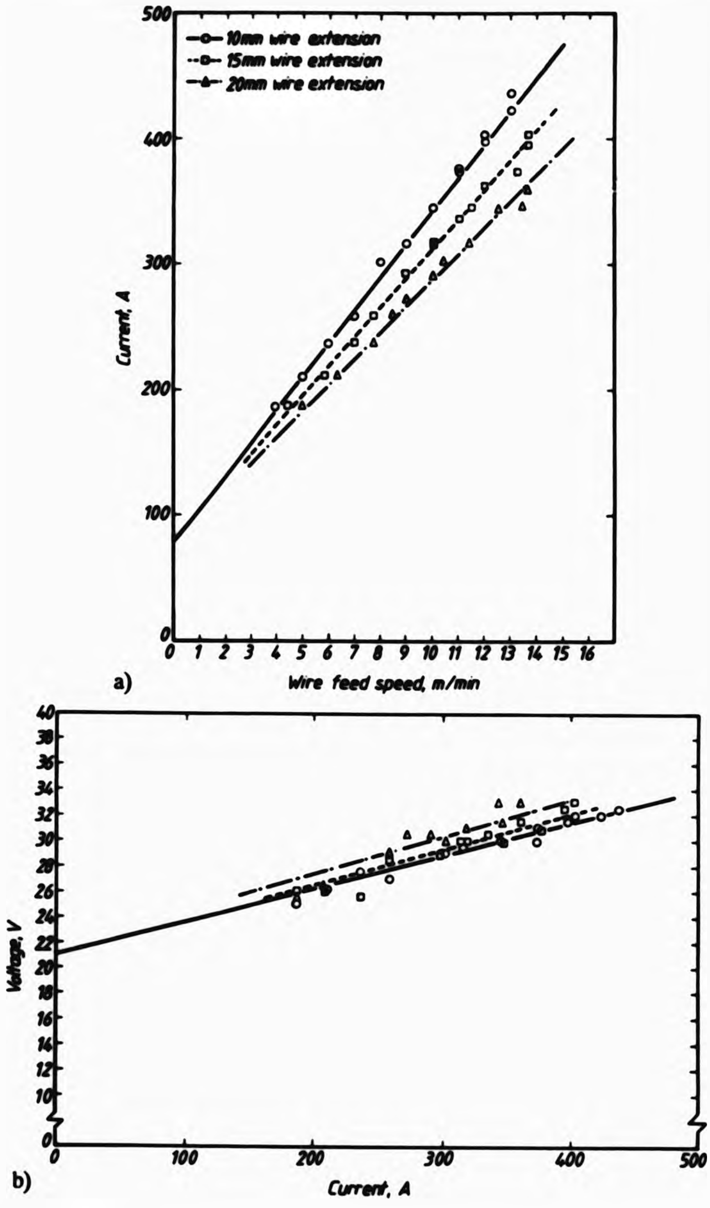


Fig. 4-3. Effect of wire extension on the basic relationships using a mild steel wire/1.2 mm diameter/Ar+5%CO_2 combination at fixed 5 mm visible arc length: a) burnoff relationships, b) voltage-current relationships.

For 15 mm wire extension:

$$I = 24.0\ W + 80 \qquad [4\text{–}3a]$$

$$V = 0.028\ I + 21 \qquad [4\text{–}3b]$$

For 20 mm wire extension:

$$I = 20.0\ W + 80 \qquad [4\text{–}4a]$$

$$V = 0.029\ I + 21.5 \qquad [4\text{–}4b]$$

The increase in wire extension from 10 to 15 to 20 mm decreased the slope of the burnoff relationship from 26.4 to 24.0 to 20.0 A/m/min, respectively, whereas the intercept remained constant at 80 A.

The voltage–current relationships for 15 and 20 mm wire extension (equations [4–3b] and [4–4b]) are practically identical to that for 10 mm wire extension (equation [4–1b]). Hence the change in wire extension from 10 to 20 mm has no significant effect on the voltage–current relationship.

Furthermore, both the relationships in each pair, for 15 and 20 mm wire extensions, are linear like those for 10 mm wire extension. Therefore, the change in wire extension from 10 to 20 mm has no effect on the linearity of the basic relationships.

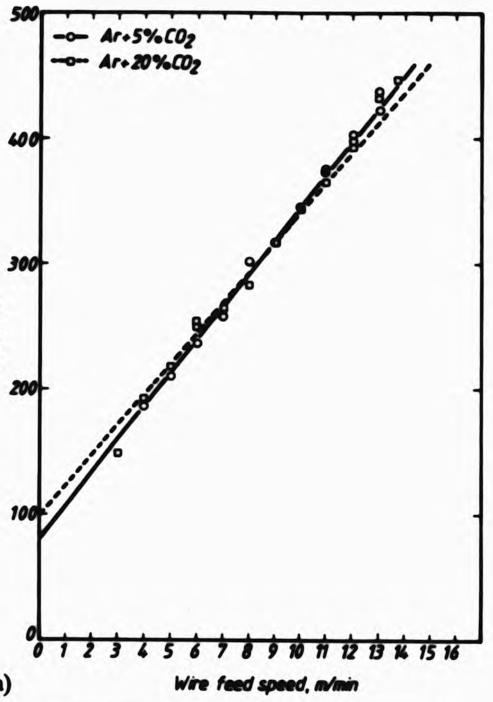
c). Shielding gas

For the arc operation in Ar+20%CO_2 shielding gas, at 5 mm arc length and 10 mm wire extension, the basic relationships obtained are plotted in Fig. 4–4, together with those previously obtained for Ar+5%CO_2. These can be expressed by the following equations:

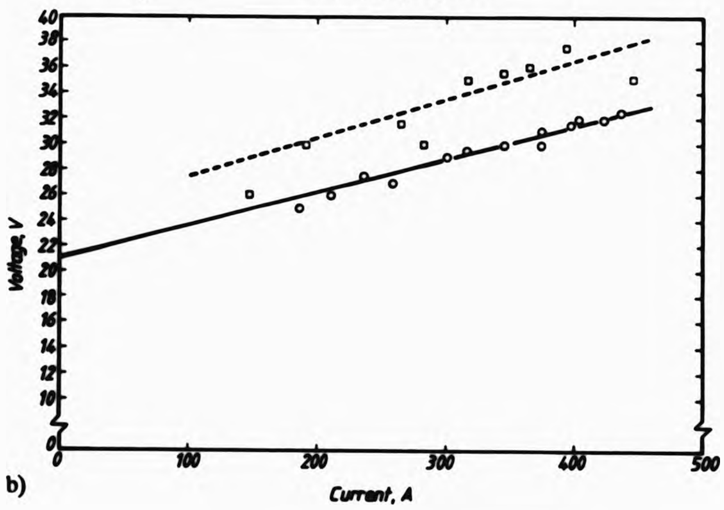
$$I = 24.0\ W + 100 \qquad [4\text{–}5a]$$

$$V = 0.030\ I + 24.5 \qquad [4\text{–}5b]$$

As both the equations are linear, like those for Ar+5%CO_2 , a change of CO_2



a)



b)

Fig. 4–4. Effect of shielding gas on the basic relationships, at fixed 5 mm visible arc length and 10 mm wire extension, using 1.2 mm diameter mild steel wire:
a) burnoff relationships, b) voltage–current relationships.

content in Ar from 5 to 20% has no effect on the linearity of the basic relationships.

d). Wire diameter

The basic relationships relevant to 1.0 mm diameter, at 5 mm arc length and 10 mm wire extension in Ar+5%CO_2 , can be represented by the following equations:

$$I = 18.4\ W + 50 \qquad [4\text{–}6a]$$

$$V = 0.031\ I + 22 \qquad [4\text{–}6b]$$

The decrease in wire diameter from 1.2 to 1.0 mm decreased the slope of the burnoff relationship from 26.4 to 18.4 A/m/min, and the intercept from 80 to 50 A. For the voltage–current relationship, the slope increased from 0.028 to 0.031 V/A, and the intercept from 21 to 22 V. These effects are shown in Fig. 4–5. The relationships for 1.0 mm diameter are linear, like those for 1.2 mm diameter.

4.1.3. Generalised basic relationships

As established in Sections 4.1.1. and 4.1.2., the specific burnoff and voltage–current relationships were found to be linear over the 5–10 mm range of arc lengths, 10–20 mm range of wire extensions, 5–20% range of CO_2 content in the Ar shielding gas and 1.0–1.2 mm range of wire diameters. Therefore, the generalised burnoff relationship over the operating ranges of the parameters can be represented by the following linear equation:

$$I = m_i W + C_i \qquad [4\text{–}7a]$$

Where

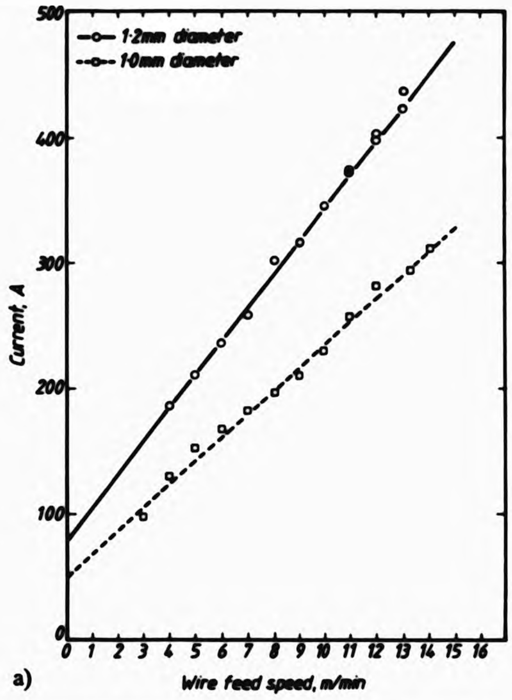
I is the current, A;

W is the wire feed speed, m/min;

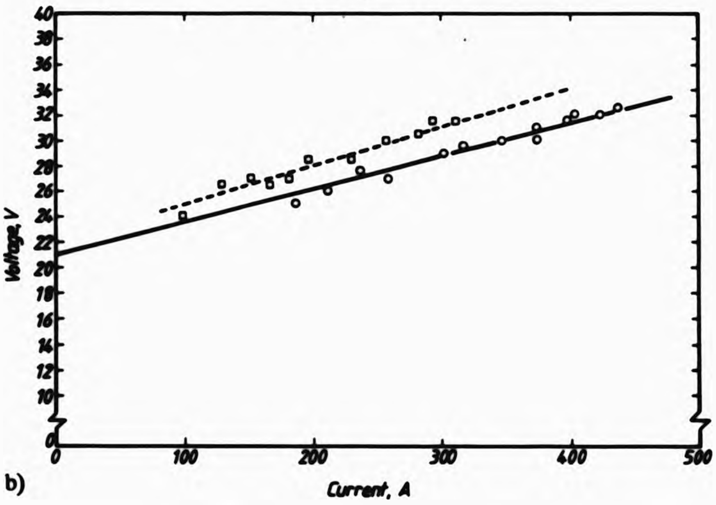
m_i is the slope, A/m/min;

C_i is the intercept, A.

Subscript i refers to current.



a)



b)

Fig. 4–5. Effect of wire diameter on the basic relationships, at fixed 5 mm visible arc length and 10 mm wire extension, using a mild steel wire in Ar+5%CO_2 shielding gas:
a) burnoff relationships, b) voltage–current relationships.

The equation has W as an independent variable representing required wire feed speed, and I is the corresponding dependent variable. The equation is specified by the slope m_i and the intercept C_i, for the operation with any required wire material/diameter/shielding gas combination, at a given arc length and wire extension.

Similarly, the generalised voltage–current relationship can be represented by the following linear equation:

$$V = m_v I + C_v \qquad [4\text{–}7b]$$

Where

V is the voltage, V;

I is the current, A;

m_v is the slope, V/A;

C_v is the intercept, V.

Subscript v refers to voltage.

The equation has I as independent variable for the required current, and V as the corresponding dependent variable. The equation is specified by the slope m_v and the intercept C_v, for any required wire material/diameter/shielding gas combination, together with a specified arc length and wire extension.

4.2. SHORT CIRCUITING ARC OPERATION

The burnoff relationships for four wire diameter/shielding gas combinations, comprising 1.0 and 1.2 mm diameters and Ar+20%CO_2 and CO_2 shielding gases for each diameter with wire extension of 12 mm, are plotted in Fig. 4–6. For the operating wire feed speed range of about 2–7 m/min, the corresponding current range is specific for each combination. All the relationships are similar in shape; however, these are not linear but curved.

For the four combinations, the voltage–current relationships are shown in Fig. 4–7 for the optimum arc operation whereby the voltage was tuned to obtain regular short circuits and consistent metal transfer. However, each relationship has a working tolerance up to about 2 V above and below the voltage for the optimum operation shown, for example, in Fig. 4–8 for the mild steel/1.2 mm diameter/CO_2

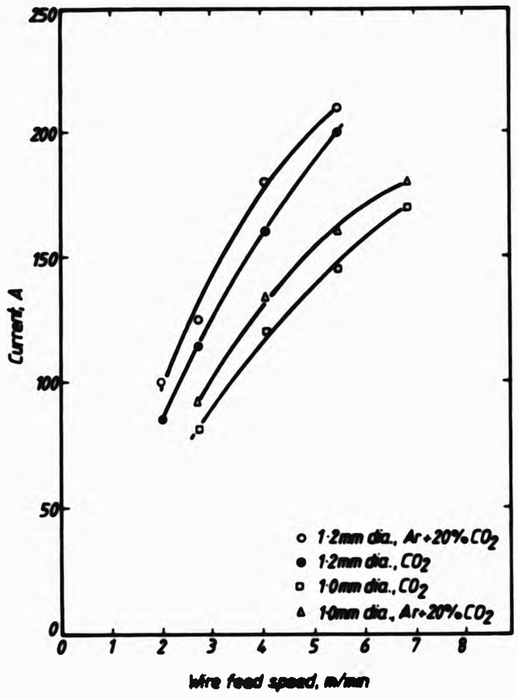


Fig. 4–6. Burnoff relationships for short circuiting arc operation, using 1.0 and 1.2 mm diameter mild steel wires and CO_2 and Ar+20%CO_2 shielding gases, with 12 mm wire extension.

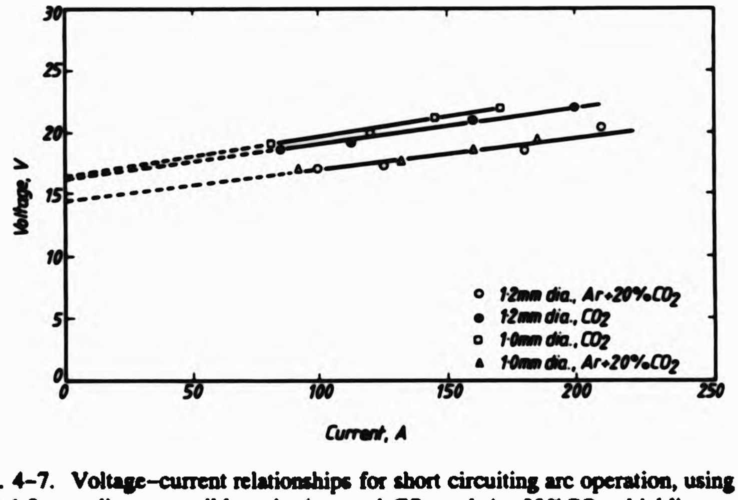


Fig. 4–7. Voltage–current relationships for short circuiting arc operation, using 1.0 and 1.2 mm diameter mild steel wires and CO_2 and Ar+20%CO_2 shielding gases, with 12 mm wire extension.

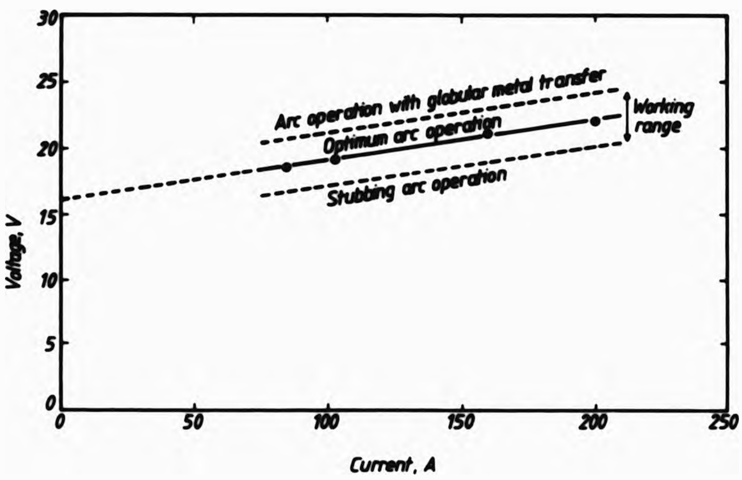


Fig. 4–8. Voltage range for the short circuiting arc operation, using 1.2 mm diameter mild steel wire and CO_2 shielding gas.

combination. A lower voltage setting causes progressively prolonged short circuits which result in stubbing arc operation. Whereas an excessively high voltage causes excessive arcing periods and results in an arc operation with inadequate short circuiting frequency and globular metal transfer.

For the optimum operation, all the relationships are linear and can be expressed by the following equations:

$$V_{av} = 0.032 I_{av} + 16.4 \quad \textit{for 1 mm diameter/}CO_2\textit{ combination}$$

$$V_{av} = 0.028 I_{av} + 16.2 \quad \textit{for 1.2 mm diameter/}CO_2\textit{ combination}$$

$$V_{av} = 0.027 I_{av} + 14.6 \quad \textit{for 1 mm diameter/}Ar+20\%CO_2\textit{ combination}$$

$$V_{av} = 0.026 I_{av} + 14.4 \quad \textit{for 1.2 mm diameter/}Ar+20\%CO_2\textit{ combination}$$

As all the relationships are linear, the generalised voltage-current relationship can be represented by the following linear equation:

$$V_{av} = m_v I_{av} + C_v \qquad [4\text{-}8]$$

Where

V_{av} is the average voltage, V;

I_{av} is the average current, A;

m_v is the slope, V/A;

C_v is the intercept, V.

The equation has I_{av} as an independent variable for the required current, and V_{av} as the corresponding dependent variable. The equation is specified by the slope m_v and the intercept C_v, for operation with any required wire material/diameter/shielding gas combination, at a specified wire extension.

4.3. DISCUSSION

Steady DC open arc operation has been characterised entirely by the two generalised linear equations. Each equation includes two operating variables, and the slope and intercept to be specified for a given wire material/diameter/shielding gas combination together with the required arc length and wire extension. These are not valid for the current range below the 'critical' level which is unusable for steady DC open arc operation, because the relevant metal transfer is globular and unsuitable for welding. Above this level, where the metal transfer comprises a series of small droplets or 'spray', the two equations together could specify any required operating point, coordinating wire feed speed, current and voltage, constituting a stable welding condition.

Similarly, short circuiting arc operation has been characterised by the burnoff relationship and the average voltage – average current relationship. These are valid for the wire feed speed range of about 2–7 m/min (average current range about 80–200 A). At wire feed speed less than 2 m/min or higher than 7 m/min, the arc operation tends to become unstable such that the weld bead is irregular and excessive spatter is produced.

4.3.1. Effect of process parameters

4.3.1.1. *Steady DC open arc operation*

To adapt the generalised equations to given combination of process parameters, such as wire material, diameter, shielding gas, arc length and wire extension, the relevant values of the parametric constants need to be specified. Therefore the effects of the process parameters on the slope and intercept are considered below.

a). Burnoff relationship

In general a change in any of the process parameters alters the slope and intercept of the burnoff relationship. The degree of change has been found to be greater than the experimental error (up to about 5%) for the change from 5 to 10 mm arc length, 10 to 20 mm wire extension, 5 to 20% CO_2 in Ar shielding gas or 1.0 to 1.2 mm wire diameter. If two or more parameters are to be changed together, then the effect on slope and intercept may become annulled or accentuated.

Therefore, to specify the burnoff relationship for a given combination of process parameters, the slope and intercept must be determined. As the relationship is linear, these parameters could easily be derived from two data points, requiring only two arc tests.

b). Voltage–current relationship

Effect on the slope m_v

For open arc operation, the values of the slope m_v are given in Table 4–1 and Table 4–2, for various parametric combinations comprising mild steel wire of 1.0 and 1.2 mm diameter, Ar+5%CO_2 and Ar+20%CO_2 shielding gas, 5 and 10 mm arc length, and 10 and 20 mm wire extension. Over the entire range of combinations, m_v varies between 0.025 V/A and 0.031 V/A. As the difference of about ±12% from the maximum and minimum values is greater than the normally achievable experimental error of ±5%, the overall variation in m_v appears to be significant. However, m_v is included in the minor term m_vI of the relationship:

$$V = m_v I + C_v$$

The contribution of m_vI to the total voltage, obtained by evaluating the equation over the current range 100–500 A, are given in Table 4–3. The variation in m_v by ±12% causes variation in the total voltage of only about ±3% at 300 A, which is insignificant. Therefore, the slope m_v could be considered constant at 0.0284 V/A for all the combinations of the process parameters over the operating ranges.

Effect on the intercept C_v

The values of C_v for various combinations of the process parameters are compared in Table 4–4 for 1.0 and 1.2 mm wire diameter, in Table 4–5 for 10, 15 and 20 mm wire extensions, in Table 4–6 for Ar+5%CO_2 and Ar+20%CO_2 shielding gases, and in Table 4–7 for 5 and 10 mm arc lengths. It can be seen that no adjustment would be required in the intercept C_v for a variable wire diameter (Table 4–4) and wire extension (Table 4–5), but the value of C_v must be adjusted for a change in the shielding gas (Table 4–6) and arc length (Table 4–7).

Table 4–1. Values of parametric constants m_v and C_v, for various wire material/wire diameter/shielding gas/arc length/contact tube to workpiece distance combinations relevant to steady DC open arc operation.

Shielding gas	Contact tube to workpiece distance, mm	Wire extension, mm	Arc length, mm	Parametric constants	
				m_v, V/A	C_v, V
1.2 mm diameter mild steel wire					
Ar+5%CO_2	15	10	5	0.028	21
Ar+5%CO_2	15	5	10	0.029	23
Ar+20%CO_2	15	10	5	0.030	24.5
Ar+20%CO_2	15	5	10	0.025	30
1.0 mm diameter mild steel wire					
Ar+5%CO_2	15	10	5	0.031	22
Ar+5%CO_2	15	5	10	0.030	23
Ar+20%CO_2	15	10	5	0.030	25
Ar+20%CO_2	15	10	5	0.028	30.5

Table 4–2. Values of parametric constants m_v and C_v, using variable contact tube to workpiece distance and constant arc length, for 1.2 mm diameter mild steel wire, relevant to steady DC open arc operation.

Shielding gas	Contact tube to workpiece distance, mm	Wire extension, mm	Arc length, mm	Parametric constants	
				m_v, V/A	C_v, V
Ar+5%CO_2	15	10	5	0.028	21
Ar+5%CO_2	20	15	5	0.028	21
Ar+5%CO_2	25	20	5	0.029	21.5
Ar+20%CO_2	15	10	5	0.030	24.5
Ar+20%CO_2	20	15	5	0.030	25.5
Ar+20%CO_2	25	20	5	0.033	25.0

Table 4–3. Typical contributions made by the minor (m_vI) and major (C_v) terms* to the total voltage given by the voltage–current equation, $V = m_vI + C_v$, for the current range 100–500 A.

I, A	m_vI, V	Total voltage, V
100	2.84	27.84
200	5.68	30.68
300	8.52	33.52
400	11.36	36.36
500	14.20	39.20

*m_v = 0.0284 V/A, C_v = 25 V

Table 4–4. Effect of wire diameter on C_v for various shielding gas/arc length combinations, using 15 mm contact tube to workpiece distance.

Shielding gas	Arc length, mm	Wire extension, mm	C_v, V			% variation relative to mean
			1.2 mm diameter	1.0 mm diameter	Mean	
Ar+5%CO_2	5	10	21.0	22.0	21.5	±2.3
Ar+5%CO_2	10	5	23.0	23.0	23.0	±0.0
Ar+20%CO_2	5	10	24.5	25.0	24.75	±1.0
Ar+20%CO_2	10	5	30.0	30.5	30.25	±.08

Table 4–5. Effect of wire extension on C_v for constant arc length using 1.2 mm diameter mild steel wire.

Contact tube to workpiece distance, mm	Arc length, mm	Wire extension, mm	C_v, V		% variation relative to mean
			specific	Mean	
$Ar+5\%CO_2$					
15	5	10	21.0		
20	5	15	21.0	21.2	±1.4
25	5	20	21.5		
$Ar+20\%CO_2$					
15	5	10	24.4		
20	5	15	25.5	25.0	±2.0
25	5	20	25.0		

Table 4–6. Effect of shielding gas on C_v for various wire diameter/arc length combinations, using 15 mm contact tube to workpiece distance.

Wire diameter, mm	Arc length, mm	Wire extension, mm	C_v, V			% variation relative to mean
			$Ar+5\%CO_2$	$Ar+20\%CO_2$	Mean	
1.2	5	10	21.0	24.5	22.75	± 8
1.2	10	5	23.0	30.0	26.50	±13
1.0	5	10	22.0	25.0	23.50	±6.4
1.0	10	5	23.0	30.5	26.75	±14

Table 4–7. Effect of arc length on C_v for various wire diameter/shielding gas combinations, using 15 mm contact tube to workpiece distance.

Wire diameter, mm	Shielding gas	Contact tube to workpiece distance, mm	C_v, V			% variation relative to mean
			5 mm arc length	10 mm arc length	Mean	
1.2	Ar+5%CO_2	15	21.0	23.0	22.0	± 5
1.2	Ar+20%CO_2	15	24.5	30.0	27.25	±10
1.0	Ar+5%CO_2	15	22.0	23.0	22.50	± 2.2
1.0	Ar+20%CO_2	15	25.0	30.5	27.75	±10

Table 4–8. Values of parametric constants m_v and C_v, for various wire material/wire diameter/shielding gas/arc length/contact tube to workpiece distance combinations relevant to short circuiting arc operation.

Shielding gas	Contact tube to workpiece distance, mm	Wire extension, mm	Arc length, mm	Parametric constants	
				m_v, V/A	C_v, V
1.2 mm diameter mild steel wire					
Ar+20%CO_2	12	12	—	0.026	14.4
CO_2	12	12	—	0.028	16.2
1.0 mm diameter mild steel wire					
Ar+20%CO_2	12	12	—	0.027	14.6
CO_2	12	12	—	0.032	16.4

4.3.1.2. *Short circuiting arc operation*

The generalised voltage–current relationship [4–8] is essentially similar to that for the steady DC open arc operation, equation [4–7b]. Therefore, in principle, the effects of the parameters on both m_v and C_v are similar to those described in Section 4.3.1. for the steady DC open arc operation.

a). Effect on the slope m_v

The relevant values of the slope m_v are given in Table 4–8 for parametric combinations comprising mild steel wire of 1.0 and 1.2 mm diameter, Ar+20%CO_2 and CO_2 shielding gas, for a fixed wire extension of 12 mm.

The average value of m_v is 0.0283 V/A and its variation is about ±13%. This causes variation in the total average voltage V_{av} of only about ±2.2% typically at 100 A, which is insignificant. Therefore, the slope m_v could be considered constant at 0.0283 V/A for all the combinations of the process parameters over the operating ranges.

b). Effect on the intercept C_v

It can be seen from the Table 4–8 that no adjustment would be required in the intercept C_v for a variable wire diameter, but the values of C_v must be adjusted for a change in the shielding gas.

4.3.2. Application of the generalised equations

The generalised parametric relationships described have formed a basis for developing synergic control systems which are described in Chapters 5 and 6.

CHAPTER 5
SYNERGIC CONTROL USING A TRANSISTOR CONTROLLED POWER SOURCE

5.1. APPROACH

The generalised parametric relationships described in the previous chapter have been used to derive synergic control equations. To accomplish synergic control in practice, hard-wired electronic control units were designed and constructed to drive a transistor controlled power source. Finally, the performance of these systems was tested comprehensively for bead-on-plate runs and welds with any type of wire feed speed whether maintained constant, varied gradually or modulated with a square or triangular waveform.

5.2. DEVELOPMENT OF SYNERGIC CONTROL EQUATIONS

5.2.1. Steady DC open arc operation

Steady DC open arc operation has been characterised entirely by the generalised burnoff and voltage-current relationships [4-7a] and [4-7b]. Based on these relationships, an equation was derived relating arc power and current as variables. Because the equation is quadratic in current, it will be identified as the quadratic power-current equation. In addition, another equation relating arc power and current was obtained as an approximation of the quadratic equation. The equation is linear; therefore it will be called the linear power-current equation. Both these equations were used to accomplish synergic control, whereby stable arc operation could be achieved automatically for any wire feed speed. Furthermore, the basic voltage-current relationship was also used to accomplish the synergic operation. This equation will be identified as the linear voltage-current equation.

5.2.1.1. *Quadratic power-current equation*

For stable arc operation with a given wire feed speed and arc length, the current is specified by the burnoff relationship and, corresponding to the required current, the voltage is specified by the voltage–current relationship. This means that the arc power is specified, which is the product of the required current and voltage. Therefore, over the operating wire feed speed range, the corresponding power range can be obtained by multiplying the basic relationships [4–7a] and [4–7b]. Thus, the derived equation is:

$$P = m_v I^2 + C_v I \qquad [5-1]$$

Where

P is the arc power, W;

m_v is the slope of the voltage–current relationship, V/A;

C_v is the intercept of the voltage–current relationship, V.

This is the required synergic quadratic power–current equation. It has I as independent input variable, and P as output variable which must be maintained by the arc for stable operation. The equation is specified by the parametric constants m_v and C_v for any required wire material/diameter/shielding gas combination, at a given arc length and wire extension. These constants must be predetermined to evaluate the equation.

Selection of parametric constants

The parametric constants m_v and C_v included in the control equation [5–1] are specified by the wire material/diameter/shielding gas combination to be operated at a given arc length and wire extension. The values of both the constants, determined experimentally for various combinations, at a constant contact tube to workpiece distance of 15 mm, using 5 and 10 mm arc lengths, are given in Table 4–1. In addition, those for variable contact tube to workpiece distance of 15 to 25 mm, using a constant arc length of 5 mm, are given in Table 4–2.

5.2.1.2. *Linear power–current equation*

This equation is an approximation of the quadratic power–current equation [5–1] which, for example, is plotted (solid line) in Fig. 5–1 for the mild steel/1.2 mm

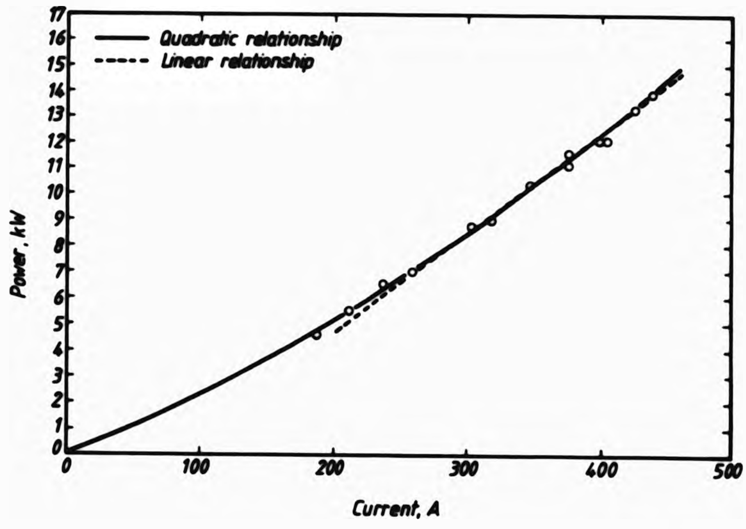


Fig. 5–1. Quadratic and linear power–current relationships for 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas, at fixed 5 mm visible arc length and 10 mm wire extension.

diameter/$Ar+5\%CO_2$ combination, operating at 5 mm arc length and 10 mm wire extension. The operating current range in practice is only from 240 A upwards, because the relevant metal transfer is the desired spray type; whereas, the lower current range is unusable for welding because the associated metal transfer is the undesired globular type. Over the operating current range, from 240 A upwards, the power–current relationship when represented by a straight line (dotted line in Fig. 5–1), introduces a maximum error in power of less than ±3%, which is not significant. Therefore the power–current relationship [5–1], over the operating range, can be approximated by the linear equation:

$$P = m_a I - C_a \qquad [5\text{–}2]$$

Where

- P is the arc power, W;
- I is the current, A;
- m_a is the slope of the straight line, V;
- C_a is the intercept, W.

Expression [5–2] is the required linear power–current equation for the synergic operation. It has I as independent input variable, and P as output variable which must be maintained by the arc for stable operation. The equation is specified by the parametric constants m_a and C_a for any required wire material/diameter/shielding gas combination, at a required arc length and wire extension. These constants must be predetermined to evaluate the equation. (It is noted that, while the variables I and P are the same for both the control relationships [5–1] and [5–2], the parametric constants m_a and C_a are specific only to equation [5–2].)

The parametric constants m_a and C_a, for any specified wire material, diameter, shielding gas, arc length and wire extension, can be determined directly from the points coordinating power and current, obtained from equation [5–1].

5.2.1.3. *Linear voltage–current equation*

The generalised voltage–current equation [4–7b], which is:

$$V = m_v I + C_v$$

is the required relationship providing another option to accomplish the synergic operation. It has I as independent input variable and V as the output variable which must be maintained by the arc for stable operation. The equation is specified by parametric constants m_v and C_v, which are the same as those included in the quadratic equation, relevant to any given wire material/diameter/shielding gas combination, at a specified arc length and wire extension. The values of the constants for various combinations are given in Table 4–1 for a constant contact tube to workpiece distance of 15 mm, and in Table 4–2 for a variable contact tube to workpiece distance from 15 to 25 mm.

5.2.2. Short circuiting arc operation

The equation used to accomplish synergic control was the generalised voltage–current relationship [4–8], which is:

$$V_{av} = m_v I_{av} + C_v$$

This equation in principle is similar to the linear voltage–current relationship [4–7b] used for steady DC open arc operation, except that the variables I_{av} and V_{av} used in the above equation represent the average current and voltage. Furthermore, the parametric constants m_v and C_v specifying the equation, relevant to a given wire material/diameter/shielding gas combination, are specified by the voltage–current relationship for the short circuiting arc operation. Empirically derived values for m_v and C_v are shown in Table 4–8.

5.3. DEVELOPMENT OF CONTROL UNITS

To accomplish the synergic control in practice, a hard–wired electronic control unit was designed and constructed specifically for each control equation. The control unit for the quadratic or linear power–current equation, used a current signal which was obtained from a static transducer (a shunt) connected in the arc circuit as input, and computed the corresponding power (equation [5–1] or [5–2]) to provide the 'reference' signal. In addition, a 'feedback' power signal was computed from the current signal together with another input measuring the arc voltage. The feedback was subtracted from the reference to obtain an 'error' signal as output of the control unit. This signal was used to drive the power source, either in constant current or in constant voltage mode, adjusting the power required for stable arc operation.

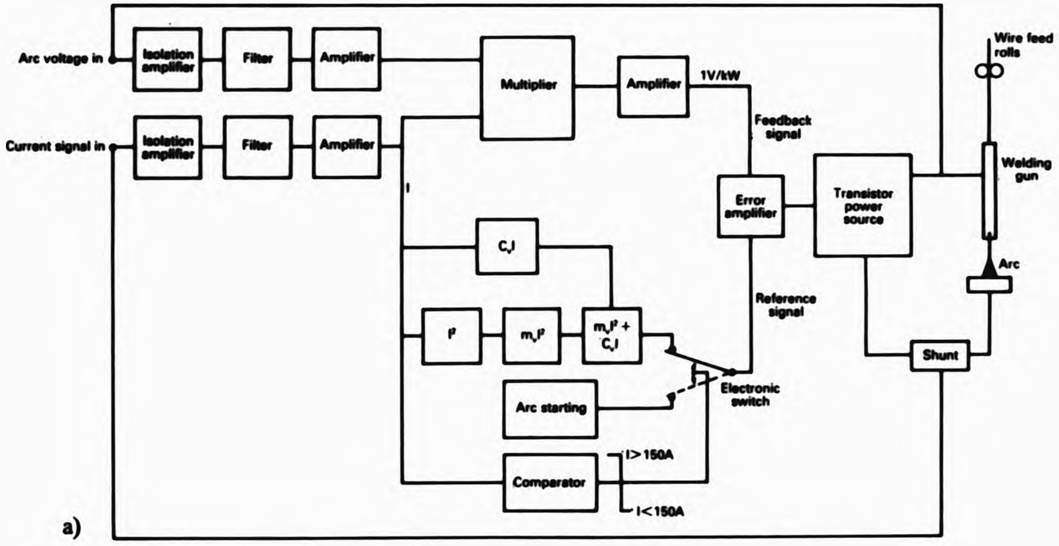
The control unit designed to execute the linear voltage–current equation used the current signal as input and computed the required voltage. This voltage comprised the output signal of the control unit, which was used to drive the power source in the constant voltage mode, adjusting the voltage required for the stable arc operation. This unit could be used for both the steady DC arc and the short circuiting arc operations.

The circuit details for each control unit are described below.

5.3.1. Control unit for quadratic power–current equation

The circuit arrangement of the control unit is shown as a block diagram in Fig. 5–2a and as a functional diagram in Fig. 5–2b. Both the input channels, Fig. 5–2a, one dedicated to the current input and the other dedicated to the arc voltage input, were essentially similar in construction and in the signal processing operations. Each channel comprised an isolation amplifier, a filtering circuit and a rescaling and buffer amplifier. The isolation amplifier isolated the control circuit from the welding equipment (welding rig or power source) to safeguard the circuit from any earthing problem. In addition, the amplifier provided the necessary gain such that 0–1000 A current, or 0–100 V arc voltage, was scaled to 0–10 V, to match the range of the following electronic device. The scaled signal was applied to the filtering circuit to eliminate or reduce the undesired electrical noise which would otherwise have degraded the useful information. Any voltage loss in the filter was compensated by the following amplifier.

The processed voltage and current signals from both channels were supplied to



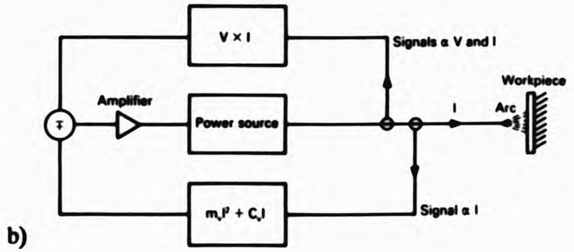


Fig. 5–2. Circuit arrangement of the control unit based on the quadratic power–current relationship:
a) block diagram, b) functional diagram.

a multiplier which computed the actual operating power, constituting the feedback signal.

To obtain the reference signal corresponding to the required power as determined by the control equation, the circuit comprised a multiplier connected in series with an operational amplifier, to compute the term $m_v I^2$. (The parametric constant m_v could be adjusted as required by means of a potentiometer.) These elements were connected in parallel with another amplifier computing the term $C_v I$, where C_v could be adjusted as required by means of a potentiometer. Both of these terms were added by a further amplifier which provided an output constituting the reference signal.

The reference and feedback signals were then connected to an 'error' amplifier, which subtracted them. The error signal was amplified by the following amplifier, which had a gain adjusted for optimum response, and provided the output signal driving the power source.

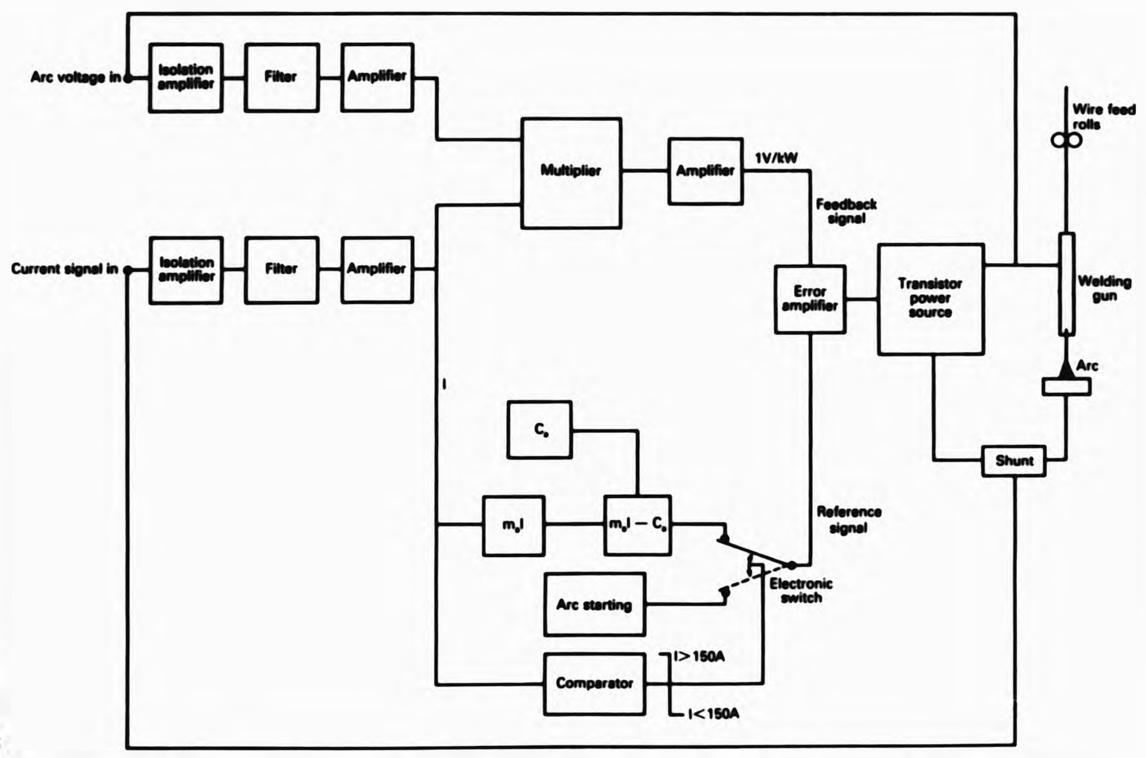
To accomplish the arc initiation automatically, a reference signal would be required even with the operating current at zero. This reference was provided by an 'arc starting' circuit connected in parallel with that computing the control equation. If the arc current was less than, say 150 A, which was taken as the threshold for steady DC open arc operation giving spray metal transfer, then a comparator operated the electronic switch to connect the arc starting circuit until the arc initiated. The switch then isolated this circuit and connected the circuit computing the control equation for stable arc operation.

5.3.2. Control unit for linear power–current equation

The circuit arrangement of the control unit is shown as a block diagram in Fig. 5–3a and as a functional diagram in Fig. 5–3b. The circuit is similar in construction and operation to that shown in Fig. 5–2, except that the reference signal was computed by a simpler circuit comprising two operational amplifiers. To avoid repetition, both the circuits were constructed together, shown photographically in Fig. 5–3c.

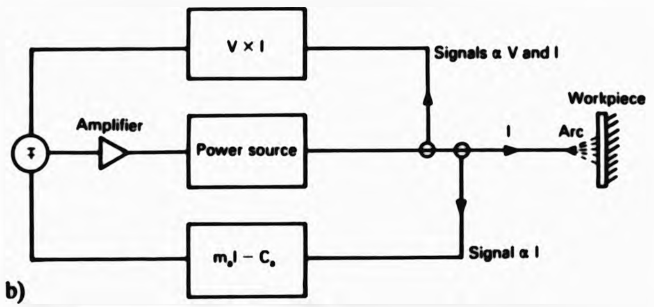
5.3.3. Control unit for linear voltage–current equation

The block diagram, functional diagram and photograph of the electronic control



a)

Fig. 5-3. Circuit arrangement of the control unit based on the linear power-current relationship:
a) block diagram.



b)

c)

Fig. 5–3. contd. Circuit arrangement of the control unit based on the linear power–current relationship:
b) functional diagram, c) photograph.

circuit executing the voltage–current relationship are given in Fig. 5–4. The circuit comprised an isolation amplifier, a filtering circuit and two operational amplifiers, all connected in series. The isolation amplifier isolated the control circuit from the welding equipment (welding rig or power source) to protect the circuit from any earthing problem. Furthermore, the amplifier scaled the input current signal such that 0–1000 A corresponded to 0–10 V. The scaled signal was applied to the filter to reduce the undesired electrical noise which would otherwise have degraded the useful information. The following operational amplifiers together, where the parametric constants m_v and C_v could be adjusted as required by means of the potentiometers, computed the voltage relevant to the control equation. This provided the output signal which was used as a reference to drive the power source set in the constant voltage mode, to provide the voltage required for the stable arc operation.

5.4. CONTROL PERFORMANCE

5.4.1. Steady DC open arc operation

Using each of the three control units, the control performance was tested for bead–on–plate test runs with the wire feed speed maintained constant at different levels over the operating range, and modulated automatically with square or triangular waveforms. The wire used was 1.2 mm diameter mild steel in Ar+5%CO_2 shielding gas.

5.4.1.1. *Control units based on the power–current equations*

The control performance of the control unit based on the quadratic power–current relationship was practically identical to that based on the linear relationship. Although the performance of each control unit was tested with the power source set in the constant voltage mode, the majority of the tests were conducted with the power source set in the constant current mode. As this mode does not provide self–adjustment due to the power supply, any error in the control performance would be identified readily.

a). Arc initiation

For any wire feed speed, the control unit initiated the arc readily (in about 60 msec)

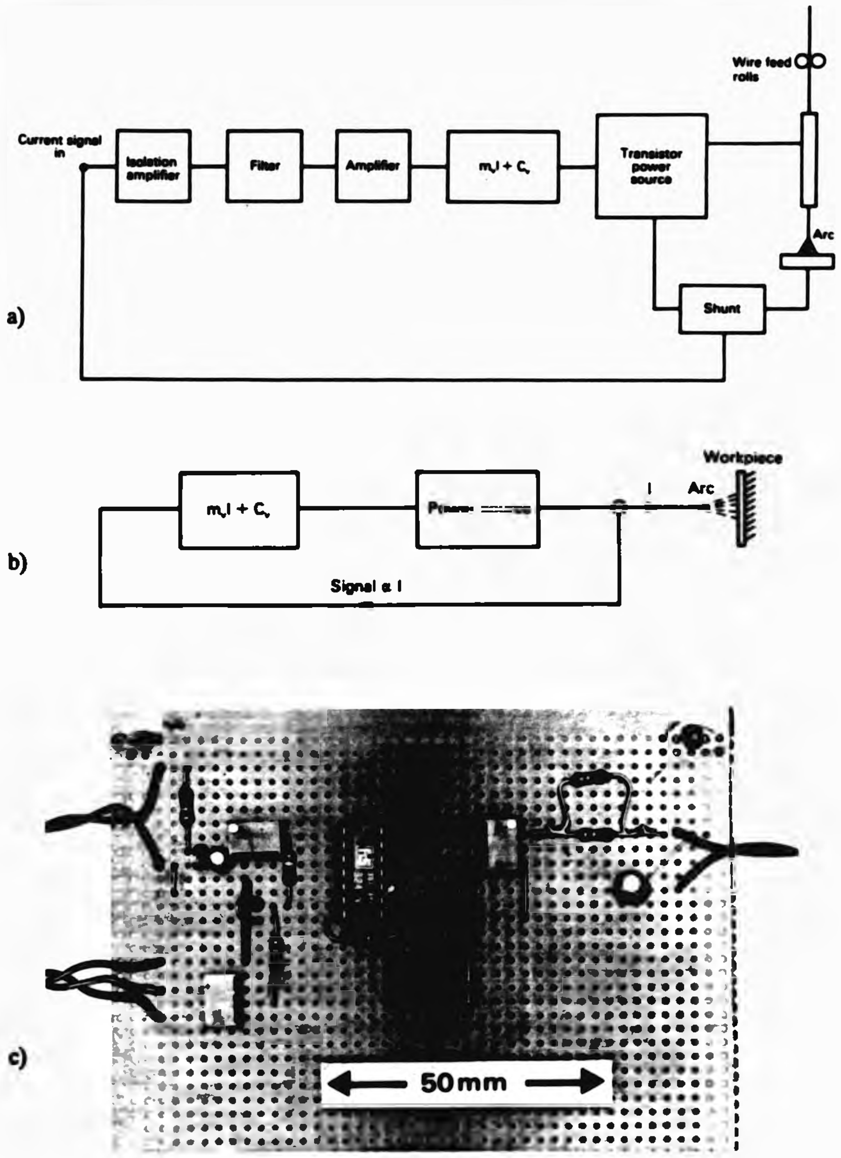


Fig. 5-4. Circuit arrangement of the control unit based on the linear voltage-current relationship:
a) block diagram, b) functional diagram, c) photograph.

by a high current which was supplied while the wire electrode touched the workpiece. As the arc initiated, the current was rapidly (in about 250 msec) stabilised at the level consistent with the operating wire feed speed. The typical arc starting behaviour is shown in Fig. 5–5.

b). Constant wire feed speed

For any set wire feed speed over the operating range, a steady current was supplied automatically at the level relevant to the feed speed and given arc length, such that a stable arc and spray type metal transfer were maintained throughout the test run. The consistency of the operating current and the stability of the arc can be seen from a typical oscillogram shown in Fig. 5–6.

The stability of the arc operation, which the control unit provided, resulted in very regular and spatter-free bead deposits. Typical bead-on-plate deposits using 9.5 and 12.5 m/min feed speeds are shown in Fig. 5–7.

c). Variable wire feed speed

The capability of the control system to respond to a varying wire feed speed was tested with weld runs which were started at the relatively low wire feed speed of 8.5 m/min, this then being increased gradually to about 14 m/min (while the workpiece was traversed at a constant speed of 0.5 m/min).

As soon as the wire feed speed was changed during welding, the control unit supplied the appropriate reference to the power source according to the wire feed speed, so that the arc length was maintained constant during the test. The stability of the current and voltage throughout a test run is shown in Fig. 5–8, and regularity of the weld deposit is shown in Fig. 5–9.

d). Modulated wire feed speed

Modulated wire feed speed, or thermal pulsing, is a technique whereby the arc current is modulated in response to the wire feed speed modulation between a low and high level. The control system was found to be capable of maintaining stable arc operation with the wire feed speed modulated between any two levels within the operating range 6–15 m/min, because the control system could adjust the current rapidly, not

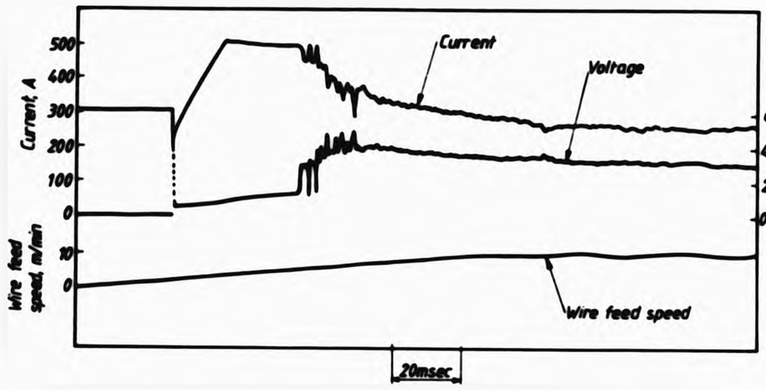


Fig. 5–5. Typical arc starting behaviour with the control unit based on the power–current relationships, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas.

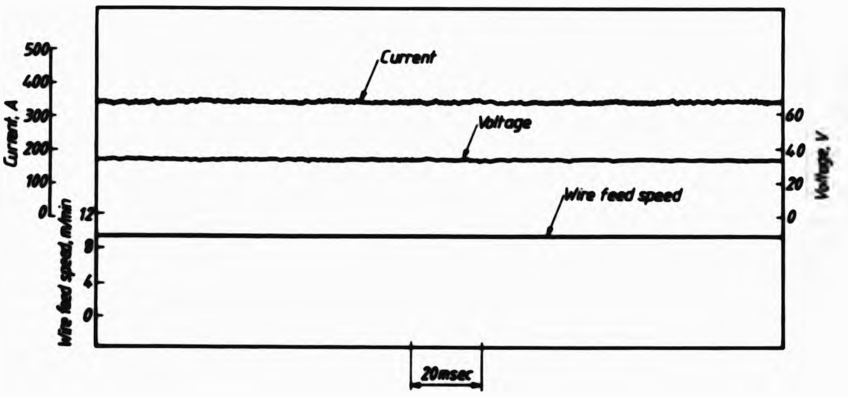
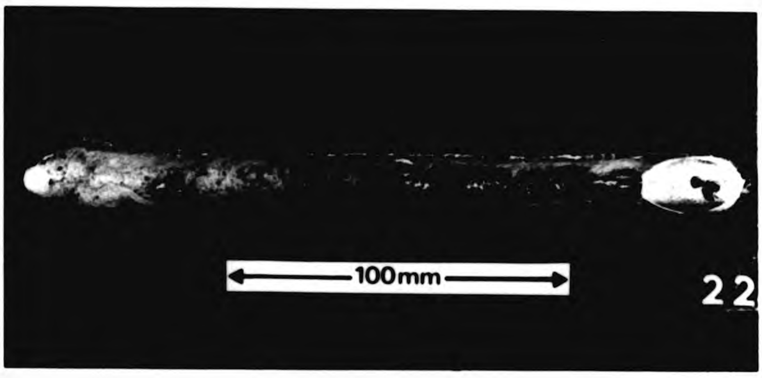


Fig. 5–6. Oscillograms of current, voltage, and wire feed speed, showing consistency of current and stability of the arc for a constant wire feed speed, provided by the control unit based on the power–current relationship, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas.

a)



b)

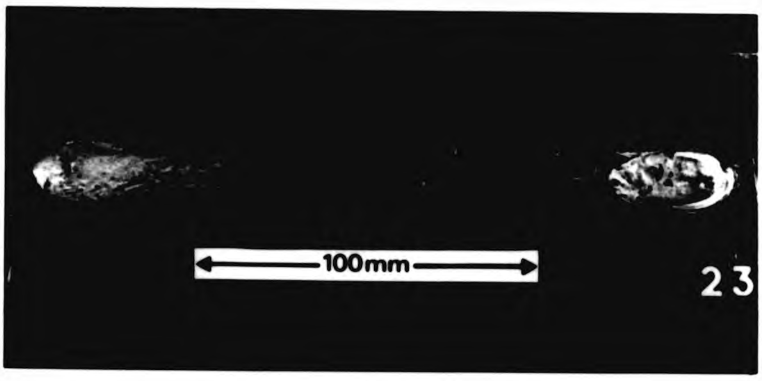


Fig. 5–7. Typical bead–on–plate deposits, with the control unit based on power–current relationship, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas, with the wire feed speed being maintained constant:
a) 9.5 m/min, b) 12.5 m/min.

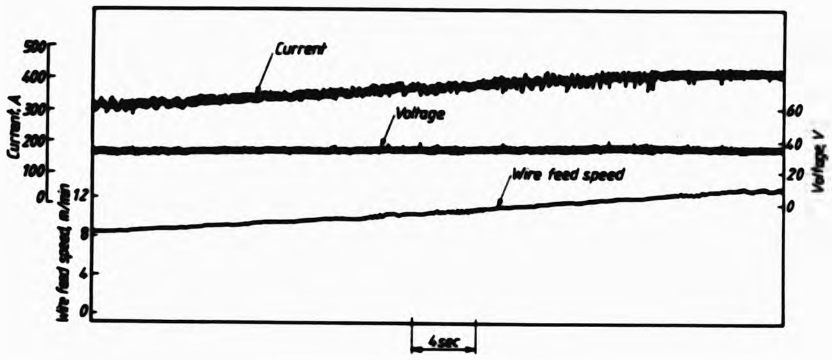


Fig. 5-8. Oscillograms of current, voltage and wire feed speed, showing stability of the arc with the wire feed speed being varied gradually from 8.5 to 14 m/min, for the control unit based on the power-current relationship, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas.

Fig. 5-9. Bead deposit with the wire feed speed being varied gradually from 8.5 to 14 m/min, while maintaining the traverse speed constant at 0.5 m/min, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas.

only compatible with the low and high levels of feed speed, but also with the transitions between the levels. Even when the difference between the low and high speeds was large, 8–14 m/min, the arc length changed by only about 2 mm during a modulation period, while the overall arc stability remained unaffected. Typical examples of the current and voltage response to the modulating wire feed speed, together with the bead deposits, are shown in Fig. 5–10 for the square wave modulation, and in Fig. 5–11 for the triangular wave modulation.

e). *Effect of wire extension*

To test how the control system would respond to a gradually varying wire extension, weld runs were made on a wedge-shaped workpiece, Fig. 5–12a. In addition, the control response to a sudden increase in the wire extension was tested on a workpiece which had its thickness reduced in three steps, from 48 to 29 mm, each step being 6.4 mm, Fig. 5–12b.

For a constant as well as modulated wire feed speed, the arc operation was found to be stable, such that the arc length remained constant (at about 6 mm) while the wire extension increased from about 14 to 34 mm, without any adjustment being made on the control unit which modified the current automatically as the distance between the welding head and workpiece increased from 20 to 40 mm, either gradually or in steps. Over the entire length of weld runs, the current and voltage adjustment by the control unit for a constant and modulated wire feed speed, can be seen from Fig. 5–13 for the gradually varying wire extension. The regularity of the bead deposits for the constant and modulated wire feed speed is shown in Fig. 5–12a for the gradually varying wire extension, and in Fig. 5–12b for the wire extension increasing in steps.

f). *Effect of wire diameter*

For operation with 1.0 mm diameter wire, the settings of the parametric constants on the control unit were practically the same as for 1.2 mm diameter. That is, no adjustment of the parametric constants was required on the control unit because, for a given power (i.e. current and voltage), the amount of metal transferred per unit time was approximately the same for both the diameters (although the wire feed speeds

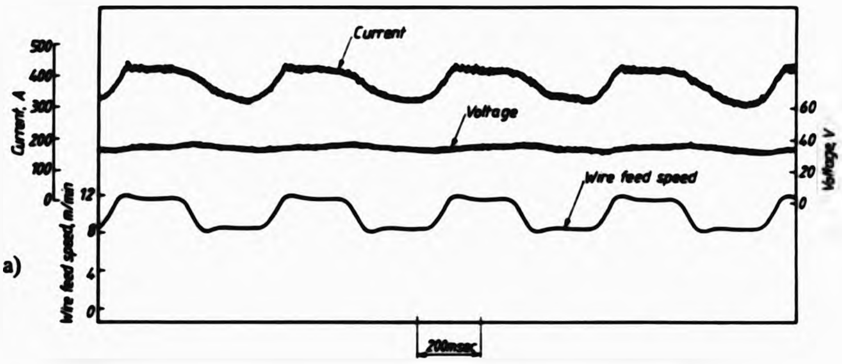


Fig. 5-10. Current and voltage response and regularity of the bead deposit, for the wire feed speed being modulated with square wave from 8.5 to 12.5 m/min at 2 Hz, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas:
a) oscillogram of current, voltage and wire feed speed,
b) bead deposit.

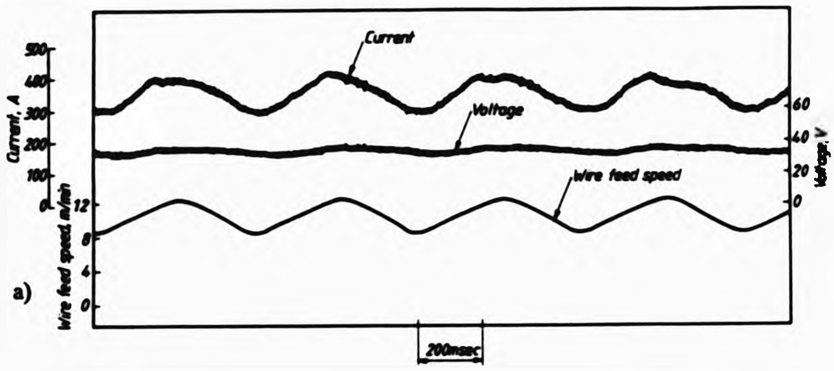
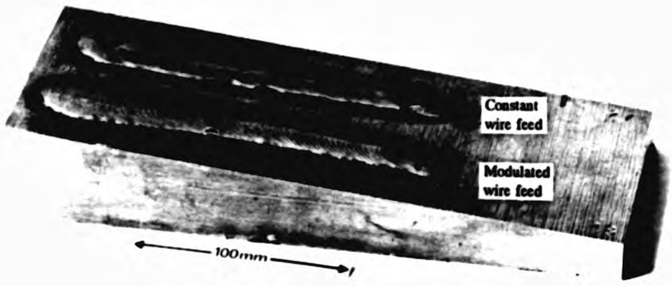


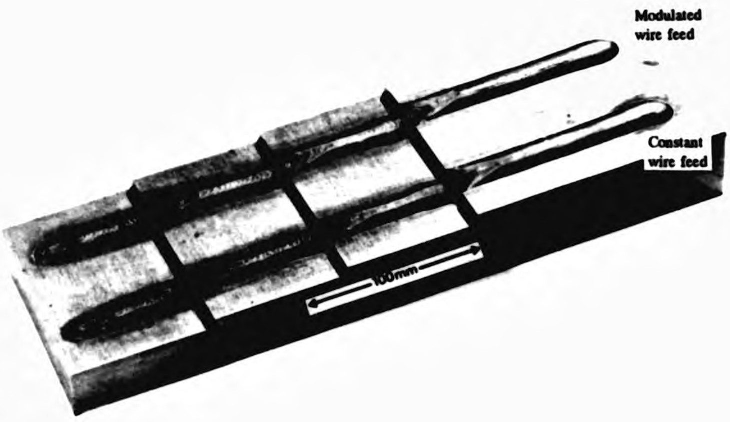
Fig. 5–11. Current and voltage response and regularity of the bead deposit, for the wire feed speed being modulated with triangular wave from 8.5 to 12.5 m/min at 2 Hz, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas:

a) oscillogram of current, voltage and wire feed speed,

b) bead deposit.



a)



b)

Fig. 5–12. Regularity of bead deposits for the wire feed speed maintained constant at 11.2 m/min and modulated from 8.5 to 12.5 m/min at 2 Hz, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas, for different types of wire extension:
a) gradual, **b)** in steps.

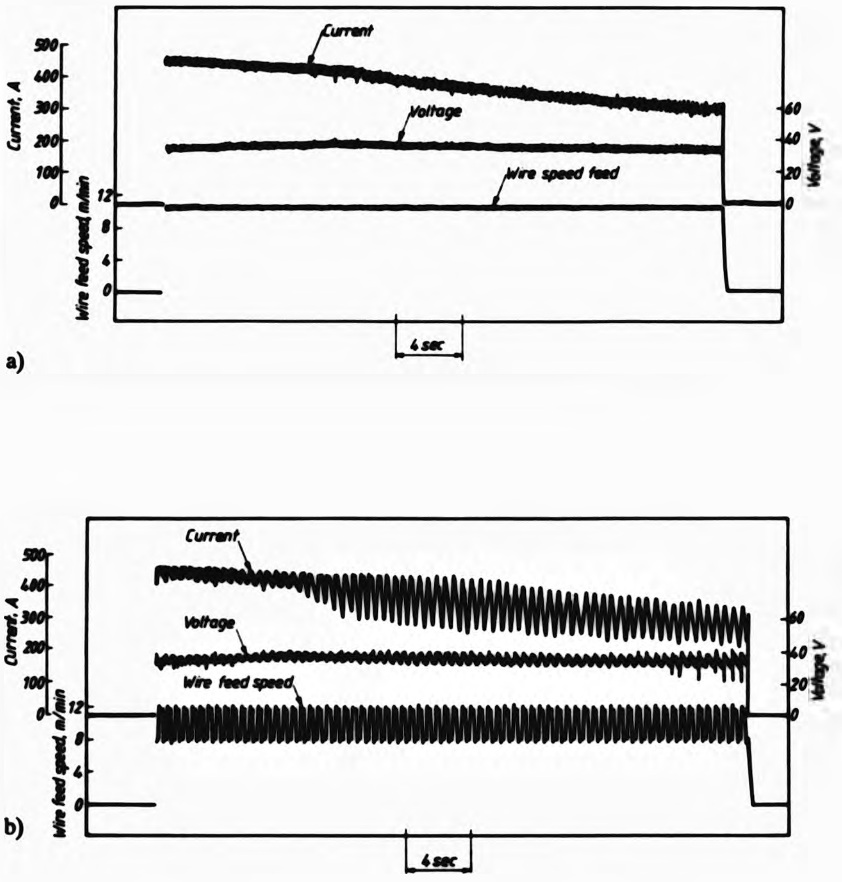


Fig. 5-13. Current and voltage adjustment by the control unit for the gradually varying wire extension from about 14 to 34 mm, using 1.2 mm diameter mild steel wire in $Ar+5\%CO_2$, for different types of wire feed speed:

a) constant at 11.2 m/min,

b) being modulated from 8.5 to 12.5 m/min at 2 Hz.

were different).

The control unit was found to adjust arc current and voltage automatically giving stable arc operation for any wire feed speed over the operating range. The stable operation resulted in regular bead deposits, which are shown in Fig. 5–14 for the wire feed speed maintained constant at 9.8 m/min, then varied gradually from 8.5 to 15 m/min, and modulated with square wave from 8.5 to 12.5 m/min at 2 Hz.

g). Power source set in constant voltage mode

The performance of the control unit in providing stable arc operation with any constant or variable wire feed speed with the power source set in the constant voltage mode was practically no different from that with the power source set in the constant current mode. Typical oscillograms showing current and voltage adjustment for stable arc operation with the wire feed speed maintained constant at 11.2 m/min and with that being modulated from 8.5 to 12.5 m/min at 2 Hz, are given in Fig. 5–15.

5.4.1.2. *Control unit based on the voltage–current equation*

As soon as the parametric constants m_v and C_v, relevant to a given wire material/diameter/shielding gas combination, were set by means of two potentiometers provided on the control unit, the control system was ready for the welding operation. For a given combination at any wire feed speed, the control unit initiated the arc readily, and then maintained the arc voltage compatible with the operating wire feed speed, such that a stable arc and spray type metal transfer were maintained throughout the weld runs. Typical oscillograms, showing consistency of the operating current and voltage for the wire feed speed being maintained constant, varied gradually and modulated with square wave, are given in Fig. 5–16. The stable arc operation which the control unit provided resulted in regular bead deposits. For the three types of wire feed speed, the typical bead deposits are shown in Fig. 5–17 for 1.2 mm diameter wire and in Fig. 5–18 for 1.0 mm diameter wire.

5.4.2. Short circuiting arc operation

The control unit based on the voltage–current relationship, used for steady DC open arc operation, was also capable of controlling short circuiting arc operation when

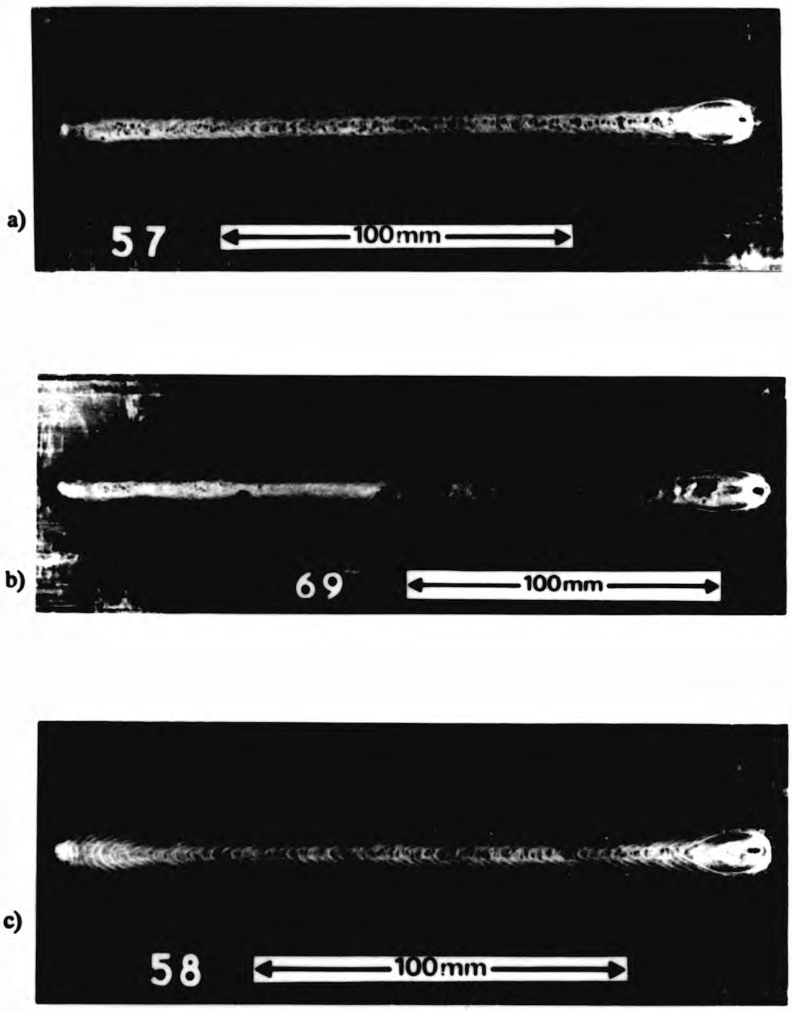
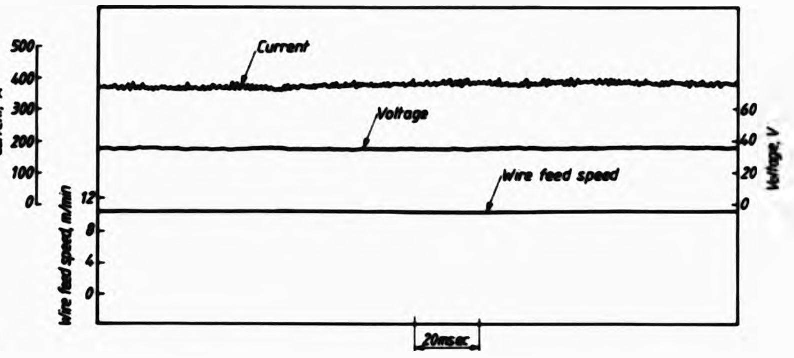
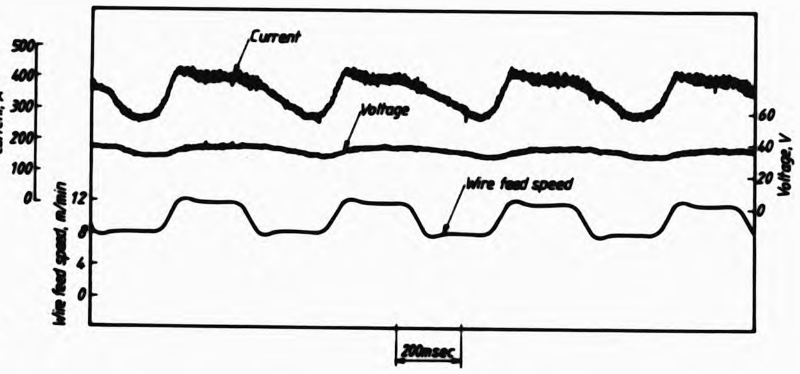


Fig. 5–14. Bead deposits showing stability of arc operation with 1.0 mm diameter mild steel wire in Ar+5%CO_2 for different types of wire feed speed:

a) constant at 9.8 m/min,
b) varied gradually from 8.5 to 15 m/min,
c) modulated with square wave from 8.5 to 12.5 m/min at 2 Hz.



a)



b)

Fig. 5-15. Oscillograms showing adjustment of current and voltage, with the power source set in constant voltage mode, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas, for different types of wire feed speeds:

a) constant at 11.2 m/min,

b) modulated with square wave from 8.5 to 12.5 m/min at 2 Hz.

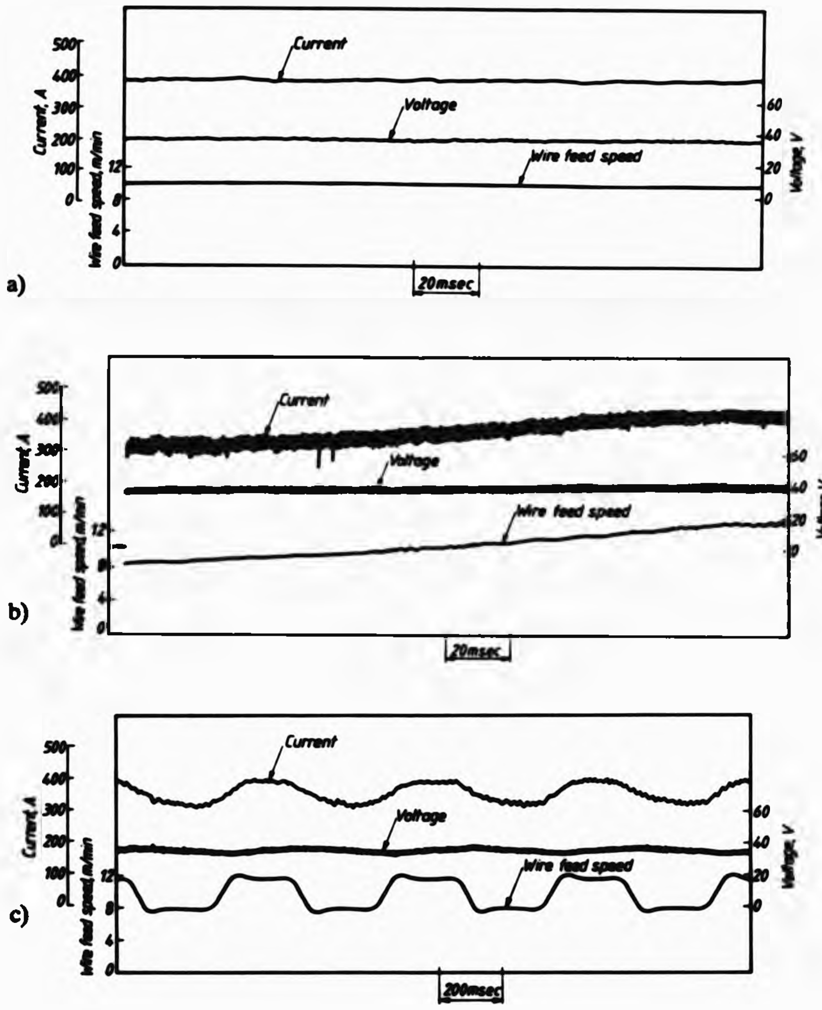


Fig. 5–16. Typical oscillograms showing consistency of the operating current and voltage, using 1.2 mm diameter mild steel wire in Ar+5%CO_2 shielding gas, for different types of wire feed speed:
a) constant at 10.5 m/min, b) varied gradually from 8.5 to 14 m/min,
c) modulated with square wave from 8.5 to 12.5 m/min at 2 Hz.

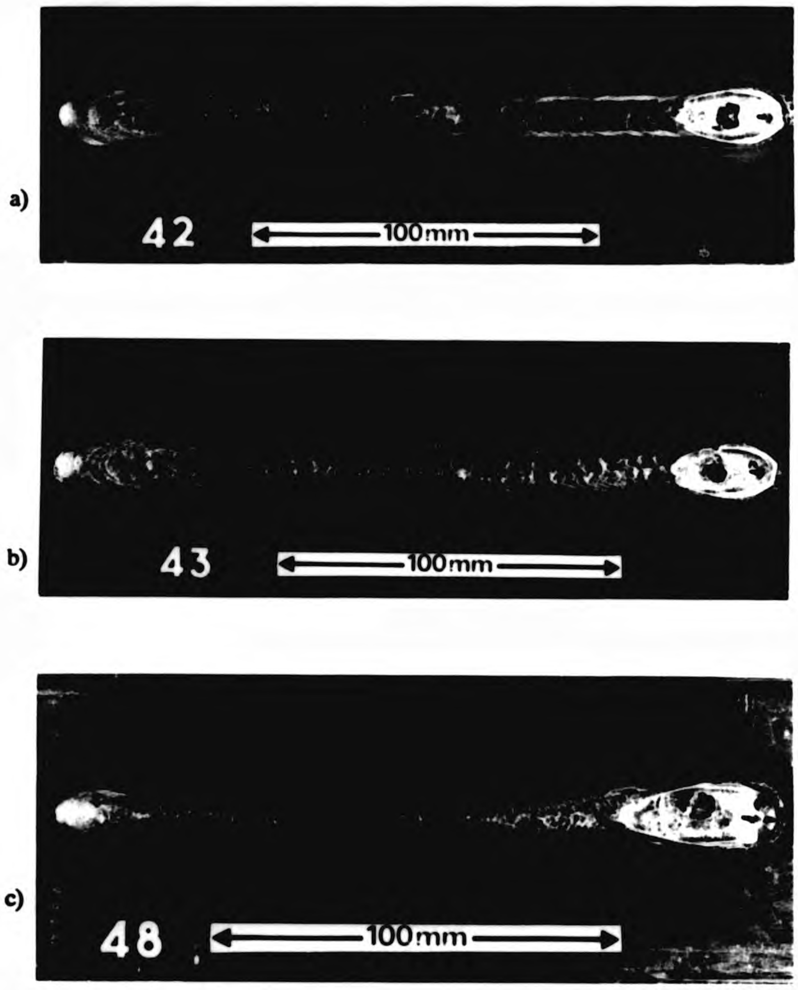


Fig. 5–17. Typical bead deposits showing stability of arc operation, using 1.2 mm diameter mild steel wire in Ar+5% CO_2 shielding gas, for different types of wire feed speed:
a) constant at 10.5 m/min,
b) modulated with square wave from 8.5 to 12.5 m/min at 2 Hz,
c) varied gradually from 8.5 to 14 m/min.

a)
b)
c)

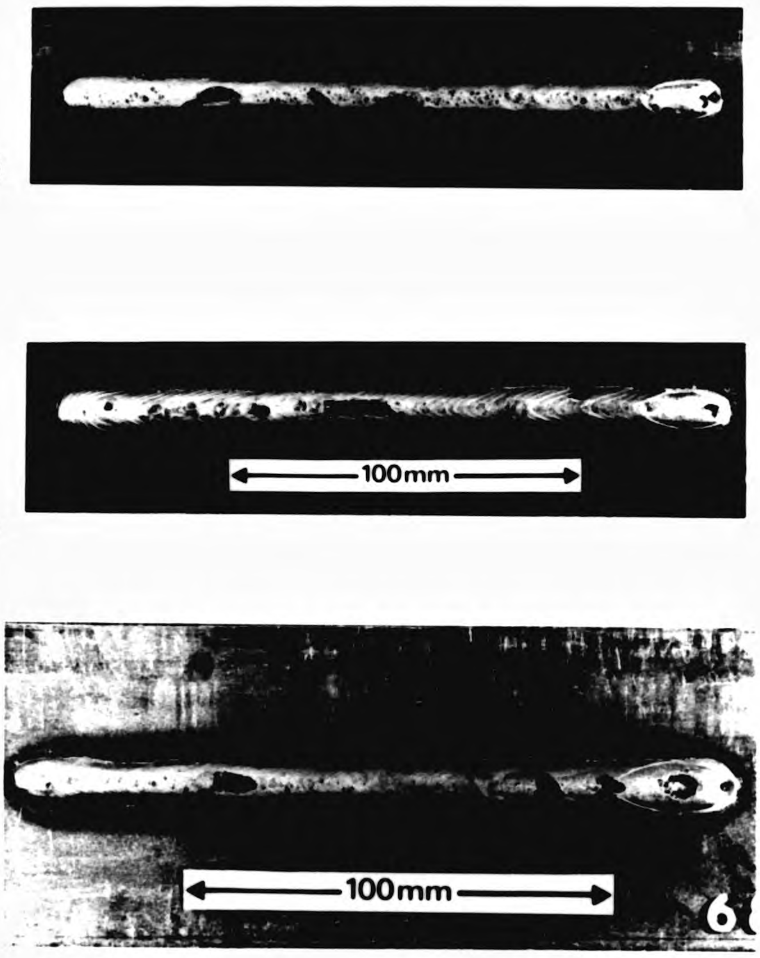


Fig. 5-18. Typical bead deposits showing stability of arc operation, using 1.0 mm diameter mild steel wire in Ar+5% CO_2 shielding gas, for different types of wire feed speed:

a) constant at 10.5 m/min,
b) modulated with square wave from 8.5 to 12.5 m/min at 2 Hz,
c) varied gradually from 7.7 to 14 m/min.

programmed with the relevant parametric constants. For stable short circuiting arc operation, it is essential to control the dynamic behaviour of the arc current. This was achieved by adjusting the output characteristic of the power source at 4 V/100 A, together with the introduction of a suitable inductance by means of a control knob on the power source.

The performance of the control system (control unit and the transistor power source) was tested for four wire material/diameter/shielding gas combinations, comprising 1.0 and 1.2 mm diameter mild steel wires and Ar+20%CO_2 and CO_2 shielding gases for each diameter. For each combination, the control unit was found to maintain a stable arc automatically for any wire feed speed, whether held constant, varied gradually or modulated between two levels over the operating range. Typical oscillograms of current and voltage for the three types of wire feed speed are shown in Fig. 5-19. Furthermore, the stable arc operation which the control unit provided, resulted in bead deposits which were regular, possessed good characteristics and produced practically no spatter. Typical bead deposits with the wire feed speed maintained constant, modulated and varied gradually are shown in Fig. 5-20 for 1.0 mm diameter/Ar+20% CO_2, in Fig. 5-21 for 1.0 mm diameter/CO_2, in Fig. 5-22 for 1.2 mm diameter/Ar+20%CO_2, and in Fig. 5-23 for 1.2 mm diameter/CO_2 combination.

5.5. WELDING PERFORMANCE

The welding performance was evaluated for the steady DC arc operation, using the control unit based on the power-current relationship. The performance was tested mainly for butt joint applications, using 1.2 mm diameter mild steel wire, modulated (square wave) wire feed speed, and Ar+5%CO_2, Ar+20%CO_2 and Ar+15%CO_2 shielding gases. For each gas, a series of joints were welded which comprised 25 and 12.5 mm thick mild steel plates, with 'V' preparation, having 30° included angle, and without root face. Some joints had a square preparation. The details of all the joints and the welding conditions used are given in Table 5-1.

a)

b)

c)

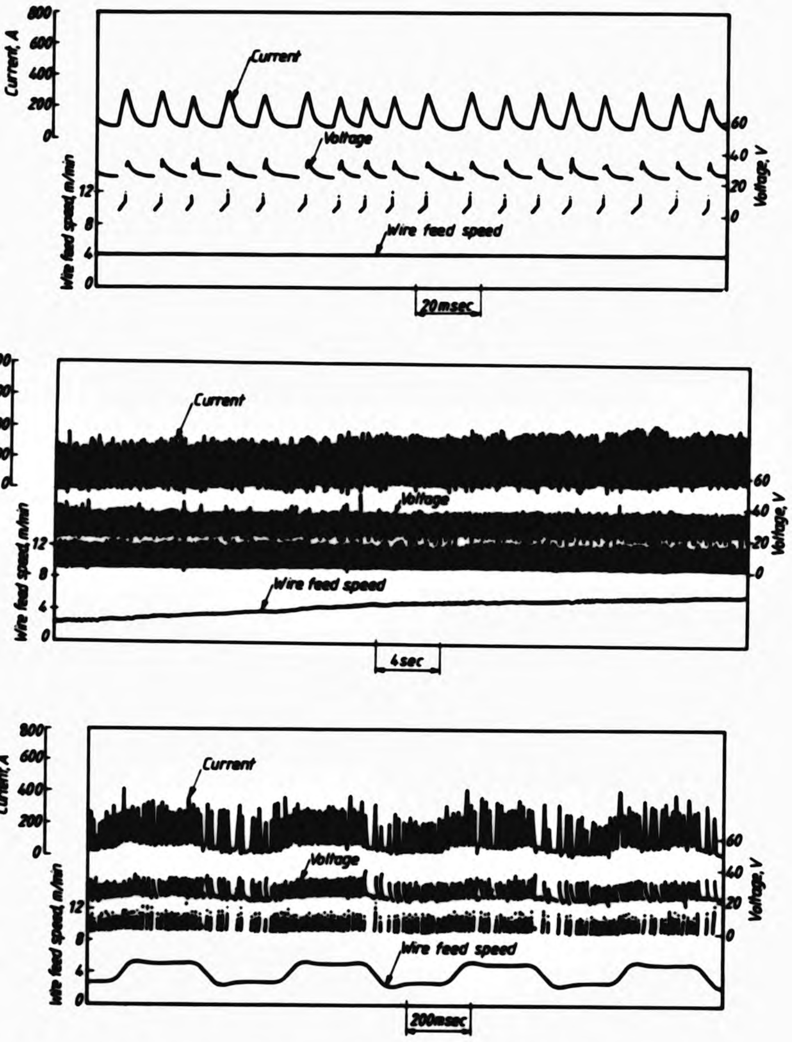
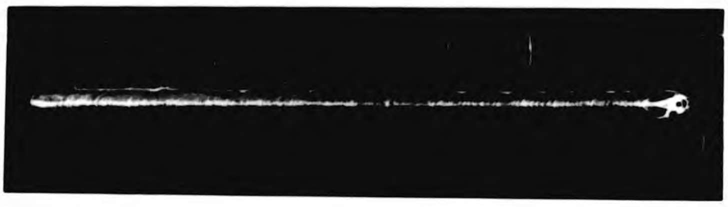


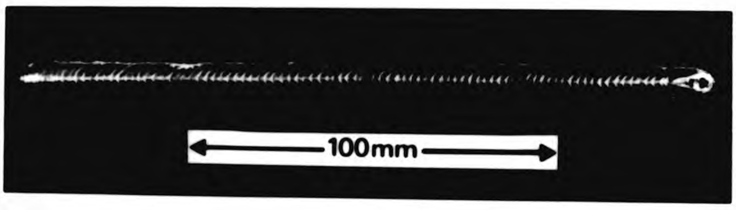
Fig. 5–19. Typical oscillograms of current and voltage showing stable arc operation, using 1.0 mm diameter mild steel wire in CO_2 shielding gas, for different types of wire feed speed:

a) constant at 4.2 m/min,
b) varied gradually from 2 to 6.7 m/min,
c) modulated with square wave from 2.8 to 5.6 m/min at 2 Hz.

a)



b)



c)

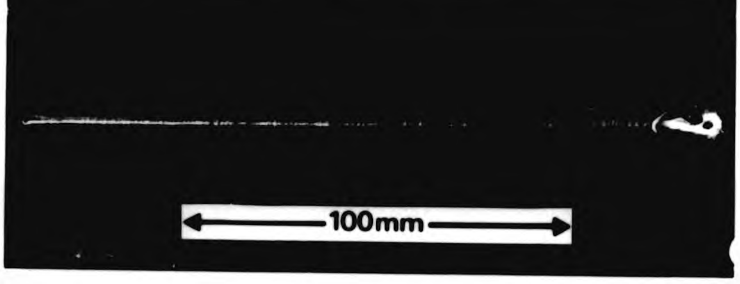
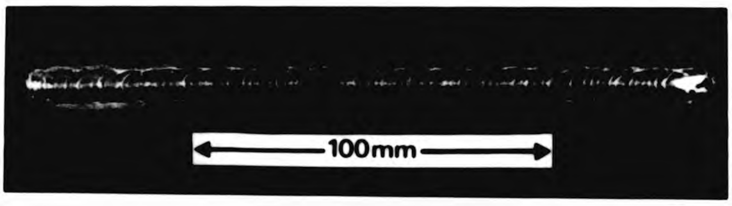


Fig. 5–20. Typical bead deposits for 1.0 mm diameter mild steel wire in Ar+20%CO_2 shielding gas, using different types of wire feed speed:
a) constant at 4.2 m/min,
b) modulated with square wave from 2.8 to 5.6 m/min at 2 Hz,
c) varied gradually from 2 to 6.7 m/min.

a)

b)



c)

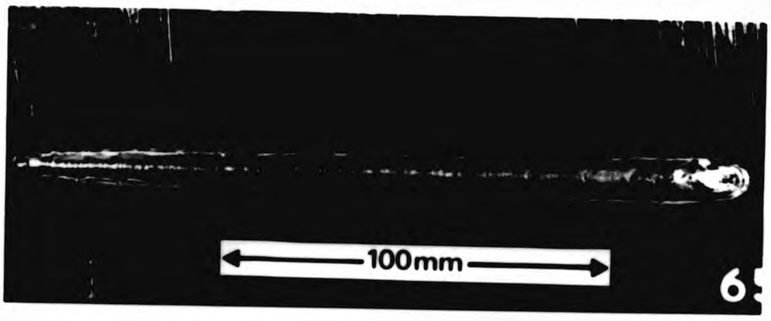


Fig. 5–21. Typical bead deposits for 1.0 mm diameter mild steel wire in CO_2 shielding gas, using different types of wire feed speed:

a) constant at 4.2 m/min,

b) modulated with square wave from 2.8 to 5.6 m/min at 2 Hz,

c) varied gradually from 2 to 6.7 m/min.

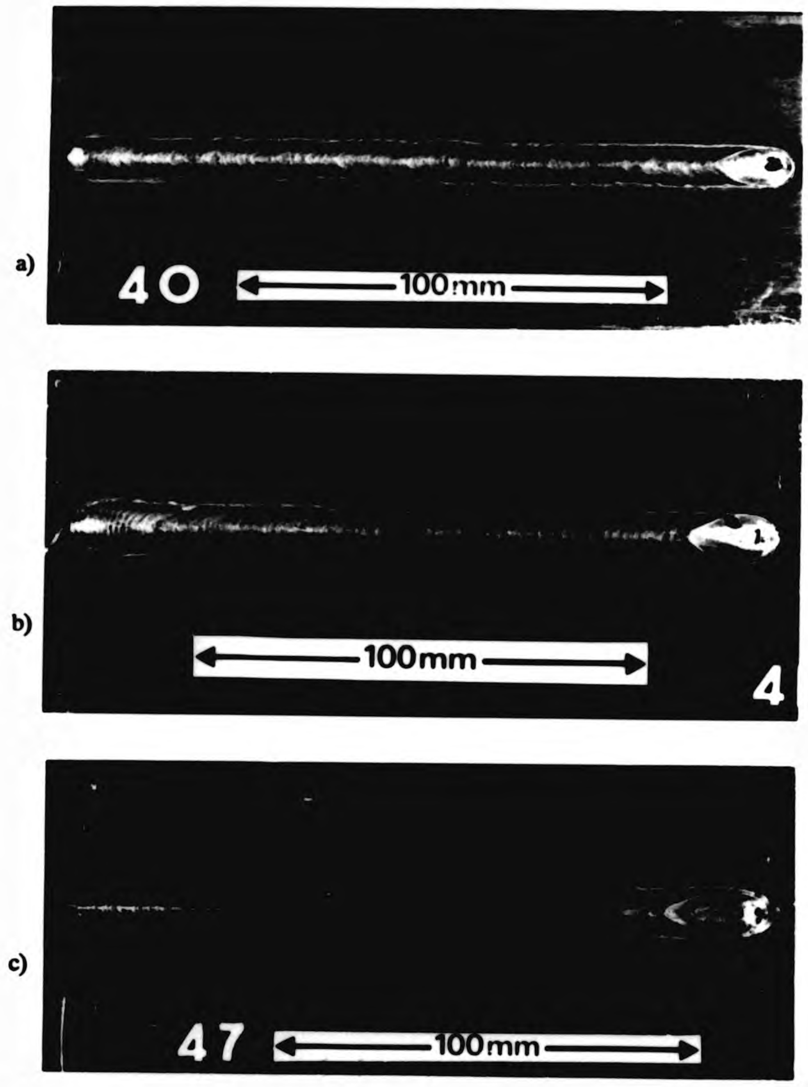


Fig. 5–22. Typical bead deposits for 1.2 mm diameter mild steel wire in Ar+20%CO_2 shielding gas, using different types of wire feed speed:
a) constant at 4.2 m/min,
b) modulated with square wave from 3.5 to 5.6 m/min,
c) varied gradually from 2 to 8.4 m/min.

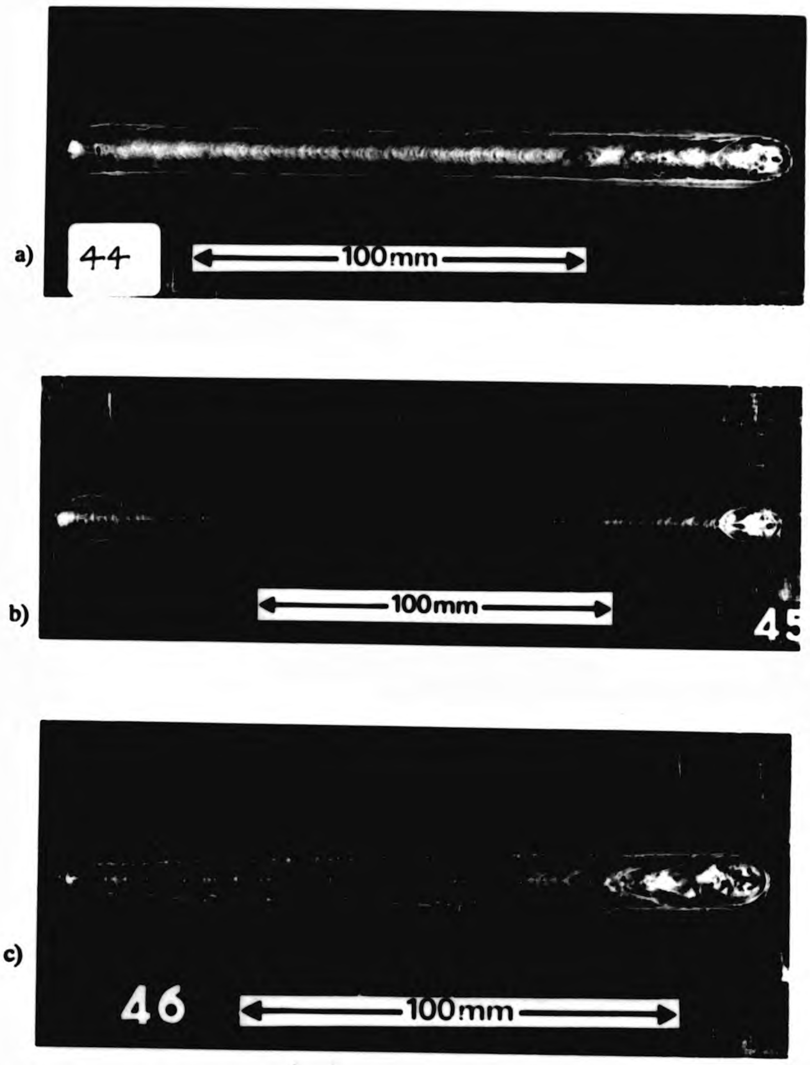


Fig. 5–23. Typical bead deposits for 1.2 mm diameter mild steel wire in CO_2 shielding gas, using different types of wire feed speed:
a) constant at 4.2 m/min,
b) modulated with square wave from 3.5 to 5.6 m/min at 2 Hz,
c) varied gradually from 2 to 7.4 m/min.

Table 5–1. Details of joint type, thickness and preparation, and welding conditions used for evaluating the control unit for steady DC arc operation; using 1.2 mm mild steel wire and modulated (square wave) wire feed speed with low and high levels set at 8.5 and 14 m/min, at 2 Hz.

Fig. no.	Material thickness, mm	Included angle	Root Gap, mm	Backing	No. of passes	Traverse speed, m/min	
						Filling passes	Capping pass
Butt Welds *$Ar+5\%CO_2$*							
5–24a	25	30°	7	Steel strip	5	0.31	0.25
5–24b	25	30°	7	Steel strip	5	0.31	0.25
5–24c	25	30°	7	Steel strip	5	0.31	0.25
5–24d	12.5	Square	10	Steel Strip	2	0.31	0.25
$Ar+20\%CO_2$							
5–25a	25	30°	7	Steel strip	5	0.31	0.25
5–25b	25	30°	3	Ceramic	4	0.31	0.25
5–25c	25	30°	2	Ceramic	4	0.31	0.25
5–25d	12.5	30°	5	Steel strip	3	0.31	o.25
5–25e	12.5	30°	3	Ceramic	2	0.31	0.25
5–25f	12.5	30°	2	Ceramic	2	0.31	0.25
5–25g	12.5	Square	10	Steel strip	3	0.31	0.25
$Ar+15\%CO_2$							
5–26a	25	30°	7	Steel strip	5	0.31	0.25
5–26b	25	30°	3	Ceramic	4	0.31	0.25
5–26c	25	30°	2	Ceramic	3	0.31	0.25
5–26d	12.5	30°	6	Steel strip	2	0.31	0.25
5–26e	12.5	30°	3	Ceramic	2	0.31	0.25
5–26f	12.5	Square	3	Ceramic	1	-	0.25
Fillet welds *$Ar+15\%CO_2$*							
5–27a*	12.5	90°	-	-	1	-	0.31
5–27b**	12.5	90°	-	-	1	-	0.31

* Constant wire feed speed at 10.5 m/min
** Modulated wire feed speed with low and high levels set at 8.5 and 12.5 m/min, at 2 Hz

5.5.1. Arc and metal transfer characteristics

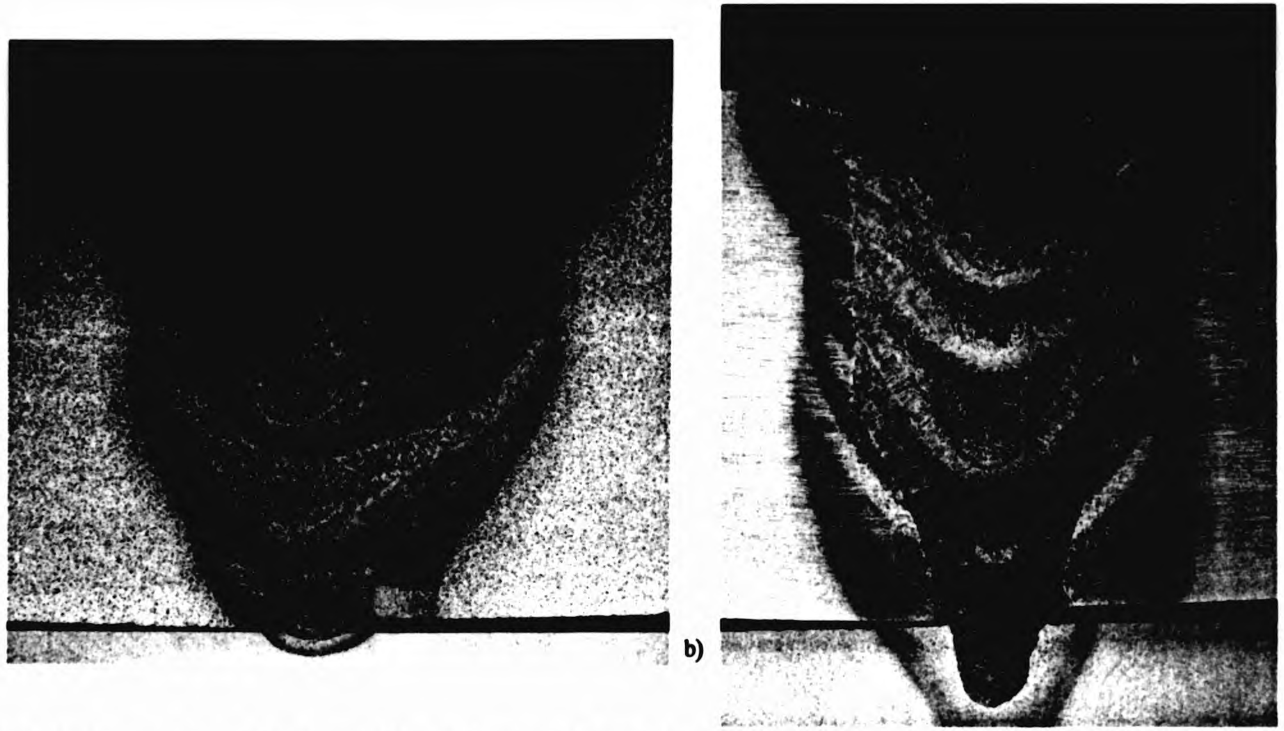
For any joint type and shielding gas combination, the arc operation was very stable such that the arc column did not deflect towards either side of the joint. While the wire feed speed modulated between 8.5 and 14 m/min, at 2 Hz, the intensity and width of the arc column also modulated, which fused the joint uniformly as well as stirred the weld pool to give better wetting onto the joint walls. Over the wire feed speed range used, the metal transfer was found to be spray type.

5.5.2. Butt welds

Macrosections of the four welds made using Ar+5%CO_2 shielding gas are shown in Fig. 5-24a to d. The main feature of each weld is that the bead deposit is symmetrical which indicates that the arc column did not deflect towards either side of the joint, but the welds are unacceptable because of porosity and, in addition, two welds (Fig. 5-24a and b) had lack of sidewall fusion in the root runs.

Using Ar+20%CO_2 shielding gas, macrosections of the seven welds made are shown in Fig. 5-25a to g. Each weld is symmetrical and free from defects. The penetration profile for each weld run was broad bowl type which is desirable to avoid lack of sidewall fusion defects. The process is tolerant to the variation of root gap because, using the same welding conditions, the welds remained sound although the root gap was varied from 7 mm (Fig. 5-25a) to 3 mm (Fig. 5-25b) to 2 mm (Fig. 5-25c), for the three joints comprising 25 mm thick plates. Similar tolerance of the process to the root gap variations was also found for the joint in 12.5 mm thick plates, because sound welds were produced when the root gap was varied from 5 mm (Fig. 5-25d) to 3 mm (Fig. 5-25e) to 2 mm (Fig. 5-25f). Furthermore, even for square butt joint with 10 mm gap (Fig. 5-25g), the weld produced was found to be sound. However, for all the welds, Ar+20%CO_2 shielding gas produced some spatter on the joint surface.

The macrosections of the six welds made using Ar+15%CO_2 shielding gas are shown in Fig. 5-26a to f. Each bead deposit was symmetrical with respect to the joint, and free from any defect, except that shown in Fig. 5-26f which contained one small pore. The deposit profile for each weld run was regular with broad bowl type penetration and good wetting-in to the joint surface. The top bead surface was



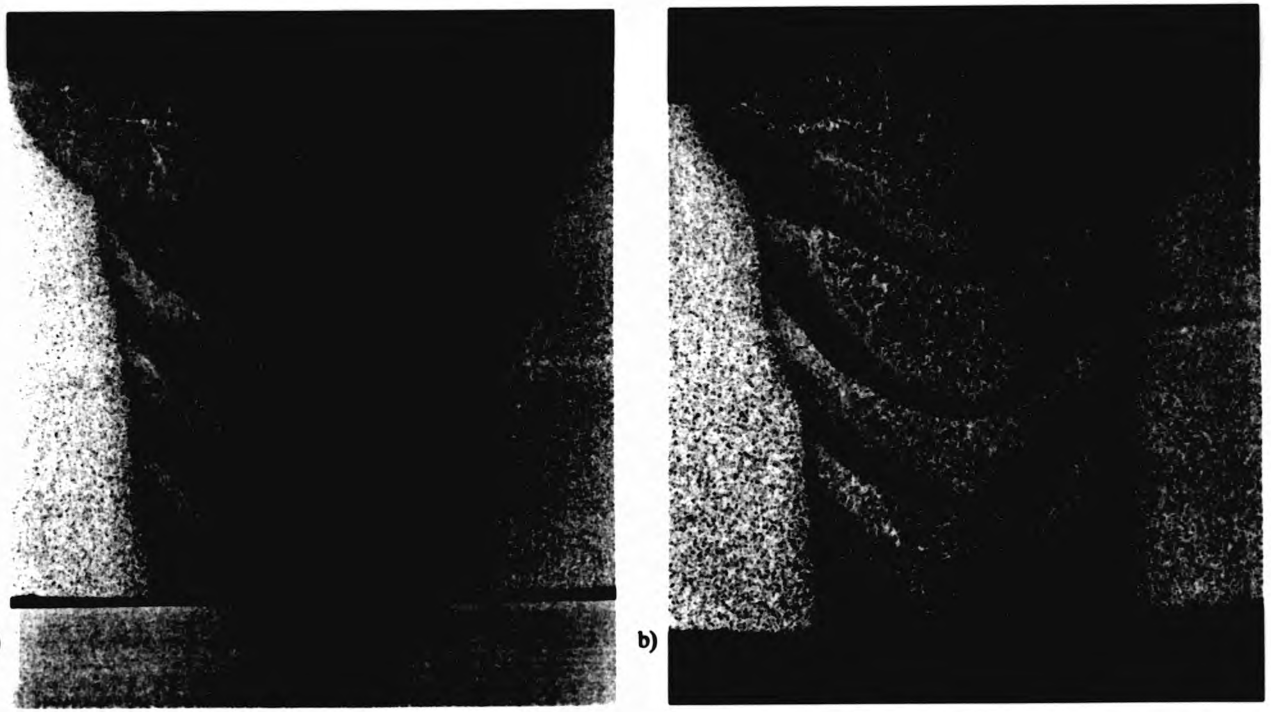
a) b)

Fig. 5–24. Macrosections of the four welds made for Ar+5%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
a) 25 mm, 30°, flat; b) 25 mm, 30°, flat.

c)

d)

Fig. 5-24. contd. Macrosections of the four welds made for Ar+5%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
c) 25 mm, 30°, flat; d) 12.5 mm, 30°, flat.



a) b)

Fig. 5–25. Macrosections of the seven welds made for Ar+20%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
a) 25 mm, 30°, flat; b) 25 mm, 30°, flat.

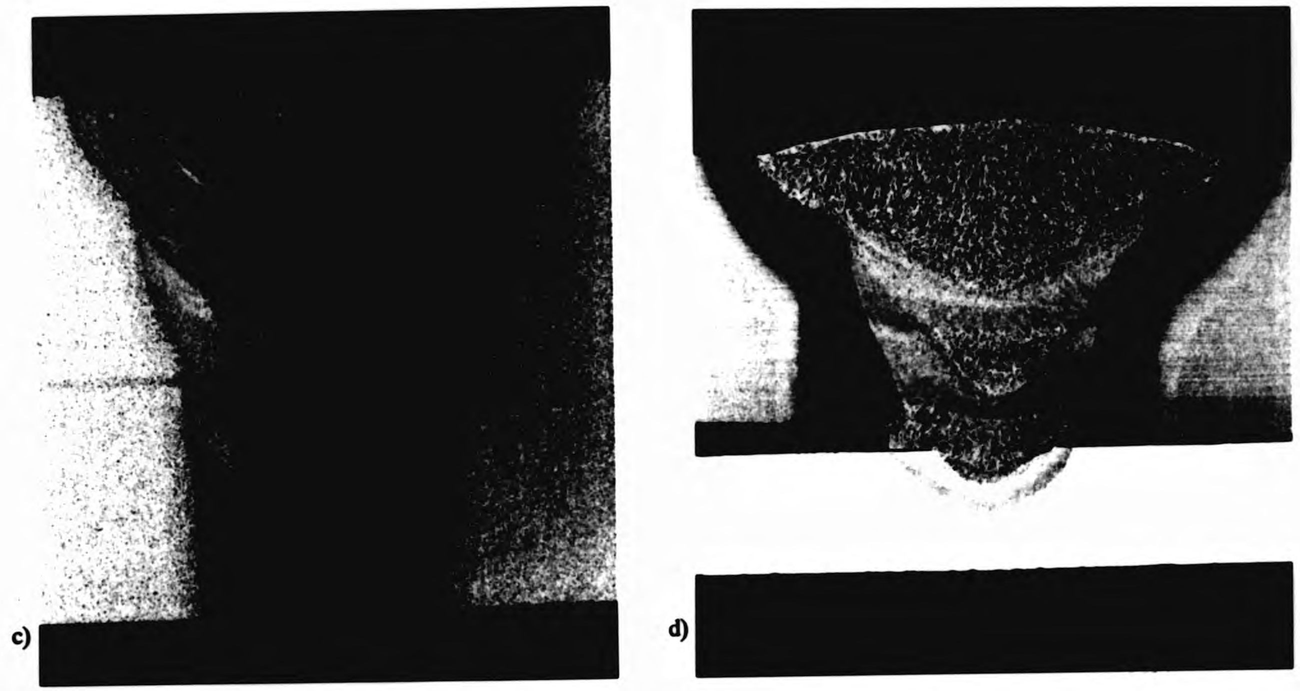


Fig. 5–25. contd. Macrosections of the seven welds made for Ar+20%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
c) 25 mm, 30°, flat; d) 12.5 mm, 30°,flat.

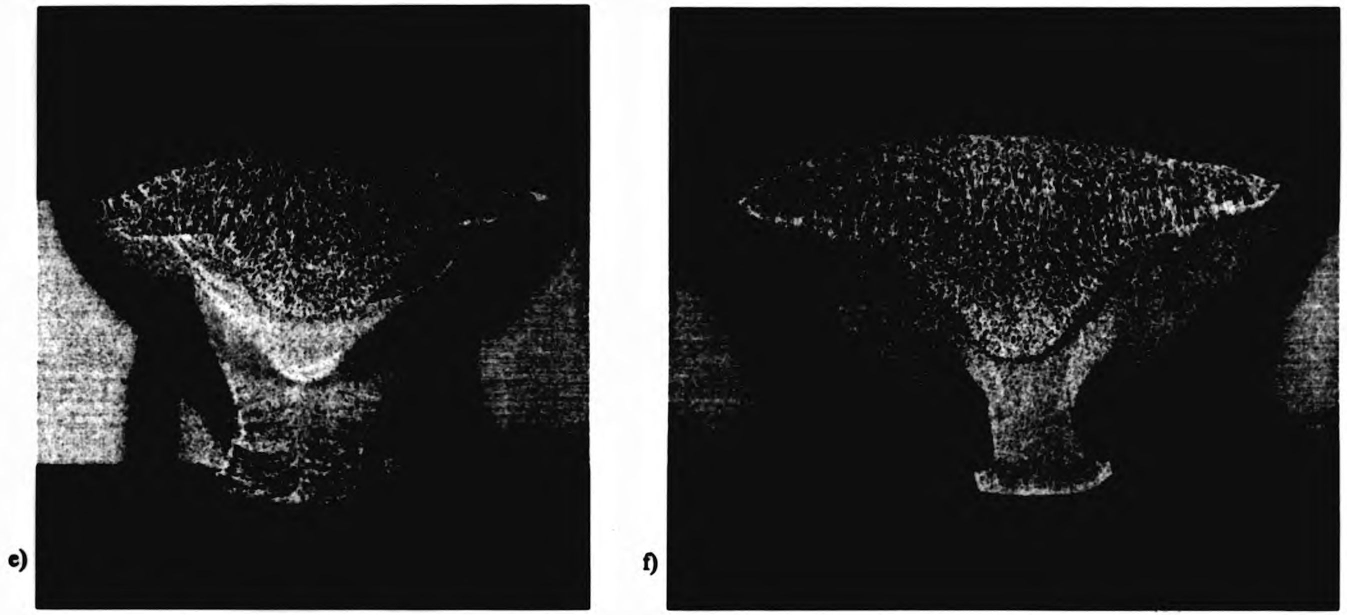
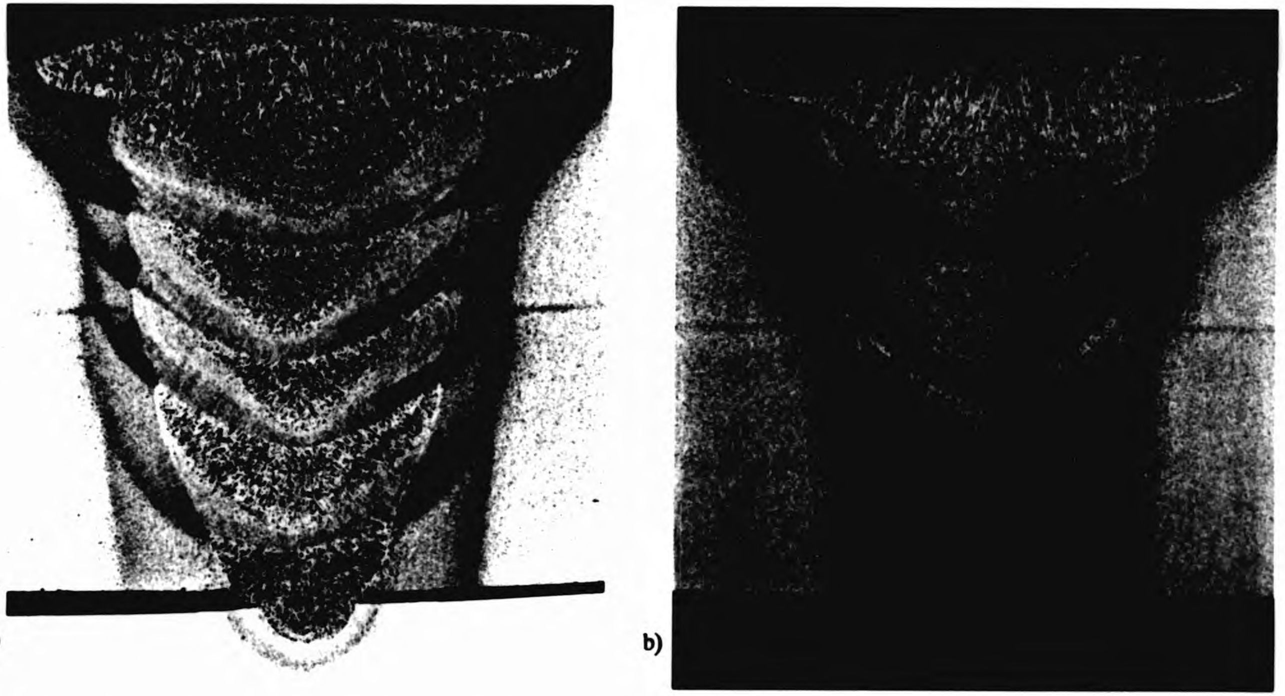


Fig. 5–25. contd. Macrosections of the seven welds made for Ar+20%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
e) 12.5 mm, 30°, flat; f) 12.5 mm, 30°, flat.

g)

Fig. 5-25. contd. Macrosections of the seven welds made for Ar+20% CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:

g) 12.5 mm, square, flat.



a) b)

Fig. 5–26. Macrosections of the six welds made for Ar+15%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
a) 25 mm, 30°, flat; b) 25 mm, 30°, flat.

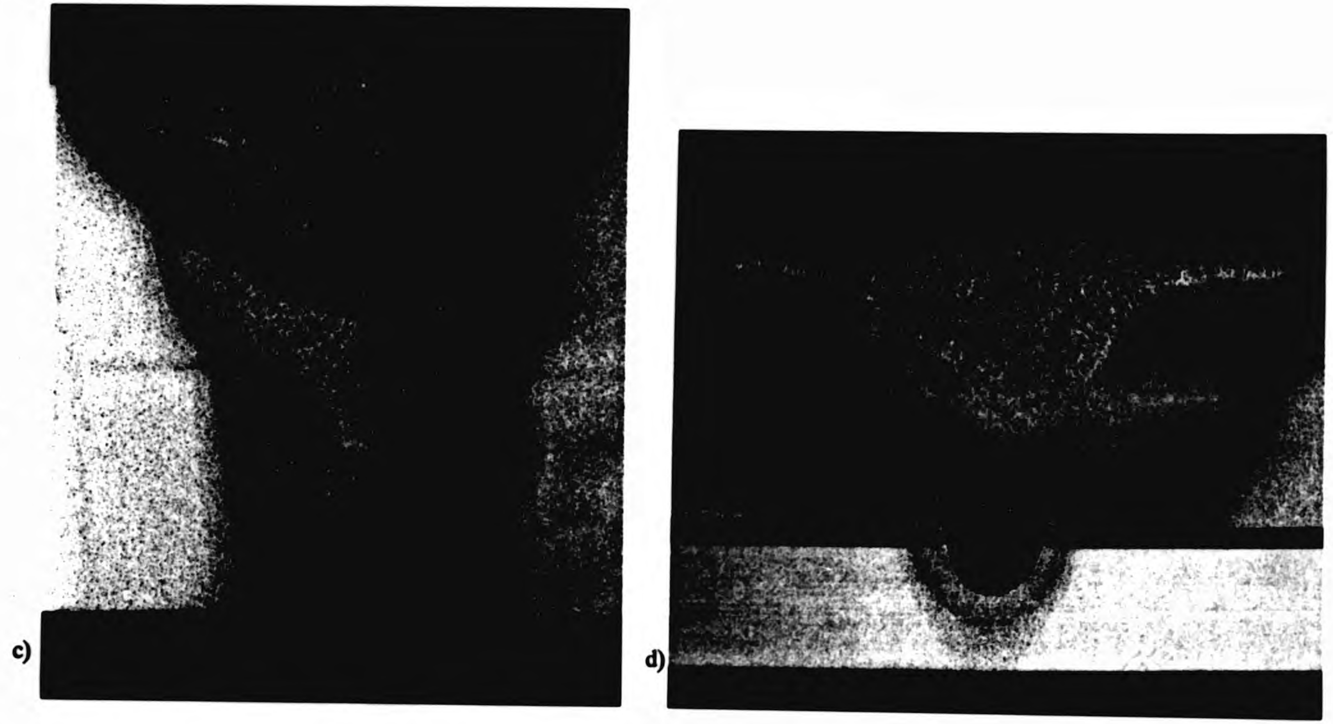
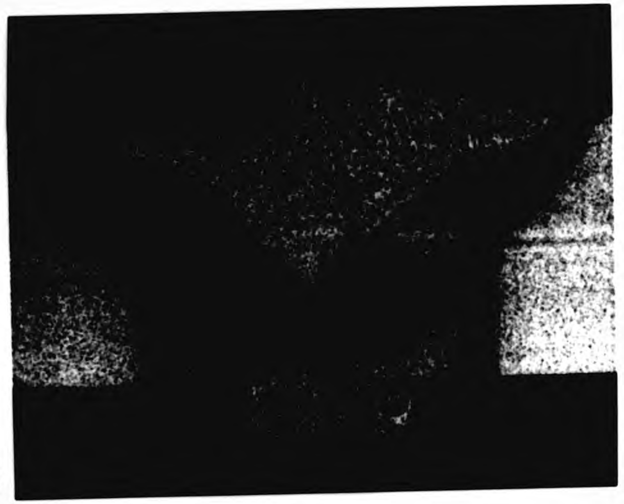


Fig. 5–26. contd. Macrosections of the six welds made for $Ar+15\%CO_2$ shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
c) 25 mm, 30°, flat; d) 12.5 mm, 30°, flat.

e)



f)

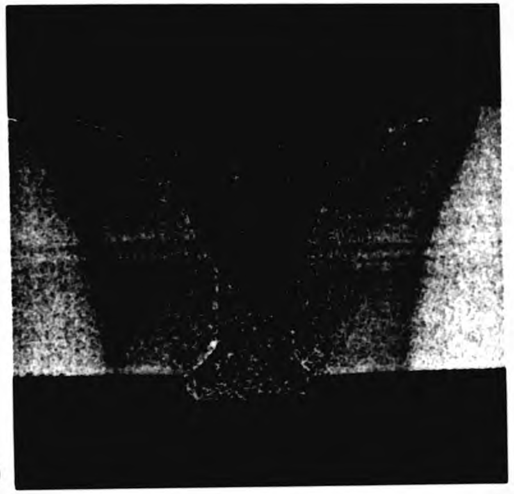


Fig. 5–26. contd. Macrosections of the six welds made for Ar+15%CO_2 shielding gas, using 1.2 mm diameter mild steel wire and modulated (square wave) wire feed speed from 8.5 to 14 m/min at 2 Hz, ×4:
e) 12.5 mm, 30°, flat; f) 12.5 mm, square, flat.

relatively flat, and free from undercut.

Also with this shielding gas, the process was tolerant to variation of root gap, sound welds were made, using the same welding conditions, when the root gap was varied from 7 mm (Fig. 5–26a) to 3 mm (Fig. 5–26b) to 2 mm (Fig. 5–26c), for the three joints in 25 mm plates. Similar tolerance was found for the joints in 12.5 mm thick plates, sound welds were obtained when the root gap was varied from 6 mm (Fig. 5–26d) to 3 mm (Fig. 5–26e) to square butt with 3 mm gap for which single weld run was required to complete the weld (Fig. 5–26f). All the welds were free from spatter.

5.5.3. Fillet welds

Two fillet joints were welded in 12.5 mm plate in the flat position. One weld was made with a constant wire feed speed of 10.5 m/min (Fig. 5–27a), and the other with the wire feed speed modulated between 8.5 and 12.5 m/min (mean wire feed speed of 10.5 m/min) at 2 Hz (Fig. 5–27b). The bead profiles of these welds are shown in Fig. 5–28a and b. Both the bead deposits are symmetrical relative to the joint, indicating that the arc did not deflect towards either sidewall. However, the overall weld characteristics for weld shown in Fig. 5–27b were better than those for weld shown in Fig. 5–27a, since the latter had undercut, but the former was free from any weld defect. Furthermore, the penetration produced in weld shown in Fig. 5–27b was deeper (about 4 mm) than that of weld shown in Fig. 5–27a (2.5 mm).

5.6. DISCUSSION

5.6.1. Control equations

The steady DC open arc operation has been characterised entirely by the two basic relationships; one specifying current for a given wire feed speed, and the other specifying the voltage corresponding to a specific current. Therefore, for any given wire feed speed, the arc power, the product of the current and voltage, can be specified using the basic relationships. In this work, the concept of power has been utilised to combine the basic relationships to obtain a single quadratic equation [5–1], which can be used to facilitate the steady DC open arc operation.

The main attribute of the control equation is that it is simple. It includes only

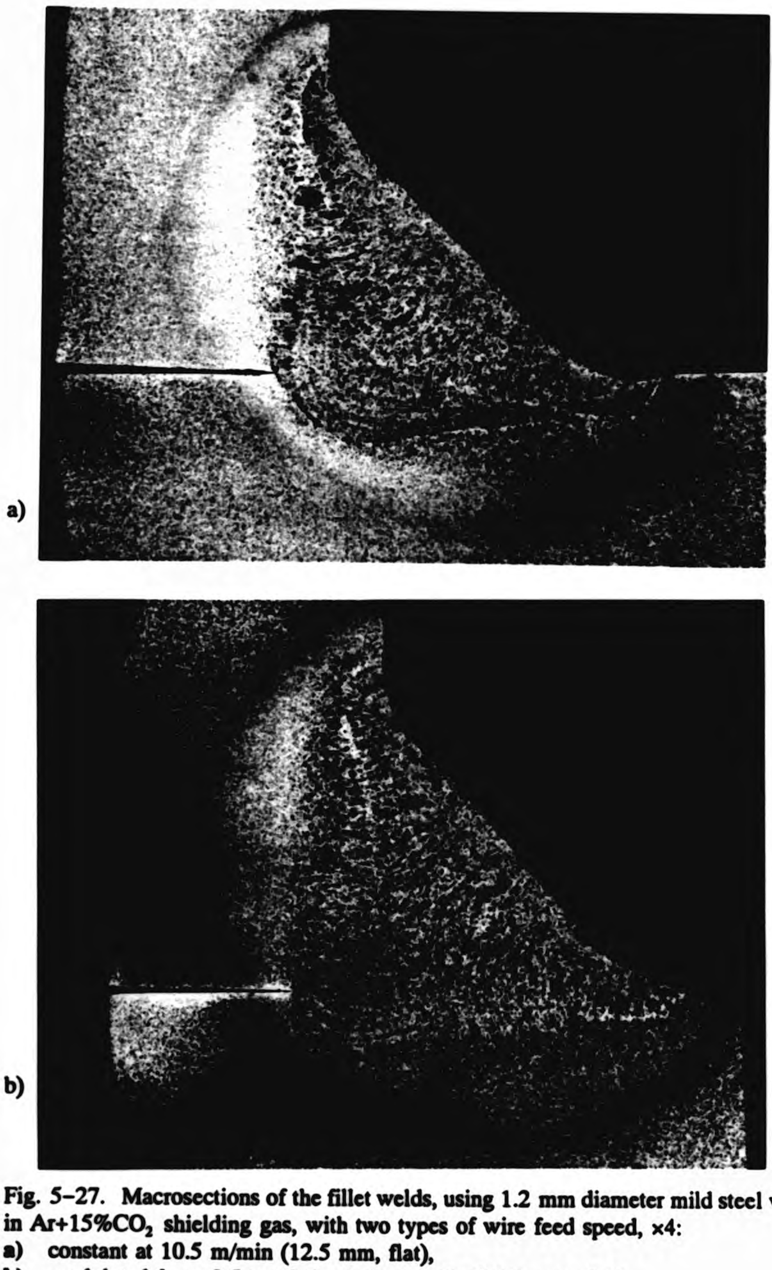
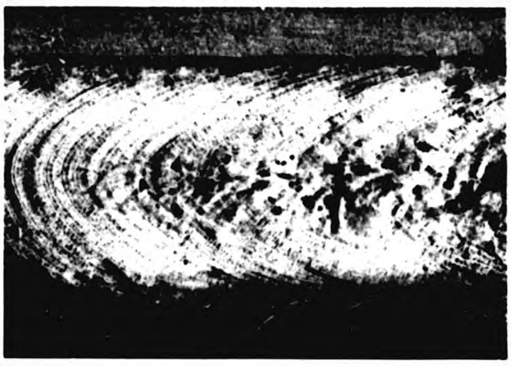


Fig. 5–27. Macrosections of the fillet welds, using 1.2 mm diameter mild steel wire in Ar+15%CO_2 shielding gas, with two types of wire feed speed, ×4:
a) constant at 10.5 m/min (12.5 mm, flat),
b) modulated from 8.5 to 12.5 m/min at 2 Hz (12.5 mm, flat).

a)



b)

Fig. 5–28. Bead profiles of the fillet welds, shown in Fig. 5–27, using 1.2 mm diameter mild steel wire in Ar+15%CO_2 shielding gas, with two types of wire feed speed:
a) constant at 10.5 m/min, ×2;
b) modulated from 8.5 to 12.5 m/min at 2 Hz, ×2.

current and power as the operating variables, and the slope (m_v) and intercept (C_v) of the voltage–current relationship as the parametric constants to be specified for a given wire material/diameter/shielding gas combination, together with the required arc length and wire extension.

The quadratic power–current control equation has been approximated to obtain a linear power–current control equation, which is even simpler. This is not valid for the current range below 200 A which is not usable for the steady DC open arc operation, because the relevant metal transfer is globular and not suitable for welding. For the usable current range, from 200 A upwards, the linear equation is approximately identical to the accurate quadratic relationship as the maximum difference between the two relationships is less than ±3% over the operating current range.

The third control equation, linear voltage–current relationship, is equally simple; it includes only current and voltage as the operating variables and only two parametric constants (m_v and C_v) to be specified for a given combination.

Each of the three equations could be used to regulate stable synergic operation. However, the voltage–current approach is limited because the power source could be operated only in the constant voltage mode. Whereas, both the power–current approaches are versatile in that the power source could have any output (V–I) characteristic, whether constant voltage, constant current or any intermediate slope.

5.6.2. Effect of process parameters on the parametric constants specifying the control equations

In general, to adapt a control equation to a given combination of the process parameters, such as wire material, diameter, shielding gas, arc length and wire extension, the relevant values of the parametric constants require to be specified. Information on the degree by which these parametric constants must be adjusted to cope with the operating range of a specific process parameter is essential for the effective design and operation of the control unit regulating the equation. Therefore, for mild steel wire, the effect of the process parameters is discussed on m_v and C_v, which are directly included in the two equations, and also determine m_a and C_a which are included in a third control equation.

5.6.2.1. *Effect on m_v*

The values of the parametric constant m_v are given in Tables 4–1 and 4–2 for the steady DC open arc operation, using the combinations of the process parameters, including mild steel wire of 1.0 and 1.2 mm diameters, Ar+5% CO_2 and Ar+20% CO_2 shielding gases, 5 and 10 mm arc lengths, and 10 to 20 mm wire extensions. Over the range of the combinations, the mean value of m_v is 0.0294 V/A, so that the overall maximum variation is less than ± 15%. As this variation is greater than the normally achievable experimental error of ± 5%, the variation in m_v appears to be significant. However, for the quadratic power–current equation, m_v is included in the minor term m_vI^2. For example, the contributions of m_vI^2 to the total power, obtained by evaluating the equation for the current range 100–500 A, are given in Table 5–2. The variation in m_v by ±15% causes variation in the total power of only less than 3.6% at 400 A, which is insignificant. Furthermore, for the linear voltage–current equation, m_v is included in the minor term m_vI. The variation in m_v by ±15% causes variation in the total voltage of only less than ±3.8% at 400 A, which is also insignificant. Therefore, for both the equations, the parametric constant m_v could be considered constant at 0.0294 V/A for all the combinations of the process parameters over the operating ranges.

5.6.2.2. *Effect on C_v*

a). Wire diameter

For a constant contact tube to workpiece distance of 15 mm, the experimental values of C_v relevant to 1.0 and 1.2 mm wire diameters are given in Table 4–4, using four shielding gas/arc length combinations. For any given combination, the values of C_v are practically the same (within ±3% relative to the mean value) for the two diameters. That is, for a given shielding gas and arc length, the change in wire diameter has no effect on the parametric constant C_v.

b). Shielding gas

For four wire diameter/arc length combinations, the values of C_v for Ar+5%CO_2 and Ar+20%CO_2 shielding gases are compared in Table 4–6. For any specific combination, C_v is significantly different for the two gases. Therefore, the value of

Table 5–2. Typical contributions made by the minor (m_vI^2) and major (C_vI) terms to the total power given by the control equation $P = m_vI^2 + C_vI$, for the current range 100–500 A.

	m_vI^2, W	C_vI, W	P, W
100	294	2500	2794
200	1176	5000	6176
300	2646	7500	10146
400	4704	10000	14704
500	7350	12500	19850

$m_v = 0.0294$ V/A $C_v = 25$ V

C_v must be adjusted for a change in the shielding gas.

c). Arc length

For various wire diameter/shielding gas combinations, the values of C_v relevant to 5 and 10 mm arc lengths are compared in Table 4–7. For any given combination, C_v is significantly different for the two arc lengths. Therefore, the parametric constant C_v would need to be adjusted corresponding to the required arc length.

d). Wire extension

The values of C_v are given in Table 4–5 for the wire extension range 10–20 mm, at constant arc length, using Ar+5%CO_2 and Ar+20%CO_2 shielding gases. For each shielding gas, over the range of wire extension, the variation in C_v relative to the mean value, is less than $\pm$ 2.5%, which is considered insignificant. Therefore, for operation at a constant arc length, no adjustment would be required in C_v for a variable wire extension.

5.6.3. Control units

The electronic circuits of all the three control units, which have been developed for regulating the three control equations, are very simple. These circuits can be constructed readily with only a few inexpensive electronic components.

Furthermore, each control unit operates from the current signal (or together with the voltage signal) which is obtained conveniently from a static transducer, a shunt, connected in the welding circuit. The operation is entirely independent of any dynamic transducer, such as a tachogenerator measuring the wire feed speed, which could be liable to provide erroneous information due to, for example, any slipping problems. Therefore, the operation of the three control units is immune from any problem external to the control units.

With the parametric constants preset in the controls, it has been found that each control unit initiates the arc readily and then maintains the current and voltage compatible with the operating wire feed speed, so that stable arc operation is maintained. In operation, if the required arc length is changed, the corrective action is immediately taken to stabilise the arc.

The two control units based on the power–current relationships can operate a steady DC open arc with the power source set in the constant current mode, constant voltage mode or any intermediate mode of the output characteristic. The constant voltage mode has self–adjustment due to the power supply and the intermediate mode has a degree of self–adjustment depending on the slope of the output characteristic; but, even for the constant current mode, which does not provide any self–adjustment due to the power supply, a high degree of adjustment is achieved by relating the current to the power.

The control unit regulating the voltage–current relationship operates with the power source set in the constant voltage mode. The principal feature of the control unit is that it can be used for both the steady DC open arc and short circuiting arc operations. The control unit is adapted to the required operation simply by presetting the relevant parametric constants. In addition, for the short circuiting arc operation, a suitable inductance must be included in the arc circuit, which is essential to control the dynamic behaviour of the arc current for stable arc operation.

Each of the three control units is capable of synergic operation, whereby stable arc operation is maintained automatically for any wire feed speed, whether maintained constant, varied gradually or modulated. Apart from the relative simplicity and flexibility of the synergic controls, one major advantage is in the application of the modulated wire feed speed technique to thermal pulsing, where the current is modulated by changing the wire feed speed at relatively low frequencies of the order of 1–5 Hz. This is possible because with the synergic controls, a stable arc is maintained at all the wire feed speeds. Therefore, the modulation can be applied to virtually any high and low levels of feed speed over the operating range, and furthermore, the transitions can be as slow or as fast as desired. Practical applications of this technique have yet to be exploited fully, but in principle the synergic controls should open the way to various forms of thermal pulsing with wide ranges of wire feed speed and rates of change readily usable.

Another feature of the synergic controls is that the arc length is maintained constant for any variation in the wire extension. A typical application of this feature would be in the mechanised multipass circumferential welding of pipes, whereby the pipes could be rotated under the welding head continuously. At the completion of each pass, the wire extension would decrease for a set standoff distance, but the operating arc length would remain unaltered. Therefore, as no adjustment of the standoff distance would be required between passes to maintain the required arc length, the multipass weld could be completed in a single run. By this procedure, apart from saving time, any defects which would occur due to stopping and restarting the arc, for readjusting the standoff distance at the completion of each pass, would be avoided. Similarly, the multipass linear joints could also be welded, for example, traversing the joint back and forth continuously underneath the welding head until the weld is completed.

Furthermore, as variations in the wire feed speed do not cause arc length instability under the synergic controls, the wire feed speed can be changed during joint filling as required without necessitating any other control. For example, for a wide root gap the current can be reduced to avoid excessive burnthrough by reducing the wire feed speed alone. Similarly in the filling passes the wire feed speed can be freely altered to obtain the required metal deposition rate; and for the capping pass, the wire feed speed can be varied to achieve the required bead profile.

5.6.4. Welding performance

In this work, only the control unit based on the power–current relationship was evaluated for the welding performance. In general, the control unit is capable of making sound and spatter free welds for butt joints and fillet joints in the flat position, with the modulated wire feed speed technique, using Ar+15% CO_2 shielding gas. All the welds made have good weld characteristics, in particular the weld deposits are symmetrical and the sidewall fusion is relatively deep and gently rounded so that lack of sidewall fusion, lack of interpass fusion or lack of root fusion defects are unlikely to be formed even in an industrial environment.

However, using Ar+5%CO_2 shielding gas, the welds made contained porosity. This can be identified as resulting from inadequate shielding of the weld pool for the modulated arc at high current operation, together with a relatively long wire extension needed for the narrow 'V' joint welding using a conventional welding torch. In addition, Ar+5%CO_2 causes lack of sidewall fusion because the arc power generated is inadequate for the application. Both the defects can be avoided using Ar+20%CO_2

shielding gas, but this causes spatter. The failure to make sound or spatter free welds does not indicate unsatisfactory performance of the control unit, but it does demonstrate the need for making a judicious selection of the shielding gas.

5.7. CONCLUSIONS

A study has been made of the feasibility of developing synergic control for steady DC open arc and short circuiting arc MIG welding in conjunction with a transistor controlled power source. The main conclusions of this study are listed below.

a). Steady DC open arc operation

1. An electronic control unit has been designed and constructed to provide synergic control of steady DC open arc welding. It is based on a quadratic power–current equation derived from the generalised linear burnoff and voltage–current relationships.

2. An alternative control unit for synergic steady DC open arc operation has been designed and constructed based on an approximate linear power–current relationship.

3. Both the control units can operate with the power source set in the constant current, constant voltage, or any intermediate mode of output characteristics.

4. A third electronic control unit has been specifically designed and constructed to regulate the voltage–current relationship in order to achieve the synergic steady DC open arc operation. This control unit operates with the power source set in nominally constant voltage mode.

5. Each control unit operates from the current signal (or together with the voltage signal) which is obtained conveniently from a static transducer (a shunt) connected in the arc circuit. Because the transducer is static, the control units are immune from any external problems.

6. The three control units are shown to be capable of performing the synergic operation, whereby stable arc operation is maintained automatically, for any wire feed speed whether held constant, varied gradually or modulated with any waveform. Thus, the steady DC open arc MIG operation is not only simplified but also its range of application is extended.

7. The control units regulating the power–current relationships have been shown to be capable of making sound welds for the narrow 'V' butt joints and fillet joints with 12.5 to 25 mm thick plates.

b). Short circuiting arc operation

8. The electronic control unit regulating the voltage–current relationship for steady DC open arc operation can be adapted to provide synergic operation for the short circuiting arc operation, simply by programming the relevant parametric constants.

9. The control unit is shown to be capable of providing synergic operation, whereby stable arc operation is maintained automatically, for any wire feed speed whether maintained constant, varied gradually or modulated. Thus, the short circuiting arc operation is simplified and also its range of application extended.

CHAPTER 6
SYNERGIC CONTROL USING A THYRISTOR CONTROLLED POWER SOURCE

6.1. INTRODUCTION

The development of synergic control systems for steady DC open arc and short circuiting arc MIG welding, using a feedback controlled transistor power source, has been described in Chapter 5. This type of power source provides the desired output of precisely controlled and ripple free current or voltage, together with a fast response, but tends to be energy inefficient, bulky and expensive. Therefore, its use is normally restricted to general research in the laboratory and high quality applications. Therefore, to facilitate the transfer of the synergic control technology into industry, interfacing techniques have also been developed to adapt the control units to work with a low cost commonly used thyristor controlled power source. The adaptation techniques and evaluation of the control systems, comprising the control units and a thyristor controlled power source, are described in this chapter.

6.2. INPUT-OUTPUT RELATIONSHIPS FOR THE THYRISTOR CONTROLLED POWER SOURCE

As designed, the power source has a control mechanism to control the output, which is operated from an internal reference supplied by the 'voltage control' knob. To establish the input-output relationships, this voltage control was disconnected and a reference signal of known voltage was supplied from an independent variable voltage power supply.

6.2.1. Static output characteristics

For the entire range of input reference signal from 0 to 15 V, there is a family of voltage-current output characteristics from a minimum to a maximum level. For a series of selected reference voltage settings, the static output characteristics were established using a variable load resistor, as shown in Fig. 6-1. For currents less than

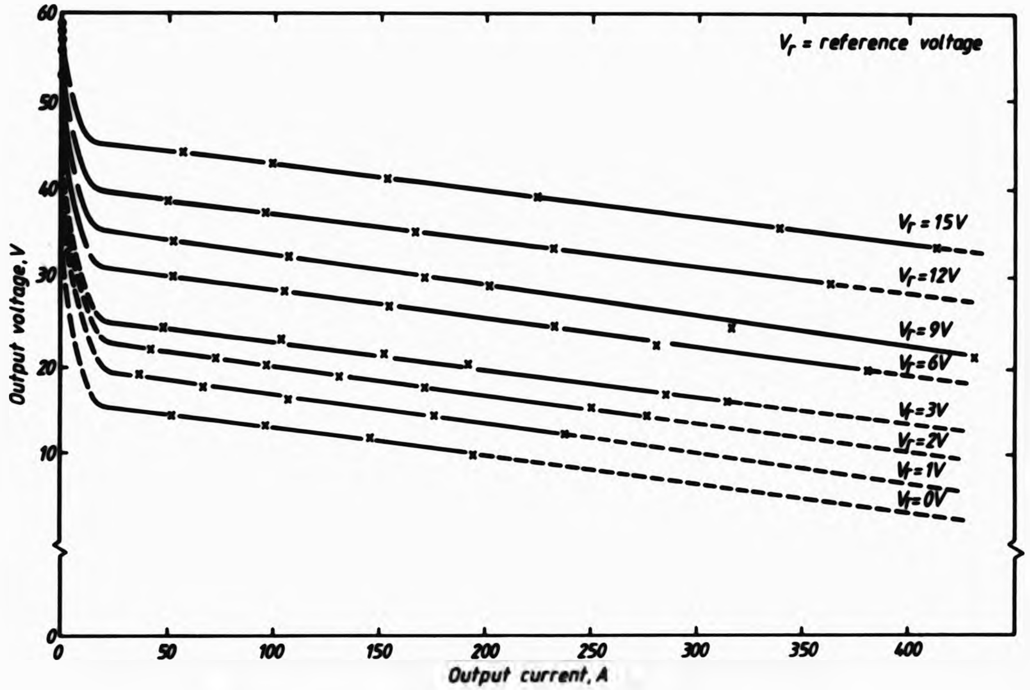


Fig. 6–1. Output characteristics of the thyristor power source.

50 A, the output voltage rises to an open circuit value of 57 V for the maximum reference voltage 15 V, and 46 V for the minimum reference voltage 0 V. At higher output currents, from 50 A upwards, the characteristics are linear and substantially parallel. For example, the characteristics relevant to the maximum and minimum reference voltage settings can be expressed by the following equations:

$V_p = -0.0297 I + 46$ *for the maximum voltage setting*

Where

V_p is the output voltage, V;

I is the output current, A.

Subscript p refers to power source output characteristics.

For the maximum setting, the output voltage at 50 A is 44.5 V and decreases gradually at about 3 V per 100 A to 35.5 V at the maximum rated current of 350 A. For the minimum setting, the voltage at 50 A is 14.5 V and decreases to 5 V at 350 A. By varying the reference voltage from the minimum (0 V) to the maximum (15 V) value, the characteristic could be raised continuously from the minimum to the maximum level, so that the current/voltage zone with a voltage range of about 31 V could be obtained for any given output current. Any point within this zone represents a potential welding condition.

Generalised equation

For usable currents, from 50 A upwards, the characteristics are linear and substantially parallel. Together, these can be described by the general linear equation:

$$V_p = m_p I + C_p \qquad \textit{for } I \geq 50A \qquad [6\text{–}1]$$

Where

V_p is the output voltage, V;

I is the output current, A;

m_p is the slope, V/A;

C_p is the intercept at zero current, V.

The equation is specified by the slope m_p and intercept C_p for a given input reference voltage V_r. The slope is constant with the average value at –0.0307 V/A, but the intercept is variable, from 16 to 46 V, related to the reference.

6.2.2. Relationship between intercept C_p of the output characteristics and the input reference V_r

The relationship between the input reference voltage, V_r, and the intercept, C_p, for output characteristics of the power source is plotted in Fig. 6–2. This relationship is linear but not proportional as it makes an intercept V_o, on the C_p axis for V_r at zero value. The relationship can be expressed by the following equation:

$$C_p = m_o V_r + C_o \qquad [6\text{–}2]$$

Where

C_p is the intercept of the output characteristics;

V_r is the input reference voltage to the power source;

m_o is the slope of the C_p–V_r relationship;

C_o is the intercept of the C_p–V_r relationship.

In this equation V_r is the independent variable, and C_p the corresponding dependent variable. The equation is specified by the slope m_o and intercept C_o.

6.3. ADAPTATION OF THE CONTROL UNIT

The function of the control unit is to execute the operating linear voltage–current relationship relevant to a given material/wire diameter/shielding gas combination, and determine the reference voltage according to a given current (or wire feed speed). This signal drives the power source to establish the required arc voltage providing stable arc operation. If the power source had a 'perfect', constant voltage characteristic then the required voltage would be maintained for any current, as specified by the reference. However, unlike the transistor controlled power source originally used,

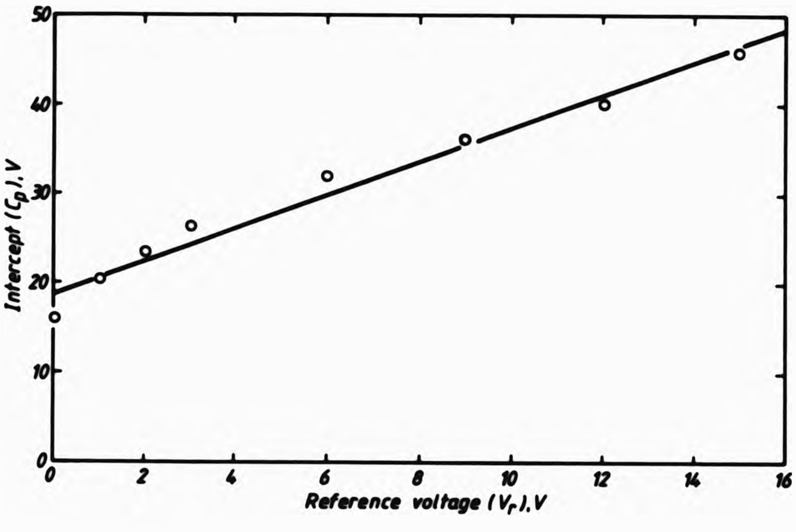


Fig. 6–2. Intercept–reference voltage relationship relevant to a family of output characteristics of the thyristor power source.

(1,2) the output voltage of the thyristor controlled power source is not constant but decreases as the current increases at a rate given by the slope (−0.0307 V/A). Therefore, the adaptation technique must accommodate this variation in the output voltage relative to the current.

Furthermore, as indicated by Fig. 6–2, the input/output of the power source is linear but, unlike that for the transistor controlled power source, it is not proportional. Therefore, the adaptation technique must also take into account the non-proportionality.

Adaptation techniques

Three techniques have been used to adapt the three synergic control units to operate with the thyristor controlled power source.

These are:

a). Generalised 'reference voltage–output current' control equation;

b). 'Voltage feedback control';

c). Scaling the output.

The techniques a) and b) were used for the linear voltage–current control unit, and both b) and c) for each of the quadratic and linear power–current control units. Thus, six control systems, two for each control unit, were made available, as shown in Fig. 6–3.

6.3.1. Linear voltage–current control units

6.3.1.1. *Generalised 'Reference voltage–output current' control equation*

The equation includes current as independent variable and the reference voltage as dependent variable. In addition, it includes parametric constants relevant to the operating arc relationship and also those relevant to the output characteristics of the power source. As all the parameters relevant to the input/output relationships of the power source are incorporated, the equation inherently takes into account the effects of both the slope of the output characteristics and non–proportionality of the relationship between the input reference and the intercept of the output characteristics. The overall control equation could be obtained analytically as well as graphically.

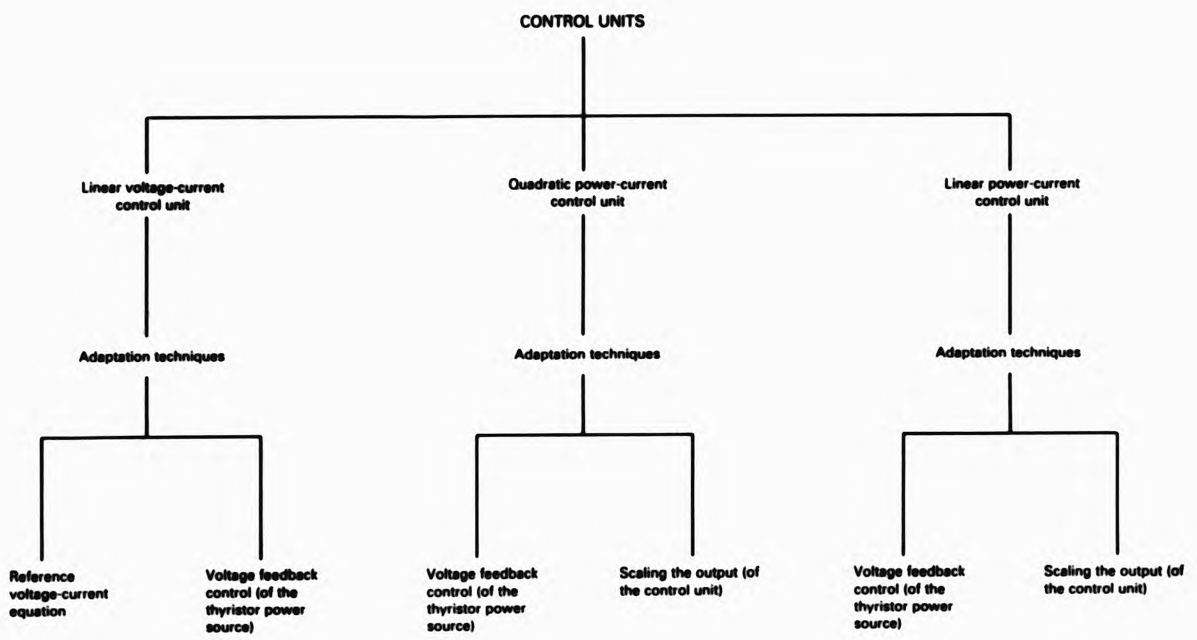


Fig. 6–3. Flow chart of control unit/adaptation technique combinations.

Analytical method

The required control equation has been derived from the four primary equations. First is the generalised equation for the static output characteristic of the power source (Fig. 6–1):

$$V_p = m_p I + C_p \qquad [6\text{–}1]$$

Second is the generalised 'reference voltage–intercept' equation relevant to the input/output of the power source(Fig. 6–2):

$$C_p = m_e V_r + C_e \qquad [6\text{–}2]$$

Substitution for C_p from Eq. [6–2] into Eq. [6–1] gives:

$$V_p = m_p I + m_e V_r + C_e \qquad [6\text{–}3]$$

This is the generalised output characteristic of the power source. The equation has two independent input variables: the input reference voltage V_r to the power source, and the output current I. V_p is the corresponding dependent variable.

The parametric constants m_p, m_e and C_e for the specified power source can be determined directly from the output characteristics established experimentally for a range of input reference voltage V_r.

Third is the generalised voltage–current relationship for stable arc operation (Fig. 6–4):

$$V = m_v I + C_v \qquad [6\text{–}4]$$

Where

V is the arc voltage, V;

I is the arc current, A;

m_v is the slope, V/A;

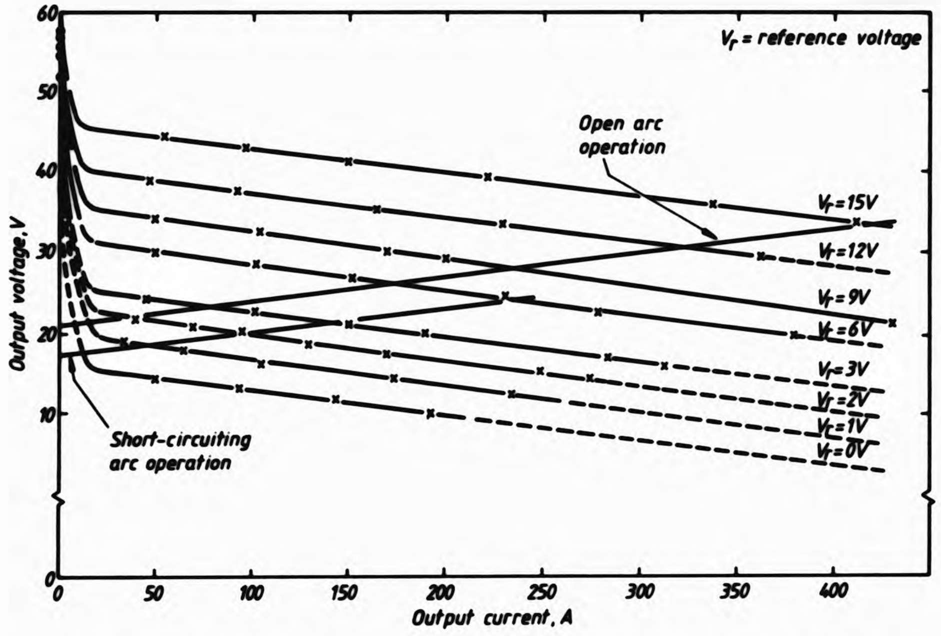


Fig. 6–4. Typical voltage–current relationships for arc operation plotted together with the family of output characteristics of the thyristor power source: open arc operation with 1.2 mm diameter mild steel wire in Ar+5%CO_2, and short circuiting arc operation with 1.0 mm diameter mild steel wire in CO_2.

C_v is the intercept at zero current, V.

Fourth is the generalised necessary condition to establish an operating point. That is, the power source output voltage V_p must coincide with the required arc voltage V for any current. The equation is:

$$V_p = V \qquad [6\text{–}5]$$

As derived from Eqs. [6–3] to [6–5] or directly from Eqs. [6–1], [6–2], [6–4] and [6–5], the required generalised 'reference voltage–output current' control equation is:

$$V_r = \left(\frac{m_v - m_p}{m_o}\right) I + \frac{C_v - C_o}{m_o} \qquad [6\text{–}6]$$

This equation has been implemented by the synergic control unit to provide the reference voltage V_r for driving the power source, such that the arc voltage is adjusted automatically according to the required arc current I.

Typical values of m_v and C_v for the steady DC open arc and short circuiting arc operation are given in Table 6–1. The values of m_p, m_o and C_o relevant to the thyristor controlled power source, together with those for the transistor controlled power source previously used, are given in Table 6–2.

Graphical method

Unlike the analytical method which provides the generalised control equation, the graphical method determines the control relationship for a specific material/wire diameter/shielding gas combination. The relationship has been obtained from the graphical solution of the voltage–current relationship for arc operation together with the family of the output characteristics of the power source. The two relationships have been plotted together in Fig. 6–4. The intersection points together with the relevant reference levels provided the required 'reference voltage–output current'

Table 6–1. Values of parametric constants m_v and C_v, for various wire material/wire diameter/shielding gas combinations.

Shielding gas	contact tube to workpiece distance, mm	Wire extension, mm	Arc length, mm	Parametric constants	
				m_v, V/A	C_v, V
Steady DC open arc operation 1.2 mm diameter mild steel wire					
Ar+5%CO_2	15	10	5	0.028	21
Ar+5%CO_2	15	5	10	0.029	23
Ar+20%CO_2	15	10	5	0.030	24.5
Ar+20%CO_2	15	5	10	0.025	30
1.0 mm diameter mild steel wire					
Ar+5%CO_2	15	10	5	0.031	22
Ar+5%CO_2	15	5	10	0.030	23
Ar+20%CO_2	15	10	5	0.030	25
Ar+20%CO_2	15	10	5	0.028	30.5
Short circuiting arc operation 1.2 mm diameter mild steel wire					
Ar+20%CO_2	12	12	—	0.026	14.4
CO_2	12	12	—	0.028	16.2
1.0 mm diameter mild steel wire					
Ar+20%CO_2	12	12	—	0.027	14.6
CO_2	12	12	—	0.032	16.4

Table 6–2. Values of parametric constants m_p, m_e and C_e, for the transistor and thyristor controlled power sources.

Power source	m_p, V/A	m_e	C_e, V
Transistor power source (constant voltage operation)	0	10	0
Thyristor power source	–0.03	1.9	18.5

relationship, for example shown in Fig. 6–5.

Control unit
Both the block and functional diagrams of the control circuit executing the control equation [6–6] are shown in Fig. 6–6. The main feature of the circuit is that it is simple, small and low cost, comprising only a few integrated circuit units.

6.3.1.2. *Voltage feedback control*
To accommodate the effects of the slope and non-proportionality automatically, a 'voltage feedback control' circuit has been added between the original control unit and the power source, Fig. 6–7. This circuit has two inputs. One is the 'reference' provided by the control unit, and the other is 'feedback' taken from the electrodes to represent the operating arc voltage. The feedback is subtracted from the reference to obtain an 'error' signal. This signal is amplified and then used to drive the power source. In essence, the feedback control circuit causes the power source to simulate near-perfect constant voltage operation similar to that provided by the transistor controlled power source originally used.

6.3.2. Power–current control units
Both the quadratic and linear power–current control units are similar in operation and construction. In principle, adaptation of these control units to the thyristor power source is also similar. To adapt either control unit, two techniques have been used. One is the 'voltage feedback control of the power source' and the other is 'scaling of the control unit output'.

6.3.2.1. *Voltage feedback control*
This technique is the same as described above for the linear voltage–current control unit. That is, no alteration has been made in the basic power–current control unit, but addition of an interface circuit provided voltage feedback control of the thyristor power source. The block diagram of this system is shown in Fig. 6–8.

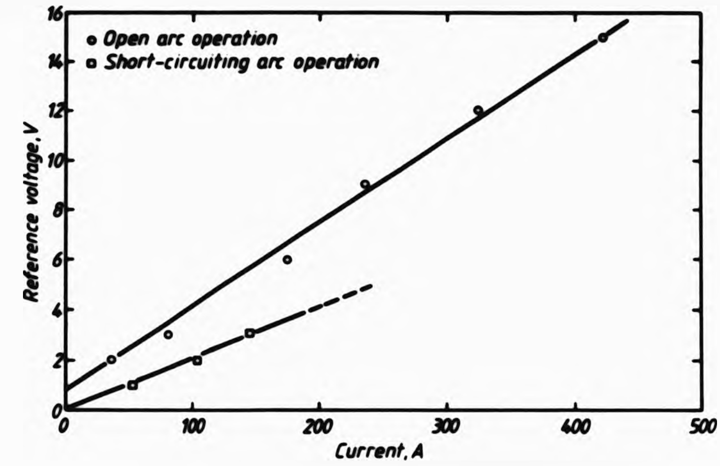


Fig. 6–5. Typical reference voltage–current relationships for the steady DC open arc and short circuiting arc operations, as obtained from Fig. 6–4.

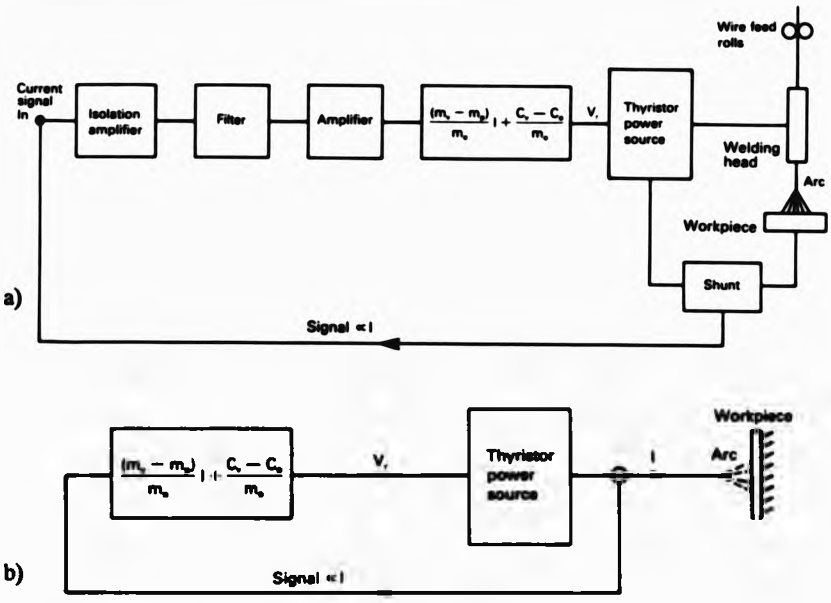


Fig. 6–6. Circuit arrangement of the control unit based on the reference voltage–current relationship:
a) block diagram, b) functional diagram.

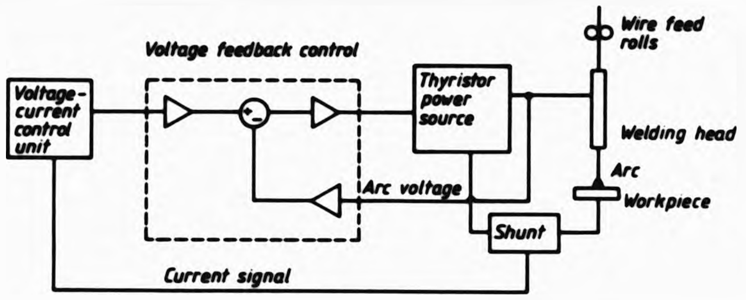


Fig. 6–7. Block diagram for the voltage feedback control of the thyristor power source, operating with the voltage–current control unit.

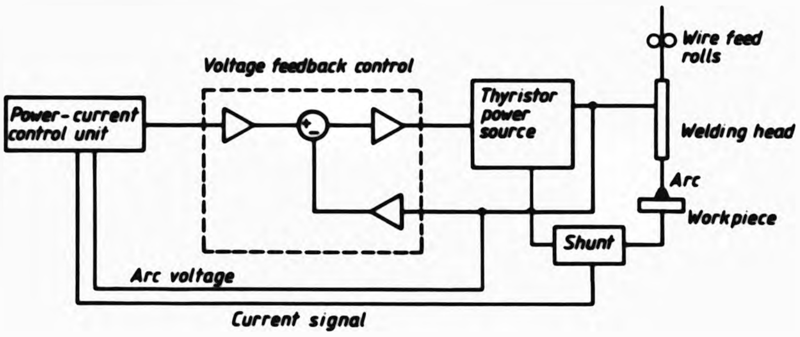


Fig. 6–8. Block diagram for the voltage feedback control of the thyristor power source, operating with the power–current control unit.

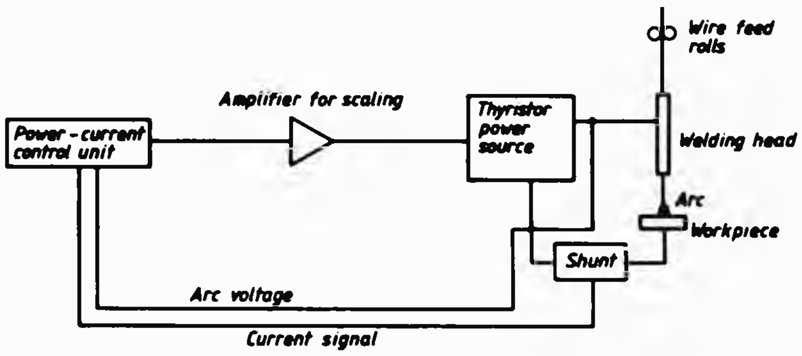


Fig. 6–9. Block diagram for scaling the output of the power–current control unit to drive the thyristor power source.

6.3.2.2. *Scaling the output*

The power–current control unit originally provided 0–5 V output, equal to the input reference voltage range of the transistor power source previously used. But the reference range of the thyristor power source presently used is 0–15 V. Therefore, the range of the control unit output has been scaled to provide 0–15 V by means of an amplifier, Fig. 6–9. This system does not require any further modification due to change of power source, since the control unit is independent of power source characteristics.

6.4. EVALUATION

Three control units, each adapted by two adaptation techniques to the power source provided six control systems (Fig. 6–3). These have been evaluated for control performance and welding performance.

Control performance assessed the capability of a system to regulate output of the power source automatically relevant to any wire feed speed, whether set constant, varied gradually or modulated. Furthermore, how the system would respond to changes in wire extension, wire diameter or shielding gas, for both constant and modulated wire feed, has been tested. The welding performance assessed the capability of a system to provide stable arc operation and make sound welds in butt and fillet joints, using both mechanised and manual techniques.

The evaluation of each control unit adapted to the thyristor power source is described in the following sections.

6.4.1. Linear voltage–current control unit

The control unit adapted to the thyristor controlled power source using either the reference voltage–current relationship or the voltage feedback control of the power source was capable of controlling both the steady DC open arc and short circuiting arc operation.

6.4.1.1. *'Reference voltage–current' control equation*

To prepare the control system for welding operation, the control unit was programmed with the parametric constants m_p, m_e and C_e relevant to the thyristor controlled power source, and in addition, with m_v and C_v relevant to the required material/wire diameter/shielding gas combination and mode of arc operation.

Steady DC open arc operation

Control performance

a). Arc initiation

The arc was initiated readily (in about 33 msec) by the control system, which supplied a high short circuit current while the wire electrode remained in contact with the workpiece. As the arc initiated, both the current and voltage (in about 100 msec) stabilised at the levels consistent with the operating wire feed speed. A typical arc starting behaviour is shown in Fig. 6–10.

b). Constant wire feed

For any wire feed speed maintained constant over the operating range, the control system adjusted the voltage automatically, such that stable arc with a constant length and spray metal transfer were maintained throughout the test runs. The consistency of the operating current and voltage, which indicates arc stability, is shown in Fig. 6–11a. The stable arc operation resulted in consistent and spatter-free bead deposits, Fig. 6–11b.

c). Variable wire feed

To test the capability of the control system to respond to a gradually varying wire feed speed, the test run was started at a relatively low feed speed of 7.5 m/min, which was then increased steadily to 12.5 m/min (while the workpiece was traversed at a constant speed of 0.30 m/min).

In operation, as the wire feed speed was increased gradually, the control system adjusted the arc voltage automatically compatible with the current corresponding to the feed speed, Fig. 6–12a. Therefore, the arc operation remained perfectly stable with the arc length being maintained constant, and spray metal transfer was produced throughout the weld run without any spatter. The stable arc performance resulted in the regular bead deposit, Fig. 6–12b.

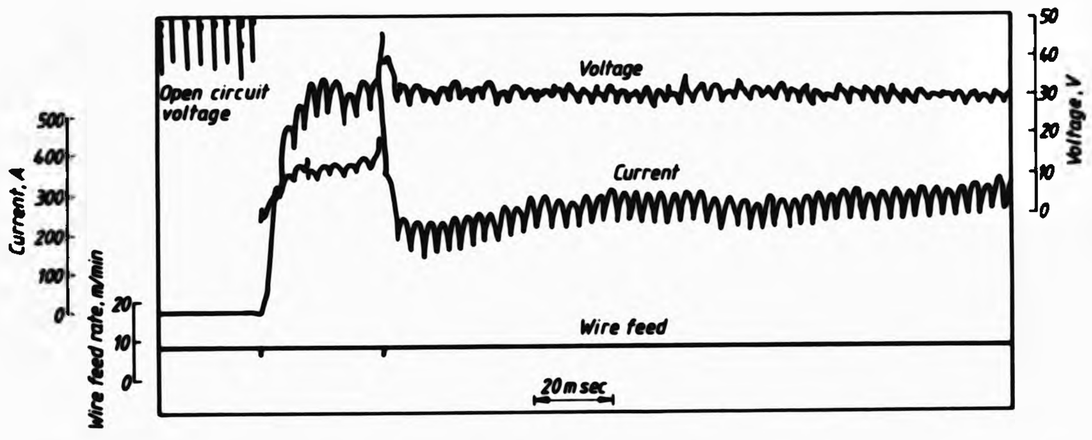
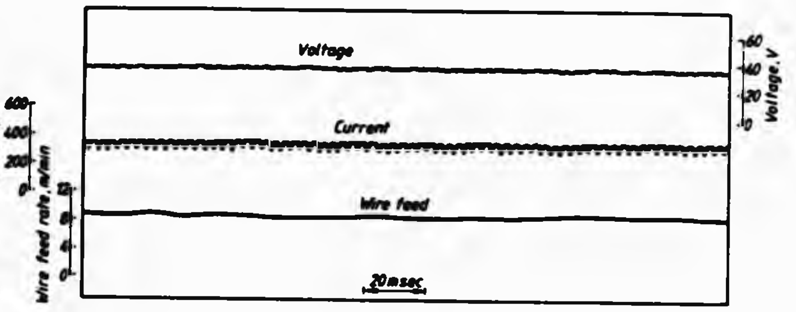


Fig. 6–10. Typical arc starting behaviour with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2.

a)



b)

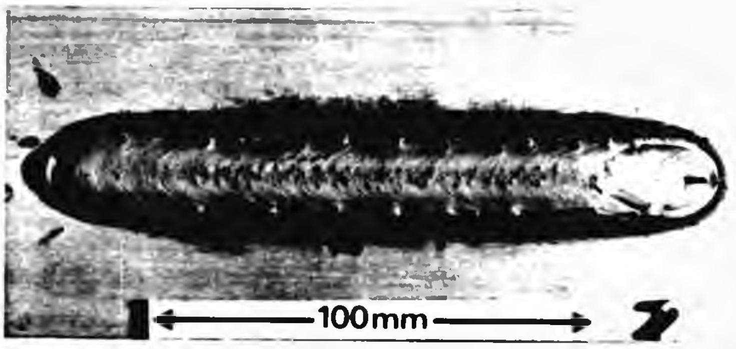
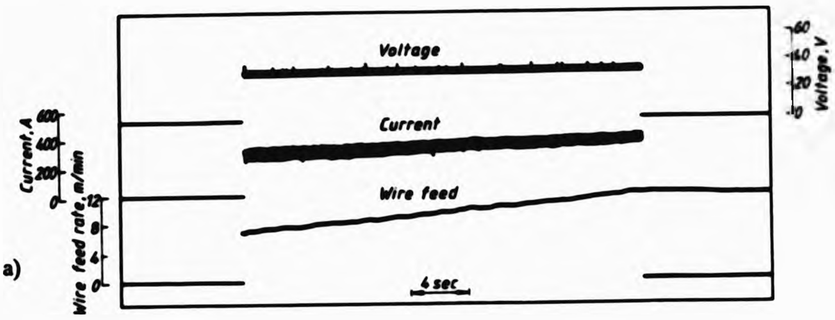


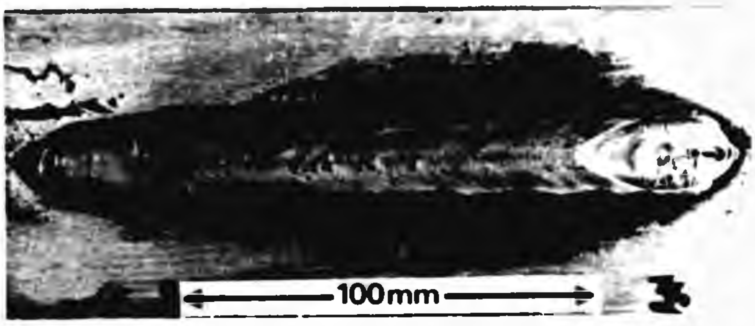
Fig. 6–11. Current and voltage adjustment and regularity of the bead deposit, indicating stability of the arc operation for the wire feed speed being maintained constant at 9 m/min, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) current and voltage adjustment relevant to the wire feed,

b) bead deposit.



a)



b)

Fig. 6–12. Current and voltage adjustment and regularity of the bead deposit, indicating stability of the arc operation, for the wire feed speed being increased from 7.5 to 12.5 m/min, while maintaining the traverse speed at 0.3 m/min, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) current and voltage adjustment relevant to the wire feed,
b) bead deposit.

d). *Modulated wire feed*

How the control system would respond to a sudden change in the wire feed speed was tested with bead runs made using square wave modulated wire feed with a modulation frequency of 2 Hz.

The control system was found to be capable of adjusting the arc voltage automatically relevant to the modulation in the wire feed speed, Fig. 6–13a. Both the current and voltage were adjusted rapidly, not only compatible with the low and high levels of feed speed, but also consistent with the transitions between the levels. Therefore, the overall arc operation remained stable even when the low feed speed was as low as permitted by the onset of the desired spray type metal transfer (7.5 m/min) and the high level as large as allowed by the power source output rating (10.5 m/min). Even with these levels the arc length changed by only about 3 mm during a modulation period. The consistent arc operation produced regular bead deposits, Fig. 6–13b.

e). *Effect of wire extension*

For the gradually varying wire extension, using either constant or modulated wire feed speed, the arc operation was found to be stable, such that the arc length remained substantially constant (at about 7 mm) while the wire extension increased from about 11 to 23 mm. This was obtained without any adjustment being made on the control unit, which modified the voltage automatically as the distance between the welding head and workpiece increased from 18 to 30 mm, Fig. 6–14a and b. The regularity of the bead deposits for the constant and modulated wire feed is shown in Fig. 6–14c.

In addition, for the wire extension increasing in steps, using either constant or modulated wire feed, the control system adjusted the arc voltage automatically, Fig. 6–15a and b, such that the overall arc length remained constant (at about 8 mm) while the wire extension increased from 10 to 15 to 20 to 25 mm, as the distance between the welding head and workpiece increased from 18 to 33 mm in three steps. The arc operation was found to be very stable throughout the bead runs, even at transitions between the steps, without any fluctuation or deflection being produced in the arc column. The stable arc operation resulted in regular bead deposits for both

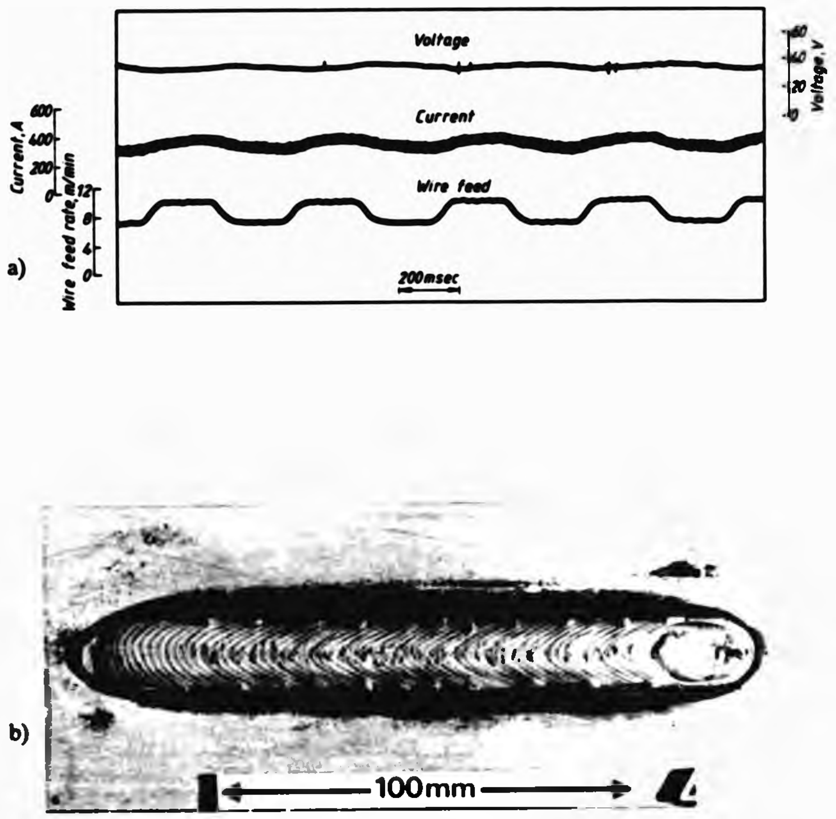


Fig. 6–13. Current and voltage response and regularity of the bead deposit indicating, stability of the arc operation, for the wire feed speed being modulated with square wave from 7.5 to 10.5 m/min at 2 Hz, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in $Ar+5\%CO_2$:

a) current and voltage adjustment relevant to the wire feed,
b) bead deposit.

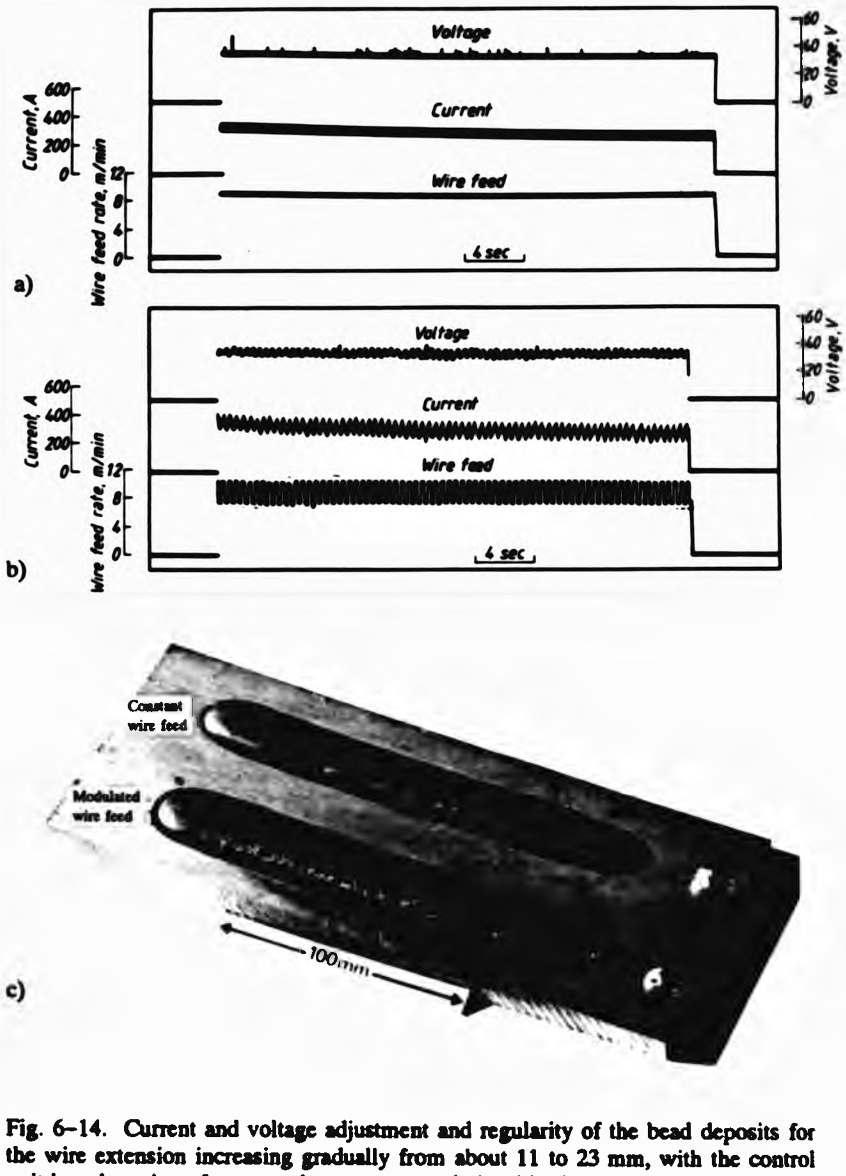


Fig. 6–14. Current and voltage adjustment and regularity of the bead deposits for the wire extension increasing gradually from about 11 to 23 mm, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) wire feed being maintained constant at 9 m/min,

b) wire feed being modulated from 7.5 to 10.5 m/min at 2 Hz,

c) bead deposits.

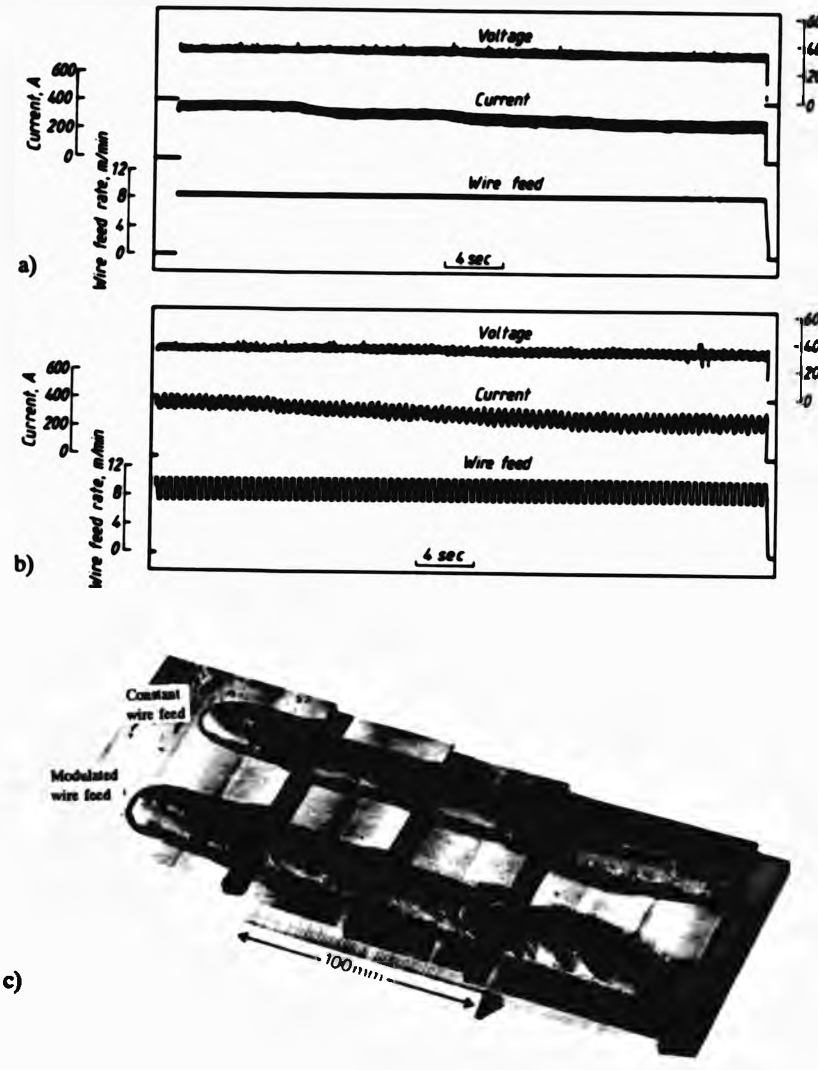


Fig. 6–15. Current and voltage adjustment and regularity of the bead deposits for the wire extension increasing in steps from 10 to 15 to 20 to 25 mm, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) wire feed being maintained constant at 9 m/min,
b) wire feed being modulated from 7.5 to 10.5 m/min at 2 Hz,
c) bead deposits

the constant and modulated wire feed speed, Fig. 6–15c.

f). Effect of wire diameter

For operation with 1.0 mm diameter mild steel wire, practically no adjustment of the parametric constants m_v and C_v was required on the control unit. The control system adjusted the arc voltage automatically providing stable arc operation and consistent bead deposits for any wire feed speed whether maintained constant, varied gradually or modulated.

Welding performance

The welding performance was tested with both mechanised and manual techniques. The details of all the joints and welding conditions used are given in Table 6–3.

a). Mechanised operation

For each joint, the arc operation was very stable such that the arc column did not deflect towards either side of the joint. The metal transfer was stable spray type without any spatter.

The main feature of each weld, Fig. 6–16, is that the bead deposit is symmetrical relative to the joint and free from any defect. The deposit profile is regular with good wetting–in to the joint surface. For the butt weld, the penetration profile is broad bowl type which is desirable to avoid lack of sidewall fusion and lack of root fusion defects.

b). Manual operation

Even with the manual technique, the arc operation was found to be stable without significant fluctuations or deflections in the arc column. The metal transfer was also stable without spatter being produced over the weld runs.

Macrosections of the welds are shown in Fig. 6–17. The main characteristics of these welds are similar to those made with the mechanised operation. All the welds are free from any defect such as lack of root fusion or lack of sidewall fusion.

Table 6–3. Details of joints and welding conditions for evaluating the linear voltage–current control unit adapted to the thyristor controlled power source using the reference voltage–current equation, with 1.2 mm diameter mild steel wire in Ar+15%CO_2 for steady DC open arc operation.

Figure no.	Joint				Backing	Welding								
	Type	Material thickness, mm	Preparation			Position	Technique		Conditions					
			Included angle	Root gap, mm			Number of runs	Run number	Mean current, A	Mean voltage, V	Wire feed speed, m/min	Modulation frequency, Hz	Traverse speed, m/min	Gas flow rate, l/min
Mechanised operation														
6–16a	Butt	25	15°–V	3	Ceramic	Flat	5	1st	-	-	Modulated, 7.5–10.5	2	0.25	30
								2nd	-	-	Modulated, 7.5–10.5	2	0.25	30
								3rd	-	-	Modulated, 7.5–10.5	2	0.30	30
								4th	-	-	Modulated, 7.5–10.5	2	0.30	30
								5th	-	-	Modulated, 7.5–10.5	2	0.15	30
6–16b	Fillet	9.5	90°	-	-	Flat	1	-	-	-	Modulated, 7.5–10.5	2	0.20	24
6–16c	Fillet	9.5	90°	-	-	Flat	1	-	-	-	Constant, 9.0	-	0.20	24
Manual operation														
6–17a	Butt	25	60°–V	3	Ceramic	Flat	8	1st	250	29	Constant	-	-	24
								2nd	250	29	Constant	-	-	24
								3rd	260	29	Constant	-	-	24
								4th	260	29	Constant	-	-	24
								5th	260	29	Constant	-	-	24
								6th	250	29	Constant	-	-	24
								7th	250	29	Constant	-	-	24
								8th	250	29	Constant	-	-	24
6–17b	Butt	12.7	30°–V	2	Ceramic	Flat	3	1st	250	29	Constant	-	-	24
								2nd	300	31	Constant	-	-	24
								3rd	270	31	Constant	-	-	24
6–17c	Fillet	12.7	90°	-	-	h.v.	1	-	270	30	Constant	-	-	24

h = Horizontal
v = Vertical
Gas nozzle diameter for mechanised welding = 22 mm, and for manual welding = 15 mm

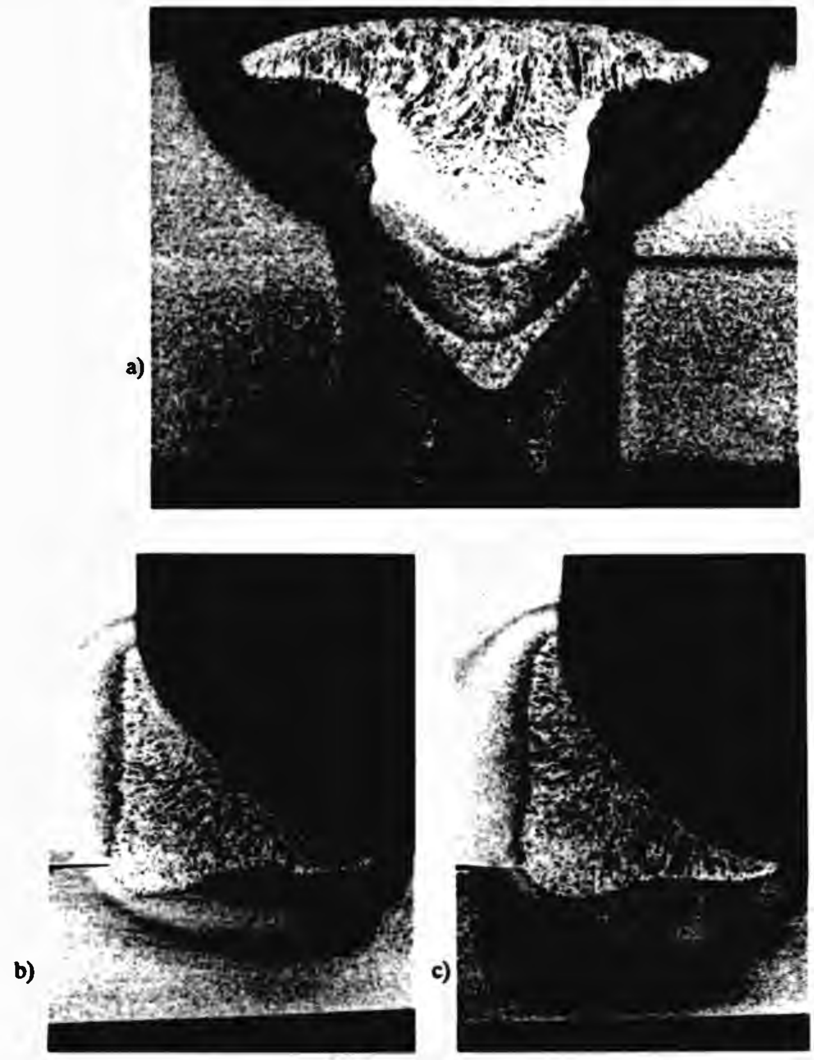


Fig. 6–16. Macrosections of the welds made for the mechanised operation, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+15%CO_2:

a) butt weld, 25 mm, 15°, 3 mm root gap, flat, 5 runs, wire feed speed modulated from 7.5 to 10.5 m/min at 2 Hz, ×3;

b) fillet weld, 9.5 mm, 90°, flat, 1 run, wire feed speed modulated from 7.5 to 10.5 m/min at 2 Hz, ×3;

c) fillet weld, 9.5 mm, 90°, flat, 1 run, wire feed speed constant at 9 m/min, ×3.

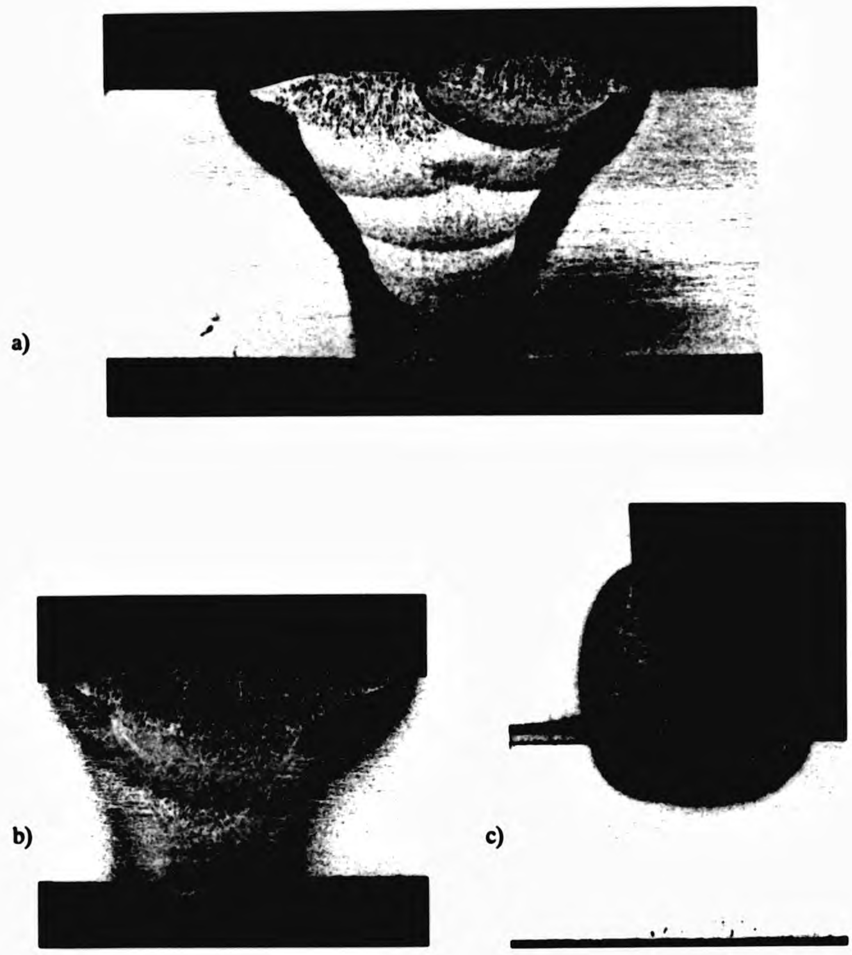


Fig. 6–17. Macrosections of the welds made for manual operation, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+15%CO_2:
a) butt weld, 25 mm, 60°, 3 mm root gap, flat, 8 runs, ×2;
b) butt weld, 12.7 mm, 30°, 2 mm root gap, flat, 3 runs, ×3;
c) fillet weld, 12.7 mm, 90°, horizontal/vertical, 1 run, ×3.

Short circuiting arc operation

Control performance

For each of the four material/wire diameter/shielding gas combinations, comprising 1.0 and 1.2 mm diameter mild steel wires in both CO_2 and Ar+20%CO_2 , the control system was found to adjust the arc voltage automatically compatible with mean current corresponding to any wire feed speed whether maintained constant, varied gradually or modulated with square waveform. Therefore, the arc operation remained stable with consistent short circuiting frequency and practically no spatter. The stable arc operation produced regular bead deposits. Typical oscillograms of current and voltage for the three types of wire feed, and the regularity of the bead deposits are shown in Fig. 6–18 and 6–19 for the mild steel/1.0 mm diameter/CO_2 combination.

Effect of wire extension

To test how the control system would respond to a gradually varying wire extension, test runs were made with a constant and modulated wire feed using 1.2 mm diameter mild steel wire in Ar+20%CO_2. In addition, the control response to sudden changes in wire extension was tested with a constant wire feed speed using 1.0 mm diameter wire in both CO_2 and Ar+20% CO_2 shielding gases.

For the gradually varying wire extension, the control system provided stable arc operation throughout the test runs, without any adjustment being made on the control unit. Over the runs, the short circuiting frequency remained consistent while the wire extension increased from 10 to 20 mm, because the system automatically supplied arc voltage compatible with the current relevant to the wire extension, Fig. 6–20a and b. For both constant and modulated wire feed, regular and spatter-free bead deposits were produced, Fig. 6–20c.

For a given material/wire diameter/shielding gas combination, the control system was found to be capable of adjusting the arc voltage compatible with a series of sudden changes in wire extension by 3 mm, Fig. 6–21a and b. This adjustment provided very stable arc operation, maintaining consistent short circuiting frequency on the square crests and troughs throughout the weld runs. The stability of arc operation resulted in regular and spatter-free bead deposits, Fig. 6–21c.

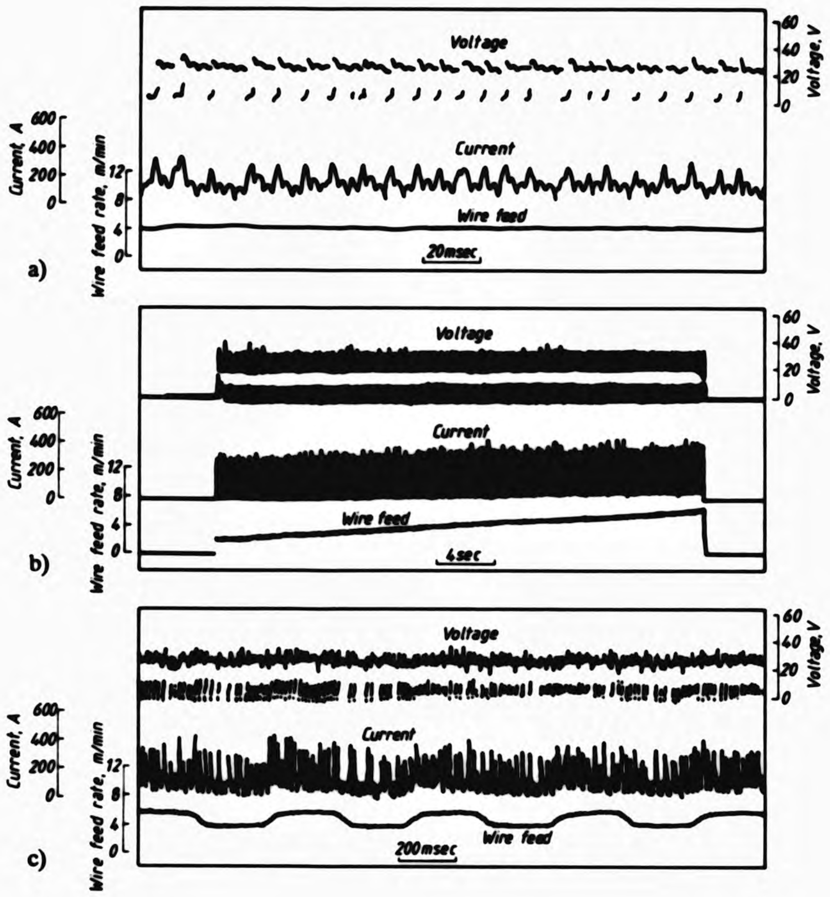


Fig. 6–18. Current and voltage adjustment indicating stability for short circuiting arc operation, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.0 mm diameter mild steel wire in CO_2, for three types of wire feed speed:

a) constant at 4 m/min,

b) varied gradually from 2 to 6.55 m/min,

c) modulated with square wave from 3.5 to 5.5 m/min at 2 Hz.

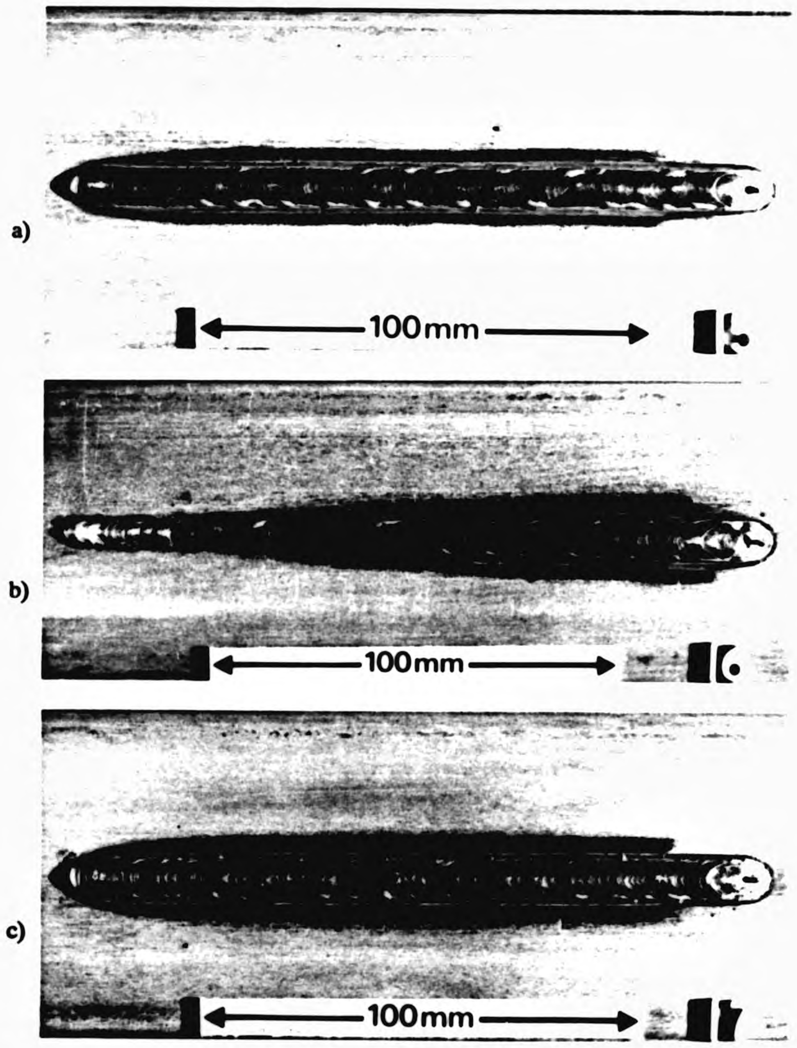


Fig. 6–19. Bead deposits showing stability for short circuiting arc operation, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.0 mm diameter mild steel wire in CO_2, for different types of wire feed speed:

a) constant at 4 m/min,
b) varied gradually from 2 to 6.55 m/min,
c) modulated with square wave from 3.5 to 5.5 m/min at 2 Hz.

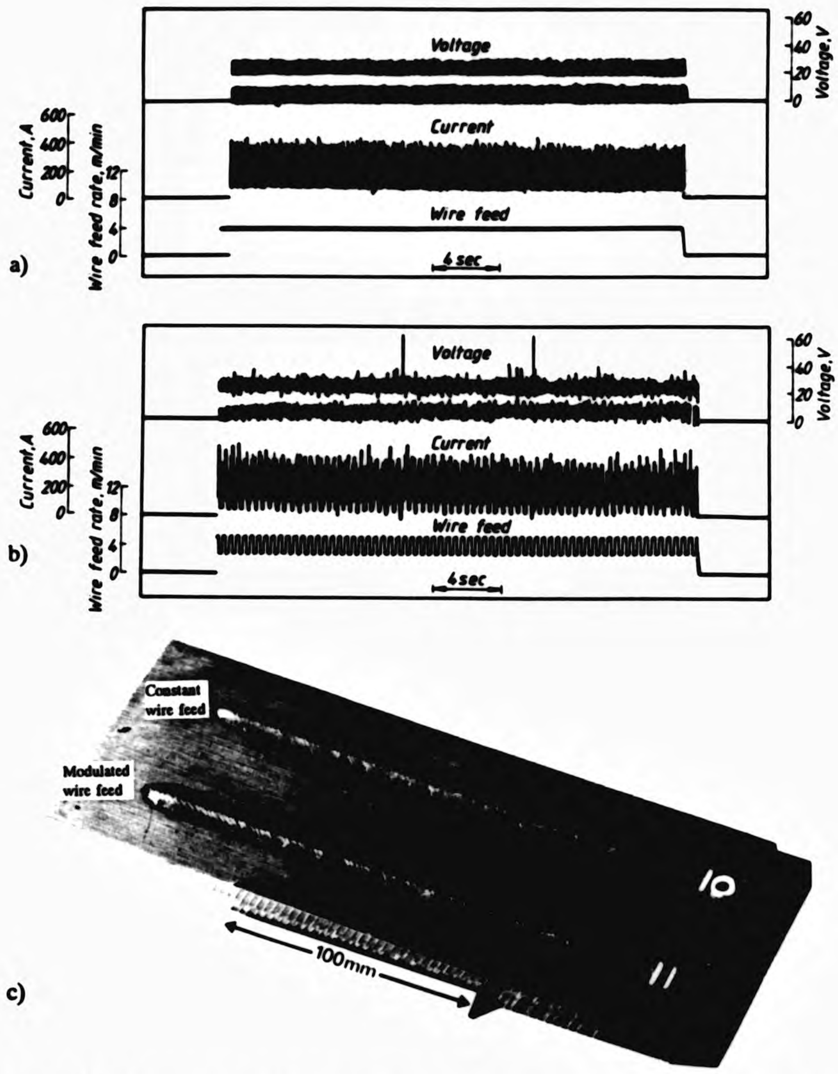


Fig. 6–20. Current and voltage adjustment and regularity of the bead deposits, indicating stability of the arc operation, for the wire extension increasing gradually from about 10 to 20 mm, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.2 mm diameter mild steel wire in $Ar+20\%CO_2$:

a) wire feed being maintained constant at 4 m/min,
b) wire feed being modulated from 2.5 to 5 m/min at 2 Hz,
c) bead deposits.

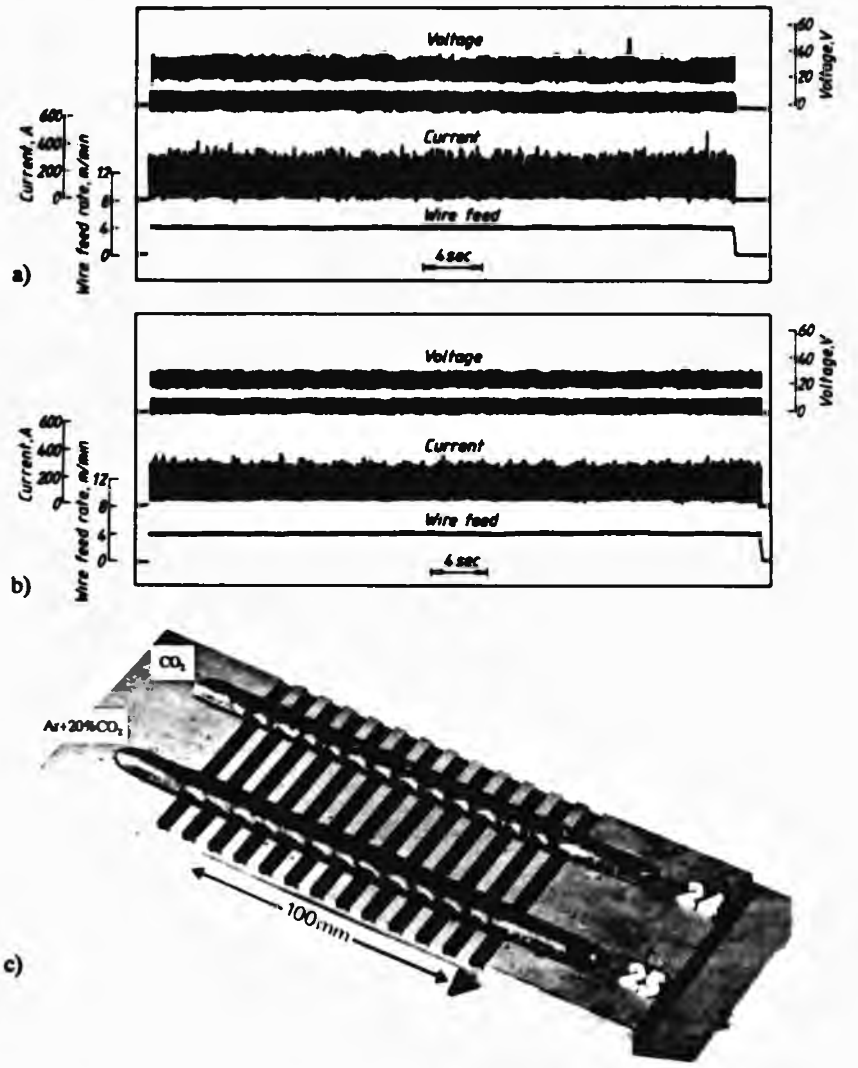


Fig. 6–21. Current and voltage adjustment and regularity of the bead deposits, indicating stability of the arc operation, for a series of sudden changes in wire extension by 3 mm, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.0 mm diameter mild steel wire at constant wire feed speed of 4 m/min:

a) current and voltage adjustment in CO_2,
b) current and voltage adjustment in Ar+20%CO_2,
c) bead deposits.

Welding performance

The welding performance was tested for the fillet joints, using 1.0 mm diameter wire in CO_2 shielding gas. The details of all the joints and the welding conditions used are given in Table 6–4.

For both mechanised and manual welding techniques, the arc operation was found to be very stable throughout the weld runs. The short circuiting frequency remained consistent for the constant as well as the modulated wire feed, and practically no spatter was produced.

Macrosections of all the welds are shown in Fig. 6–22. The weld deposit of each weld is symmetrical. All the welds are considered to be acceptable as these are free from any defect such as lack of sidewall fusion or lack of root fusion.

6.4.1.2 *Voltage feedback control*

For steady DC open arc operation, the performance of the control system with feedback control of the power source was found to be essentially similar to that for the control system with the control unit adapted using the reference voltage–current equation, as described above. In operation, the system initiated the arc readily, and then adjusted the arc voltage automatically consistent with the current relevant to any operating wire feed speed, whether maintained constant, varied gradually, or modulated with square wave, Fig. 6–23. The adjustment provided stable arc operation throughout the weld runs, such that the overall arc length was maintained constant (at about 7 mm). Even with the modulated wire feed over the entire operating range, from 7.5 to 10.5 m/min at 2 Hz, the arc length changed by only about 2 mm during a modulation period. The stable arc operation resulted in regular bead deposits, shown in Fig. 6–24 for the constant, variable and modulated wire feed.

For the short circuiting arc operation, the control system adjusted the arc voltage automatically relevant to the mean current corresponding to any wire feed speed over the operating range, whether maintained constant, varied gradually or modulated with square wave, Fig. 6–25. Therefore, the arc operated with consistent short circuiting frequency without any spatter being produced. The stable arc operation, which the control system provided, resulted in regular bead deposits, Fig. 6–26.

Table 6–4. Details of joints and welding conditions for evaluating the linear voltage–current control unit adapted to the thyristor controlled power source using the reference voltage–current equation, with 1.0 mm diameter mild steel wire in CO_2 for short circuiting arc operation.

Figure no.	Joint				Backing	Welding								
	Type	Material thickness, mm	Preparation			Position	Technique		Conditions					
			Included angle	Root gap, mm			Number of runs	Run number	Mean current, A	Mean voltage, V	Wire feed speed, m/min	Modulation frequency, Hz	Traverse speed, m/min	Gas flow rate, l/min
Mechanised operation														
6–22a	fillet	5	90°	–	–	Flat	1	–	–	–	Constant, 4	–	0.2	18.5
6–22b	Fillet	5	90°	–	–	Flat	1	–	–	–	Modulated, 3–5	2	0.2	18.5
Manual operation														
6–22c	Fillet	6.4	90°	–	–	h.v	1	–	140	20	Constant	–	–	14
6–22d	Fillet	3.2	90°	–	–	h.v	1	–	120	20	Constant	–	–	14
6–22e	Fillet	3.2	90°	–	–	v–down	1	–	120	20	Constant	–	–	14

h = Horizontal
v = Vertical
Gas nozzle diameter for mechanised welding = 22 mm, and for manual welding = 15 mm

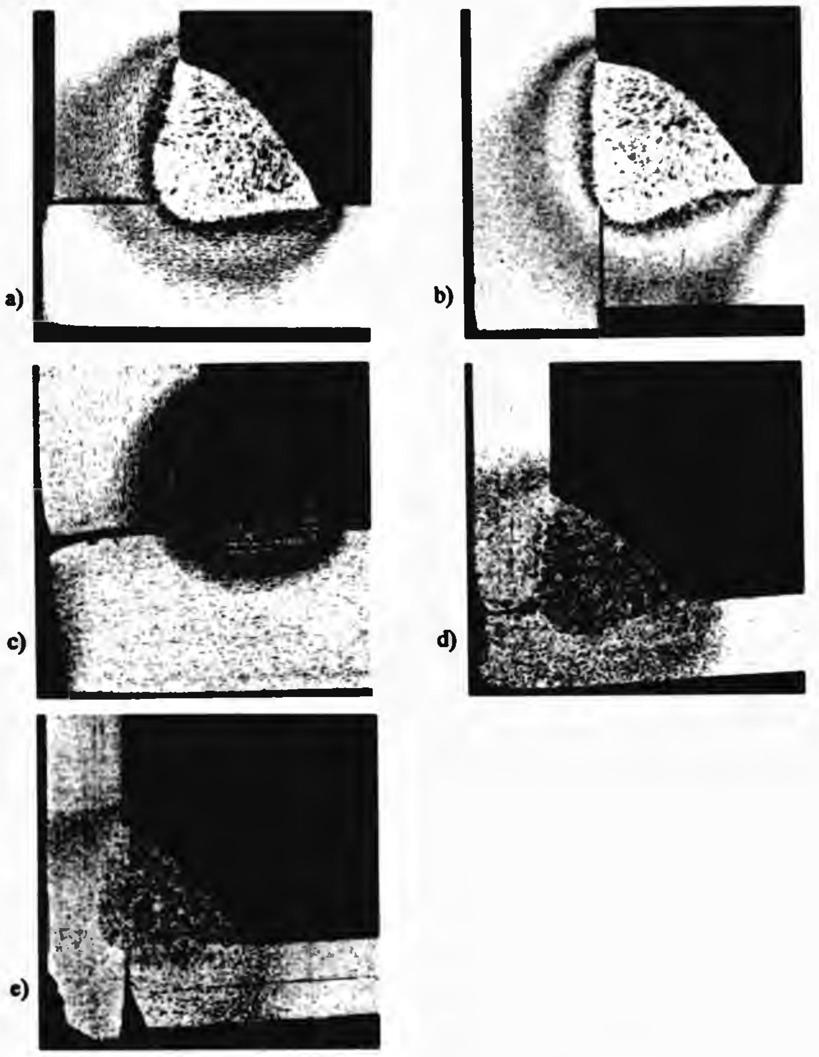


Fig. 6–22. Macrosections of fillet welds made for short circuiting arc operation, with the control unit based on the reference voltage–current relationship driving the thyristor power source, using 1.0 mm diameter mild steel wire in CO_2, ×5:

a) mechanised, 5 mm, 90°, flat, wire feed speed constant at 4 m/min;

b) mechanised, 5 mm, 90°, flat, wire feed speed modulated with square wave from 3 to 5 m/min at 2 Hz;

c) manual, 6.4 mm, 90°, horizontal/vertical, 140 A, 20 V;

d) manual, 3.2 mm, 90°, horizontal/vertical, 120 A, 20 V;

e) manual, 3.2 mm, 90°, vertical–down, 120 A, 20 V.

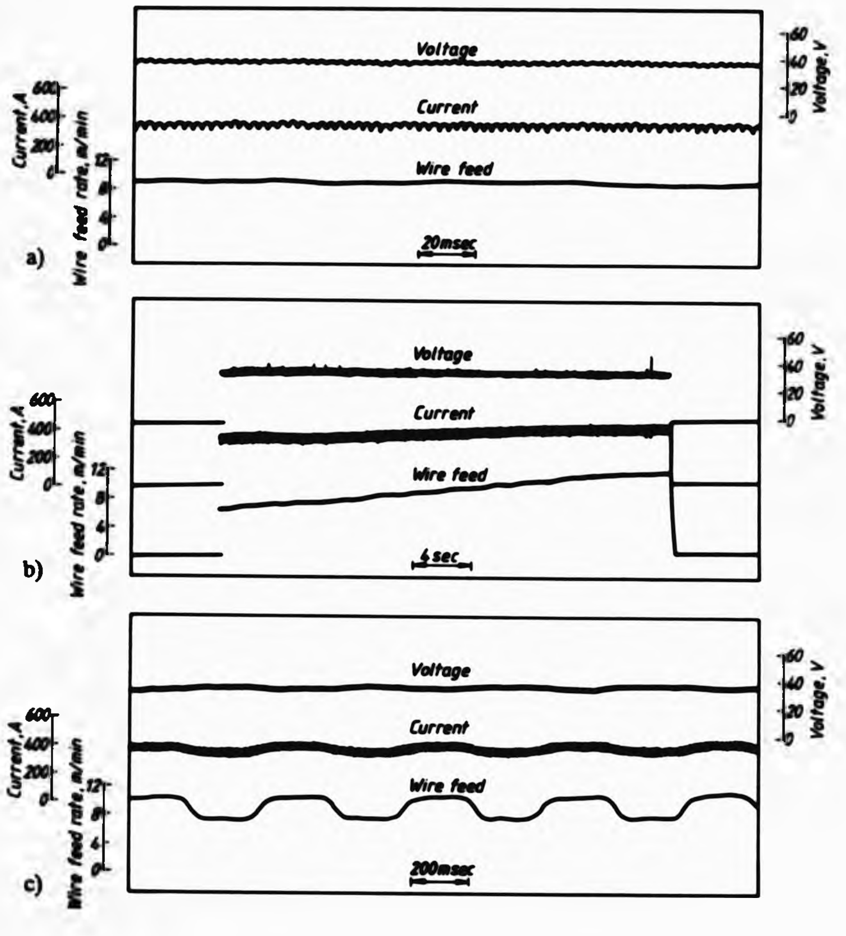


Fig. 6–23. Current and voltage adjustment with the voltage–current control unit and feedback control of the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for different types of wire feed speed:

a) constant at 9 m/min,

b) varied gradually from 6.75 to 11.25 m/min,

c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

a)

b)

c)

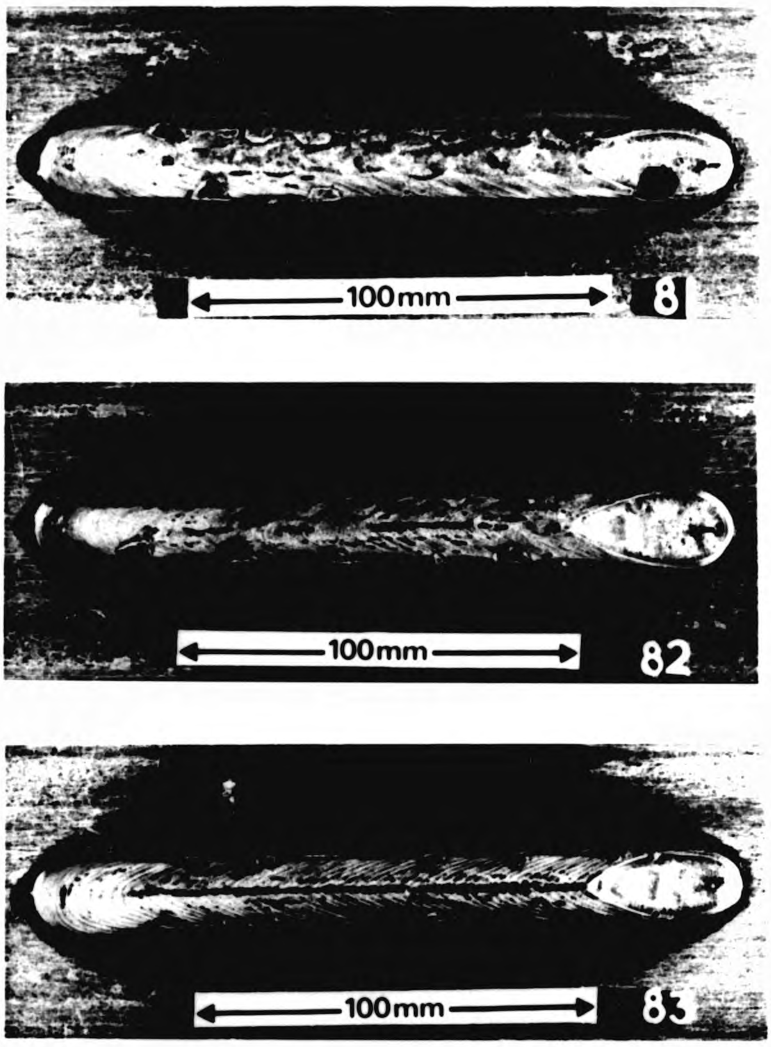


Fig. 6–24. Bead deposits showing stability of the arc operation, with the voltage–current control unit and feedback control of the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for different types of wire feed speed:

a) constant at 9 m/min,
b) varied gradually from 6.75 to 11.25 m/min,
c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

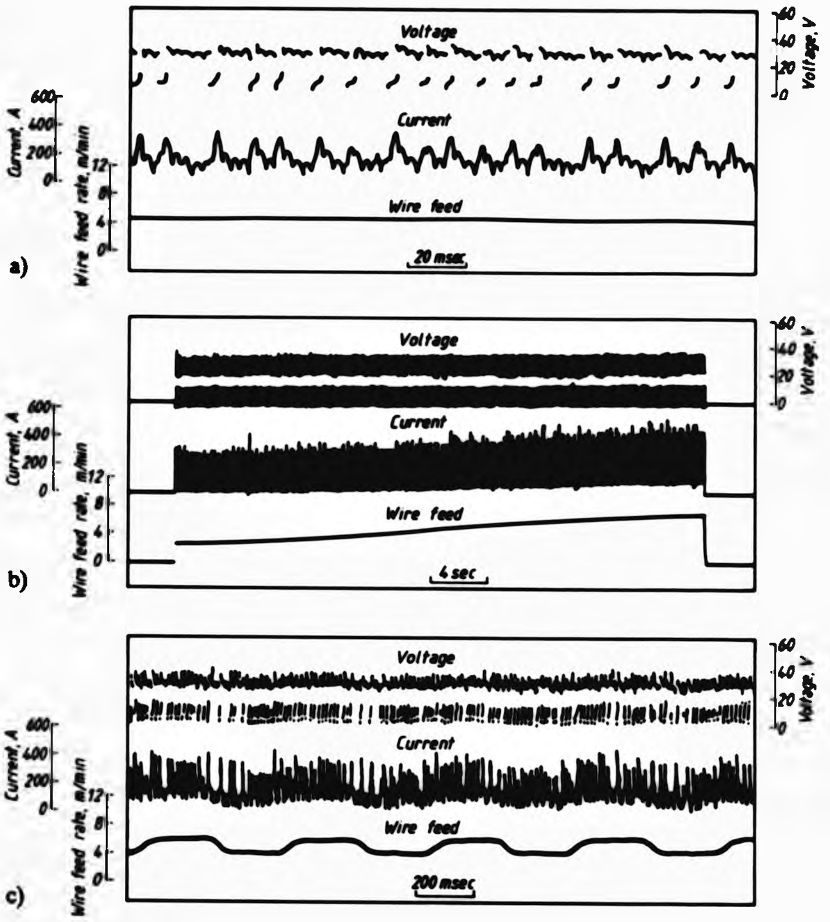


Fig. 6–25. Current and voltage adjustment for short circuiting arc operation, with the voltage–current control unit and feedback control of the thyristor power source, using 1.0 mm diameter mild steel wire in CO_2, for different types of wire feed speed:

a) constant at 4.5 m/min,

b) varied gradually from 2.4 to 7.26 m/min,

c) modulated with square wave from 4 to 6 m/min at 2 Hz.

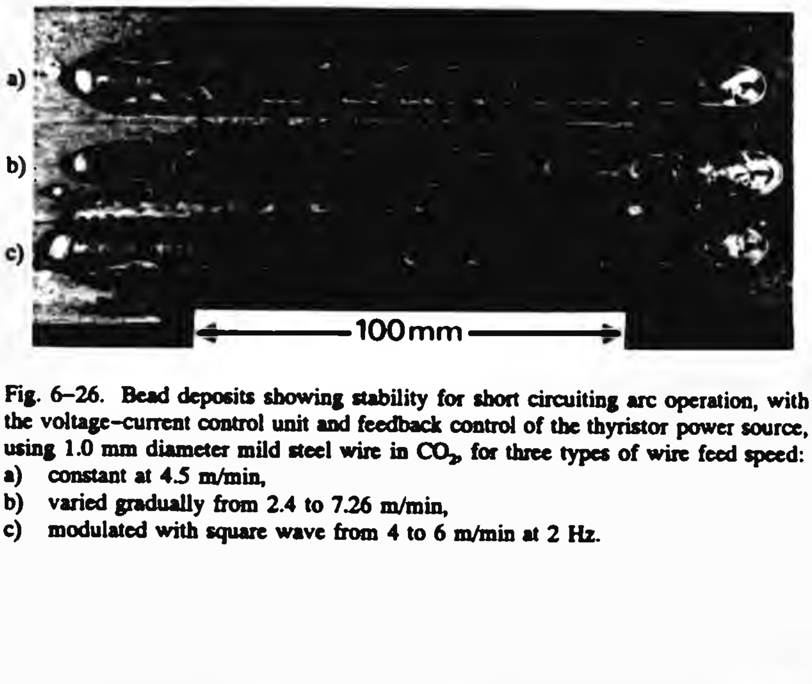


Fig. 6–26. Bead deposits showing stability for short circuiting arc operation, with the voltage–current control unit and feedback control of the thyristor power source, using 1.0 mm diameter mild steel wire in CO_2, for three types of wire feed speed:
a) constant at 4.5 m/min,
b) varied gradually from 2.4 to 7.26 m/min,
c) modulated with square wave from 4 to 6 m/min at 2 Hz.

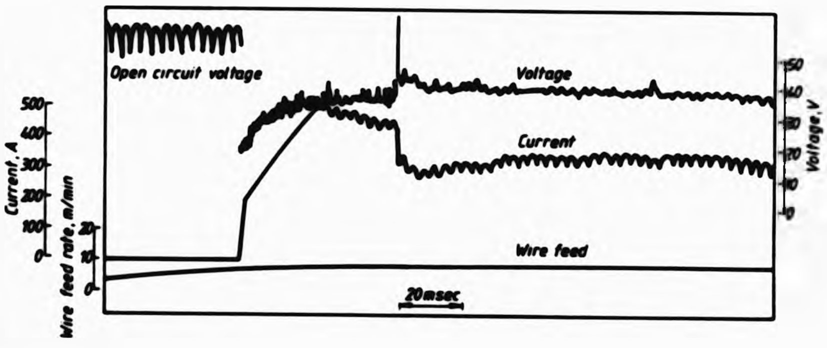


Fig. 6–27. Typical arc starting behaviour with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2.

6.4.2. Power–current control units

Both the quadratic and linear power–current control units provide synergic control only for the steady DC open arc operation. Prior to testing with any wire diameter/shielding gas combination, the quadratic power–current control unit was programmed with the relevant parametric constants m_v and C_v, and the linear power–current control unit with m_s and C_s. In practice, the performance of both the control units was found to be similar.

6.4.2.1. *Scaling the output*

Control performance

The control system with either the quadratic or the linear power–current control unit, initiated the arc readily, Fig. 6–27, and then provided arc current and voltage at levels compatible with any wire feed speed, such that stable arc operation and spray metal transfer were maintained throughout a test run. The consistency of the operating current and voltage for the wire feed speed being maintained constant, varied gradually or modulated with square waveform is shown in Fig. 6–28. The stable arc operation resulted in uniform and consistent bead deposits, Fig. 6–29.

For any change in wire extension, either varied gradually or in steps, no adjustment was required on the control units using a constant or modulated wire feed speed. For the gradually varying wire extension, the control system continuously adjusted the arc current and voltage consistent with the wire extension, Fig. 6–30a and b, such that the arc operation remained stable. The arc length was maintained constant throughout the test runs at about 7 mm as the wire extension increased gradually from 11 to 23 mm, corresponding to the standoff distance increasing from 18 to 30 mm. The stable arc operation, resulted in uniform and consistent bead deposits for both the constant and modulated wire feed, Fig. 6–30c.

Even with the wire extension increasing in steps, the control system was found to be capable of adjusting the output of the power source automatically, Fig. 6–31a and b. The arc operation remained stable with an arc length of about 7–9 mm throughout the test runs, as the wire extension increased from 10 to 15 to 20 to 25 mm relevant to the standoff distance increasing from 18 to 33 mm in three 5 mm steps. With this wide range of wire extension, the control system produced regular

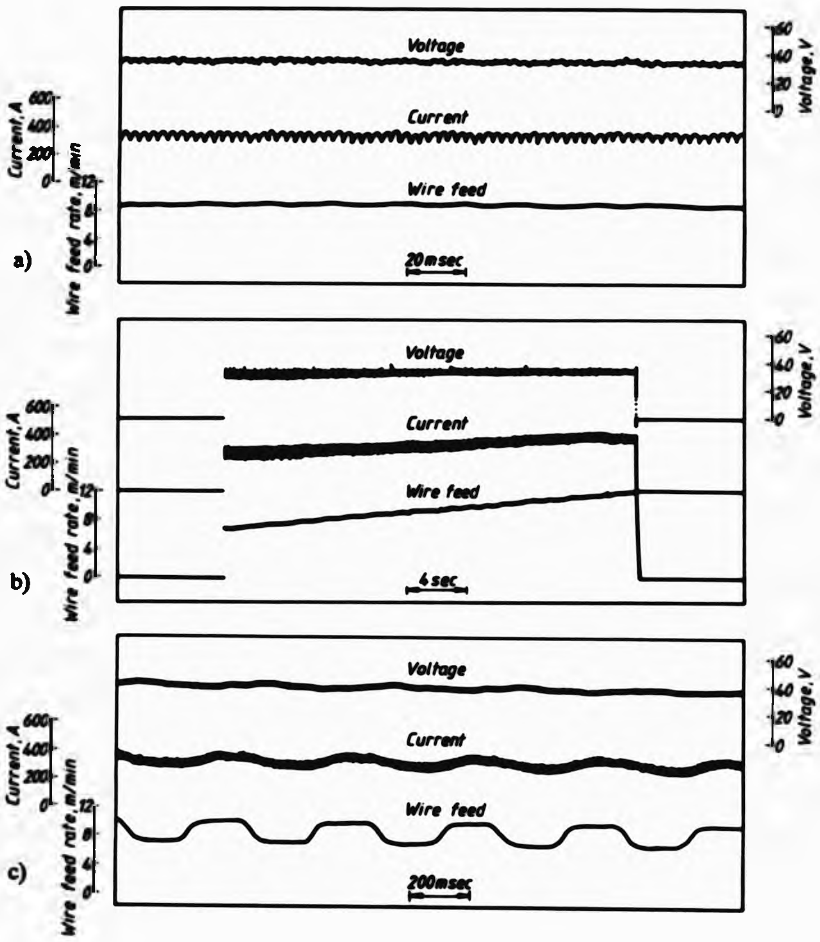


Fig. 6–28. Current and voltage adjustment with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for different types of wire feed speed:

a) constant at 9 m/min,

b) varied gradually from 7.5 to 12.98 m/min,

c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

a)
b)
c)

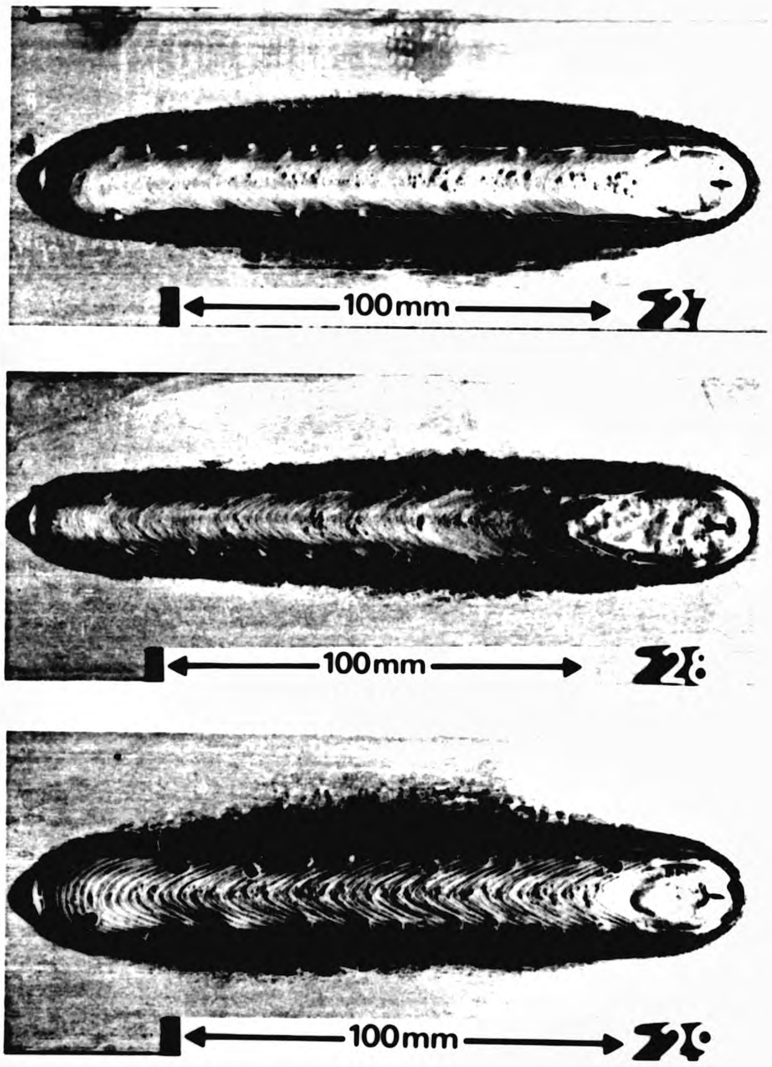


Fig. 6–29. Bead deposits showing stability of arc operation with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for different types of wire feed speed:
a) constant at 9 m/min,
b) varied gradually from 7.5 to 12.98 m/min,
c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

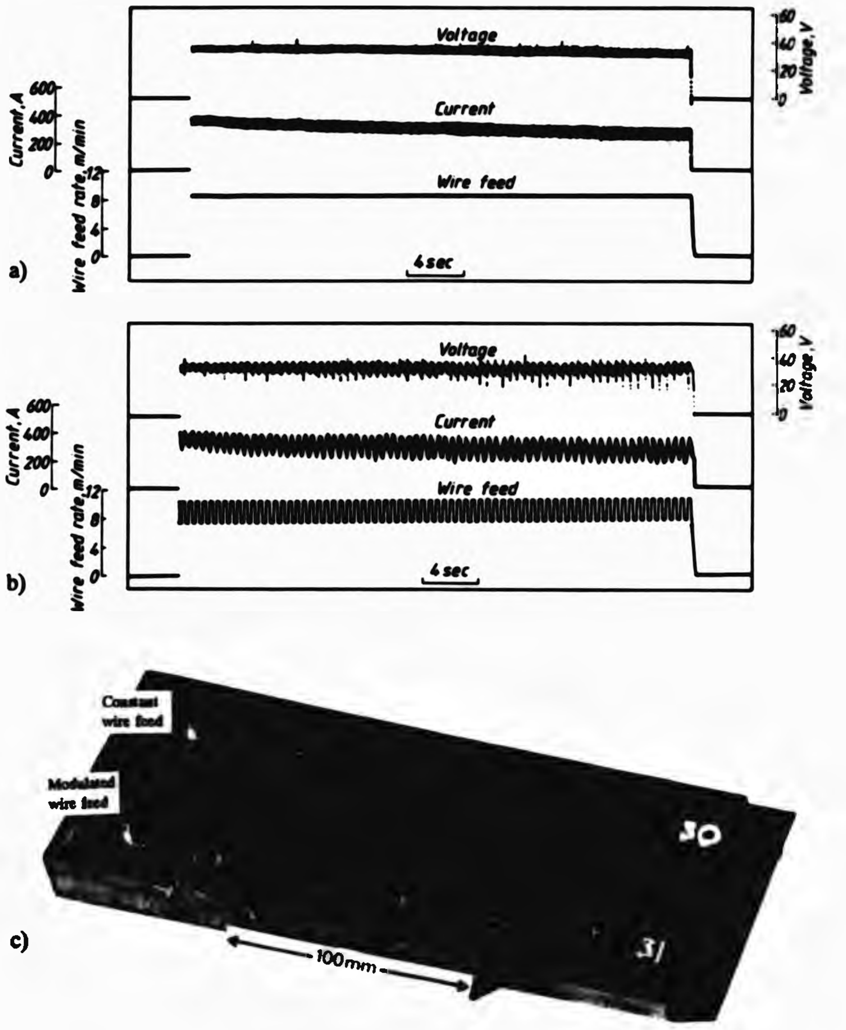


Fig. 6–30. Current and voltage adjustment and regularity of the bead deposits, indicating stability of arc operation, for the wire extension increasing gradually from about 11 to 23 mm, with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) wire feed being maintained constant at 9 m/min,

b) wire feed being modulated from 7.5 to 10.5 m/min at 2 Hz,

c) bead deposits.

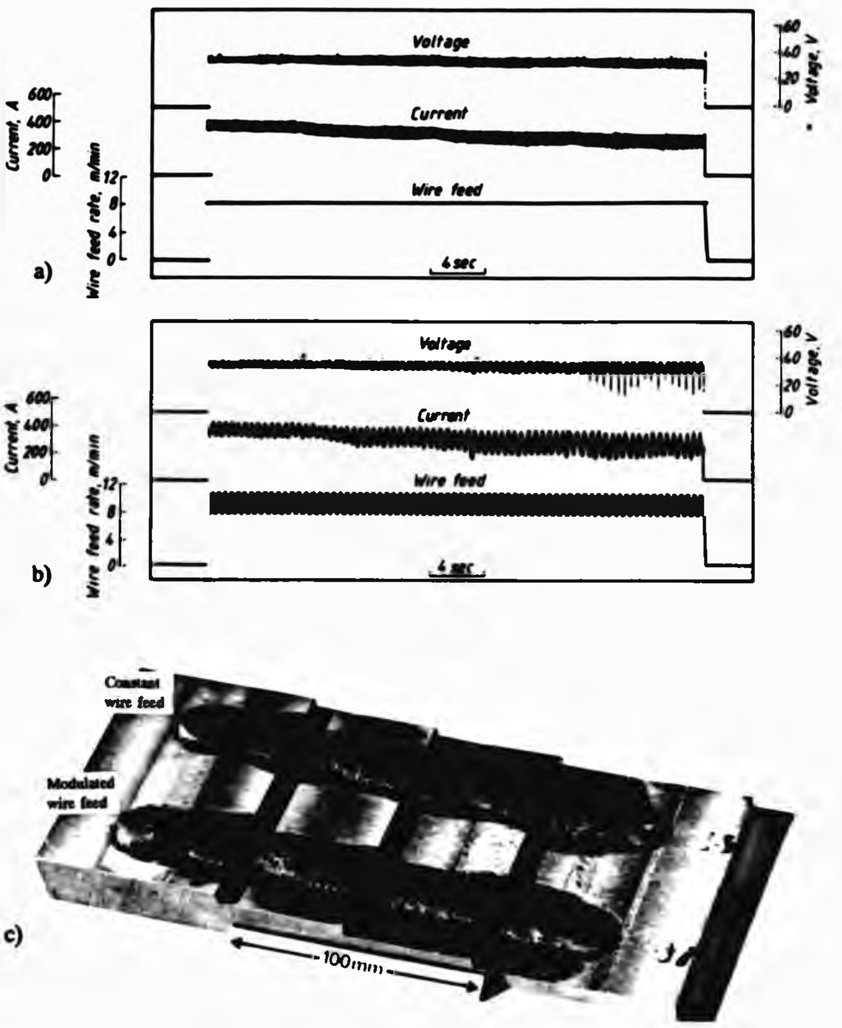


Fig. 6–31. Current and voltage adjustment and regularity of the bead deposits, indicating stability of arc operation, for the wire extension increasing in steps from 10 to 15 to 20 to 25 mm, with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2:

a) wire feed being maintained constant at 9 m/min,

b) wire feed being modulated from 7.5 to 10.5 m/min at 2 Hz,

c) bead deposits.

bead deposits with the constant as well as modulated wire feed, Fig. 6–31c.

For the change in wire diameter from 1.2 to 1.0 mm, no adjustment was required on the control unit because, for a given power (i.e. current and voltage), the volume of the wire melted per unit time was the same for both the diameters (whereas the wire feed speeds were different). The control system was found to be capable of adjusting the arc current and voltage automatically giving stable arc operation for any wire feed over the operating range, whether maintained constant, varied gradually or modulated with square wave. The stable arc operation produced regular bead deposits for the three types of wire feed.

Welding performance

Welding performance was tested using both mechanised and manual techniques for butt and fillet joints using 1.2 mm diameter mild steel wire in Ar+15% CO_2 shielding gas. The details of all the joints and the welding conditions are given in Table 6–5.

For both the mechanised and manual operation, stable arc and spray metal transfer without spatter were maintained throughout the weld runs. The arc column operated coaxially with the wire without any deflection towards either sidewall of the joint. The weld deposits are symmetrical relative to the joints and free from any defect such as lack of sidewall fusion or lack of root fusion. The weld profiles are regular with good wetting–in to the joint surfaces. The macrosections of the welds are shown in Fig. 6–32 for mechanised operation, and in Fig. 6–33 for manual operation.

6.4.2.2. *Voltage feedback control*

Both the quadratic and linear power–current control units were also found to have similar performance when adapted by the technique of voltage feedback control of the power source. For any given wire feed speed, whether held constant, varied gradually or modulated with square wave, the control system adjusted the arc current and voltage automatically according to the operating wire feed speed. This adjustment provided stable arc operation with spray metal transfer throughout the weld runs, such that the arc length remained at about 8 mm for the constant and variable wire feed, and varied between 5 and 7 mm when modulating the wire feed speed between 7.5

Table 6–5. Details of joints and welding conditions for evaluating the quadratic power–current control unit adapted to the thyristor controlled power source using 'scaling the output' technique, with 1.2 mm diameter mild steel wire in Ar+15%CO_2 for steady DC open arc operation.

Figure no.	Joint		Joint preparation		Backing	Welding								
	Type	Material thickness, mm	Included angle	Root gap, mm		Position	Technique: Number of runs	Technique: Run number	Conditions: Mean current, A	Mean voltage, V	Wire feed speed, m/min	Modulation frequency, Hz	Traverse speed, m/min	Gas flow rate, l/min
Mechanised operation														
6–32a	Butt	25	15°–V	3	Ceramic	Flat	5	1st	-	-	Modulated, 7.5–10.5	2	0.25	30
								2nd	-	-	Modulated, 7.5–10.5	2	0.25	30
								3rd	-	-	Modulated, 7.5–10.5	2	0.30	30
								4th	-	-	Modulated, 7.5–10.5	2	0.30	30
								5th	-	-	Modulated, 7.5–10.5	2	0.15	30
6–32b	Fillet	9.5	90°	-	-	Flat	1	-	-	-	Constant, 10.5	-	-	24
6–32c	Fillet	9.5	90°	-	-	Flat	1	-	-	-	Modulated, 9–12	2	0.20	24
Manual operation														
6–33a	Butt	12.5	30°–V	2	Ceramic	Flat	3	1st	260	30	Constant	-	-	24
								2nd	280	31	Constant	-	-	24
								3rd	300	32	Constant	-	-	24
6–33b	Fillet	12.7	90°	-	-	h,v	1	-	270	30	Constant	-	-	24

h = Horizontal
v = Vertical
Gas nozzle diameter for mechanised welding = 22 mm, and for manual welding = 15 mm

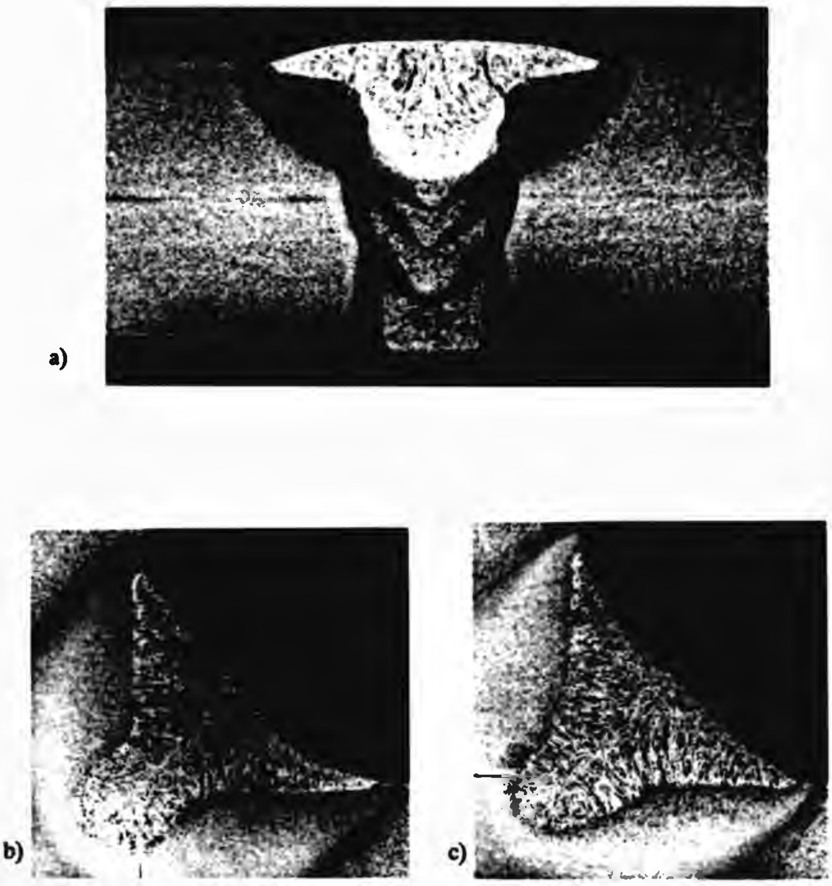
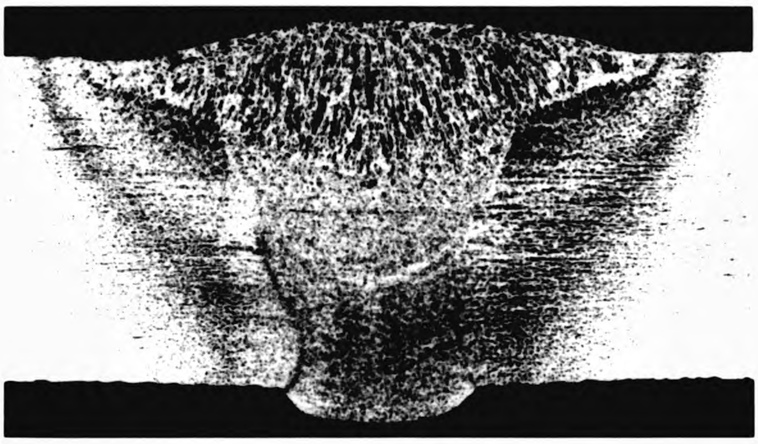


Fig. 6–32. Macrosections of the welds made for mechanised welding operation, with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+15%CO_2:

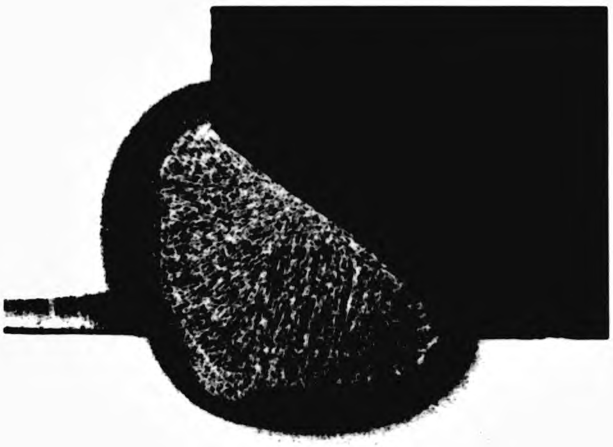
a) butt weld, 25 mm, 15°, 3 mm root gap, flat, ceramic backing, wire feed speed modulated from 7.5 to 10.5 m/min at 2 Hz, ×2;

b) fillet weld, 9.5 mm, 90°, flat, wire feed speed constant at 10.5 m/min, ×3;

c) fillet weld, 9.5 mm, 90°, flat, wire feed speed modulated with square wave from 9 to 12 m/min at 2 Hz, ×3.



a)



b)

Fig. 6–33. Macrosections of the welds made for manual operation, with the quadratic power–current control unit having scaled output driving the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+15%CO_2:
a) butt weld, 12.7 mm, 30°, 2 mm root gap, flat, 280 A, 31 V, ×5;
b) fillet weld, 12.7 mm, 90°, horizontal/vertical, 270 A, 30 V, ×5.

and 10.5 m/min at 2 Hz. The stable arc operation resulted in uniform and consistent bead deposits. The consistency of the current and voltage relative to the wire feed speed and regularity of the bead deposits, for the three types of wire feed, are shown in Figs. 6–34 and 6–35 for the control system using the quadratic power–current control unit.

6.5. DISCUSSION

The performance of the three synergic control units, which had previously been developed for both steady DC open arc and short circuiting arc operation, relied on the capability of a fast response, feedback controlled transistor power source. This power source implements the output of the control units reliably, because the power source provides accurate voltage when set in constant voltage mode and accurate current for constant current mode. Furthermore, the input/output relationship of the power source is simple: the output is proportional to the input reference (0–5 V input provides 0–50 V or 0–500 A output). These features provide easy interfacing of a control unit with the power source.

By contrast, the thyristor power source used is neither feedback controlled nor does it provide output proportional to the input reference, the output voltage is not maintained constant, but it decreases as the operating current is increased according to the slope (about 3 V/100 A) of the output characteristic. These features together required, in general, interface circuits to be developed to adapt the units for driving the thyristor power source.

6.5.1. Adaptation

The approach for adapting the linear voltage–current control unit has been based on deriving a generalised reference voltage–current equation, Eq. [6–6]. This includes not only the operating voltage–current relationship, which was regulated by the original control unit, but also incorporates parametric constants relevant to the power source. These constants comprise m_p, the slope of the family of the output characteristics, m_e and C_e, the slope and intercept of the C_p–V_r relationship, Eq. [6–2]. Therefore, for any given power source to be driven by the control unit, m_p, m_e and C_e must be predetermined to be programmed in the control unit.

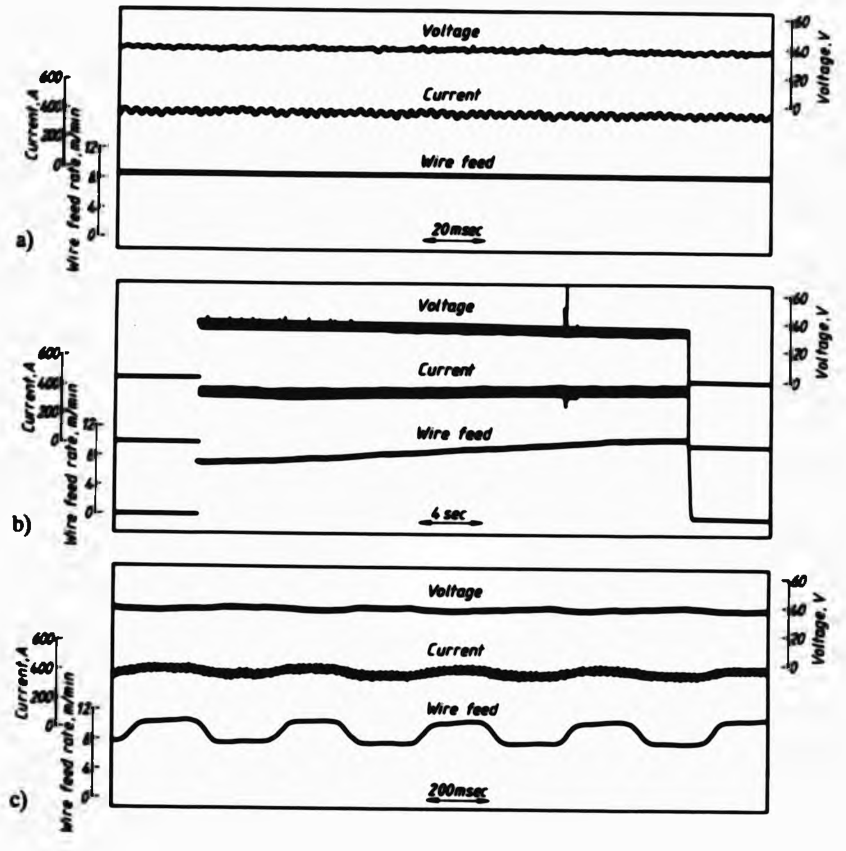


Fig. 6–34. Current and voltage adjustment, indicating stability of the arc operation, with the quadratic power–current control unit and feedback control of the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for different types of wire feed speed:

a) constant at 9 m/min,

b) varied gradually from 7.5 to 11.25 m/min,

c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

a)

b)

c)

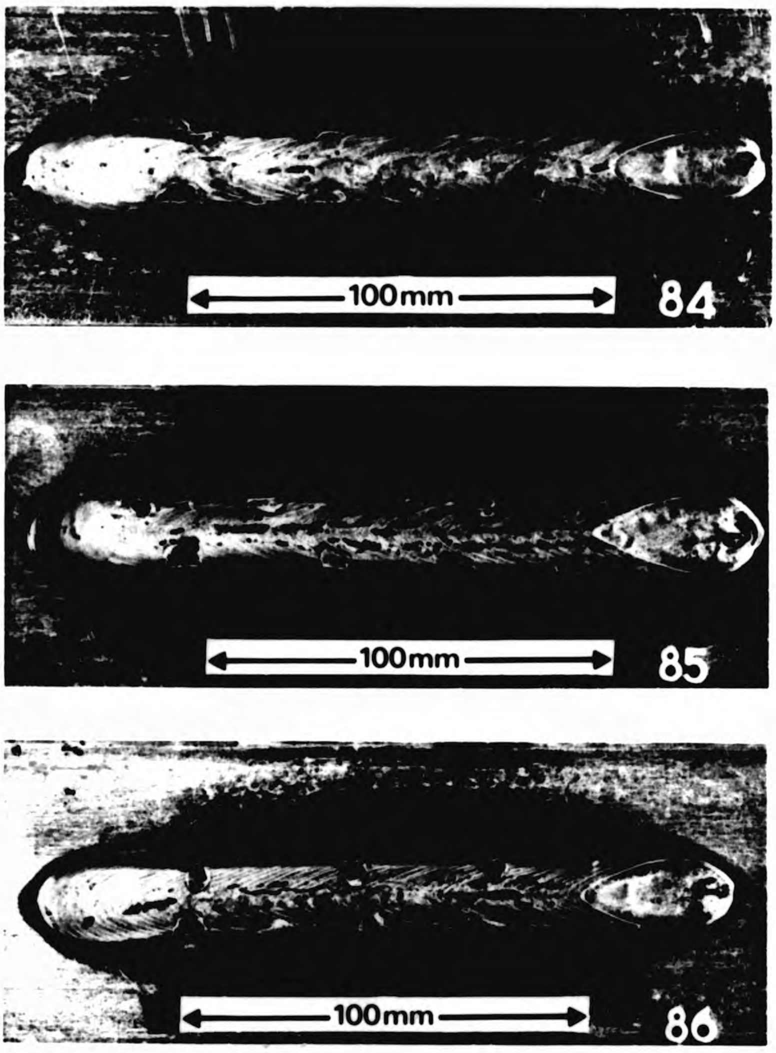


Fig. 6–35. Bead deposits showing stability of arc operation with the quadratic power–current control unit and feedback control of the thyristor power source, using 1.2 mm diameter mild steel wire in Ar+5%CO_2, for three types of wire feed speed:
a) constant at 9 m/min,
b) varied gradually from 7.5 to 11.25 m/min,
c) modulated with square wave from 7.5 to 10.5 m/min at 2 Hz.

The reference voltage–current equation is valid only for a power-source providing a family of output characteristics which are linear and have the same slope. In addition, the C_p–V_r relationship must also be linear. If either relationship is not linear, then in principle, the reference voltage–current equation could be modified but it would become complex. For a power source with non-linear characteristics, graphical or experimental methods could be used to obtain the required relationship, as described in Section 6.3.1.1. Therefore, the control unit can be adapted to any given power source, irrespective of the linearity of the characteristics, using the approach based on the reference voltage–current relationship.

An alternative approach to adapt the linear voltage–current control unit is to add a simple electronic circuit providing voltage feedback control of the power source. This control converts the power source to operate effectively in the constant voltage mode, similar to the transistor power source previously used. That is, the power source supplies output voltage reliably as instructed by the control unit. This method is simple in that it does not require any information on the characteristics of the power source.

The voltage feedback control approach has also been used successfully to adapt both the quadratic and linear power–current control units to the thyristor power source, as discussed above for the linear voltage–current control unit. Therefore, this approach is not only simple but also versatile in that it could be used to adapt all the three control units to any power source.

Alternatively, the power–current control units have been adapted by scaling their output, with the addition of an amplifier, to provide 0–15 V range as required for the thyristor power source. This simple adaptation has been possible because the operation of the control units is independent of both the input/output relationship and output characteristics of the power source. This independence is provided by the feedback control already included in the control units.

The most versatile of the three control units is the one based on the linear voltage–current relationship because it provides synergic control for both the steady DC open arc and short circuiting arc modes, whereas the other two control the steady DC open arc operation alone. Among the three adaptation techniques, the voltage feedback control is the most adaptable as it can be used for all the three control units.

Therefore, the linear voltage–current control unit/voltage feedback control technique combination should be selected for general application. However, if any difficulties arise, e.g. arc instability due to relatively large current fluctuations in welding difficult joints, the other combinations may then be considered.

6.5.2. Synergic operation

Each of the three control units, together with the thyristor power source, is capable of synergic operation, whereby stable arc operation is maintained automatically for any wire feed speed, whether held constant, varied gradually or modulated.

Any variations in the wire feed speed do not cause arc instability under the synergic controls; the wire feed speed could be changed during joint filling as required without necessitating any other control. For example, for a wide root gap, the current could be reduced to avoid excessive burnthrough by reducing the wire feed speed alone. Similarly, in the filling passes, the wire feed speed could be freely changed to obtain the required metal deposition rate, and for the capping pass, the wire feed speed could be varied to achieve the required bead profile.

The response of the control systems in adjusting current and voltage has been found adequately fast. Even with the wire feed modulated with square wave with low level set as low as permitted by the onset of the desired spray metal transfer (about 7.5 m/min) and the high level set as large as allowed by the power source output rating (about 10.5 m/min), the arc length changed by only about 2–3 mm during a modulation period. This is possible because with the synergic controls, a stable arc is maintained not only at each wire feed speed, but also during the transitions between the two feed speed levels. Therefore, the modulation can be applied to virtually any high and low levels of feed speed over the operating range, and furthermore, the transitions can be as slow or as fast as desired.

Another useful feature of the synergic controls is that the arc length is maintained practically constant for any variation in the wire extension. A typical application of this feature would be in the mechanised multipass circumferential welding of pipes, where the pipes could be rotated under the welding head continuously. At the completion of each pass, the wire extension would decrease for a set standoff distance, but the operating arc length would remain unaltered.

Therefore, as no adjustment of the standoff distance would be required between passes to maintain the required arc length, the multipass weld could be completed in a single run. By this procedure, apart from saving time, any defects which would occur due to stopping and restarting the arc, for adjusting the standoff distance at the completion of each pass, would be avoided. Similarly, the multipass linear joints could also be welded, for example, by traversing the joint back and forth continuously underneath the welding head until the weld is completed.

6.5.3. Welding performance

In general, the control units together with the thyristor power source are capable of making sound and practically spatter-free welds for open arc and short circuiting arc operation, in butt and fillet joints, with the constant as well as modulated feed speed, and using both mechanised and manual welding techniques. All the welds made have good weld characteristics. In particular, the weld deposits are symmetrical and sidewall fusion is relatively deep and smoothly rounded so that lack of sidewall fusion, lack of interpass fusion or lack of root fusion defects would be unlikely to be formed even in an industrial environment.

Therefore, for mechanised welding, the control systems could be integrated, for example, with robots, where frequent changes in the welding condition are required to suit various joints in the fabrication of complex components. It would be sufficient to program the wire feed relevant to various joint configurations. Furthermore, the systems maintain stable arc operation irrespective of any changes in wire extension, whether gradually or in steps; variations in joint preparation or effect of hand movements of the operator should be accommodated. In conclusion, these systems should increase reliability of power source performance whether used manually or mechanised and with either the steady DC open arc or short circuiting arc operation.

6.6. CONCLUSIONS

A study has been made for adaptation of the synergic control units to a commercially available thyristor controlled MIG welding power source. The main conclusions of this study are listed below:

1. Control units can be adapted to operate with a commercially available thyristor

power source. These systems are capable of performing the synergic operation.

2. The linear voltage–current control unit has been adapted by deriving a generalised 'reference voltage–current' relationship. This includes the parametric constants relevant to the output characteristics of the power source, in addition to the voltage–current relationship for the arc operation.

3. Alternatively, the control unit has been adapted by the addition of an electronic circuit providing voltage feedback control of the power source, so that the power source operates essentially in a true constant voltage mode.

4. The voltage feedback control technique has also been used to adapt both the quadratic and linear power–current control units.

5. Both the quadratic and linear power–current control units have been adapted by an alternative technique of rescaling the output to provide 0–15 V, relevant to the input reference voltage range of the thyristor power source.

6. The linear voltage–current control unit is the most versatile because it provides synergic control for both Steady DC open arc and short circuiting arc operations, and the voltage feedback control technique is the most adaptable as it can be used for all the three control units.

7. The control systems allow sound welds to be made for butt and fillet joints using both mechanised and manual techniques.

PART II

PENETRATION CONTROL IN TIG WELDING

CHAPTER 7
PREVIOUS STUDIES

7.1. INTRODUCTION

The TIG (Tungsten Inert Gas) welding process is essentially a precision technique which is widely used to produce high quality components for the power, nuclear, chemical and aeroengine component industries. One main problem in its application is that it is difficult to achieve the required degree of weld penetration consistently over the entire length of a joint. Inconsistencies in the penetration can be caused by a number of factors. These include variations in component or joint dimensions, welding parameters or material compositions (27,28,29). To improve the control of weld penetration for specific applications, techniques such as pulsed current operation, mechanisation with accurate control of the welding parameters and precise control of the joint dimensions, have been used successfully. Nevertheless, variations in weld penetration still occur under production conditions due to, for example variations in the joint fit up and welder skill. To eliminate all these variations is impracticable. Therefore, there is an urgent requirement for a control system to be developed to provide real-time regulation of the welding parameters such that uniform penetration is accomplished automatically.

7.2. OBJECTIVES

The objective of this study is to review essentially three aspects of previous work relevant to TIG welding. These are:

1. Parametric effects on arc and weld penetration;
2. Techniques to improve weld penetration;
3. Existing penetration control systems.

A knowledge of these aspects is essential both in the design and development of a new penetration control system and in its evaluation.

7.3. EFFECTS OF THE PROCESS PARAMETERS

7.3.1. Arc current and significance of power source

For DC current operation, typical relationships between penetration and current are shown in Fig. 7-1 (30). The penetration is strongly dependent on current, such that an increase in current by a factor of 2 causes an increase in penetration by a factor of about 4. Therefore, to achieve uniform penetration, the current level must be controlled accurately. That is, it is essential for the welding power source to supply a current without excessive variations for a given setting of the 'current control knob'.

For pulsed current operation, the shape of the current waveform itself has a crucial effect on control of penetration (31). Therefore, if a welding procedure is to be carried out on nominally identical power sources (i.e. same make and model), these should produce identical current waveforms for identical settings of the control knobs. However, commercially produced power sources may not give identical outputs. For example, the pulsed current waveforms obtained from the evaluation of four nominally identical power sources are shown in Fig. 7-2. Each pulse waveform is different both in shape and amount of ripple. These differences were sufficient to prevent a welding procedure to be developed which could be operated on each power source at identical settings.

Transistor controlled power sources, developed at The Welding Institute (32) provide current practically free from ripple and with an accuracy of better than 1% of the current level set by means of the relevant control knob. The power source can be driven from instruction or reference signal. The calibrated reference signal of any desired waveform can be provided internally or externally as required. This type of power source is well suited to supply accurate current for the control of weld penetration.

7.3.2. Welding speed

The effect of welding speed on penetration is shown typically in Fig. 7-3, for 6.4 mm thick, type 304 stainless steel plate (30), 5 mm arc length and 240, 200 and 150 A arc current. For a given current, the relationship between penetration and welding speed is not linear but inverse. That is, the change in penetration for a specific change in welding speed is substantially large at a low welding speed and

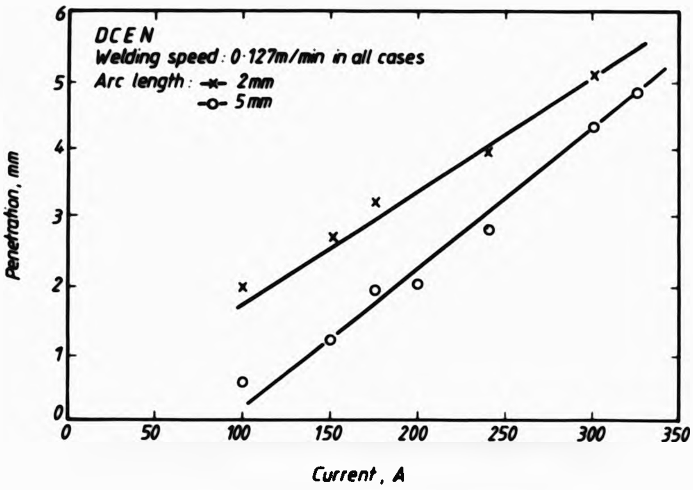


Fig. 7-1. Relationship between current and penetration in Type 304 stainless steel (30). (DCEN — Direct Current Electrode Negative).

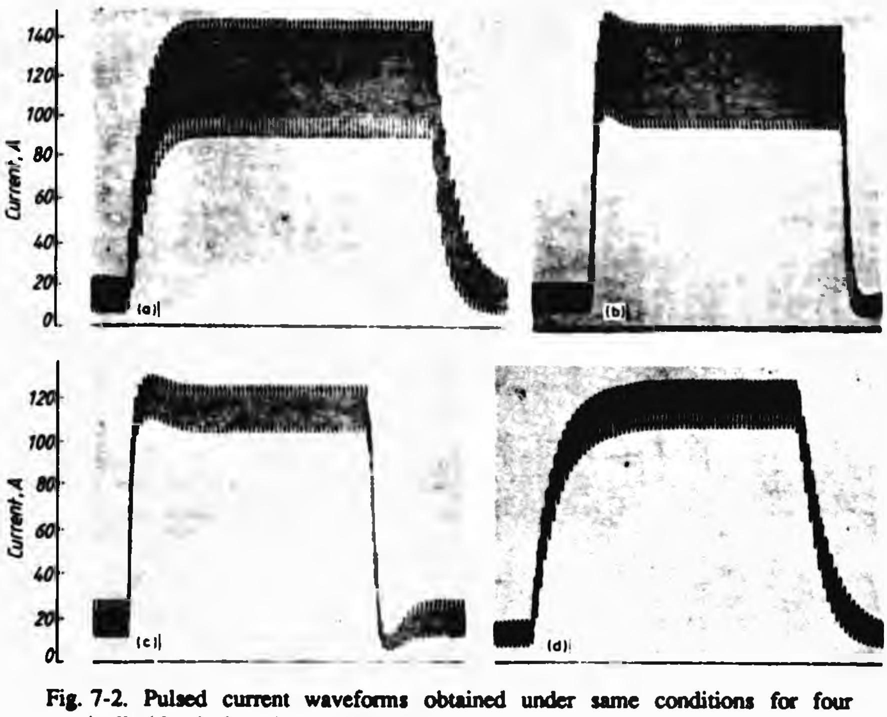


Fig. 7-2. Pulsed current waveforms obtained under same conditions for four nominally identical equipments (31).

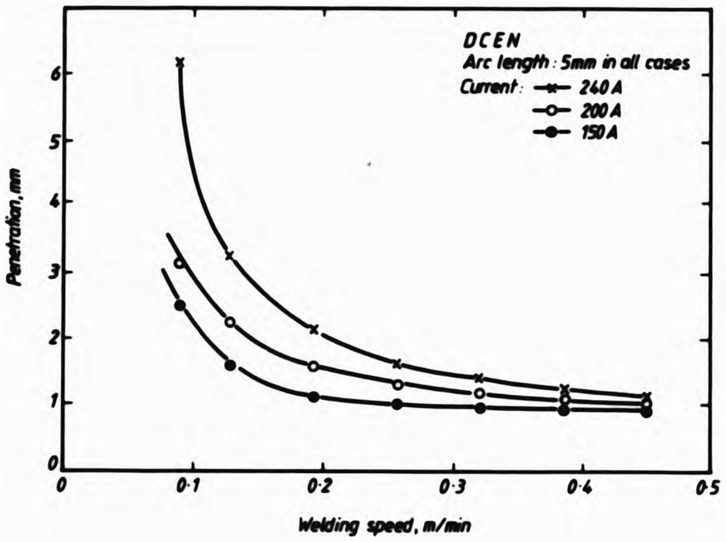


Fig. 7–3. Relationship between welding speed and penetration in Type 304 stainless steel (30).

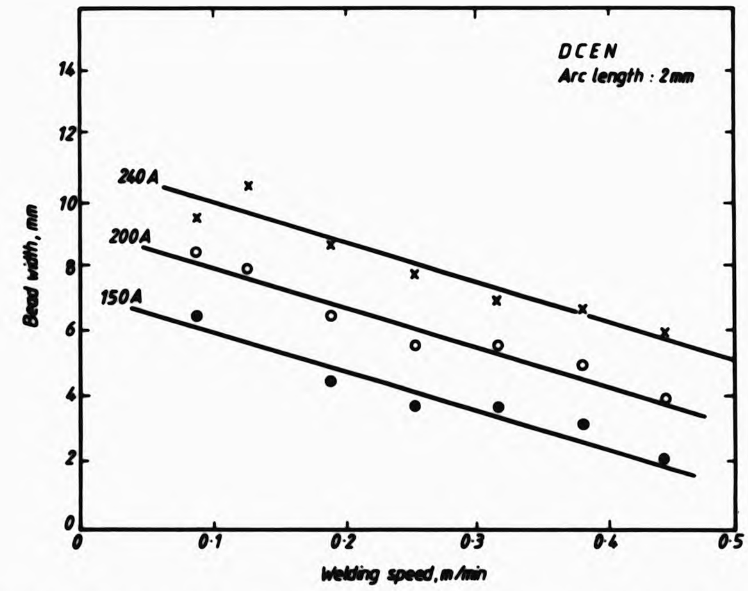


Fig. 7–4. Relationship between bead width and welding speed for Type 304 stainless steel (30).

becomes smaller progressively for the higher welding speed. For example, at a welding current of 150 A, the penetration is practically constant for the welding speed range greater than 0.2 m/min.

Based on the data relevant to Fig. 7–3, the relationships between weld bead width and welding speed are shown in Fig. 7–4 (30). For a given current, the relationship is linear such that bead width decreases as welding speed increases.

7.3.3. Arc voltage

Arc voltage is determined primarily by the arc length, shielding gas composition, current, and the vertex angle of the electrode tip. Typical voltage–current characteristics, using the vertex angle as a parameter, are shown in Fig. 7–5 (33).

In automatic welding equipment, 'arc voltage feedback' control systems are often used to control the arc length. Such systems can be beneficial for welding inclined or undulating surfaces, but any variation in electrode geometry or shielding gas composition may result in a change in arc length and this will cause variation in weld penetration.

7.3.4. Arc length

Typically, the effect of arc length on weld penetration is shown in Fig. 7–6, in type 304 stainless steel, at constant welding speed, for 300, 240 and 150 A current (30). With long arcs (e.g. longer than 3.2 mm), penetration is relatively insensitive to changes in arc length. With short arcs (e.g. shorter than 3.2 mm), penetration increases markedly as arc length is decreased. This effect however is dependent upon the value of the current used such that the change in penetration becomes less pronounced at higher currents.

Whilst the bead width increases with increasing current, the effect of a longer arc is also to widen the weld bead, Fig. 7–7.

7.3.5. Electrode diameter

For electrode diameters within the range 1.5 to 6 mm, at constant current, the use of an electrode with a diameter larger than normal reduces the depth of penetration (34). This has been attributed to a reduction in the intensity of the plasma flow or the pressure of the arc. However, the width of the bead was scarcely altered.

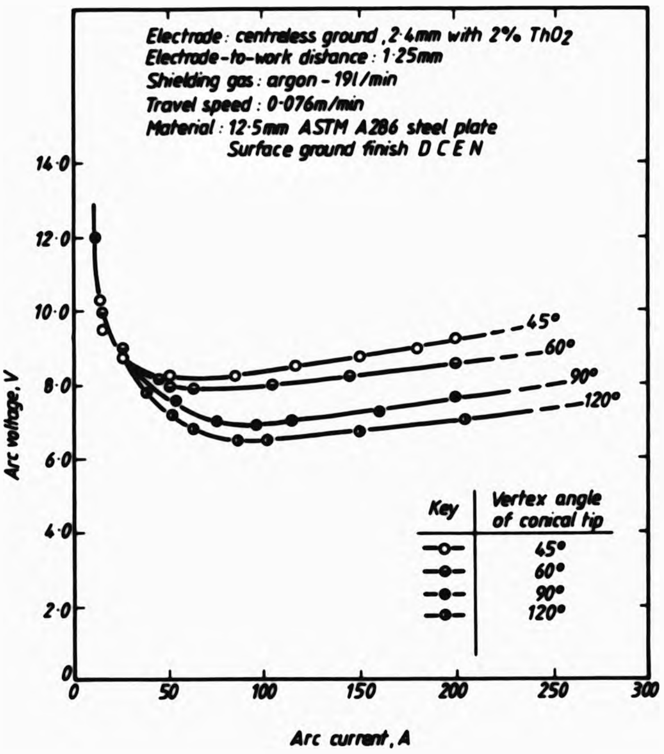


Fig. 7–5. Effect of vertex angle of conical tip on arc voltage–current characteristics (33).

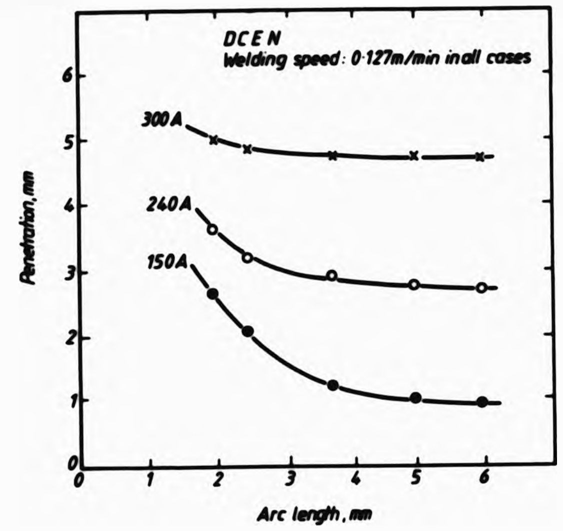


Fig. 7–6. Relationship between arc length and penetration in Type 304 stainless steel (30).

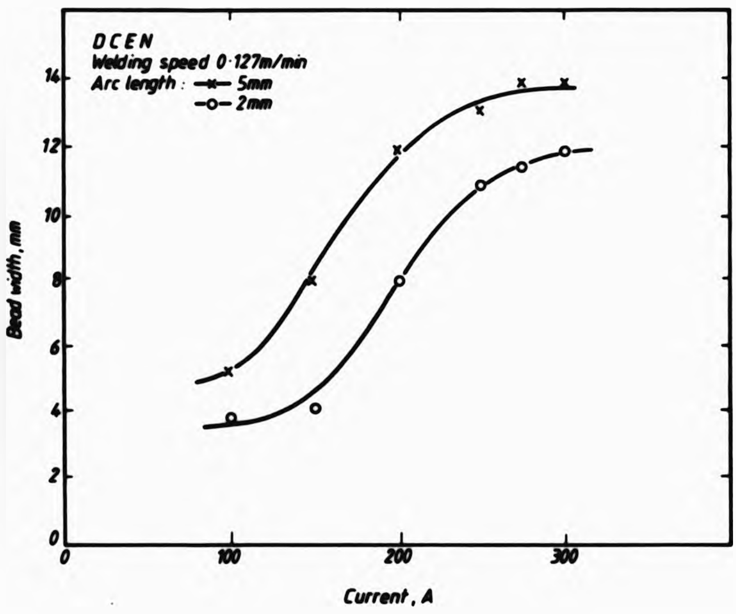


Fig. 7–7. Relationship between bead width and current in Type 304 stainless steel (30).

7.3.6. Electrode tip angle

Electrode tip angle has a significant effect on both the depth and width of the weld pool. The effects were related to variations in arc voltage which can be summarised as follows (33):

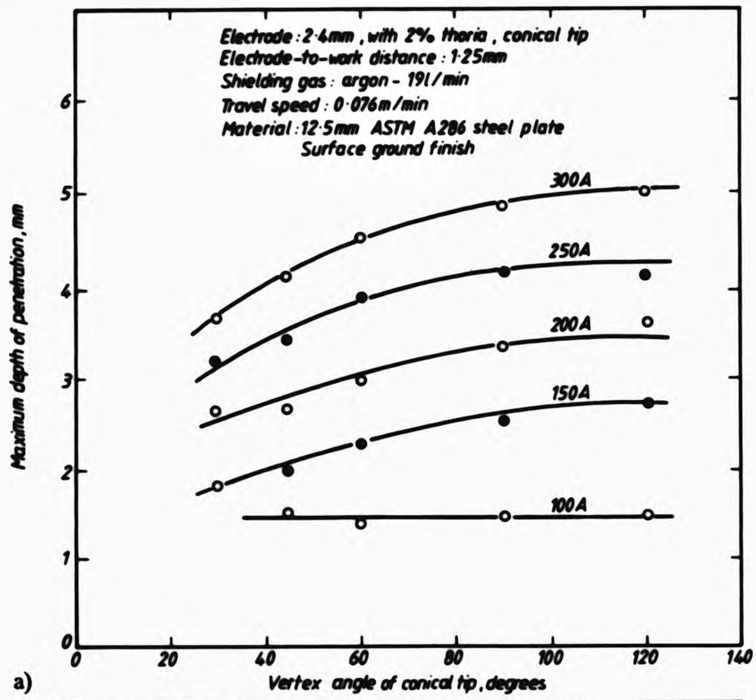
1. Arc voltage decreases with increasing tip angle, Fig. 7-5;

2. At low welding currents the effect of tip angle on arc voltage is less noticeable;

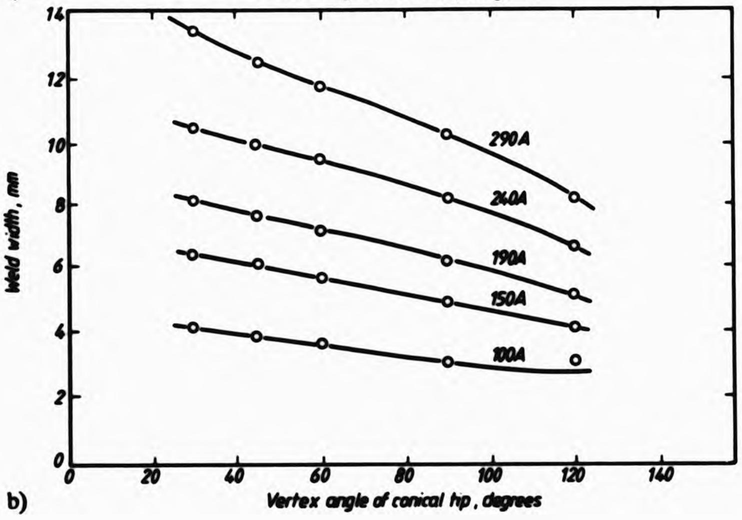
3. Weld penetration increases and weld width decreases with increasing tip angle, Fig. 7-8a and b respectively.

The influence of the tip angle on the appearance of the weld bead, Fig. 7-9, is more marked at higher current levels. For example, at a current level of 300 A the width of the weld bead decreases by a factor of approximately two as the tip angle is increased from 30° to 120°. A similar, though less pronounced, decrease in width was evident for a welding current of 100 A. A similar effect was observed on the depth of penetration in that the variation was more pronounced as the welding current was increased from 100 A to 290 A; at 300 A the penetration increased by approximately 45% when the tip angle was increased from 30° to 120° but the variation at 100 A was negligible.

A more recent investigation on the effect of tip angle for thick and thin plates, is somewhat in contradiction to the above observations (35). In particular, when welding 3.2 mm type 321 stainless steel, the depth of penetration decreased as the tip angle was increased from 30° to 120°, Fig. 7-10. This difference was attributed to a change in the arc characteristics as the tip angle increased; the appearance of the TIG arc for 30° and 120° tip angles is shown in Fig. 7-11. The effect of plate thickness was also found to be significant in that a finely tipped electrode produced very shallow penetration in thick plates, but proportionally greater penetration in thin sheet material. This was attributed to the effect of the arc jet reflected from the surface, which was greater in the thin sheet material; the reflected arc jet in thick and thin sheet material is shown schematically in Fig. 7-12.



a)



b)

Fig. 7–8. Effect of vertex angle of electrode tip on penetration and weld width for different current levels (33):
a) penetration v. vertex angle, b) weld width v. vertex angle.

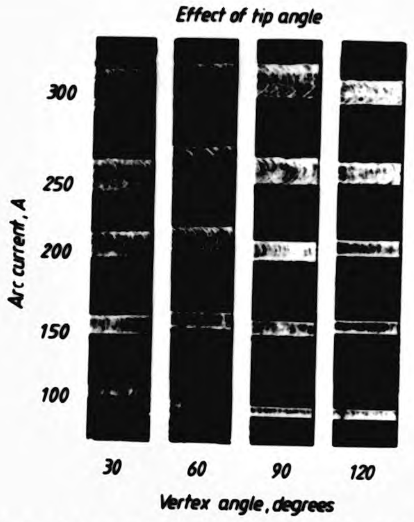


Fig. 7–9. Effect of vertex angle on weld width (33).

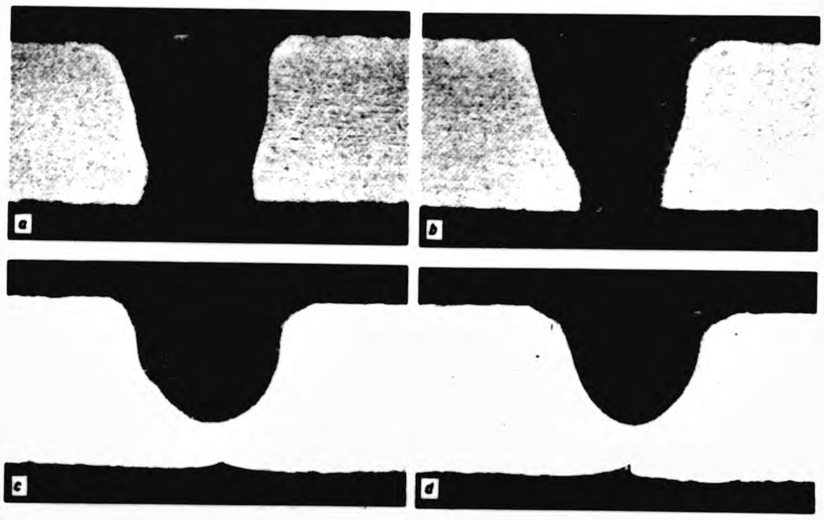


Fig. 7–10. Macrosections of fused zone for 3.2 mm stainless steel plate butt welds at 150 A arc current and 300 mm/min traverse speed. (Note: decrease in penetration with increase in vertex angle) (35).

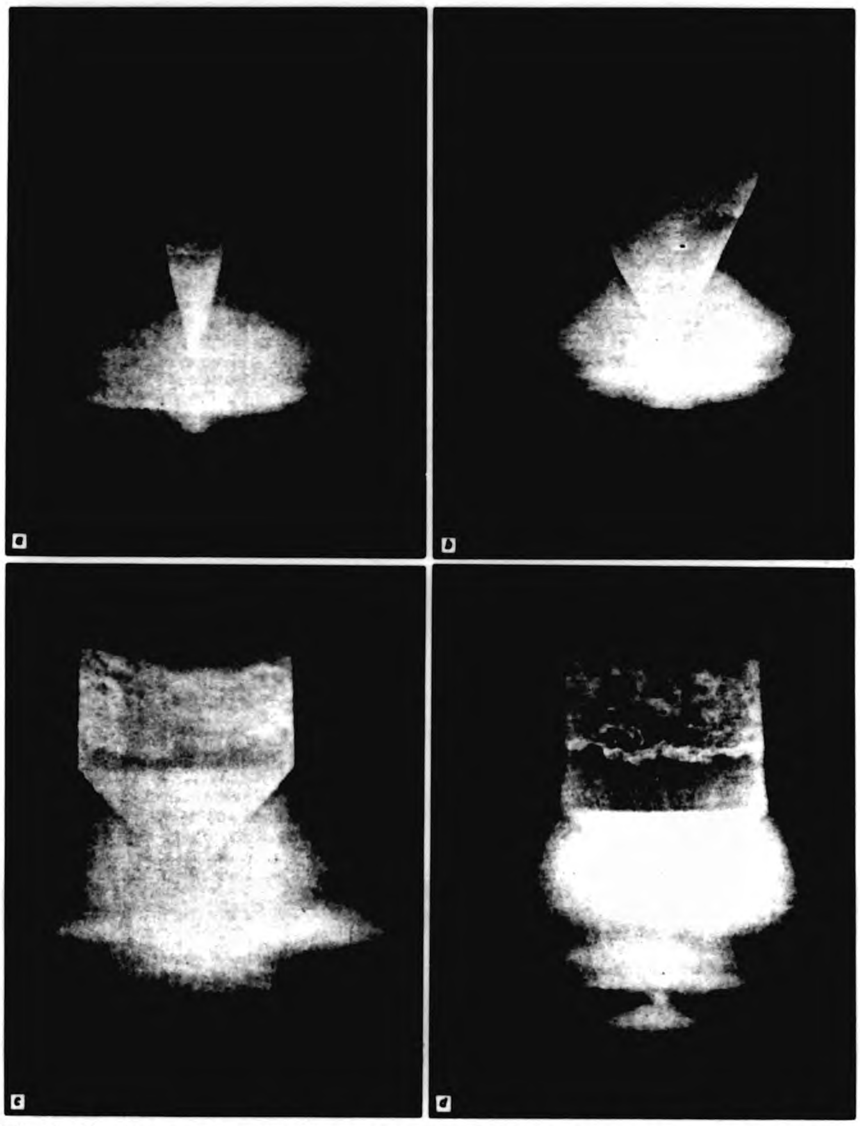


Fig. 7-11. Appearance of stationary arcs for various vertex angles at 150 A arc current with an arc gap of 1.4 mm (35):
a) 30°, b) 60°, c) 90°, d) 120°.

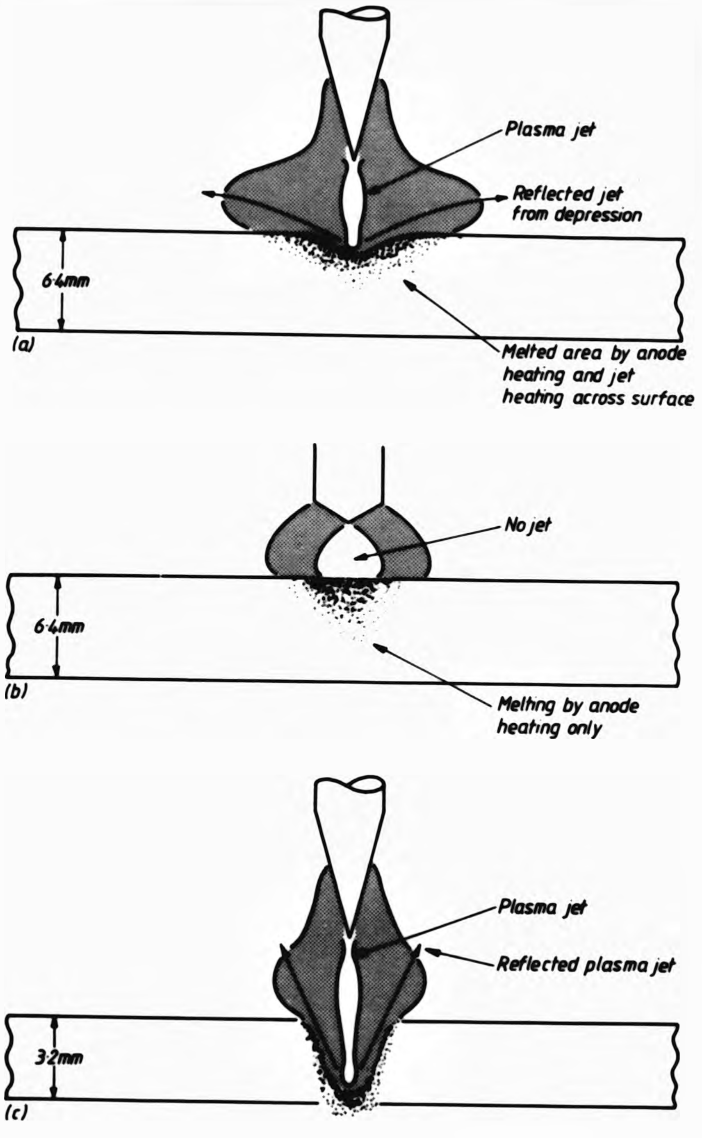


Fig. 7–12. TIG arc configuration for different vertex angles (35):
a) 30°, b) 120°, c) 30°.

7.3.7. Shielding gas

Shielding gas composition has a major influence on depth and consistency of penetration. However, no reference has been made in the literature to problems arising from minor variations in the composition of the gas or its impurity content. Nevertheless, experience has shown that the composition must be carefully controlled if consistent operation is to be achieved.

For given conditions the arc voltage is determined by the gas composition, Fig. 7–13, and the depth of penetration increases with increasing arc voltage, Fig. 7–14 (36). Greater penetration, about 60% more for steel VP25 and three times in the case of alloy OT4, was achieved by adding 1.5–2% sulphur hexafluoride in argon. Thus, in production, failure to ensure that gas composition is accurately maintained and impurities such as O_2, N_2 and moisture are not introduced, e.g. through leaking gas lines, could result in variable penetration. With regard to oxygen content, it has been recommended that when welding high integrity components, copper or Teflon lined Neoprene tubing be used in preference to polythene lines (37). Purging of the complete system should then be carried out to reduce the O_2 level to less than 200 ppm and the moisture content to less than 50 ppm. Depending on the length of piping and time the plant has been idle, etc., this can take up to 30 min to reach satisfactory levels.

7.4. MATERIAL EFFECTS

The fusion geometry of the weld pool may also vary substantially due to differences in parent material composition. Generally known as cast to cast variation, this effect has been widely reported as a major problem in mechanised TIG welding (27,28,29); two heats (casts) of material conforming to the same specification produced vastly differing weld shapes when welded with exactly the same welding procedure, as shown in Fig. 7–15.

In practice, as several casts of material may be used to produce a large number of identical components, the problem usually manifests itself as one of inconsistent or inadequate penetration. Such variations have been more widely reported in high quality TIG welding applications, especially where mechanised or fully automatic welding operations are employed (27). Here the operator has little or no control over

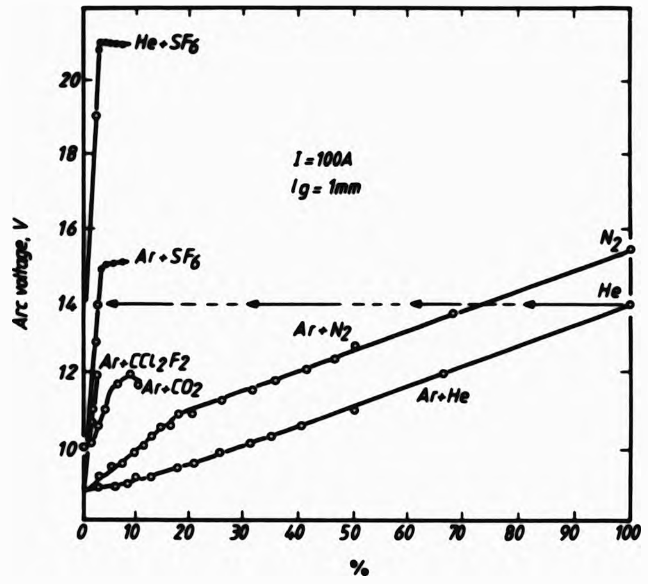


Fig. 7–13. Dependence of arc voltage on additions in the shielding gas (36).

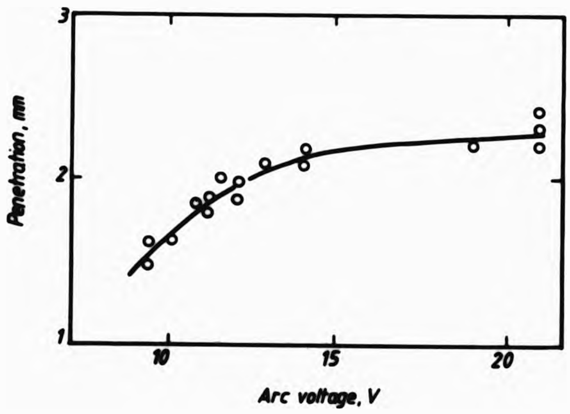
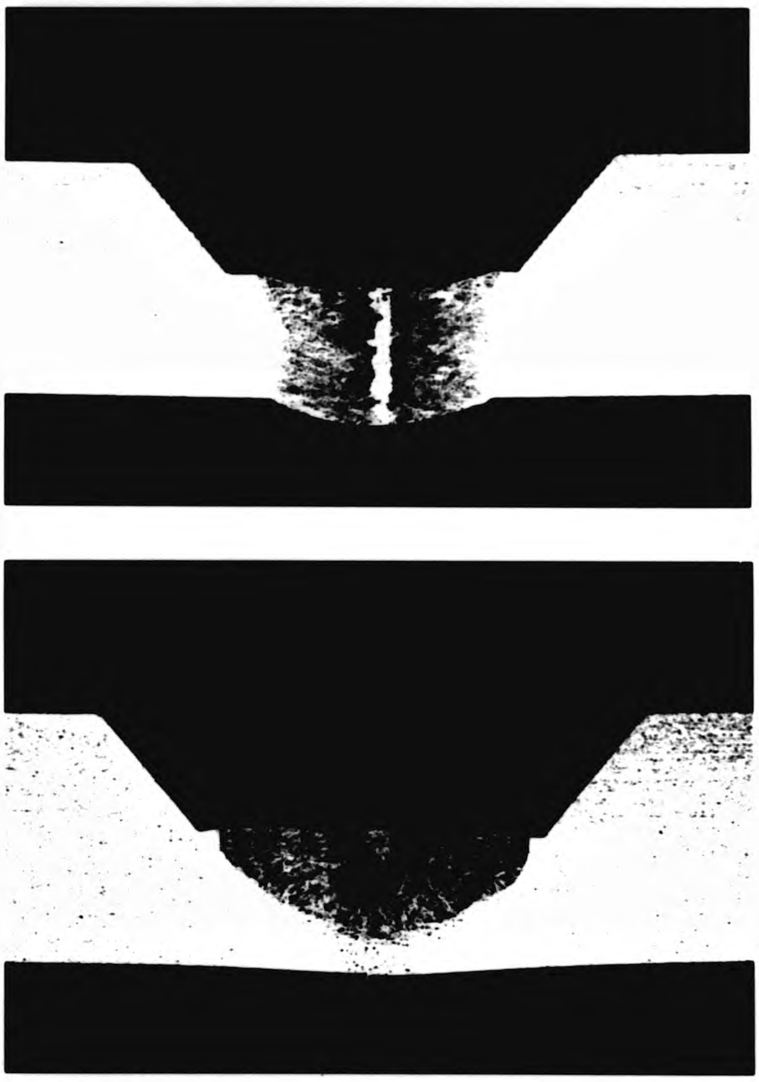


Fig. 7–14. Dependence of penetration depth in steel VP25 on arc voltage (36).



a)

b)

Fig. 7–15. The transverse sections through orbital TIG root welds (27), ×10:
a) 4.7 mm wall thickness stainless steel tube — 'good' penetration,
b) 4.7 mm wall thickness stainless steel tube — 'poor' penetration.

the weld pool behaviour, nor can he manipulate the torch as a manual welder would do in order to ensure complete penetration of the joint. Indeed, it is seldom that a cast is reported as 'unweldable' by manual techniques.

Material related problems have been encountered in a number of material types including nickel alloys and low alloy steels. However, the large majority of troublesome casts have been reported when welding the austenitic range of stainless steels. It is not known whether this is a characteristic of the material itself or simply a reflection of its widespread use for high integrity components such as in the nuclear and chemical plant industries.

The reasons for material induced variations in the weld shape are not fully understood. However, it is generally attributed to differences in the concentration of minor alloying or impurity elements such as sulphur, oxygen, aluminium, manganese, titanium and phosphorus (27). The presence or absence of these elements is thought to affect fusion behaviour in two possible ways, either separately or in combination. The first is by their evaporation from the weld pool causing a modification of arc characteristics (38), and the second is through their influence on the circulatory fluid flow patterns within the weld pool (39). The latter mechanism has gained increasing support over recent years, particularly with regard to the importance of surface tension driven convection (40). It is proposed that the penetration profile is determined by the dominant direction of surface tension activated flow, with deep penetration resulting from a radially inwards surface flow which effectively transfers the arc heat to the bottom of the weld pool, Fig. 7–16. Conversely, a radially outwards surface flow would promote an opposite convective pattern, resulting in a wide shallow weld pool.

The direction of flow in each case is thought to be governed by the presence of surface active impurities, particularly sulphur, with very clean, low sulphur casts tending to produce undesirably shallow weld beads.

Recent research on this topic has involved complex mathematical modelling of the TIG weld pool in an attempt to validate this theory (41). However, it may be some time before a complete explanation is forthcoming.

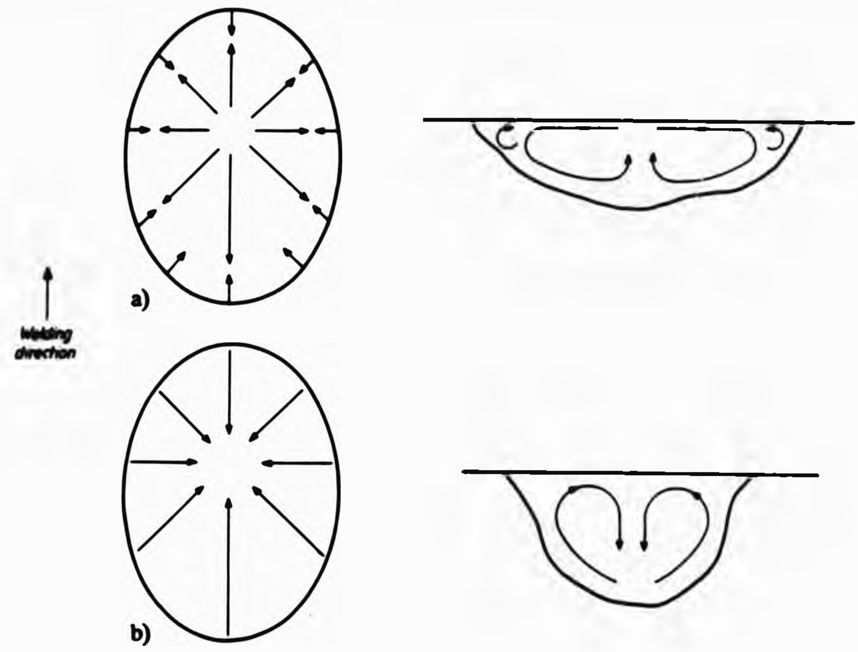


Fig. 7–16. Proposed surface and bulk pool motions to account for variable fusion geometry (40):
a) radially outwards flow produces shallow profile,
b) axially downwards flow yields deep profile.

Fig. 7–17. Surface appearance of pulsed TIG weld showing that welding progresses in a series of overlapping spot welds.

7.5. PROCESS TECHNIQUES TO IMPROVE WELD PENETRATION

Investigations have been carried out by a number of researchers to develop welding techniques which would improve the tolerance of the TIG process. The techniques include:

1. Low frequency pulsed current;
2. Modulated torch movement;
3. High frequency pulsed current;
4. Electromagnetic stirring;
5. Selection of shielding gas;
6. Surface activating fluxes.

Whilst none of the techniques has proved to have widespread application, for example in overcoming the effects of material variation, they have been shown to offer advantages in specific applications.

7.5.1. Low frequency pulsed current

The essential feature of pulsed current operation is that a high current pulse is applied causing rapid penetration of the material. As the pulse current level is some 50% greater than that required to melt the material in continuous current operation, excessive penetration and ultimately burnthrough would occur if the pulse were maintained. Therefore, the pulse is terminated after a preset time and the weld pool is allowed to solidify during a low background current or pilot arc. Thus, the weld pool progresses in a series of discrete steps with the pulse frequency matched to the traverse speed to give approximately 60% overlap of the weld spots; the characteristic appearance of a pulsed TIG weld bead is shown in Fig. 7-17. Typical pulse frequencies for welding materials of cross-section thickness 0.5 to 3 mm lie within the range 0.1 to 10 Hz (42).

The effects of low frequency current pulsing have been summarised as follows (43):

1. *Arc stiffness* — as the pulsed arc is stiffer than the conventional steady current

arc, penetration can be enhanced with better control of the weld pool shape. The latter is particularly significant when welding thin sheet material i.e. under low current operation.

2. ***Penetration depth*** — at low pulse frequencies (<10 Hz) the depth of penetration can be influenced by the selection of pulse parameters, especially the pulse current level. However, at pulse frequencies above 100 Hz, the depth of penetration is essentially independent of the pulse current level.

3. ***Weld pool agitation*** — the plasma jet emanating from the tip of the electrode tends to depress the surface of the weld pool and this effect increases as the current level is increased. The motion of the weld pool surface can be markedly stimulated by pulsing the current at, or near, the resonant frequency of the weld pool surface. This effect may be used to enhance weld pool circulation and control of the pool shape. Improved circulation may also reduce segregation and the effects of oxide films in the joint, particularly desirable when welding aluminium and its alloys.

Pulsed TIG has been found to be particularly beneficial in controlling the degree of penetration of the weld bead, especially when there is a variation in the heat sink, e.g. thick to thin sections (42). The rapidly penetrating weld pool during the pulse period and the solidification of the weld pool between the pulses markedly reduce sensitivity to component and material variations, resulting in a more uniform weld bead and less distortion. The pulsed TIG process has been widely applied in nuclear fabrication for the production of high integrity welds (44). In addition to its application to tube to tubeplate joints and orbital welding, it also reduces the effect of material (cast to cast) variation (45).

In the welding of thin sheets of Fe–26%Ni alloy, pulsed operation improves control of the weld bead profile and melting efficiency (46). These improvements were achieved by selection of pulse parameters but keeping the heat input constant.

Selection of pulse parameters has also been found to be crucial in the welding of type 304 stainless steel in that when using high amplitude current pulses the depth of penetration could be substantially improved (47).

7.5.2. Modulated torch movement

The beneficial effects which are derived from the sequential rapid melting/solidification of the weld pool, have also been reproduced by modulating torch movement (48). In this technique the torch is held stationary until complete fusion has been obtained. It is then moved to a new position to give approximately 60% overlap of the weld spots. Thus the surface appearance of the weld is similar to that produced by pulsing the current.

Although the technique is not widely applied, it has been used successfully in the manufacture of chemical plant components.

7.5.3. High frequency pulsed current

Superimposed high frequency current pulses, within the range 1 to 10 kHz, have been found to improve the stiffness and penetration capacity of the TIG welding arc (49). These effects were attributed to the increase in pressure in the arc produced by the constriction. Furthermore, it was suggested that improved consistency in behaviour of the arc was derived through the saturation of the arc pressure which occurred at frequency above 5 kHz, Fig. 7-18.

7.5.4. Electromagnetic stirring

Forced rotation of the pool by means of an externally applied magnetic field has been shown to minimise the risk of instabilities in weld pool flow (50). As motion in the weld pool is due, at least in part, to the magnetic fields caused by the passage of welding current (Lorentz forces), an externally applied magnetic field has been used to control the weld pool motion (51); the torch arrangement adopted is shown schematically in Fig. 7-19. The strength and the direction of the magnetic field were such that the weld pool was forced to rotate around the axis of the electrode.

Electromagnetic stirring was found to reduce the effect of material variation in different casts of type 316 stainless steel (52). Penetration characteristics in aluminium, titanium alloys and type 304 stainless steel were improved and a significant reduction in the porosity level in titanium was also observed.

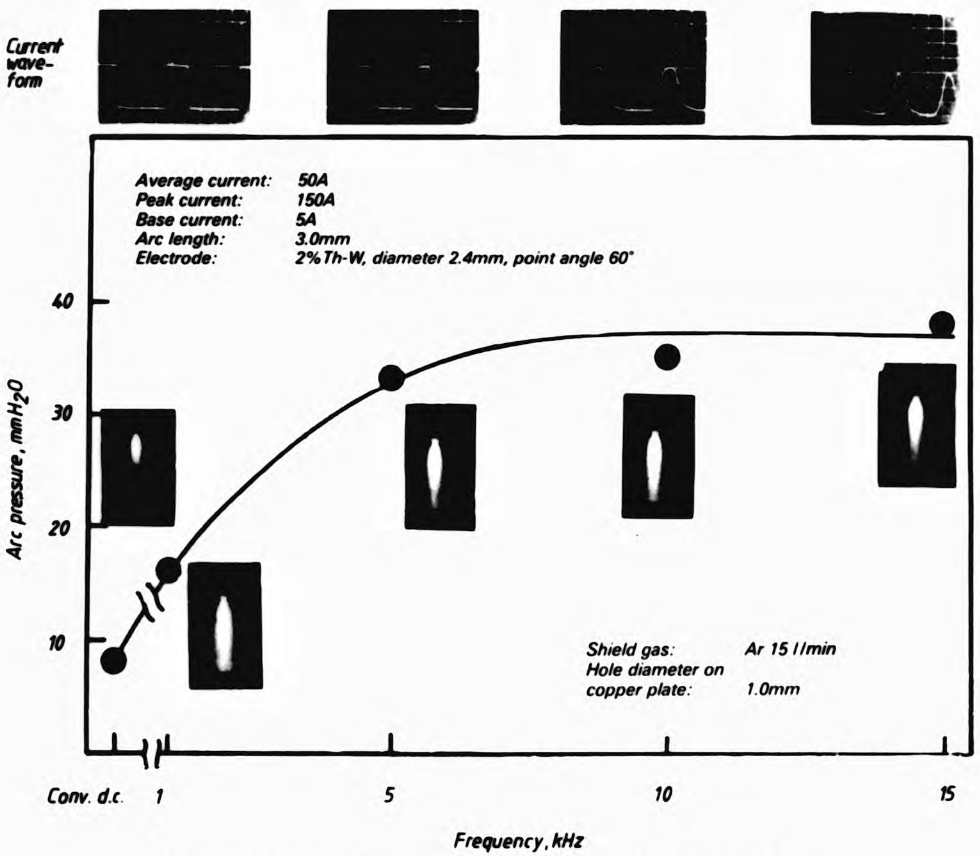


Fig. 7–18. Relationship between arc pressure and frequency (49).

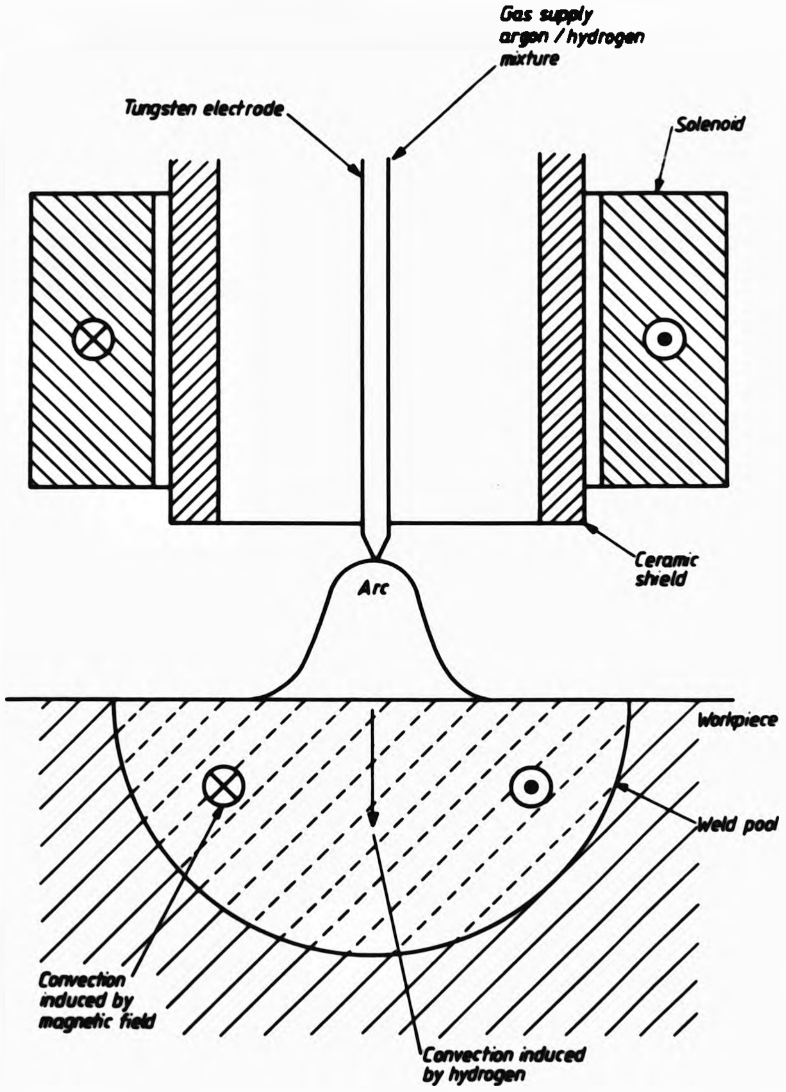


Fig. 7–19. Welding configuration (51).

7.5.5. Selection of shielding gas

Variable penetration through cast to cast material variations is a problem, especially when using a fully automatic welding technique. The ideal solution would be to identify the problematic element, or group of elements, and then to specify 'safe' compositional limits. Despite considerable research effort (28,29,28-41,53) such a solution has not been possible to date.

An alternative approach, which has been successfully applied in specific cases, has been to improve the performance of the TIG welding process by the selection of a more tolerant shielding gas mixture.

A number of shielding gas compositions were investigated in an attempt to reduce the effects of cast to cast variation in the orbital welding of stainless steel tube (54). It was found that increasing the percentage of helium in the shielding gas reduced the problem but did not eliminate. Greater success was achieved with the argon-hydrogen range of shielding gas mixtures, and in particular the Ar+5%H_2 gas mixture made a dramatic improvement in the consistency of weld shape in a range of material casts.

A more comprehensive study of the influence of shielding gas composition, travel speed and welding current on (cast to cast) weldability has been conducted (55). Two casts of type 316 stainless steel sheet (Table 7-1) which had previously been found to have very different penetration characteristics with argon shielding gas were selected, the poor cast exhibiting shallow penetration and frequently producing an unsatisfactory weld bead appearance. Various shielding gas compositions, in combination with suitable welding parameters, were investigated and the following observations were made:

1. With argon shielding and moderate welding speed, current was found to affect strongly the relative penetration behaviour of the materials. At a current of 80 A, the fusion profiles for both casts were comparable, but increasing the current up to 140 A resulted in the casts displaying very different penetration characteristics, Fig. 7-20.

2. Changing the gas composition to an He+20%Ar mixture brought about

Table 7-1. Chemical analysis of the two casts of 316 stainless steel used (55).

Sample reference number	Element, wt%													
	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Al	O_2, ppm	N_2, ppm
3D55*	0.022	0.014	0.028	0.33	1.59	11.7	16.8	2.22	0.09	0.20	<0.01	<0.01	0.008	53	190
3D56**	0.036	0.008	0.032	0.44	0.88	10.8	17.8	2.42	0.06	0.33	<0.01	<0.01	0.011	53	640

* Good penetration ** Poor penetration

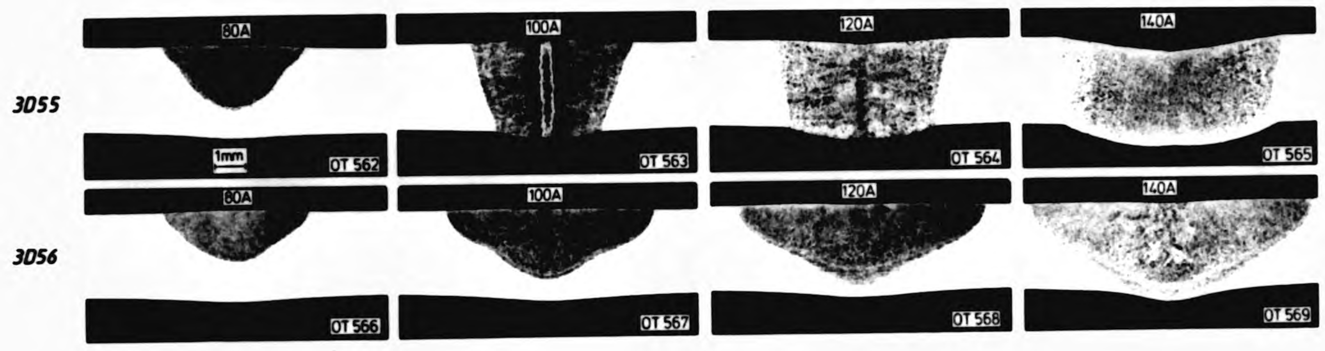


Fig. 7–20. Dependence of cast to cast weldability on current level (55). Shielding gas: Ar; welding speed: 150 mm/min.

considerable improvement in the consistency of penetration over a range of current levels, Fig. 7-21.

3. The improvement with He+20%Ar mixture was observed at a very slow welding speed of 60 mm/min, but any attempt to increase the speed resulted in a rapid deterioration of both the bead appearance and the uniformity of penetration along the weld.

4. No improvement was observed from the use of Ar+5%H_2 shielding gas over the range of welding speeds investigated.

5. The use of a three component shielding gas, He+25%Ar+5%H_2 , was found to improve weldability dramatically, with both casts producing very similar fusion profiles over a wide range of current and welding speed combinations, Fig. 7-22.

It was concluded that there appears to be no strict rules which can be applied with regard to minimising variations in fusion profile caused by the material composition. The most tolerant welding procedure optimised for one type of material and joint configuration is not likely to yield the same benefits when employed in a different application. Consequently, in deriving the most tolerant welding procedure for a given component, the potential of the various shielding gas mixtures must be investigated in combination with suitable welding parameters.

7.5.6. Surface activating fluxes

Surface activating fluxes such as FS-71 which consists of:

57.3%	milled silica (SiO_2);
6.4%	sodium fluoride (NaF);
13.6%	titanium oxide (TiO_2);
13.6%	titanium powder;
9.1%	chromium oxide (Cr_2O_3).

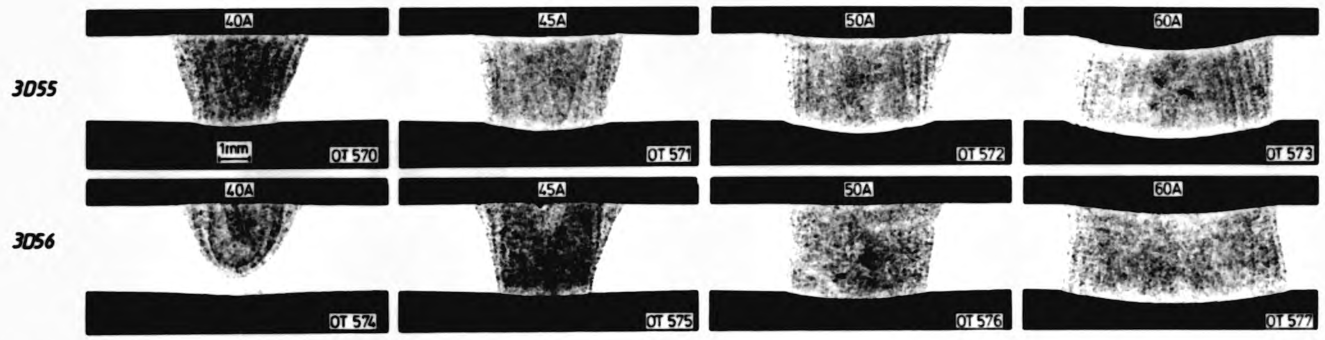


Fig. 7-21. Improved penetration consistency between the two casts (55). Shielding gas: He+20%Ar; welding speed: 60 mm/min.

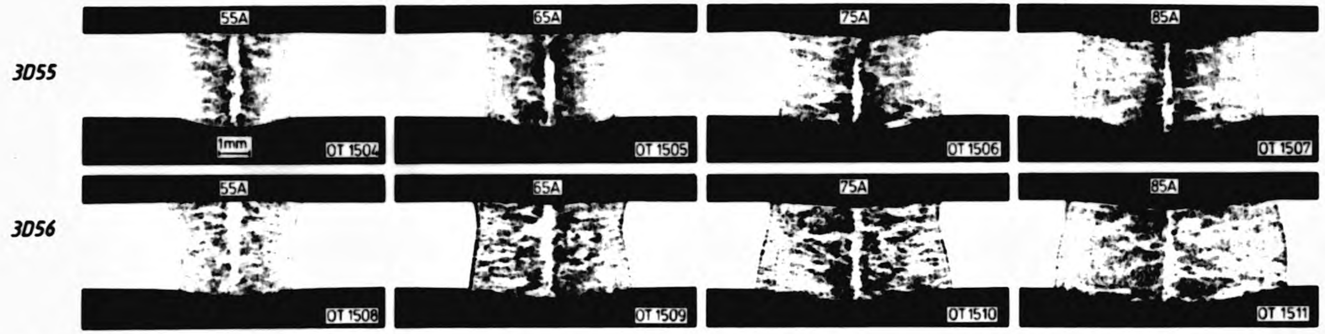


Fig. 7-22. Identical fusion behaviour for both casts (55). Shielding gas: He+25%Ar+5%H_2; welding speed: 150 mm/min.

have been used in TIG welding to enhance the performance of the arc to the extent that 8 to 10 mm thick plate can be welded in a single pass (56,57). Whilst the mechanism is not as yet fully understood, it is considered that the current density in the region of the anode spot is substantially increased.

It is envisaged that activating fluxes could offer the potential for improving the process tolerance through the more consistent behaviour of the intensified TIG arc (58).

7.6. CONTROL OF WELD POOL PENETRATION

Various techniques have been investigated for the control of weld pool penetration. These are:

1. Correlation of parameters;
2. Arc sensing;
3. Backface weld pool sensing;
4. Weld pool and position control;
5. Frontface sensing.

Only backface weld pool sensing techniques have been applied successfully in production. Nevertheless, the other techniques may offer a solution, for example, in the situation where access to the backface is restricted.

7.6.1. Correlation of parameters

A number of mathematical models have been derived which could be used to predict the weld pool behaviour.

An analytical model based on a semiempirical heat transfer analysis technique shows that solidification of the weld pool can be related to the pulse parameters (59). On the bases of the validity tests using stainless steel, mild steel and copper, the model could predict suitable welding parameters for a given joint in the development of adaptive control of the pulse welding operation.

A mathematical model has been based on the intensity of radiation from the weld pool (60). The model can be applied for the prediction and control of weld penetration.

A photodiode array has been used to measure frontface weld pool dimensions (61). A model was then used to predict the depth of penetration from the values of frontface weld pool width, arc voltage, welding current and welding speed.

An analytical as well as numerical model showed that a strong correlation exists between the weld penetration and the weld pool solidification time (62). The correlation was verified using a fibre optic sensor to measure the temperature distribution of the weld pool.

7.6.2. Voltage sensing

A penetration control technique has been based on the identification of arc voltage variation (63). In operation, when a pulse of current is applied, the weld pool rises before full penetration and then falls after the penetration. These spatial variations cause variations in the arc voltage, which could be used to indicate and control weld penetration. However, the voltage variations have been found to be inadequate to achieve reliable control of penetration.

7.6.3. Ionization sensing

A system has been based on the detection of a flux of ionized gas, from the underside of a joint, when the arc fully penetrates the material. Due to ionization of the gas, current can pass easily through the space between the weld pool and a current conducting element located underneath the workpiece along the joint line. Based on this principle, an automatic feedback control system has been developed for pulsed current operation (64). In operation, the system switched the high pulse current to a low background current level when the transducer provided information on full penetration to the control circuit.

7.6.4. Weld pool sensing

A backface weld pool penetration control system has been developed for the pulsed current operation in which a photodiode is used as a transducer placed directly beneath the weld pool (64–68). When the photodiode detected penetration of the weld pool, it provided a signal which was used to switch the high level pulsed current to a low level background current. The onset of the subsequent pulse current was determined by the preset pulse frequency, and the cycle of the events was repeated until completion of the welding operation.

An important aspect of this system was that the transducer had to distinguish the temperature of the weld pool from that of the unpenetrated plate. Sufficient distinction was achieved by means of simple optical technique of using a narrow band filter with a suitable photodiode. The system provided adequate control of weld bead penetration in mild steel and various types of stainless steel with thickness up to 6 mm.

The reliability of the above system was improved by means of a solenoid or an annular permanent magnet placed around the welding head (51,69). This device produced a magnetic field concentric with the arc, which reacted with the current flowing through the weld pool. The resultant force stirred the weld pool and caused a more uniform heating of the weld pool to eliminate or reduce the undesired random spikes in the output signal from the transducer, which would otherwise have degraded the useful information.

The system has been applied successfully in an automatic orbital TIG welding system, for the welding of stainless steel pipes which had U-groove joints of varying rootface depth (70). It is claimed that the technique is suitable for TIG welding using filler wire addition.

Another feedback control system has been developed which is based on sensing the radiation emitted from the weld pool (71). This radiation was detected by means of an array of optical fibre/photodiode combination. As the welding progressed, the amplified signal from the fibre/photodiode system was used to control both the arc current and the welding speed, such that the weld penetration was controlled adequately.

The system has been further developed for the simultaneous control of the weld pool penetration as well as its position (72). In the welding of a tube to a flange, the main requirement was a full penetration T butt weld without penetrating the tube bore. To achieve this, two photodiodes were arranged at the backface, one towards the flange and the other towards the tube. The signal from the photodiode on the flange side was used to ensure full penetration of the joint, while the signal from the other photodiode was used to deflect the arc magnetically on to the flange in preference to the tube.

7.7. DISCUSSION

The review of the articles concerned with the parametric effects on weld penetration, process techniques to improve welding performance and the weld penetration control systems, has led to the following deductions:

1. The causes of variation in weld penetration are not known definitively;

2. Welding techniques which can accommodate variations in the process parameters have not been established;

3. The penetration control systems which have been developed are based mainly on the detection of light intensity of the weld pool, but these do not necessarily indicate the actual size of the penetration.

The information on the effects of process parameters (current, voltage, electrode geometry, shielding gas) which may disturb process stability, are not reported widely. Therefore, very little guidance can be derived from the published literature on the selection of welding parameters or on the tolerance of the welding techniques themselves. Furthermore, the contradictory results of the effect of electrode tip angle on weld penetration (33,35) serve to emphasise the lack of agreement on the relative influence of the process parameters on penetration and recommendations on optimum settings. Consequently, it is recommended that in production, equipment settings such as electrode tip angle and the electrode to workpiece distance be held constant to reduce the risk of introducing variability from process parameters.

Among the techniques which have been reported, the selection of an alternative shielding gas mixture in combination with a suitable welding speed appears to offer the most promise in improving the performance of the TIG process. However, despite promising results on specific casts of material there is no one gas mixture which consistently performs better than other gases. Consequently, a range of commercial gases must be evaluated for the different types of material and joint configuration before any recommendations can be made.

Special mention has been made of the effect of material (cast to cast) variation when TIG welding. Considerable interest is being shown in this topic, both with regard to understanding the effects of small variations in material composition and to techniques to minimise these effects. From the results to date, it would appear that reducing the sulphur and oxygen concentrations from very low levels would substantially increase the risk of producing shallow penetration.

Various approaches have been conceived and implemented to develop weld penetration control systems. In general, these control approaches are based on the measurement of weld pool size on the frontface, the arc voltage variation or the light intensity of the weld pool at the backface. However, none of these systems have become popular in industry for the widespread use in the practical applications. The systems have remained largely of laboratory interest.

7.8. CONCLUSIONS

Despite the seriousness of the problem to industry there is insufficient knowledge on the effects of process and material variation to guarantee that a fully fused weld will be produced using preset welding parameters under normal operating conditions. It is therefore essential that closed loop penetration control systems are made available, particularly for the welding of critical components.

CHAPTER 8
EVALUATION OF A VIDEO-BASED PENETRATION CONTROL SYSTEM

8.1. INTRODUCTION

In TIG welding, inconsistencies in penetration occur due to variations in material compositions, component or joint dimensions or welding parameters. As these variations cannot be eliminated in practice, a real-time control method must be used to achieve uniform penetration.

A number of control systems have previously been developed (64,65,66,69,71) which are based on the technique of sensing the weld pool penetration from the backface using a photodiode or current carrying conductor as sensor. The principle of this technique is shown in Fig. 8-1. Commercially available systems have been applied successfully in the fabrication of cryogenic vessels and various tubular components.

However, the successful operation depends on the accurate positioning and alignment of the photodiode relative to the weld pool at the back face, which is not easy. Furthermore, changes in the emissivity of the weld pool surface influence the response of the system, which may be caused by a difference in the degree of cleaning of the workpiece surface, or by oxidation due to imperfect gas shielding.

An alternative system, based on a video camera, has been designed and constructed at Liverpool University (73,74), described in Section 8.3. Essentially this system measures and controls the weld pool size instead of the average level of radiation measured by a photodiode. Therefore, the performance of the system is largely independent of the emissivity of the workpiece surface and more able to accommodate variations in operating conditions, for example, variations in component fit-up.

8.2. OBJECTIVES

The objective of the work reported in this chapter is to evaluate the 'automatic control

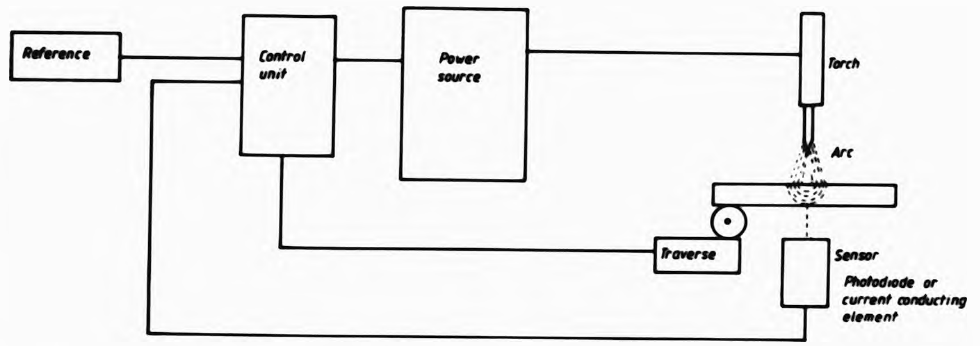


Fig. 8–1. Block diagram of backface penetration control system, using photodiode or current conducting element as a sensor indicating the moment the weld spot appears on backface.

of weld penetration' system based on a video camera, developed at the University of Liverpool.

8.3. CONTROL SYSTEM

The basic system comprised of the following components:

1. A object lens;
2. A fibre optic image guide;
3. An image guide adapter;
4. A video camera;
5. A monitor;
6. An interfacing unit;
7. A microcomputer;
8. A transistor power source;
9. A welding torch and electrode assembly;
10. A welding rig.

The vital organ in the control system was the microcomputer which performed the control, data processing and computation functions according to the software program, while the other units performed auxiliary functions of inputting or outputting the data.

The system is shown as a block diagram in Fig. 8-2a and photographically in Fig. 8-2b.

8.3.1. Transducer

The control system operates from the information supplied on the weld pool size. This information is provided by the transducer which comprised of an object lens assembly, a fibre optic image guide, an image guide adapter and a video camera.

a). Object lens

The object lens is a biconvex glass lens with a diameter of 10 mm and focal length of 10 mm. The mounting assembly provides variable focusing and thus allows the

a)

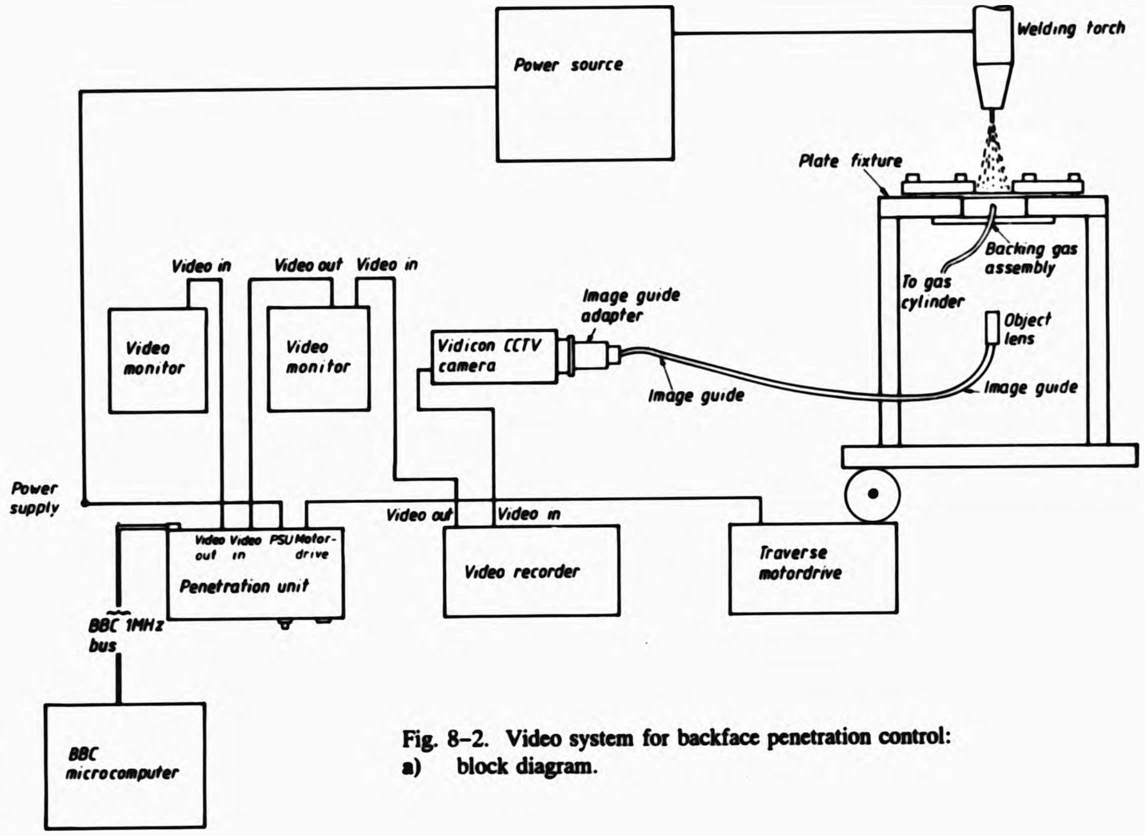


Fig. 8–2. Video system for backface penetration control:
a) block diagram.

b)

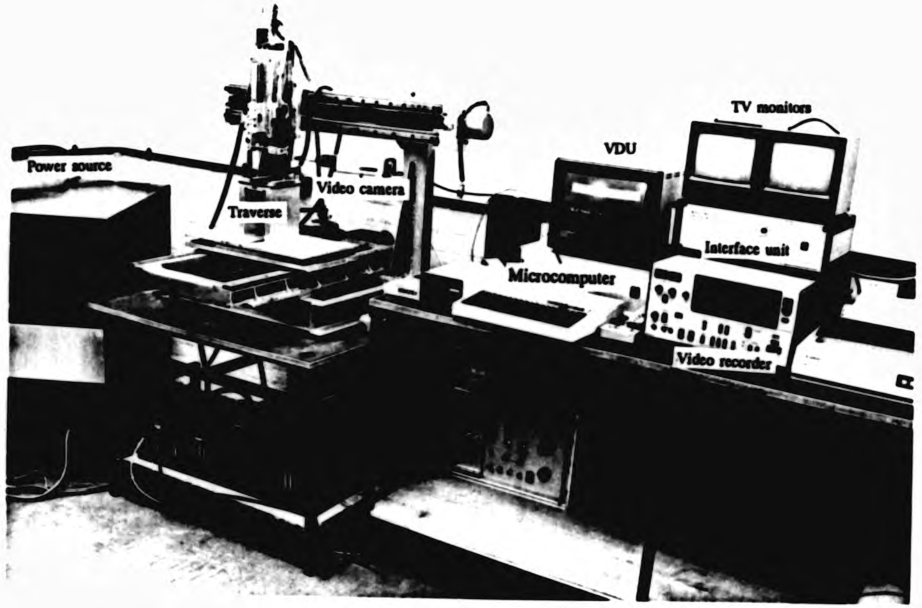


Fig. 8–2. contd. Video system for backface penetration control:
b) photograph.

distance between the lens and the backface of the workpiece to be adjusted. The lens focuses the light from the weld pool on to the fibre optic image guide attached to it.

b). Fibre optic image guide

The fibre optic image guide is comprised of a bundle of approximately 25,000 optical fibres, each with a diameter of 10 μm and provides an active viewing area of 3.1 mm^2. The guide has a length of 450 mm and minimum bend radius of 2 mm. The fibre guide transmits the optical signal from the object lens to the video camera.

c). Image guide adapter

The image guide adapter links the fibre guide to the video camera so that weld pool image is relayed to the active area of the video camera tube. The adapter also includes facilities for the focusing and aperture adjustment.

d). Video camera

The video camera is a commercially available monochrome closed circuit TV (CCTV) Hitachi video camera. The camera converts the optical signal into an electrical composite video output with a maximum value of 1 V peak to peak which needs to be terminated in a 75 Ω load. The output relevant to the weld pool size provides information to the penetration control unit.

8.3.2. Interfacing unit

The hard-wired unit comprised three separate boards to perform the interfacing, timing and pixel counting functions. The interfacing board processed the analog signals provided by the transducer to obtain the relevant digital information, and then enabled it to be transmitted to the microcomputer. In addition, the output provided by microcomputer was digital and was also processed by the interface unit to produce the relevant analog signal suitable for driving the transistor power source feeding the arc, and for controlling the traverse.

The timing board extracts the video timing information and also provides the digitised video picture on the monitor.

The pixel counting board contains the pixel counter and the background level selector.

8.3.3. Monitor

The monitor is a commercially available (Hitachi) monochromatic unit, 225 mm screen, with the facility to 'feed through' the video signal while presenting negligible load to the camera.

8.3.4. Transistor power source

The transistor power source (Polypack 300 A TIG unit), designed and developed at The Welding Institute (32), comprised of a 3-phase transformer-rectifier unit with the addition of a feedback controlled transistor series regulator. The transformer-rectifier provided DC which was then controlled by the regulator to supply the arc with any desired current waveform (e.g. smooth DC or square wave pulsing). The range of current extended from 0 to 300 A. As the frequency response of the transistor regulator extended from DC to about 10 kHz, the power source could provide a range of frequencies from DC to about 1 kHz, with pulse durations from 1 msec upwards.

The regulator was operated in the constant current mode from an instruction or reference signal, on the basis that 0-3 V reference input gave 0-300 A regulator output to the arc. The power source also included a High Frequency (HF) arc starting unit. The calibrated reference signal of the desired waveform was provided, via the interface circuit, by the control unit.

The HF arc starting could not be used because this interrupted the computer from its proper functioning. However the tests included in this chapter were carried out by using a GEC, AWP-T300EC power source which is based on a secondary chopper. High frequency arc starting was disconnected from the welding circuit and the power source was modified to accept an external reference scaled to provide 100 A/V. The arc was started manually by short circuiting the electrode and workpiece using a tungsten electrode.

8.3.5. Welding rig

To evaluate the welding performance of the control system, the tests were carried out on a precision controlled mechanised TIG robot (75). The workpiece was traversed under a stationary welding torch, which was mounted vertically such that electrode tip to workpiece distance could be easily adjusted. The traverse was driven from the reference signal provided by the microcomputer which controlled the weld penetration system.

8.4. CONTROL PROGRAM (SOFTWARE)

The control program, called WELDPEN, which resided in the microcomputer memory, is the soul of the microcomputer control: it enables the microcomputer to perform the penetration control. The software permits the operator to select any of the following nine options:

a). Input welding parameters

When the software is initialised, the microcomputer invites the operator to specify the pulsed current parameters (background current level, pulse current level, pulse frequency and the maximum pulse duration), traverse speed and direction. For normal operation, the penetration unit will determine the 'pulse–on time' (i.e. duration of each pulse) relevant to the degree of required penetration. However, a maximum value of the pulse duration must be specified which will not be exceeded for safe welding operation when a fault would occur in the control system.

b). Load welding parameters

Files which contain previously stored welding parameters can be loaded from the disc.

c). Save welding parameters

Files can be stored under selected file names for future use.

d). Delete file

Allows unwanted files to be deleted from the disc.

e). Inspect disc contents

Allows all file names on the disc to be inspected.

f). Start welding run

When all parameters have been specified and the sensor positioned correctly, the welding test can commence.

g). Pixel count from video tape

When a video recorder is used to replay the recorded welding runs, the number of pixels above the threshold level can be counted.

h). Plot graph of current pulses

When a welding run has been completed, the time for each pulse can be stored on disc for inspection when required. This routine is essentially a graph plotting program which loads the values from the disc for the pulse time and displays them on the screen.

i). Movement of traverse

The speed of the single axis traverse can be set but there are also facilities for moving the traverse prior to welding so that the routine weld jobs can be positioned correctly underneath the welding torch assembly.

8.5. SELECTION OF THE PULSE PARAMETERS

For a specific application, a suitable combination of the pulse current parameters must be predetermined and supplied to the microcomputer. For effective control of weld penetration, the pulse current level should be adequate to enable the weld pool to penetrate the workpiece rapidly. In addition, the background current and background time combination should allow the weld pool to solidify between the successive pulses. Such parameters have been determined for a range of sheet thicknesses (1.0 to 3.2 mm) and these were stored on magnetic disc. Typical values of the parameters are given in Table 8–1.

Table 8–1. Typical welding parameter settings for various stainless steel thicknesses using backface penetration control system.

Thickness, mm	Pulse–on time, sec	Pulse–off time, sec	Pulse current, A	Background current, A	Slope–up time, sec	Slope–down time, sec	Traverse speed, mm/sec	Direction of traverse
1.0	3	0.5	50	10	3	3	2	1
1.6	3	0.5	70	10	3	3	2	1
2.0	4	0.8	100	15	3	3	2	1
2.6	4	0.8	120	15	3	3	2	1
3.2	4	1.0	160	15	3	3	2	1
0 – forwards, 1 – backwards								

8.6. EXPERIMENTAL DETAILS

a). Welding torch

The welding torch used was commercial type (Interlas), water cooled with a ceramic nozzle of 12 mm.

b). Electrode

The electrode used was 2% thoriated tungsten with a diameter of 2.4 mm and 45° vertex angle, which was suitable for the required range of welding currents. The electrode tip to plate distance (standoff) was set at 1.5 mm for all the tests.

c). Shielding gas

The shielding gas used was $Ar+5\%H_2$ at a flow rate of 5 litre/min. In addition, the same gas composition was used to provide both the trailing and backing shields to protect the top bead and underbead from oxidation.

d). Material specification

The workpiece material used was 18Cr-10Ni type austenitic stainless steel plate. The dimensions of the plates were 150 mm long, 50 mm wide with 1.0, 1.6, 2.0, 2.5 and 3.2 mm thickness. The chemical analyses of the plates are given in Table 8-2.

8.7. SETTING UP THE SYSTEM

The performance of the control system relies on achieving a good quality video picture of the weld pool. To achieve this, the components of the control system were adjusted so that the following settings were derived which produced the optimum performance of the system:

1. A distance of 80 mm was set between the object lens and the plate to provide a suitable weld pool image size on the TV monitor.

2. A suitable optical filter and camera aperture were selected in combination with the focus adjustment of both the object lens and camera lens to reduce the effect of the heat affected zone to provide a well defined profile of the weld

Table 8–2. Chemical analysis of stainless steel plates used.

Plate thickness, mm	Element, wt%												
	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Co
1.0	0.045	0.005	0.027	0.59	1.46	8.7	17.1	0.21	0.04	0.27	0.01	0.03	0.12
1.6	0.044	0.009	0.025	0.60	1.37	8.8	19.0	0.26	0.03	0.27	<0.01	0.02	0.12
2.0	0.048	0.002	0.033	0.46	1.44	8.9	18.0	0.15	0.04	0.16	<0.01	0.02	0.08
2.6	0.039	0.001	0.032	0.48	1.48	8.9	17.9	0.07	0.03	0.20	<0.01	<0.01	0.11
3.2	0.042	0.005	0.025	0.76	0.99	9.1	17.1	0.22	0.05	0.17	<0.01	0.01	0.12
TWI reference number S/87/194													

pool; a Kodak filter No. 94 and camera aperture of about F8 gave the optimum image of the weld pool.

3. The scale of the feedback signal, representing the weld pool area (penetration), was adjusted for the optimum control response and the threshold level was then set for the required degree of weld pool penetration; a higher threshold level will produce a wider weld bead.

4. The grey level control, scaled 0–10, was optimised such that the sizes of both the digitised and analog video pictures of the weld spot were approximately equal, Fig. 8–3.

5. The required degree of weld penetration (i.e. size of weld underbead) was selected by means of the potentiometer control knob provided on the unit. This control selects the reference level scaled from 0 to 100, which represents the range of white pixels on the monitor screen from one screen full.

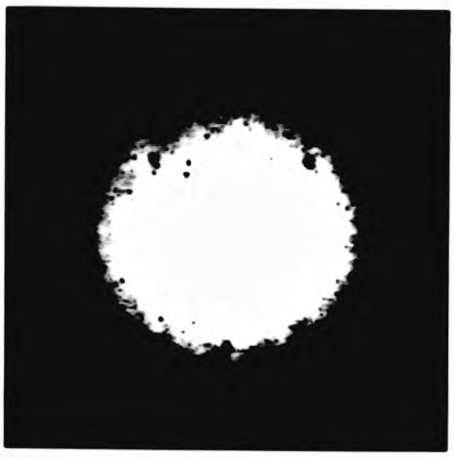
8.8. OPERATION

In operation, the pulse frequency, background current level and pulse current level were maintained constant at the preset values, while the pulse time was controlled automatically by the microcomputer in response to the comparison between the reference and feedback signal levels. When the reference level was greater, the pulse remained switched on, but as soon as the feedback level exceeded the reference level, the pulse was terminated and the current was reduced to the preset background level. The current remained at this level until the next pulse was switched on as determined by the preset pulse frequency.

8.9. TEST PROGRAMME

The performance of the control system was evaluated for the joint types given below:

1. Bead–on–plate tests, with different degrees of penetration;
2. Bead–on–plate tests, with varying plate thickness;

a) 

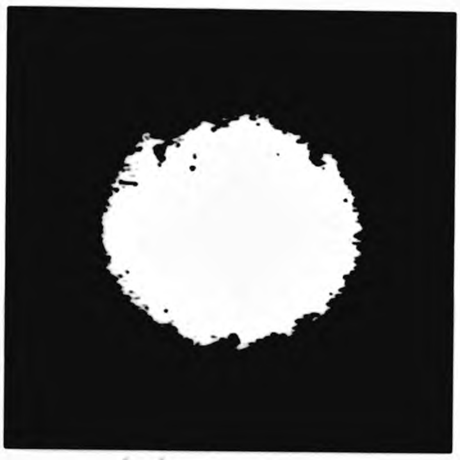
b) 

Fig. 8–3. Photographs showing video picture of weld spot:
a) normal video picture, b) digitised video picture.

3. Square-edge butt welds in plates with same thickness;
4. Square-edge butt welds in plates with different thicknesses;
5. Butt welds in V joint preparation;
6. Lap welds.

The details of the joint types, material thickness and penetration setting are given in Table 8-3.

8.10. RESULTS

8.10.1. Bead-on-plate tests — different penetration control settings

For any penetration control setting over the operating range (from 0 to 100), the control system regulated the pulse time automatically, so that the penetration or the size of the weld underbead was maintained constant. The effect of a change in the penetration control settings from 6 to 11 to 5 to 12 during a test run in 1.6 mm thick plate, together with variation in pulse time as controlled by the system, is shown in Fig. 8-4. The size of the weld underbead varied relevant to the penetration control settings.

8.10.2. Bead-on-plate tests — different plate thicknesses

Using the pulse parameters previously optimised for rapid penetration of the various plate thicknesses (Table 8-1), bead-on-plate weld runs were made on 1.0, 1.6, 2.0, 2.6, and 3.2 mm thick plates. The control system was found capable of controlling the underbead width according to the penetration control setting by adjusting the pulse-on time. The width of each weld bead was substantially uniform over the weld length and weld spots were well overlapped. The photographs of the top face, backface, weld section and graph showing pulse time as controlled by the system, for the typical welds are shown in Figs. 8-5 to 8-7.

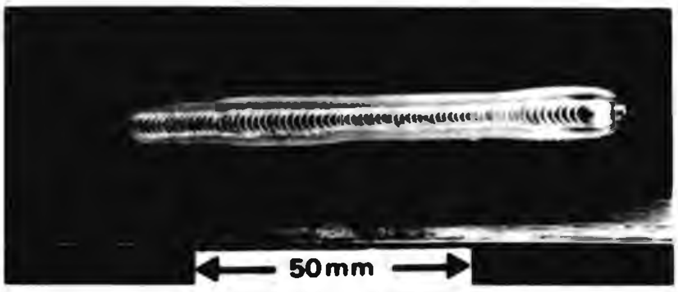
8.10.3. Bead-on-plate test — gradually varying plate thickness

The capability of the control system to control penetration in a plate with variable thickness was demonstrated by running a test on a plate which had its thickness reduced uniformly from 4 mm at one end to 1 mm at the other end. In operation, the

Table 8–3. Details of joint type, material thickness and penetration setting for welding tests using 18Cr–10Ni type stainless steel plate.

Joint type	Material thickness, mm	Penetration setting
Bead–on–plate	1.6	6–11–5–12
	1.0	6
	1.6	6
	2.0	6
	2.6	6
	3.2	6
Bead–on–plate, variable thickness	1 – 4	– Uncontrolled
	1 – 4	6 Controlled
Square butt, equal thickness	1.0 – 1.0	6
	1.6 – 1.6	6
	2.0 – 2.0	6
	3.2 – 3.2	6
Square butt, unequal thickness	2.6 – 1.0	6
	2.6 – 1.6	6
	2.6 – 2.0	6
	3.2 – 2.0	6
	3.2 – 2.6	6
V butt	6, Included angle 60°	10, Root face 2 mm
	6, Included angle 80°	10, Root face 2 mm
	6, Included angle 100°	10, Root face 2 mm
	6, Included angle 120°	10, Root face 2 mm
Overlap weld	2.0 – 1.0	6 Constant background time
	1.0 – 1.0	6 Constant background time
	2.0 – 1.0	6 Variable background time
	1.0 – 1.0	6 Variable background time
Lap weld	1.0 – 1.0	6
	2.0 – 1.0	6

a)



b)

c)

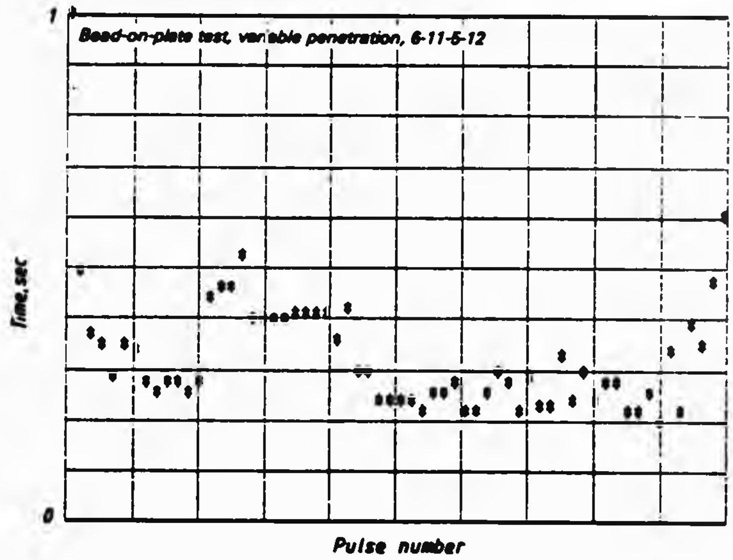


Fig. 8–4. Response of backface penetration control system to penetration knob settings being varied from 6 to 11 to 5 to 12. Grey level being maintained at 4.7. Weld bead showing variation in penetration relevant to control settings:
a) top bead, b) underbead,
c) graph showing variation in pulse time as controlled by the system.

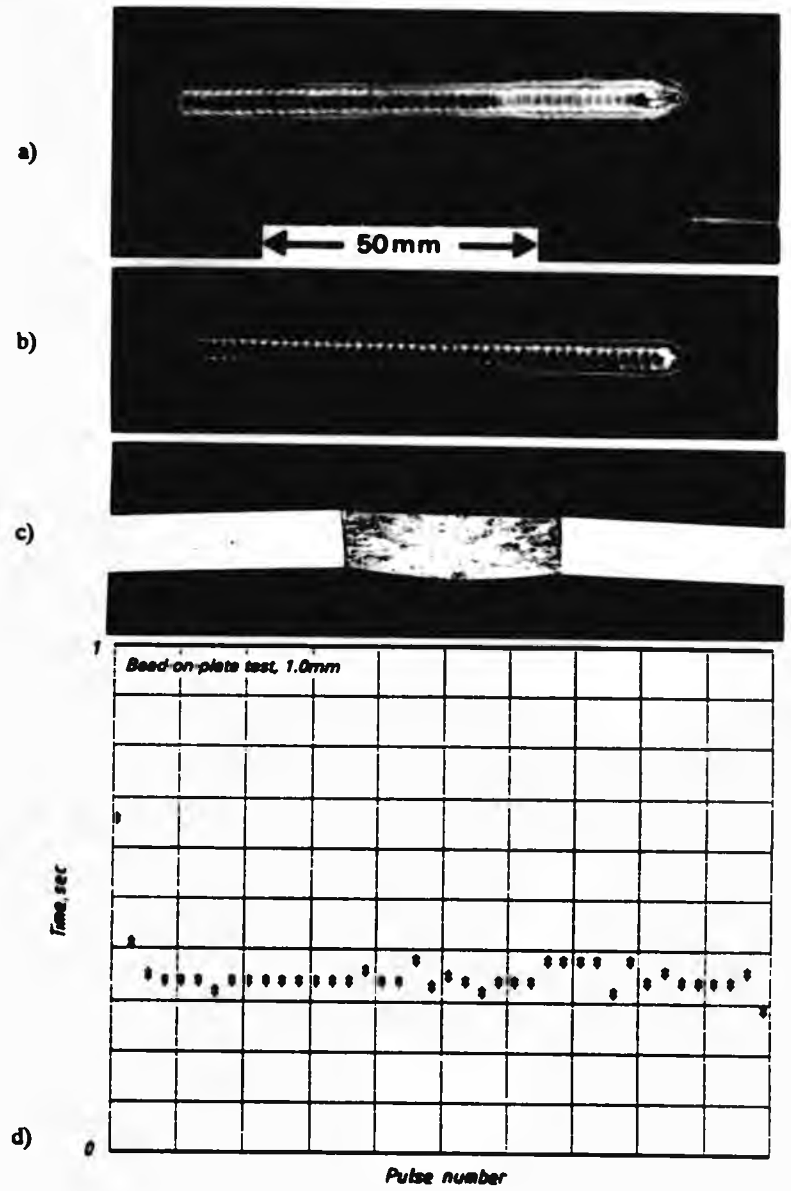
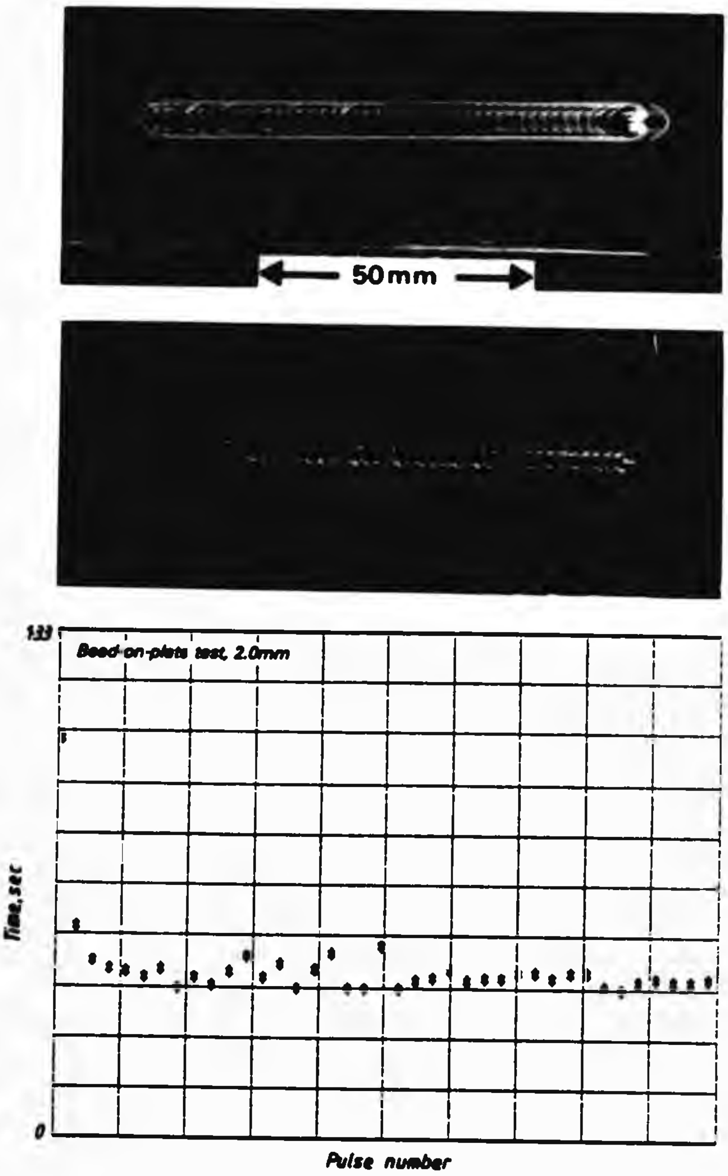


Fig. 8-5. Bead-on-plate test using 1.0 mm thick stainless steel and Ar+5%H_2 shielding gas. Weld bead showing consistency in penetration:
a) top bead, b) underbead, c) weld section, ×10,
d) graph showing pulse time as controlled by the system.



a)

b)

c)

Fig. 8–6. Bead–on–plate test on 2.0 mm thick stainless steel in Ar+5%H_2 shielding gas:
a) top bead, b) underbead,
c) graph showing pulse time as controlled by the system.

a)

b)

c)

d)

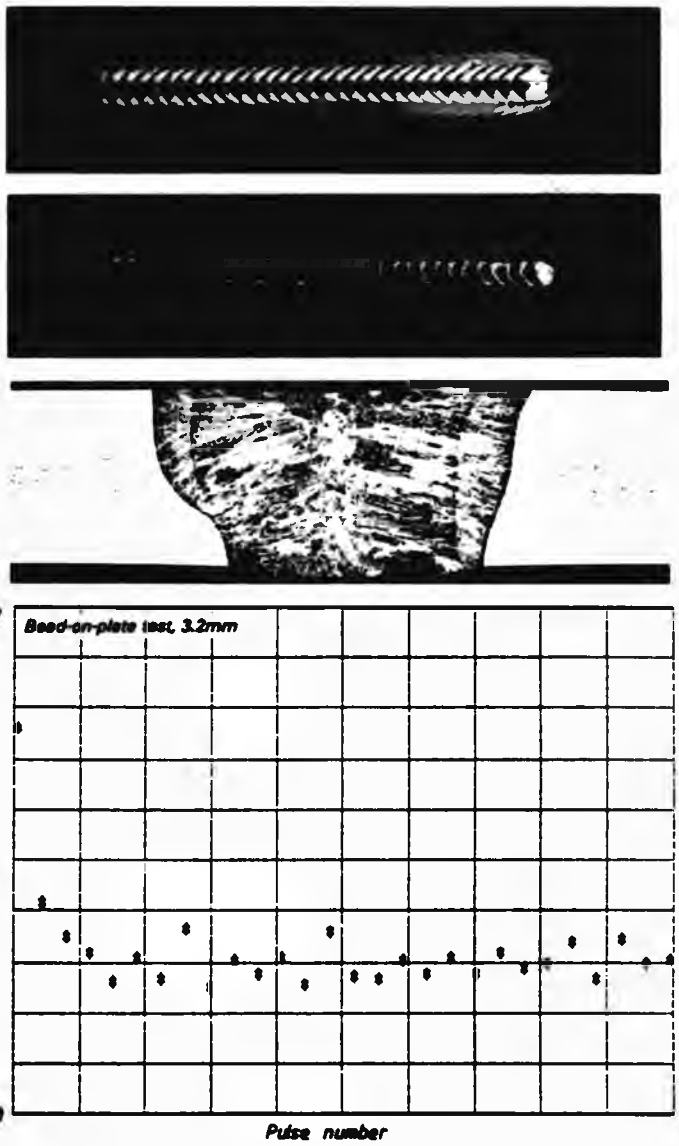


Fig. 8–7. Bead–on–plate test on 3.2 mm thick stainless steel in Ar+5%H_2 shielding gas:
a) top bead, b) underbead, c) weld section, ×10,
d) graph showing control of pulse time.

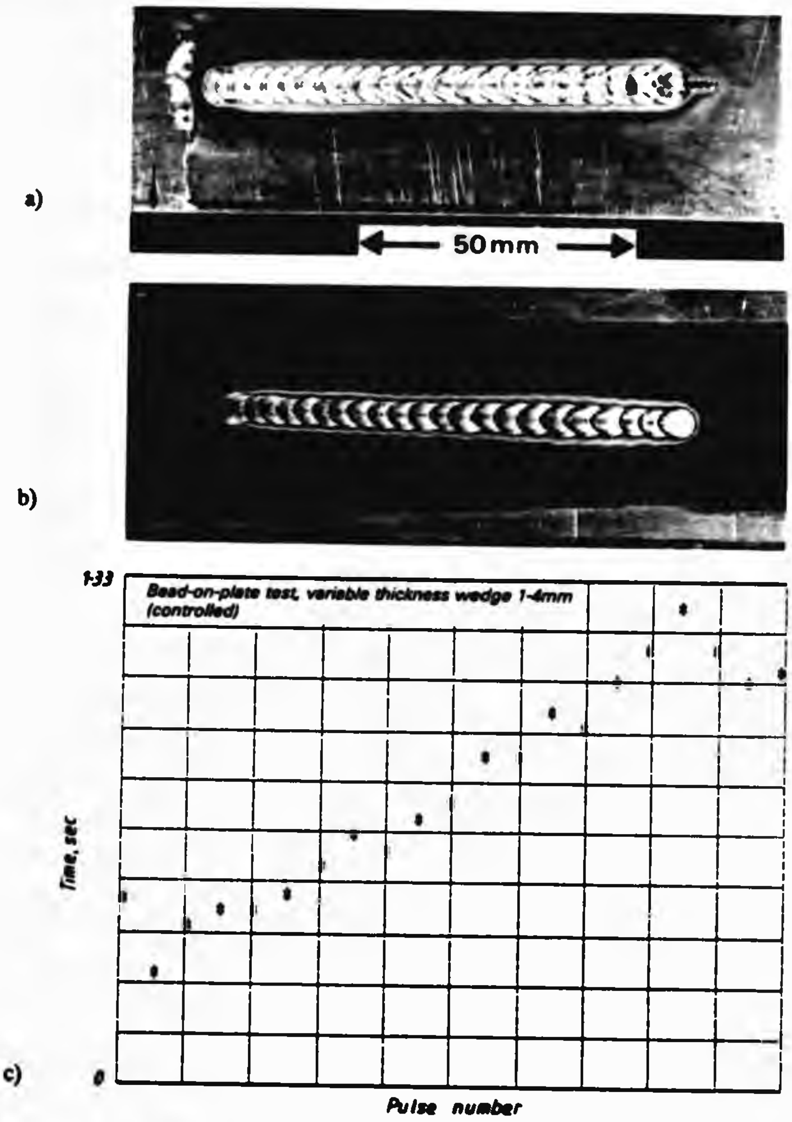


Fig. 8–8. Improved penetration characteristics achieved by the control system when test plate thickness varied gradually from 1.0 to 4.0 mm. Weld bead showing consistent weld penetration:
a) top bead, b) underbead, c) graph showing pulse time increased with material thickness as required and controlled by the system for full penetration.

system adjusted the pulse-on time as required by the weld pool to maintain a constant weld bead size throughout the weld length. The top bead, underbead and graph showing pulse time as controlled by the system are shown in Fig. 8-8. Although the overlap of the weld spots gradually reduced as the pulse-on time became longer with the increase in thickness, the system was found to be capable of controlling the size of weld spot despite a large variation in plate thickness.

In comparison, a weld made with a constant (uncontrolled) pulse-on time showed an excessive penetration at the thinner end and inadequate penetration at the thicker end. The variation in the top bead and underbead width, and graph showing pulse time for the weld run are shown in Fig. 8-9.

8.10.4. Butt welds in pairs of plates with equal and unequal thicknesses

To test the capability of the system to control penetration for a butt weld, several butt joints were welded in pairs of plates with equal thicknesses of 1.0, 1.6, 2.0 and 3.2 mm. The top beads and underbeads, together with the graph showing pulse time for the two joints in 1 mm and 3.2 mm thick plates are shown in Figs. 8-10 and 8-11. In addition, butt welds in pairs of plates with unequal thicknesses were made in 1.0-2.6 mm, 1.6-2.6 mm, 2.0-2.6 mm, 2.0-3.2 mm and 2.6-3.2 mm combinations. The top bead, underbead and graph showing pulse time for the two combinations are shown typically in Figs. 8-12 and 8-13. In all cases, the control system produced satisfactory welds maintaining a constant bead size throughout the weld run.

8.10.5. Butt welds in V joints with different included angles

Without a control system, the weld bead penetration in V-joint preparations can easily be disturbed by very small variations in the included angle. To assess the ability of the control system to control penetration in joints with different included angles, butt joints were prepared in which the included angle was varied from 60° to 120°; the specimens were machined from 6.2 mm thick stainless steel plate with 2 mm root face.

The best performance was obtained when the welding parameters were optimised for the smallest included angle and the satisfactory performance was also

a)

b)

c)

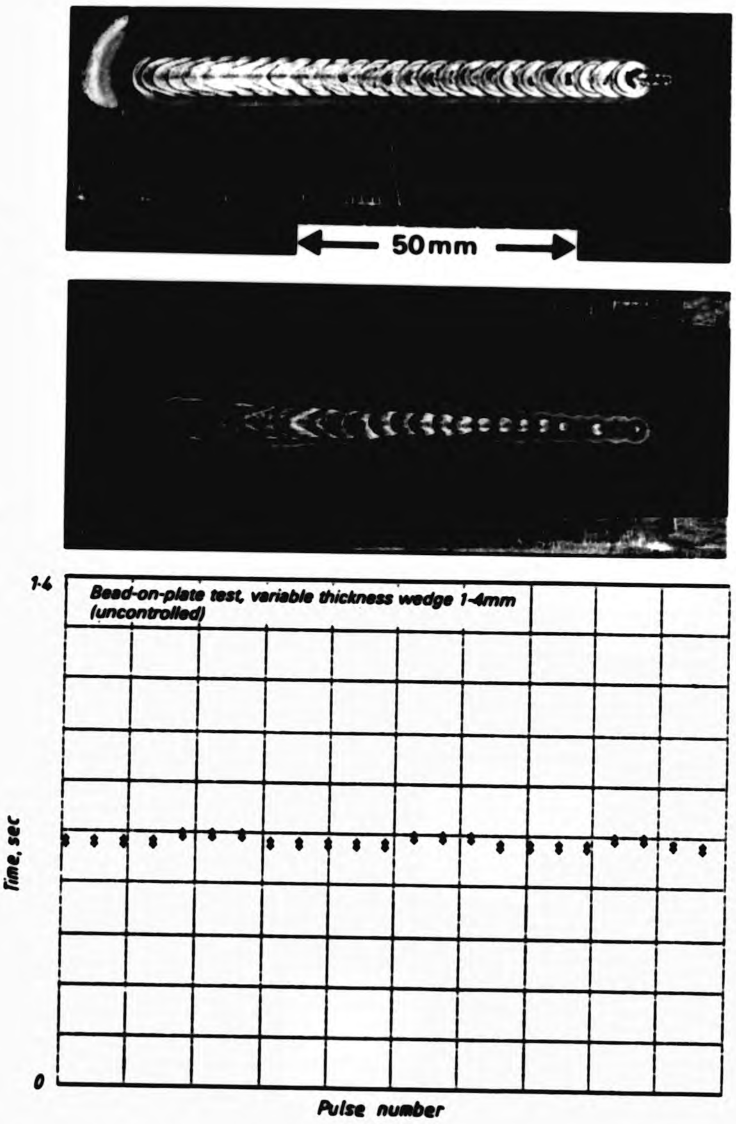


Fig. 8–9. Penetration characteristics in TIG welding using stainless steel with gradually varying thickness from 1.0 to 4.0 mm in Ar+5%H_2 shielding gas, without using the control system, showing excessive penetration at thinner end and poor penetration at the thicker end:
a) top bead, b) underbead,
c) graph showing uncontrolled pulses with constant pulse time.

a)

b)

c)

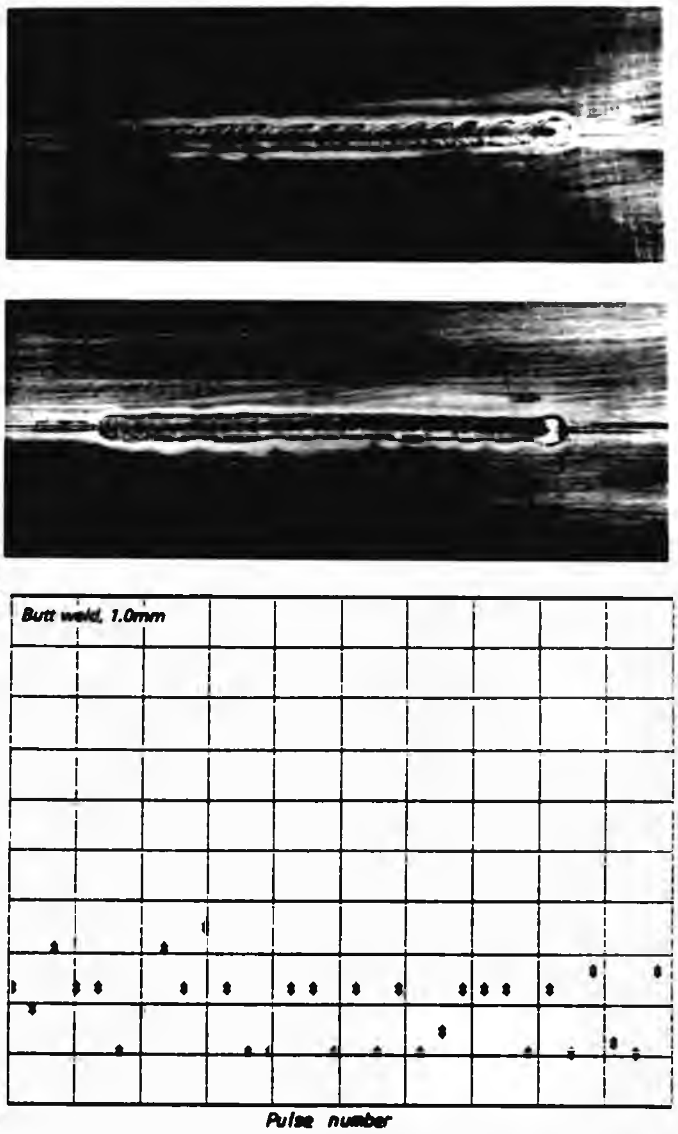


Fig. 8–10. Square butt joint in 1.0 mm thick plate showing consistency in penetration achieved by the control system:
a) top bead, b) underbead, c) graph showing pulse time.

a)

b)

c)

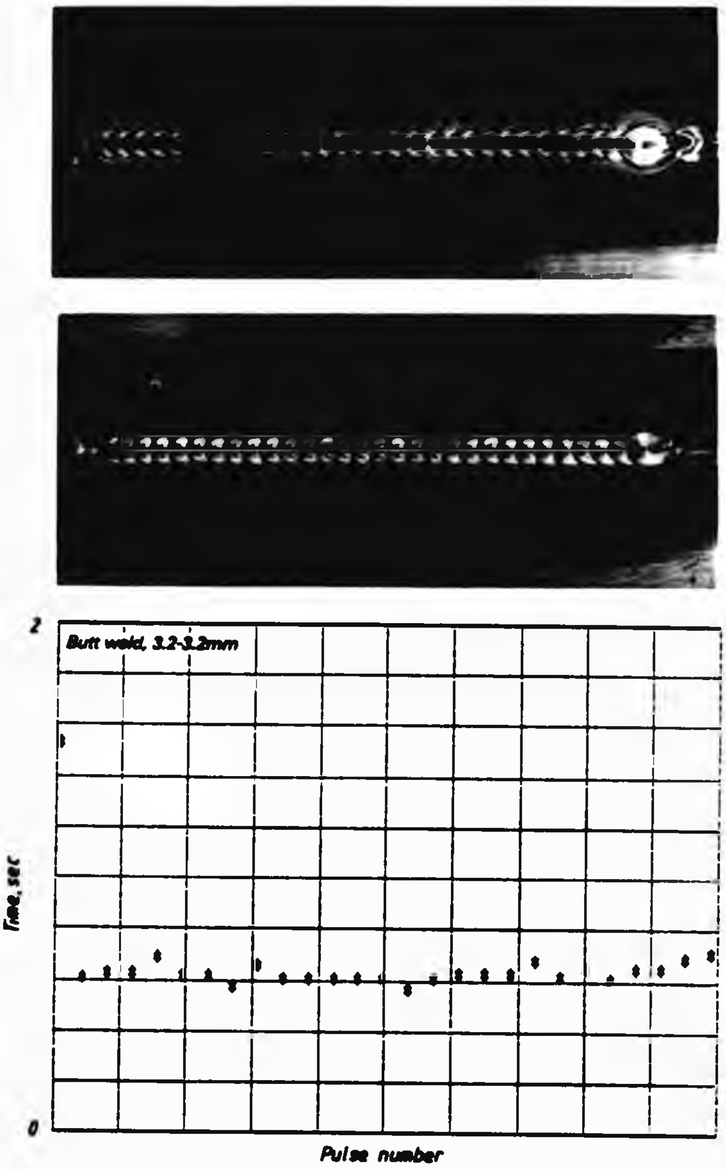


Fig. 8–11. Square butt weld using 3.2 mm thick plate:
a) top bead, b) underbead, c) graph showing pulse time.

a)

b)

c)

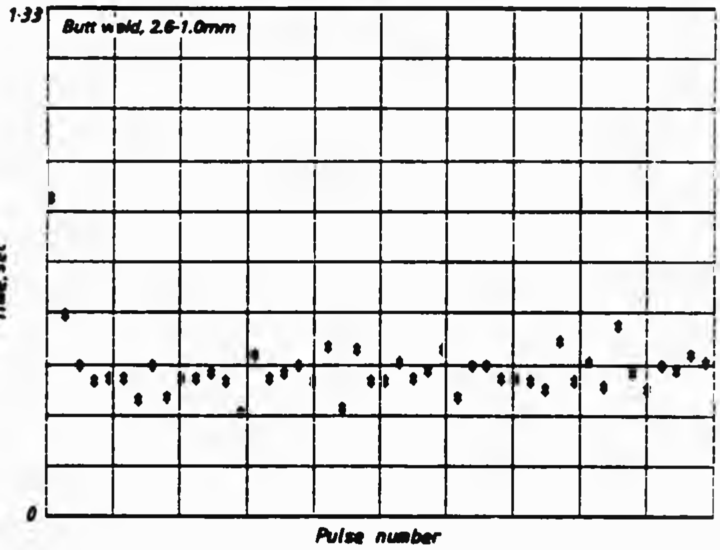


Fig. 8–12. Butt weld using stainless steel plates with unequal thickness of 1.0 mm and 2.6 mm. Control system ensured the consistent weld penetration:
a) top bead, b) underbead, c) graph showing pulse time.

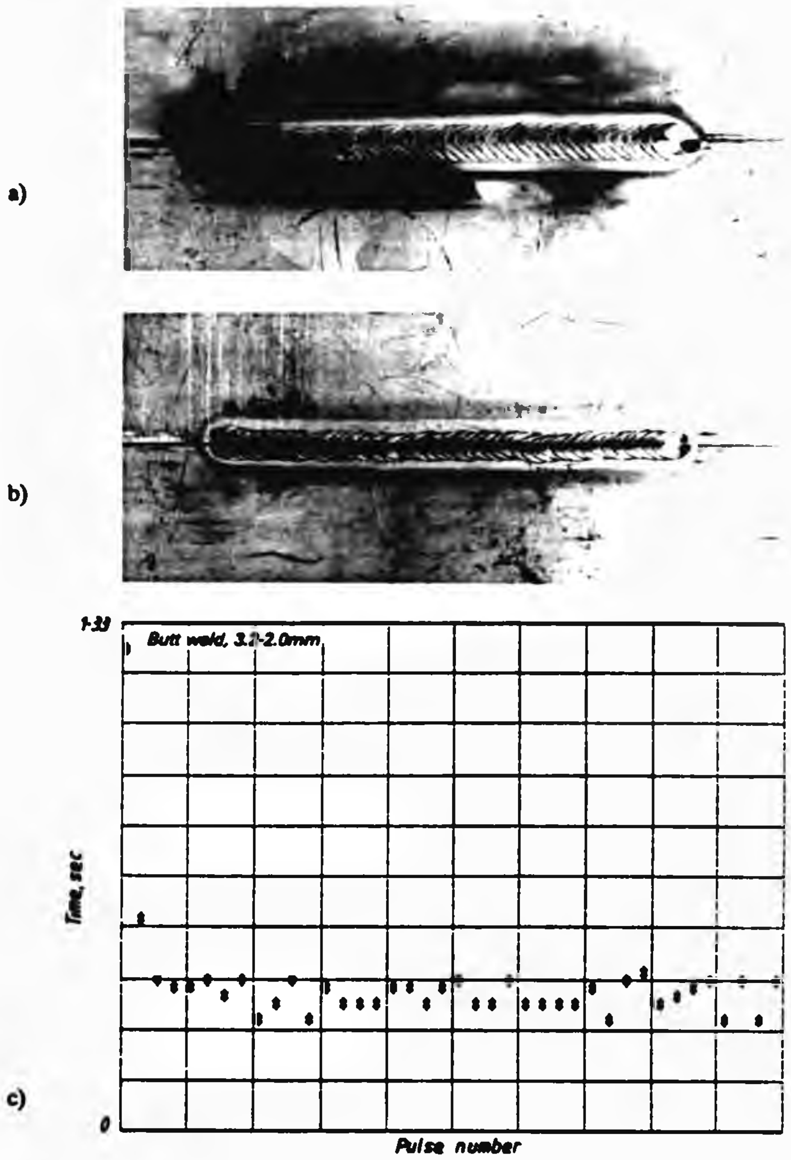


Fig. 8–13. Butt weld using 2.0 and 3.2 mm thick stainless steel plates in Ar+5%H_2 shielding gas:
a) top bead, b) underbead, c) graph showing pulse time.

obtained with the largest angle preparation. If the parameters were first optimised for the larger included angle, they were found to produce arc power which was inadequate to cause penetration of the specimens with the smaller included angle. Typically, the top bead, underbead and graph showing pulse time for the two welds in joints with 60° and 120° included angle are shown in Figs. 8–14 and 8–15. In general, the system was found to be capable of controlling the bead penetration, but because of the greater energy required to penetrate the specimens with the smaller angles, the longer pulses reduced the degree of overlap of the weld spots.

8.10.6. Weld spot overlap

To test how the control system would respond to step changes in the workpiece thickness, a test specimen was made by overlapping two plates at right angles to each other.

In operation, the system controlled weld penetration reliably, but the spot overlap was significantly reduced as the thickness increased because the system provided longer pulses to ensure penetration through the thicker material. The change in weld spot overlap due to a change in workpiece thickness for the top bead and underbead and graph showing pulse time are shown in Fig. 8–16.

In an attempt to maintain consistent overlap, trials were also carried out with a modified software which would automatically decrease the background time as the pulse time increased. Although this improved the consistency of spot overlap, the performance of the control system became unstable. The pulse time was found to oscillate giving very short to very long pulses, which produced a more uneven weld bead appearance. The top bead, underbead and graph showing pulse time, indicating unstable control operation, are shown in Fig. 8–17.

8.10.7. Lap welds

The control system was tested for welding lap joints between 1.0 to 1.0 mm and 2.0 to 1.0 mm thick plates. The system provided consistent control of weld penetration throughout the test runs. Typical characteristics of the top bead and underbead of a lap weld and graph showing pulse time are shown in Fig. 8–18.

a)

b)

c)

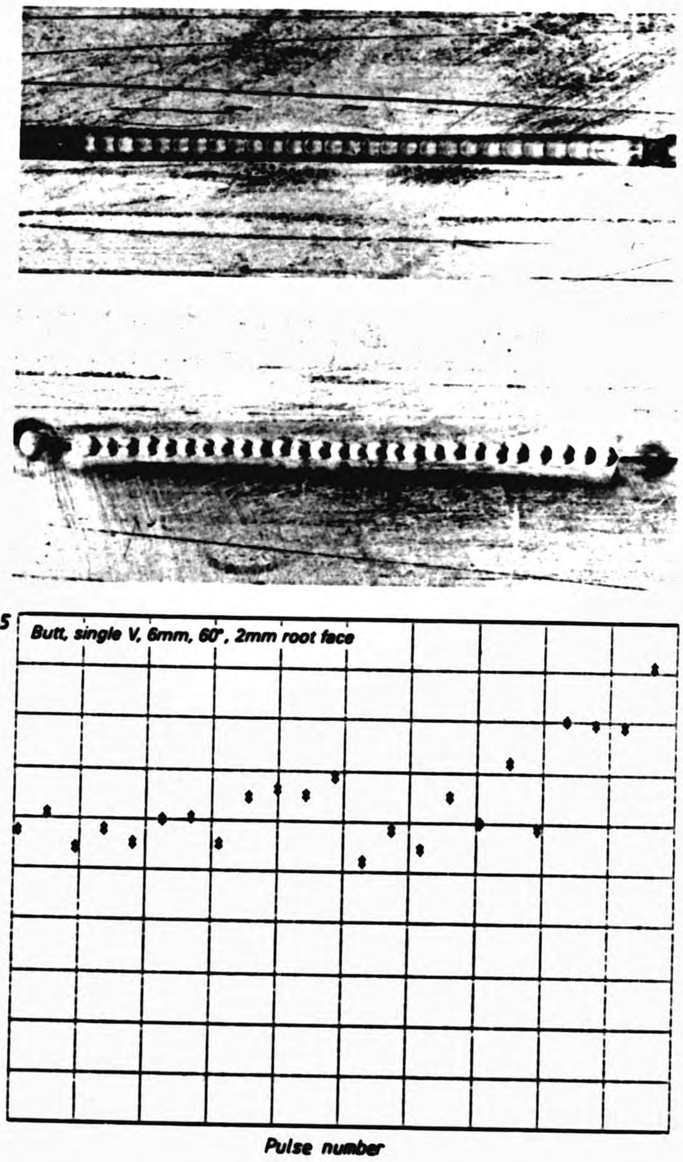
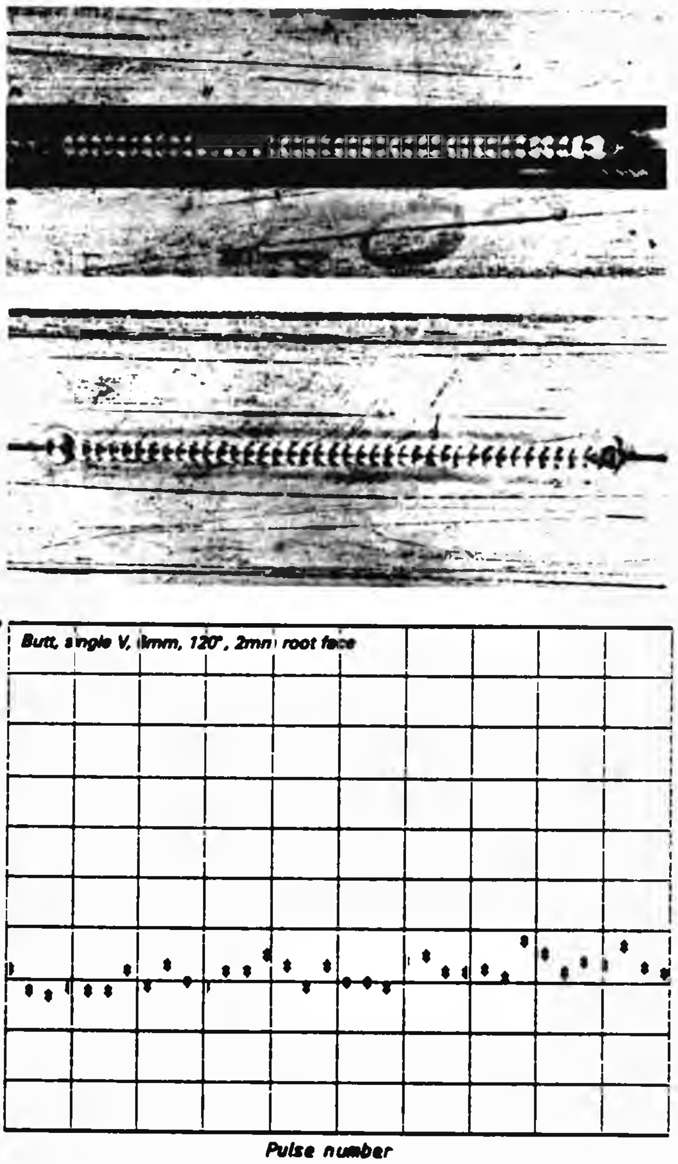


Fig. 8–14. Butt weld using 6.2 mm thick stainless steel plates with single-sided 60°–V preparation having 2 mm root face:
a) top bead, b) underbead, c) graph showing adjustment in pulse time by the system to produce consistent penetrated weld.



a) b) c)

Fig. 8–15. Butt weld using 6.2 mm thick stainless steel plates with single–sided 120°–V preparation having 2 mm root face:
a) top bead, b) underbead, c) graph showing pulse time.

a)

b)

c)

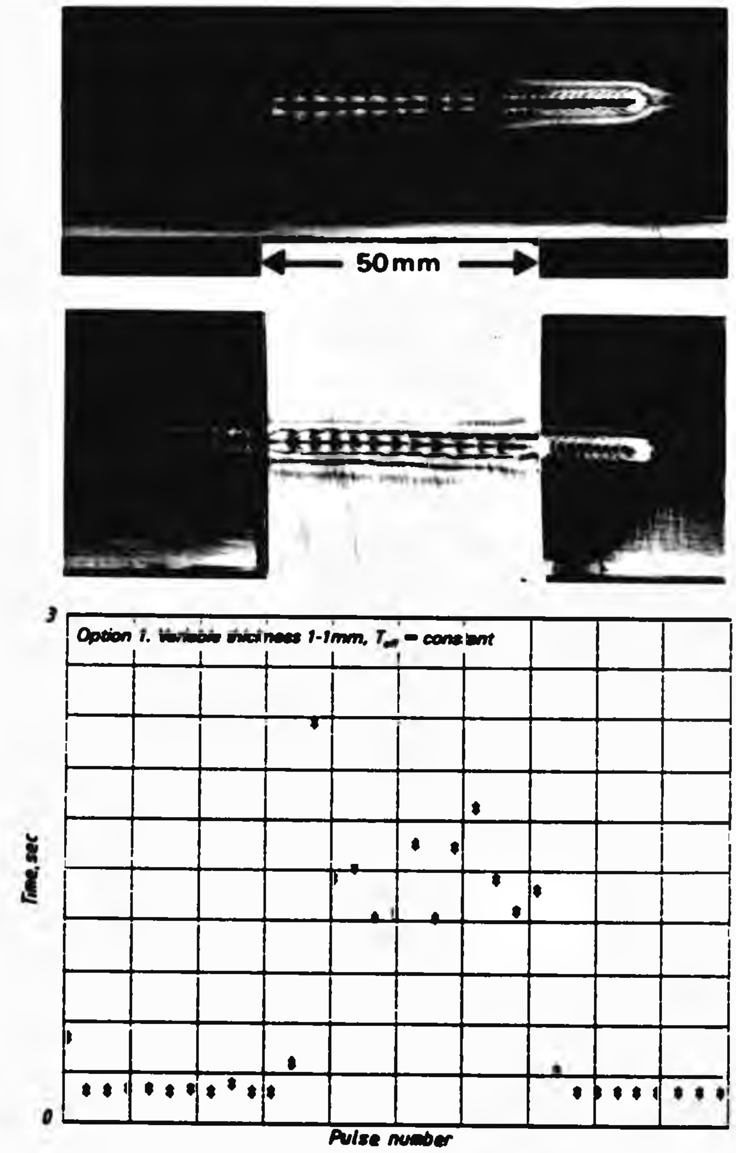


Fig. 8–16. Change in weld spot overlap with material thickness when 1.0 mm thick stainless steel plate welded with 1.0 mm backing plate:
a) top bead, b) underbead,
c) graph showing variation in pulse time.

a)

b)

c)

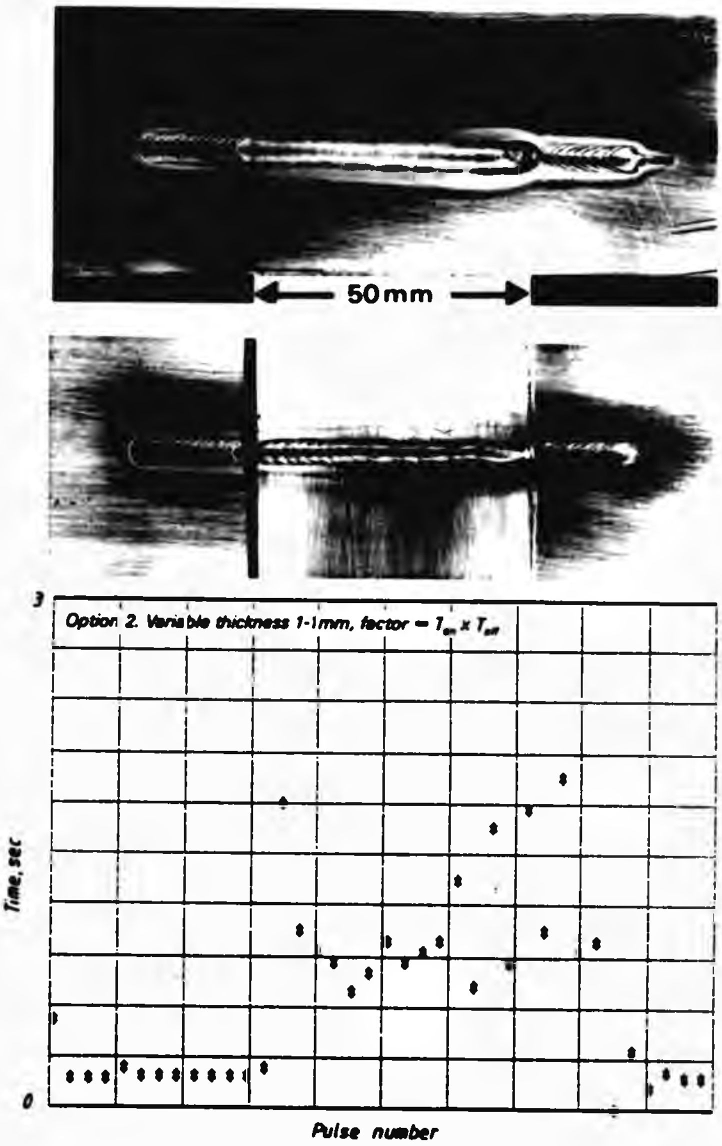


Fig. 8–17. Improved but inconsistent weld spot overlap has been achieved for 1.0 mm thick plate with 1.0 mm backing plate when control system was modified to keep product of pulse time and background time constant:
a) top bead, b) underbead,
c) graph showing the variation in pulse time, indicating unstable system.

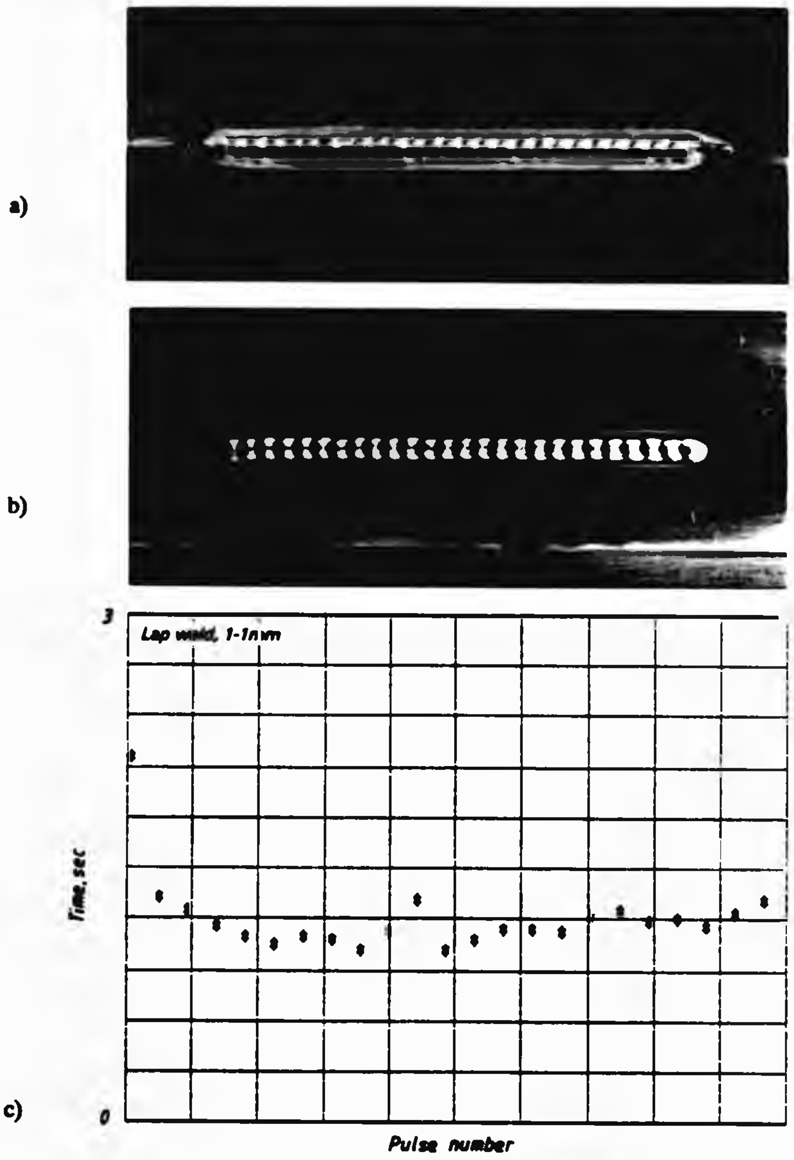


Fig. 8-18. Typical lap weld between 1.0 and 1.0 mm stainless steel plates showing the consistent control of weld penetration provided by the system:
a) top bead, b) underbead,
c) graph showing the variation in pulse time.

8.11. DISCUSSION

This work has established that the penetration control system, which is based on monitoring the size of the weld pool, has the capability of controlling penetration successfully for various types of joints, and of producing consistent welds. However, prior to application of the system to production welding some aspects should be considered carefully.

The system needs to be set up for a specific application, e.g. the light filter, camera aperture and grey level threshold should be selected such that a well defined image of the weld spot is obtained on the video monitor. The filter and camera aperture should be chosen so that the HAZ is eliminated from the video picture and only the molten weld spot is observed. In addition, the grey level control must be optimised such that the size of the digitised video picture becomes approximately equal to the picture of the weld spot displayed on the other video monitor. Among the three variables, filter, camera aperture and grey level, the adjustment of each variable will need readjustment of the other two. Therefore, it is recommended that these variables, once set at the optimum values for a specific application, should not be altered. Then, the required degree of the weld penetration should be adjusted simply by means of the penetration control knob.

To establish the optimum pulse parameters for each material thickness is a prerequisite. This is because the system controls penetration by regulating only pulse time, whereas the remaining three pulse parameters, pulse current level, background current level and background time, together with the welding speed, must be supplied to the microcomputer prior to the welding operation. If the pulse parameters relevant to a specific application are incorrect, then the control performance will be unsatisfactory. For example, if the pulse current level is inadequate, the control system will generate excessively long pulses; or if the background current is excessively high, the weld pool will not freeze during the background period, which is an essential condition for the control of penetration. In both cases, although full penetration will be achieved, the resultant weld bead will have an irregular appearance.

The principal limitation of the control system is that substantial access is required to the backface of the joint. This limit in general is similar to the alternative photodiode based control system. However, for the video based control system, the fibre optics/lens arrangement can somewhat reduce access requirements. The alignment of the system is considered to be somewhat easier for general applications in that the video camera can be located on the joint prior to welding using normal video image technique.

The advantageous feature of the control system is that its operation depends on the measurement of the size of the hot spot (weld pool). Even the edge of the digitised image represents a contour of equal brightness and this can be adjusted with grey level threshold control to ignore the HAZ. In comparison, operation of the alternative photodiode based control system depends on the measurement of the average intensity of light emitted from the HAZ and weld pool, and therefore it is affected by surface emissivity. Thus, as the video technique provides better resolution of the thermal distribution of the weld pool, the measurement and control of the penetration area is more reliable. Throughout the course of the study, no difficulties were experienced in welding plate which contained different types/levels of oxide layer.

8.12. CONCLUSIONS

1. The backface penetration control system using the fibre optics and video technique, is capable of controlling weld pool penetration using stainless steel in the TIG welding operation.

2. The system produced consistent welds in a wide range of stainless steel plate thicknesses, with different types of joint configurations.

3. The system can accommodate large variations in section thickness (in one test specimen) but the degree of spot overlap will vary significantly, producing excessive overlap at the thinner end and inadequate overlap at the thicker end.

4. Modifications to the software to keep the degree of overlap constant improved the consistency of the spot overlap but the welds had irregular profiles.

5. The system cannot be operated with an HF unit for automatic arc initiation due to corruption of software and electronic components.

CHAPTER 9
DEVELOPMENT OF A HARD-WIRED CONTROL UNIT

9.1. INTRODUCTION

A major limitation of the microcomputer based control system was that it could not be operated with high frequency (HF) arc initiation, because line and airborne HF interference would cause breakdown in the microcomputer and the associated interface unit. This limitation has now been overcome by the design and construction of a hard-wired control unit which effectively replaces the microcomputer. The design and performance of the control unit are presented in this chapter, which included bead-on-plate tests and welding trials for a range of material thicknesses. In addition, two casts of material were welded which had differences in welding behaviour under fixed duration (uncontrolled) pulses.

9.2. OBJECTIVES

The primary objective of research presented in this chapter was to design and construct a hard-wired control unit replacing the microcomputer, which would be less sensitive to HF. The secondary objective of the programme was to evaluate the system for the control of weld pool penetration in the TIG welding of plate materials of different thickness and analysis.

9.3. DESIGN OF THE CONTROL UNIT

The control unit comprised essentially two input channels, one dedicated to the video input and the other to a reference input. An additional circuit generated the pulse current waveform. A photograph and circuit arrangement of the unit are shown in Fig. 9-1.

The video input channel comprised a filtering circuit, a scaling amplifier and a level detector, all connected in series to a comparator. The video signal is a series of 'line sync' pulses with the level determined by the weld pool size. This signal was applied to the filtering circuit to eliminate the undesired 'line sync' pulses and to recover the useful information on the level of the video signal for each video frame.

a)

b)

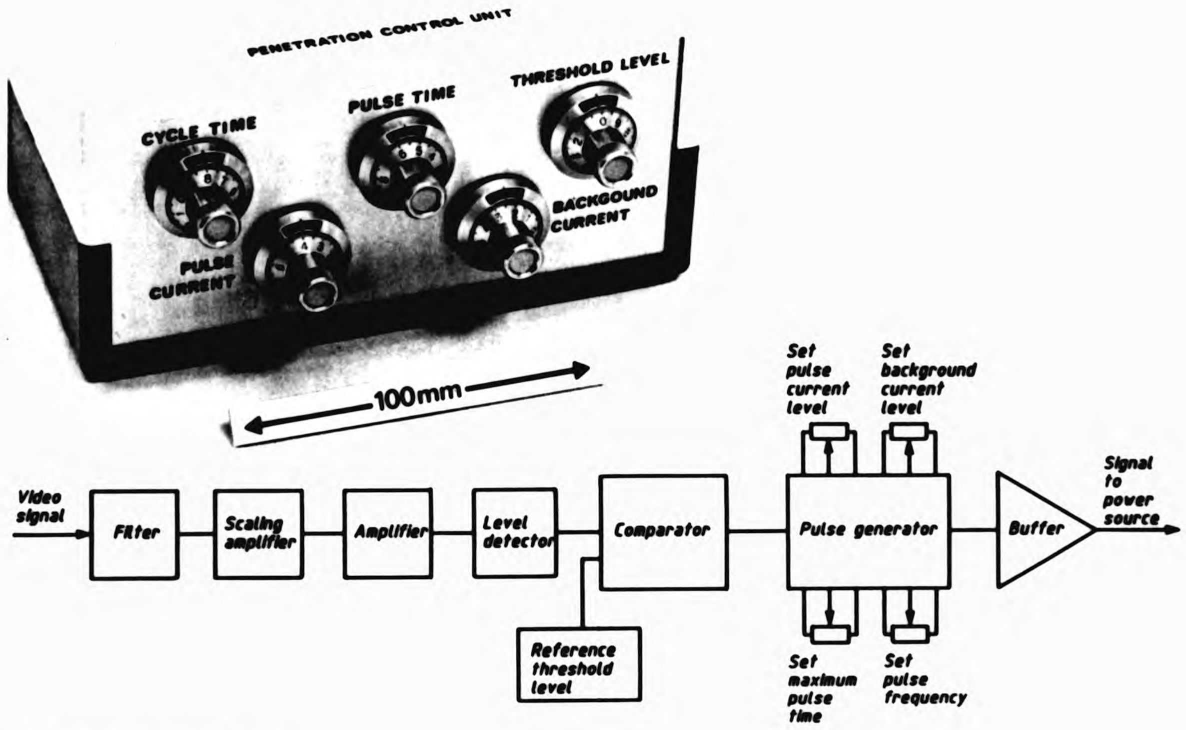


Fig. 9–1. Penetration control unit:
a) general appearance of the control unit showing control settings,
b) circuit arrangement.

The amplifier stabilised the level so that its output was maintained constant when there was no radiation from the weld pool.

The video signal was amplified and provided to the level detector. This circuit provided a saw-tooth waveform with a constant amplitude of 3 V and a constant duration at the base of 20 msec. The amplitude was then adjusted automatically according to the weld pool size which was determined by the video camera. The level detector output was supplied to the comparator and its level compared to the reference signal level which was set on the reference threshold level circuit. The reference threshold level determined the required degree of penetration. The output from the comparator was supplied to the pulse generator circuit.

The pulse generator circuit comprised four circuits, which set the following parameters:

1. Pulse frequency (cycle time);
2. Background level;
3. Pulse level;
4. Maximum pulse time at the maximum value.

The comparator output controlled only the pulse time within the maximum value according to the required penetration. The pulse generator then provided the controlled pulse current waveform signal, via the buffer, to drive the power source.

9.4. CONTROL SYSTEM

The control system was essentially the same as described in the previous chapter (Chapter 8), except that the microcomputer together with its software control program was replaced by the hard-wired control unit. In addition, the traverse was driven from a reference signal provided by a signal generator. The equipment arrangement of the control system is shown in Fig. 9-2a and a block diagram of the system is shown in Fig. 9-2b.

In addition, the selection of the pulse parameters to be set on the control unit for a specific application, and the experimental details were similar to those described in the previous chapter (Sections 8.5 and 8.6).

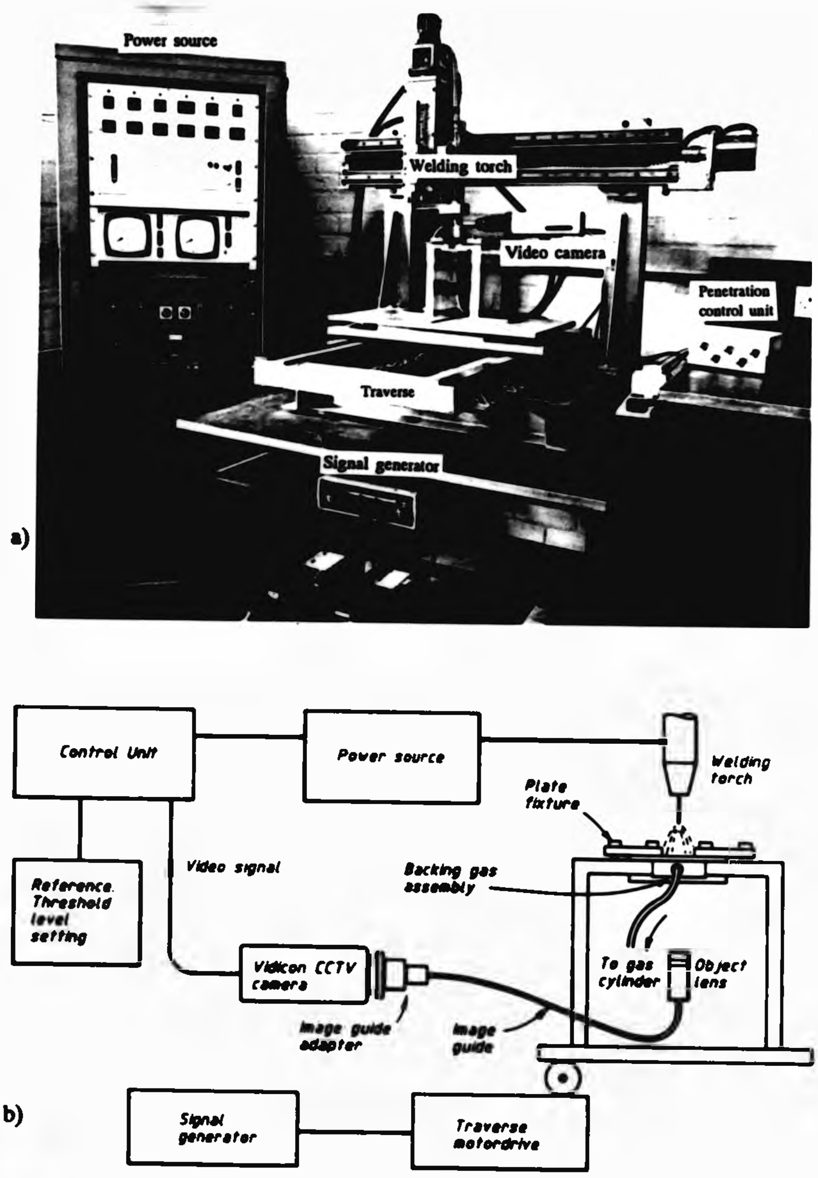


Fig. 9–2. Backface penetration control system based on a hard-wired control unit:
a) equipment arrangement, **b)** block diagram.

9.5. SETTING UP THE SYSTEM

To prepare the control system for a specific application, the control unit was programmed with four pulse parameters including pulse frequency, background current level, pulse current level and maximum pulse time; the control unit settings are shown in Fig. 9–1a. The pulse current level, in particular, was set according to the material thickness to give rapid penetration of the material, typically within 0.2 to 0.5 sec, depending on the thickness. The parameter settings are given in Table 9–1 for all the tests.

In the initial evaluation tests, the following settings were derived which produced the optimum performance of the system:

1. A distance of 80 mm was set between the object lens and the plate to provide a suitable weld pool image size on the TV monitor.

2. A suitable optical filter and camera aperture were selected in combination with the focus adjustment of both the object lens and camera lens to reduce the effect of the heat affected zone to provide a well defined profile of the weld pool; a Kodak filter No. 94 and camera aperture of about F11 gave the optimum image of the weld pool.

3. The scale of the feedback signal, representing the weld pool area (penetration), was adjusted for the optimum control response and the threshold level was then set for the required degree of weld pool penetration; a higher threshold level will produce a wider weld bead.

In operation, the pulse frequency, background current level and pulse current level were maintained constant at the preset values, while the pulse time was controlled automatically by the control unit in response to the comparison between the reference and feedback signal levels. When the feedback level was greater, the pulse was terminated and the current was reduced to the preset background level. The current continued at this level until the next pulse was switched on as determined by the preset pulse frequency.

Table 9–1. Details of welding tests using 18Cr–10Ni type stainless steel plates.

Welding parameter settings						
Material thickness, mm	Pulse current, A	Maximum pulse time, sec	Background current, A	Pulse frequency, Hz	Traverse speed, mm/sec	Comments
Without HF arc starting **Bead–on–plate** *Uniform thickness*						
1.6	60	0.8	10	1.0	1.25	Fixed pulse duration
1.6	70	0.8	16	1.0	1.25	Controlled
1.0	40	0.4	10	1.43	2.0	Controlled
2.0	100	0.8	20	1.0	1.25	Controlled
2.5	120	0.8	25	0.833	1.25	Controlled
3.2	160	1.0	30	0.667	1.25	Controlled
Bead–on–plate *Gradual varying thickness*						
3.2–1.0	100	0.8	20	1	1.5	Controlled
3.2–1.0	100	0.3	20	1	1.5	Fixed pulse duration
Bead–on–plate *Step varying thickness*						
2.0–1.0	80	0.6	8	1	1.75	Machined
1.6–2.6–1.6	80	0.8	16	1	1.25	Overlapped 1.6–1.0 mm
1.6–2.6–1.6	120	0.8	25	0.833	1.25	Overlapped 1.6–1.0 mm
Butt joints						
1.6	70	0.8	16	1	1.25	Similar thickness
2.5	120	0.6	20	1	1.75	similar thickness
1.6–2.5	120	0.6	20	1	1.75	Dissimilar thickness
With HF arc starting **Bead–on–plate** *Uniform thickness*						
1.0	40	0.4	10	1.42	1.5	Controlled
1.6	70	0.4	14	1.42	1.5	Controlled
2.0	100	0.4	16	1.42	1.5	Controlled
2.5	125	0.4	20	1.42	1.5	Controlled
3.2	165	0.4	30	1.42	1.5	Controlled
1.6	50	0.4	12	1.42	1.5	Controlled small bead, Camera set at F4
Bead–on–plate *Gradual varying thickness*						
3.2–1.0	100	0.4	20	1.42	1.5	Controlled
3.2–1.0	100	0.25	20	1.42	1.5	Fixed pulse duration
Shielding gas: composition $Ar+5\%H_2$, flow rate 5 litre/min, nozzle dia. 12 mm				Electrode: composition tungsten–2% thoria, diameter 2.4 mm, tip angle 45°		

The effect of the threshold level on the weld bead size was demonstrated in a bead–on–plate test in which the threshold level was changed from 4.5 to 3.5 V. The pulse time was reduced from about 400 to 200 msec, Fig. 9–3, and the weld bead width correspondingly decreased from about 5 to 3 mm, Fig. 9–4.

9.6. RESULTS

9.6.1. Test programme

The performance of the system was initially evaluated in bead–on–plate tests using stainless steel plate of a range of thicknesses from 1.0 to 3.2 mm. To test how the control system would respond to a gradually varying thickness of a plate, a bead–on–plate run was also made on a wedge–shaped plate which had its thickness progressively reduced from 3.2 to 1.0 mm over a length of 150 mm. In addition, the control response to a sudden change in the plate thickness was tested on a testpiece which had its thickness reduced in one step from 2.0 to 1.0 mm. The chemical analyses of stainless plates used are given in Table 9–2.

The welding performance of the system was assessed by welding a series of typical butt joints in a range of plate thicknesses, 1.6 to 2.5 mm. A dissimilar thickness joint was also welded, i.e. a 1.6 mm plate to a 2.5 mm thickness plate but with a similar butt joint configuration.

The testplates were scratch–brushed and degreased in acetone immediately prior to welding.

9.6.2. Evaluation without HF arc initiation

9.6.2.1. *Control performance, bead–on–plate*

a). Constant plate thickness

For plate thicknesses within the range 1.0 to 3.2 mm, the control system was capable of adjusting the pulse time automatically so that a constant weld pool size was maintained throughout each test run. Typical adjustment of the pulse time in the current waveform, indicating the controllability of the system, is shown in Fig. 9–5. The constant weld pool size resulted in consistent and uniform weld penetration over the weld length, as shown typically in Figs. 9–6 and 9–7 for the plate thicknesses of 1.0 and 3.2 mm respectively. The relevant pulse current and welding parameters for

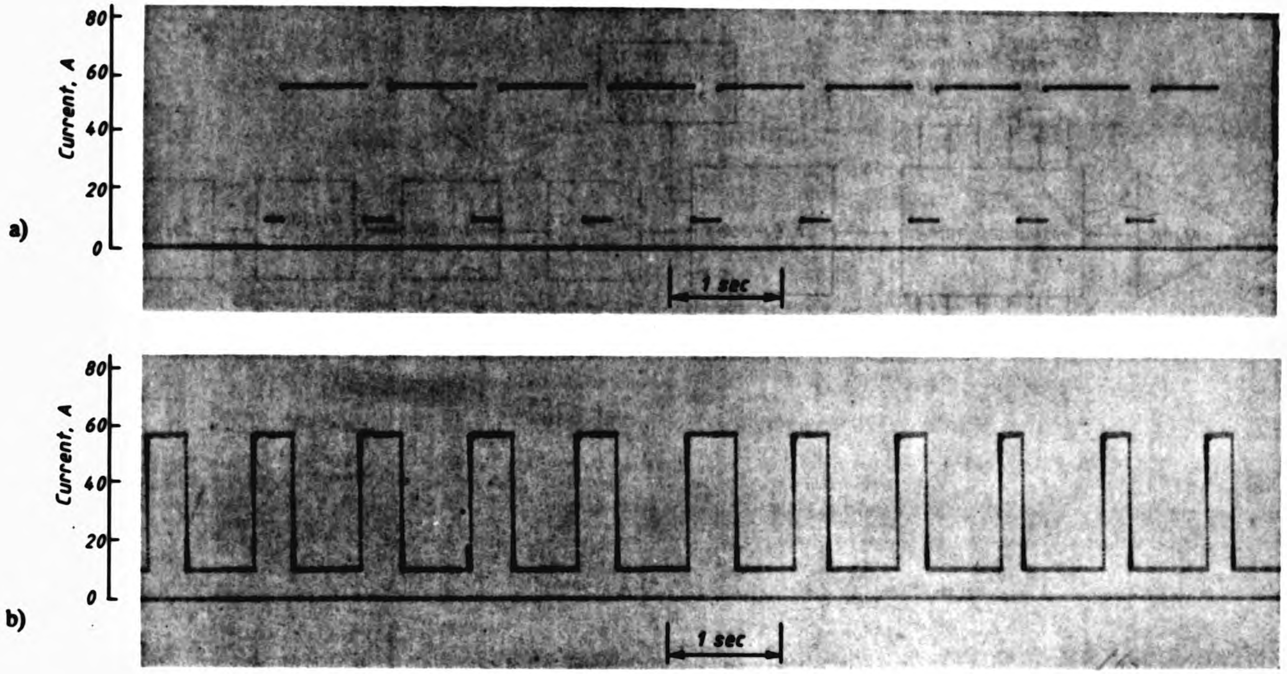
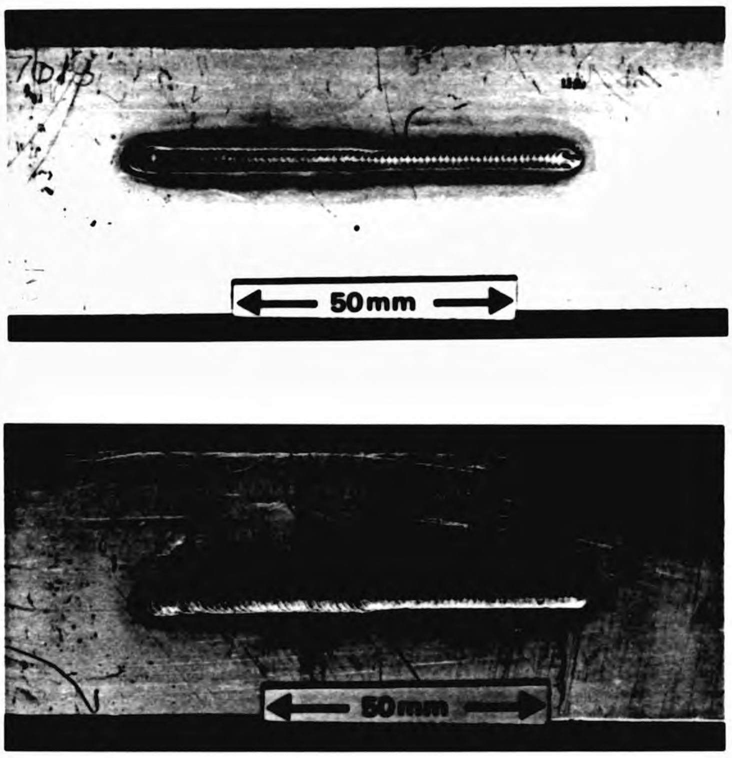


Fig. 9–3. Oscillograms showing the pulse parameters set on the control unit and the automatic adjustment of the pulse time to produce the required degree of weld penetration relevant to threshold level:
a) parameters set for maximum pulse time on the control unit,
b) parameters controlled by the unit.



a)

b)

Fig. 9–4. Effect of the reference threshold level on the degree of weld penetration; a higher threshold, 4.5 V, produces a wider bead whilst a lower threshold level, 3.5 V reduces the weld bead width:
a) top bead, b) underbead.

Table 9–2. Chemical analysis of stainless steel plates used.

Plate thickness, mm	Element, wt%												
	C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Nb	Ti	Co
1.0	0.045	0.005	0.027	0.59	1.46	8.7	17.1	0.21	0.04	0.27	0.01	0.03	0.12
1.6	0.044	0.009	0.025	0.60	1.37	8.8	19.0	0.26	0.03	0.27	<0.01	0.02	0.12
2.0	0.048	0.002	0.033	0.46	1.44	8.9	18.0	0.15	0.04	0.16	<0.01	0.02	0.08
2.6	0.039	0.001	0.032	0.48	1.48	8.9	17.9	0.07	0.03	0.20	<0.01	<0.01	0.11
3.2	0.042	0.005	0.025	0.76	0.99	9.1	17.1	0.22	0.05	0.17	<0.01	0.01	0.12
TWI reference number S/87/194													

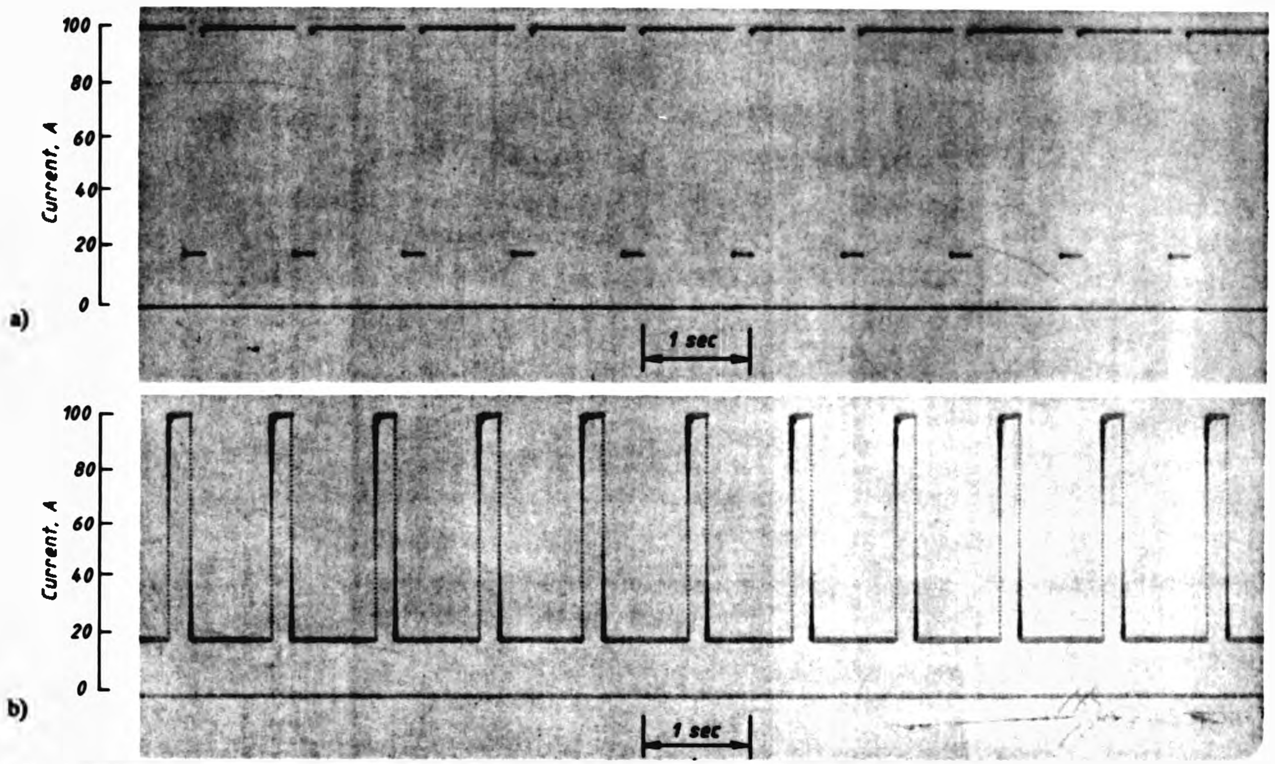
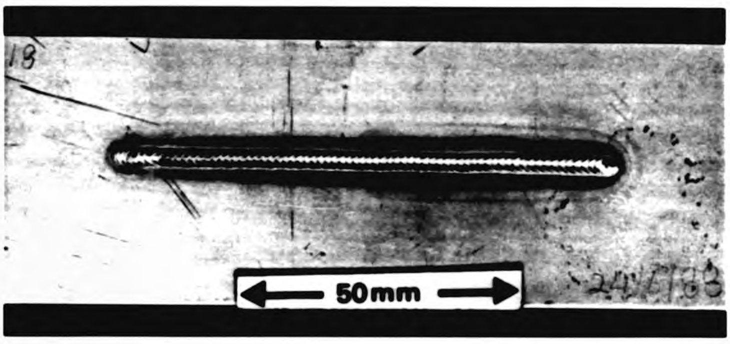


Fig. 9-5. Typical oscillograms showing the performance of the control unit in controlling weld pool:
a) pulse current level set on the control unit for maximum pulse time,
b) duration of the pulse as controlled by the unit.

a) 

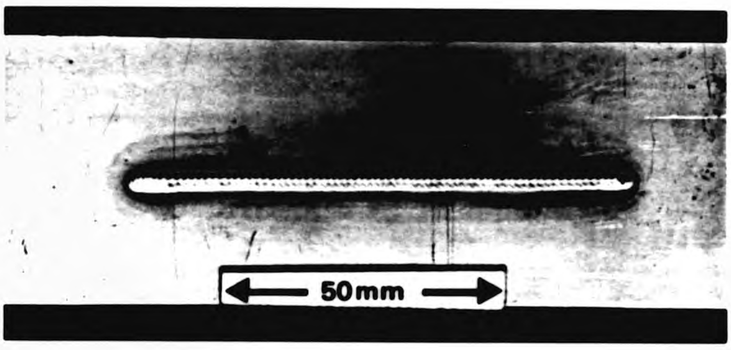
b) 

Fig. 9–6. Bead–on–plate test using 1.0 mm thick stainless steel and Ar+5%H_2 shielding gas showing consistent weld bead penetration:
a) top bead, b) underbead.

a)

b)

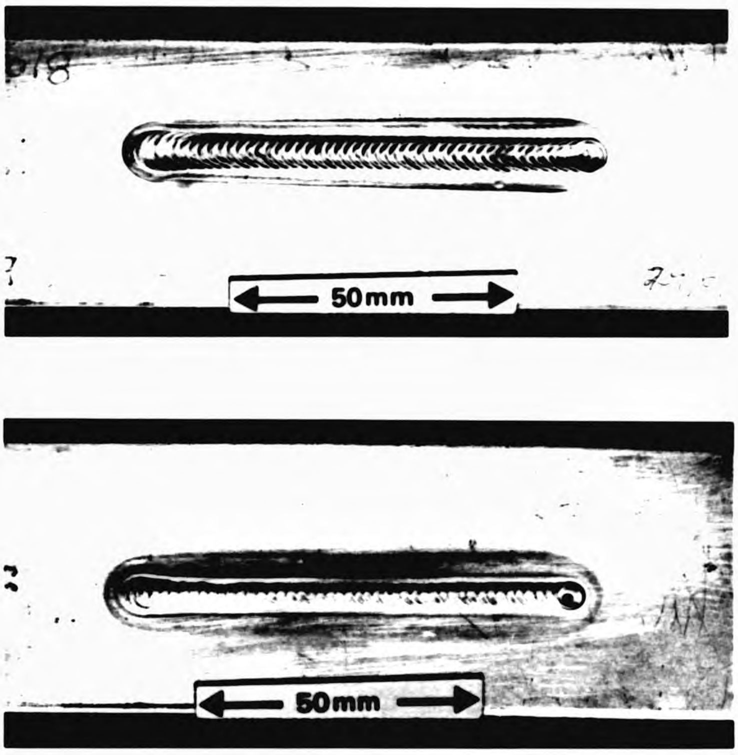


Fig. 9–7. Bead–on–plate test on 3.2 mm thick stainless steel in Ar+5%H_2:
a) top bead, b) underbead.

this range of plate thicknesses are given in Table 9–1.

b). Gradually varying plate thickness

For a testplate in which the thickness decreased gradually from 3.2 to 1.0 mm over the length of 150 mm, the control system was found to be capable of maintaining a constant weld pool size. This was achieved without any adjustment being made to the control unit and the pulse time was reduced automatically as the plate thickness decreased; the reduction in the pulse time is shown in Fig. 9–8 and the uniform appearance of the weld bead along the weld run is shown in Fig. 9–9. The pulse time was observed to reduce from typically 0.7 sec (3.2 mm) to 0.25 sec (1.6 mm).

For comparison, a testplate was welded with fixed (uncontrolled) pulse duration and a progressive increase in the width of both the top bead and underbead was produced as shown in Fig. 9–10. The width of the underbead varied from zero to approximately 5 mm over the test run, corresponding to lack of penetration at the thick end and excessive penetration at the thin end. The pulse and welding parameters for both the controlled and fixed (uncontrolled) pulse operations are given in Table 9–1.

c). Step variation in plate thickness

For the sharp step variation in the plate thickness, 2.0 to 1.0 mm, the control system likewise adjusted the pulse time automatically. The penetration was essentially consistent and uniform throughout the test run, even for transition at the step. The regularity of both the top bead and underbead is shown in Fig. 9–11 and the relevant welding parameters are given in Table 9–1.

In an additional test, two steps were constructed by cross–overlapping a 1.6 mm thick plate on to a 1.0 mm thick plate. Again the system adjusted the pulse time automatically to provide consistent and uniform penetration in both the thick and thin sections, as shown in Fig. 9–12. However, it should be noted that due to air gap between the plates at the start of the overlaps, the weld pool did not immediately penetrate at the cross–over point. In this case, the control system provided excessively long pulses of the maximum permitted duration, Fig. 9–13, until full penetration was re–established, Fig. 9–14.

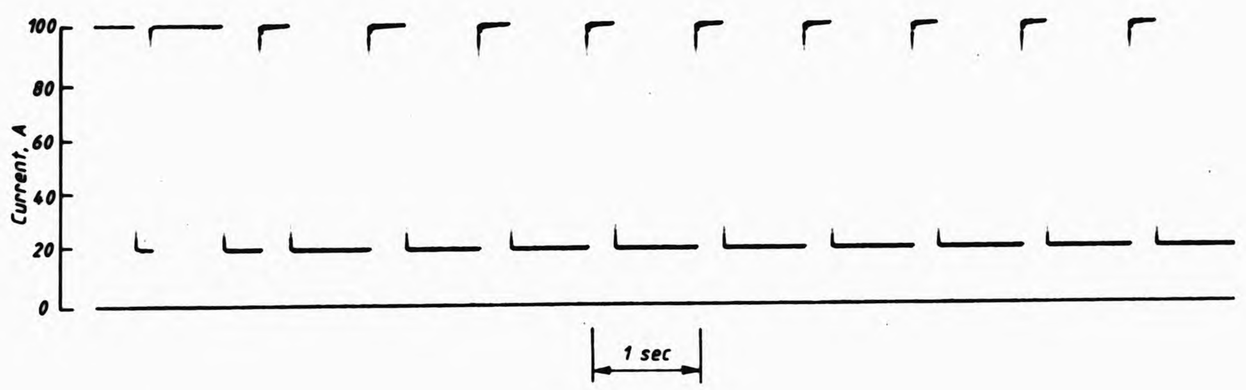
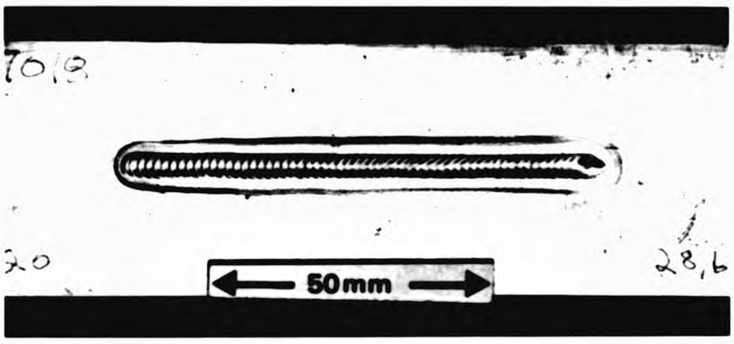


Fig. 9–8. Oscillogram showing automatic reduction in the pulse time to achieve consistent weld penetration when the test plate thickness varied gradually from 3.2 to 1.0 mm.

a)



b)

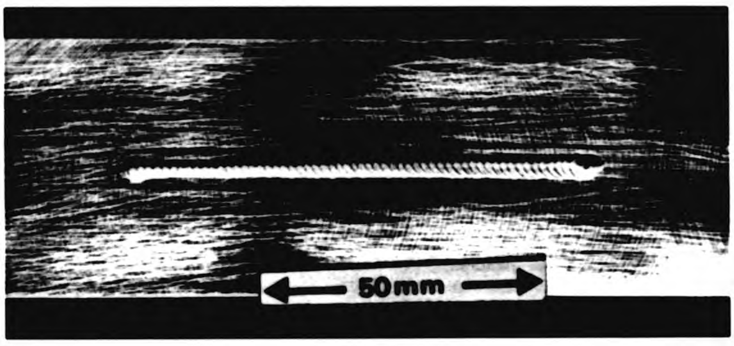


Fig. 9–9. Bead–on–plate test showing that a uniform weld bead penetration width was achieved when the testplate thickness varied gradually from 3.2 to 1.0 mm:
a) top bead, b) underbead.

a)

b)

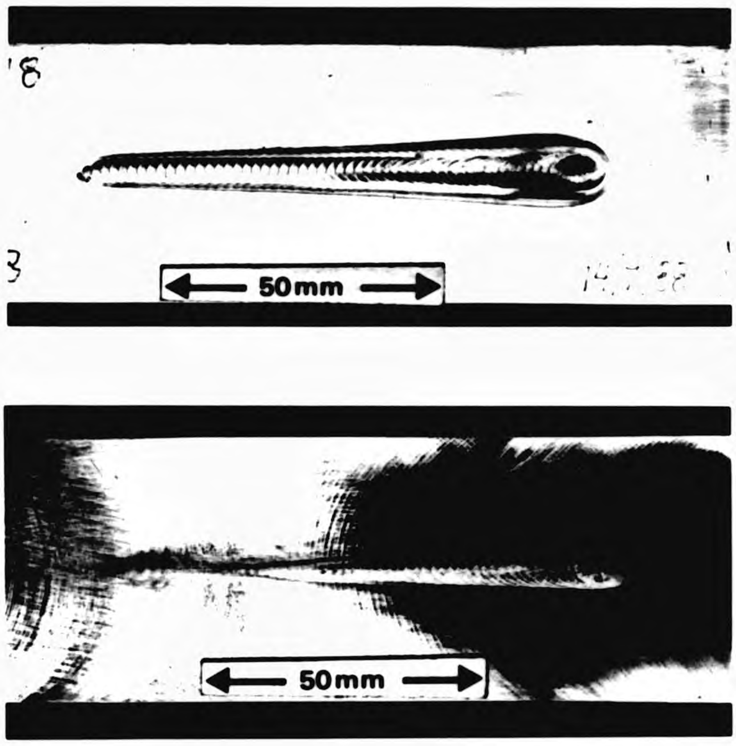
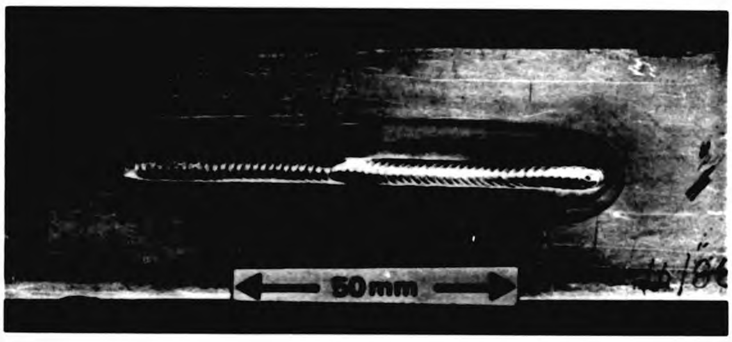


Fig. 9–10. Conventional (constant pulse time) TIG weld showing that the weld bead width increases as plate thickness is reduced; testplate thickness varies progressively from 3.2 to 1.0 mm:
a) top bead, b) underbead.

a) 

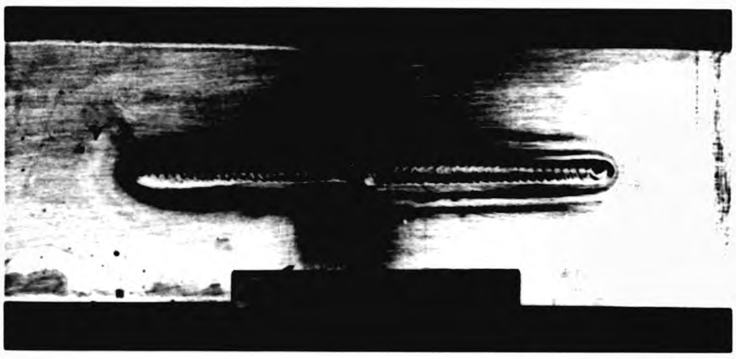
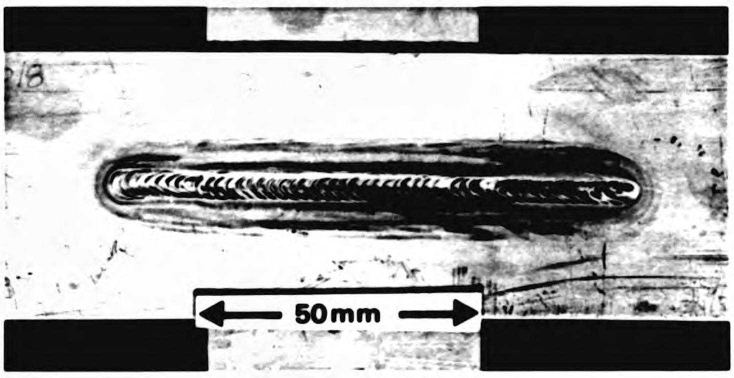
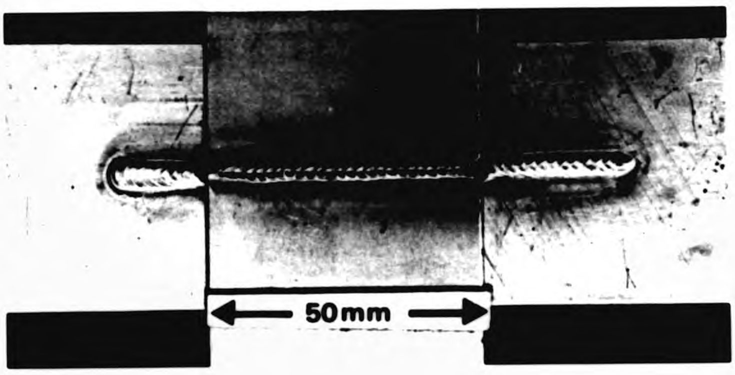
b) 

Fig. 9–11. Bead–on–plate test showing that penetration achieved by the control unit is consistent and uniform when the testplate thickness varied in one step from 2.0 to 1.0 mm:
a) top bead, b) underbead.



a)



b)

Fig. 9–12. Bead–on–plate test showing that penetration achieved by the control unit is consistent and uniform when the testplate thickness varied in two steps from 1.6 to 2.6 to 1.6 mm by cross overlapping 1.6 mm and 1.0 mm plates:
a) top bead, b) underbead.

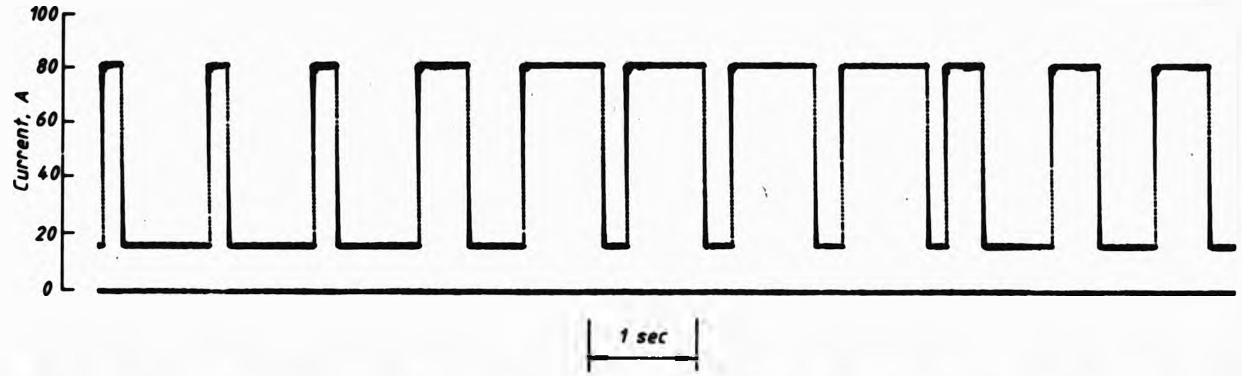
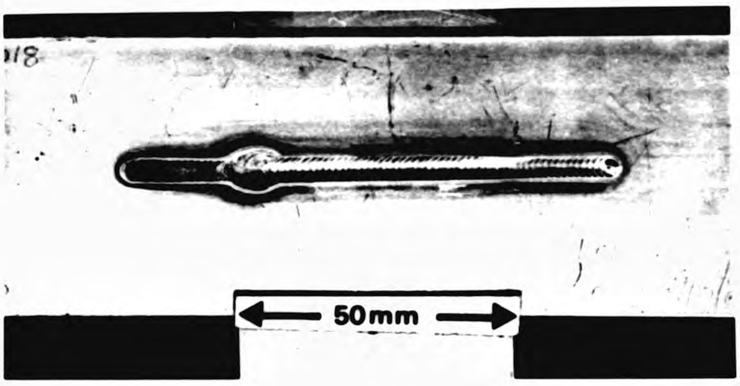


Fig. 9–13. Oscillogram of the current. Excessively long pulses are produced by the control unit in trying to achieve uniform penetration for the thick cross of the overlapping plates.

a)



b)

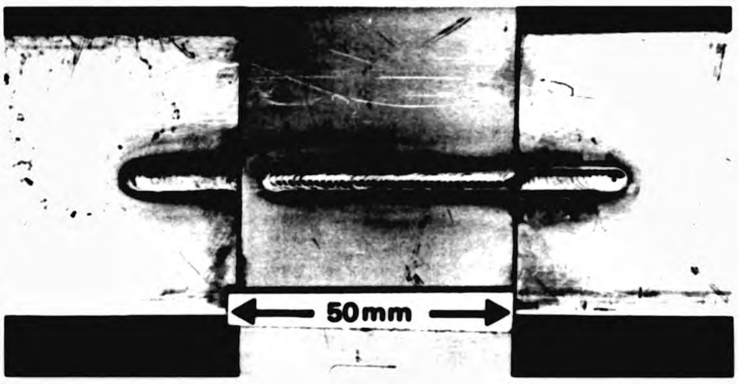


Fig. 9–14. Bead–on–plate test showing excessive width in top bead and no penetration in underbead for a portion of a joint with an air gap between the two plates:
a) top bead, b) underbead.

9.6.2.2. *Welding performance*

The performance of the control system was assessed for welding butt joints in plates with equal thickness and for plates of dissimilar thickness; the details of the joints, pulse current and welding parameters used are given in Table 9–1.

For the similar thickness joints, the system was found to be capable of maintaining a constant weld pool size by adjusting the pulse time throughout the weld run. The penetration was consistent and uniform as shown in Fig. 9–15 for the square butt joint in 2.5 mm thick plates. The butt joint in the dissimilar plate thicknesses of 1.6 and 2.6 mm, was equally successful as shown in Fig. 9–16.

9.6.3. Evaluation with HF arc initiation

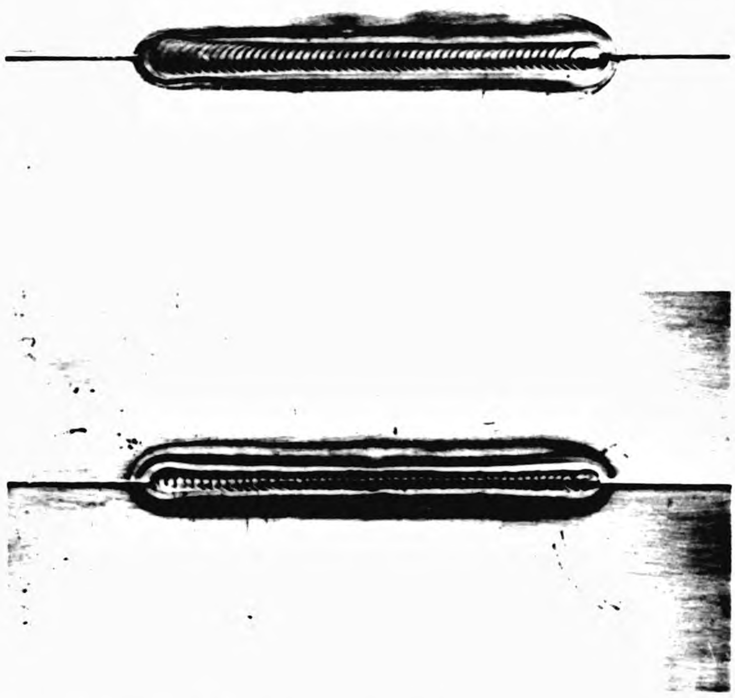
When the system was initially tested with HF arc initiation, the penetration control unit broke down. The problem was overcome by using a commercially available electronic mains filter adaptor for the mains supply of the camera. In addition, the switching sequence of the mains supply to the different equipment units was changed. For example, the mains supply for both the control unit and traverse remains switched off until the arc is established. At this instant, the HF unit is switched off and the mains supply to the control unit and traverse are switched on automatically by the power source control circuits. This sequence provided reliable arc ignition and initiation of the welding operations.

9.6.3.1. *Control performance*

The control performance was tested in bead–on–plate tests for constant plate thickness over the range of 1.0 to 3.2 mm and also for gradually varying plate thickness from 3.2 to 1.0 mm over 150 mm length. The relevant control and welding parameters are given in Table 9–1 and satisfactory results were obtained in all cases.

For the tapered plate, the progressive reduction in pulse time is shown in Fig. 9–17 and the appearance of the weld bead is shown in Fig. 9–18.

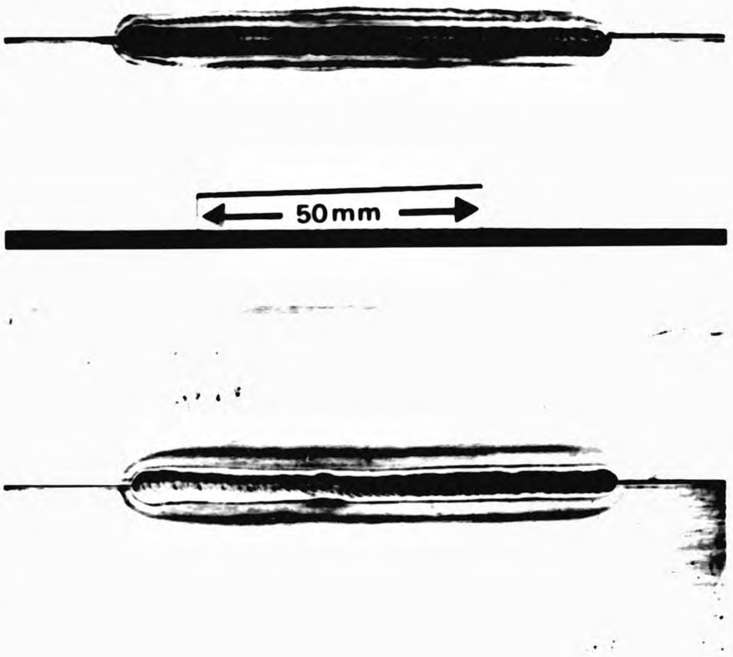
In addition, the control unit was set to produce a minimum penetration. The response of the control system was found to be sufficiently sensitive such that a weld pool of a very small size could be produced and maintained constant throughout the test run. This was obtained due to the accurate detection of the weld pool profile and



a)

b)

Fig. 9–15. Butt weld in 2.5 mm thick plate showing uniform bead penetration:
a) top bead, b) underbead.



a)

b)

Fig. 9–16. Butt weld in 1.6 to 2.6 mm thick plates showing uniform bead penetration:
a) top bead, b) underbead.

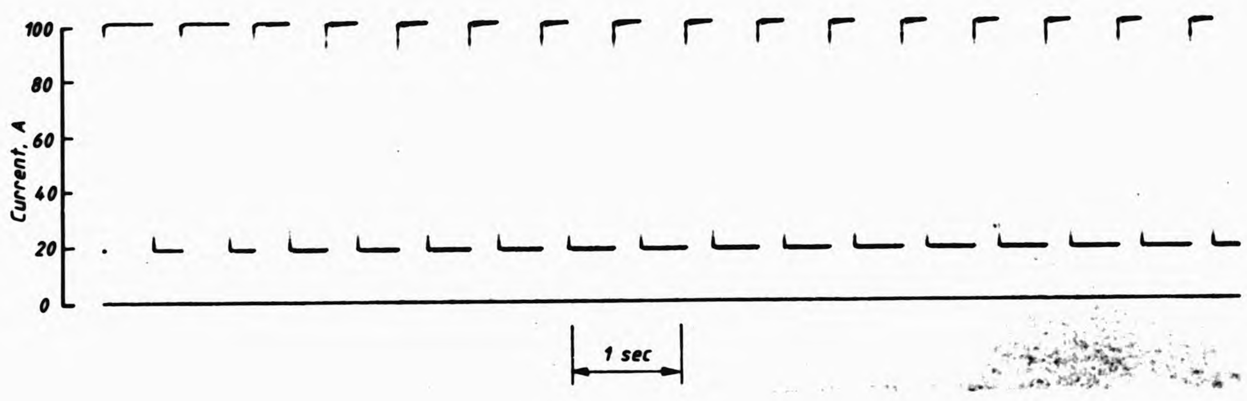
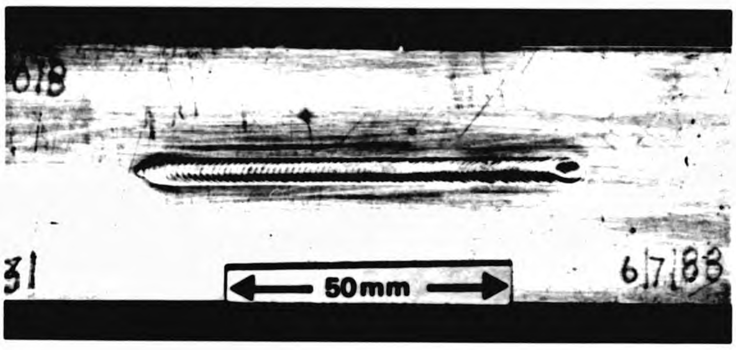


Fig. 9–17. Oscilloogram showing the adjustment in pulse time by the control unit for bead–on–plate test where the plate thickness varied gradually from 3.2 to 1.0 mm.

a)



b)

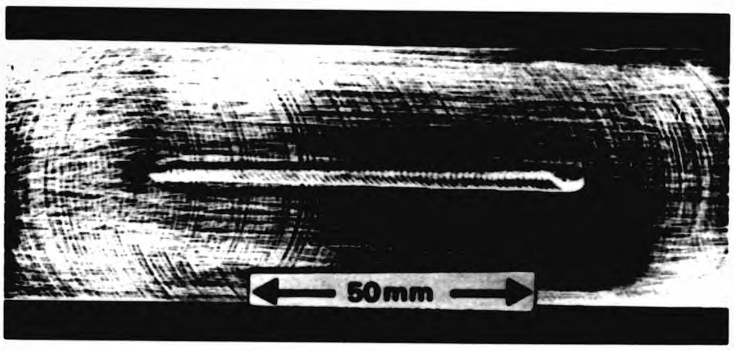


Fig. 9–18. Weld bead showing consistent and uniform penetration achieved by the control unit for bead–on–plate test when the plate thickness varied gradually from 3.2 to 1.0 mm:
a) top bead, b) underbead.

the corresponding precise control of the pulse time which is provided by the control system. The weld pool could be reliably terminated as soon as it penetrated the plate which produced an underbead width as little as about 1 mm. The consistency of the top bead and underbead are shown in Fig. 9–19.

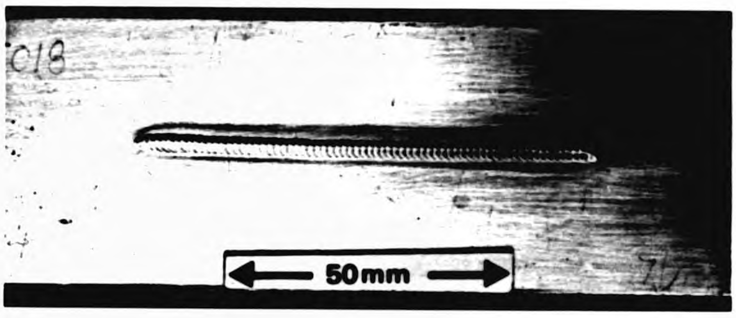
9.7. DISCUSSION

The hard–wired TIG control unit has been demonstrated to be capable of controlling weld penetration automatically by adjusting the pulse time and producing the desired degree of weld pool penetration. For a specific application, the control unit must first be preprogrammed with a suitable combination of the pulse parameters including pulse frequency, background current level, pulse current level, maximum pulse time, and the traverse speed. With an incorrect set of parameters, although the penetration would be controlled, the weld bead produced would have an irregular appearance. The pulse current level is probably the most critical parameter and this must be set according to the plate thickness to achieve rapid penetration of the material; suitable welding parameters for a range of thicknesses of stainless steel plate are provided in Table 9–1.

The selection of the 'transducer' parameters including the distance of the object lens and workpiece, optical filter, camera aperture and focus adjustments, is also crucial in producing an acceptable weld bead profile. Incorrect settings may prevent the control unit from distinguishing clearly the edge between the weld pool and the heat affected zone. It is also important that once the unit has been set up, it must remain unaltered and only the reference threshold level changed to vary the degree of penetration.

An advantageous feature of the unit compared to the microcomputer based system, is undoubtedly the automatic HF arc initiation. In the previous micro–computer based system, HF arc initiation could not be employed without the software program becoming corrupted. However, even the hard–wired control system should not be switched on simultaneously with the HF unit, because line transmitted or radiated HF emissions can cause breakdown of the electronic components. This problem was satisfactorily resolved in the overall control sequence where the penetration control unit and traverse remained switched off while the HF unit is

a)



b)

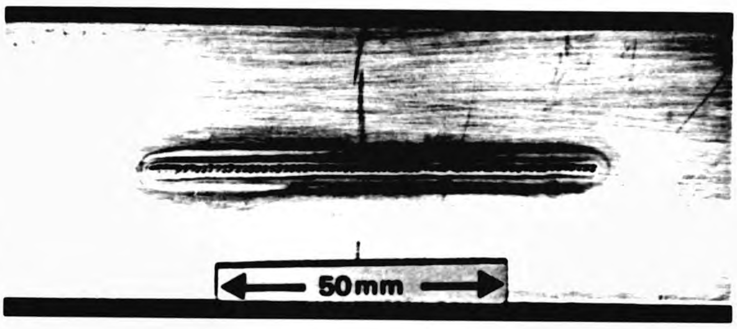


Fig. 9–19. Weld bead for which the control unit was set to produce a minimum penetration:
a) top bead, b) underbead.

switched on at the same time as the power source. As soon as the arc is established, the HF unit is switched off and both the control unit and the traverse are switched on automatically and exercise control of penetration. This sequence is fast (typically < 1 msec) and does not cause any delay in the control of weld pool penetration.

Finally, it should be noted that the use of the control unit of the type described in this report, i.e. employing a backface transducer, can only be used when there is reasonable access to backface of the joint. For the wider application of real-time control techniques in TIG welding, a frontface control technique will undoubtedly be required.

9.8. CONCLUSIONS

1. A hard-wired control unit has been developed for controlling weld pool penetration in TIG welding using a backface monitoring technique based on a fibre optica/video camera technique.

2. The system can be operated with an HF unit for automatic arc initiation without damage to the electronic components.

3. The system can produce welds with consistent bead width in a range of stainless steel plate thicknesses, 1.0 to 3.2 mm.

4. The control unit can automatically adjust the pulse time to accommodate a change in plate thickness, either a step change (2.0 to 1.0 mm) or a gradually varying change in thickness (3.2 to 1.0 mm over a length of 150 mm).

CHAPTER 10
CONCLUDING SUMMARY

This study has achieved two objectives:

1. Synergic controls (i.e. real time control methods) have been developed for two modes of MIG welding — steady DC open arc and short circuiting arc operations.

2. A microcomputer based penetration control system for TIG welding has been evaluated. In addition, a hard-wired control unit has been developed to replace the microcomputer and interfacing unit, so that the system could be used with automatic HF arc initiation.

The synergic controls are being incorporated in MIG welding power sources the world over. The penetration control is now being used in industry for critical applications.

These developments are summarised in the following sections.

10.1. SYNERGIC CONTROL IN MIG WELDING

The conventional steady DC open arc and short circuiting arc operations require not only skill and time to establish correct welding conditions, but these are impracticable for automated and robotic systems requiring a fast change in the welding conditions to suit various joints. To resolve these difficulties, synergic controls have now been developed.

Approach

The approach comprises development of basic relationships, and then design and construction of electronic control units which execute control equations and regulate a transistor power source. In operation, the control systems initiate and maintain stable arc operation automatically for any constant wire feed speed over the operating range, and also provide stable arc operation even when the wire feed speed is changing, whether gradually or modulated. Therefore, the controls not only simplify setting up the welding conditions, but also enable wire feed speed to be programmed as required to refine the welding operation. Furthermore, the control extends the scope of application of steady DC open arc and short circuiting arc to thermal pulsing, where the wire feed speed (current) is modulated automatically, to make sound welds even in joints with narrow gap preparation.

In all, three control units have been developed. The electronic circuits of these units are very simple and can be constructed readily with a few inexpensive components.

Control equations

Steady DC open arc operation has been characterised by two basic relationships. The concept of power has been used to obtain a quadratic 'power–current' equation, which is simple. Furthermore, this equation has been approximated to obtain a linear 'power–current' control equation, which is even simpler. Both the equations could be used to regulate stable synergic operation.

The power–current approaches are versatile in that the power source can be operated with its output characteristics set in constant current, constant voltage or any intermediate mode.

Although this approach can perform synergic control successfully for a steady DC open arc, it is limited in that it does not provide control for short circuiting arc operation.

In addition, the generalised linear 'voltage–current' relationship has been used to regulate steady DC open arc operation. A control unit using this relationship can only be operated with the power source set in constant voltage mode. However, the control is versatile in that it provides synergic operation successfully for both steady DC open arc and short circuiting arc operations.

Control units

The electronic circuits for three control units developed to apply the control equations are very simple and can be constructed readily with a few inexpensive components.

Furthermore, each control unit requires only a current (and voltage) signal. The current signal is obtained conveniently from a static transducer — a shunt — connected in the welding circuit, and the voltage signal is taken between the contact tube and workpiece. The operation is entirely independent of any dynamic transducer, such as a tachogenerator measuring the wire feed speed, which could be liable to errors by slippage. Therefore, the operation of the control units is immune from external problems.

Adaptation of the control units

The synergic system has attracted considerable interest but its widespread use in industry will remain restricted if the control units work only with a transistor controlled power source. This type of power source is accurate and versatile, but because of high cost, its use is restricted to high quality applications. Therefore, to facilitate transfer of the synergic control technology into industry, the control units have been adapted to work with a low cost, commonly used thyristor controlled power source.

Unlike the transistor controlled power source which provides constant voltage output for any current, the output characteristics of the thyristor controlled power source have a droop (3 V/100 A). Therefore, for a given reference signal, the voltage is not maintained constant but decreases continuously with current. Furthermore, the output voltage is not proportional to the input reference voltage.

Adaptation techniques

The following three adaptation techniques have been used:

a). Reference voltage–current relationships;
b). Voltage feedback control;
c). Scaling the output.

Techniques a) and b) have been used for the linear voltage–current control unit, and b) and c) for each of the quadratic and linear power–current control units.

In the first technique, the generalised control equation, used previously for the transistor controlled power source, has been extended to take into account the effects of both the slope of the output characteristics and non-proportionality of the input-output characteristics.

In the second technique, a 'voltage feedback' control circuit has been added between the original control unit and the power source. The circuit, in essence, causes the power source to simulate near-perfect constant voltage operation similar to that provided by the transistor controlled power source originally used.

In the third technique, the range of power-current control unit output has been extended from 0-5 V, previously used, to 0-15 V which is the reference range of the thyristor controlled power source. This system does not require any further modification because of change in the power source, because the unit is independent of power source characteristics.

Preparation of a control system

To prepare a control system for welding operation, the control unit was programmed simply with the parametric constant relevant to a given material/wire diameter/shielding gas combination (and those relevant to the power source).

Evaluation

In general, the control systems have been evaluated comprehensively for:

1. Arc initiation;
2. Constant wire feed speed;
3. Variable wire feed speed;
4. Modulated wire feed speed;
5. Effect of wire extension;
6. Effect of wire diameter;
7. Effect of shielding gas.

Furthermore, the systems have been tested for welding operation in both mechanised and manual operations.

In all cases, the systems have been found to be capable of providing synergic operation, whereby stable arc operation is maintained automatically for any operator selected wire feed speed, whether held constant, varied gradually or modulated. Thus, steady DC open arc and short circuiting arc operation have been simplified.

Conclusions

1. Two electronic control units have been developed to provide synergic control of steady DC arc welding, using a transistor controlled power source. One is based on a quadratic power-current equation, and the other is based on a linear approximation of the quadratic equation.

2. Both control units can operate with the power source set in constant current, constant voltage, or any intermediate mode of output operations.

3. A third electronic control unit has been developed to regulate the linear voltage-current relationship to provide synergic control of both steady DC open arc and short circuiting arc operation. This control unit operates with the power source set in nominally constant voltage mode.

4. Each control unit operates from the current signal (or together with the voltage signal) which is conveniently obtained from a static transducer (a shunt) connected in the arc circuit. Because the transducer is static, the control unit is immune to any external problems.

5. The three control units have been successfully adapted to operate with a commercially available thyristor controlled power source.

6. The linear voltage-current control unit has been adapted by deriving a generalised 'reference voltage-current' relationship. This includes the parametric constants relevant to the output characteristics of the power source, in addition to the voltage-current relationship for the arc operation.

7. Alternatively, the control unit has been adapted by the addition of an

electronic circuit providing voltage feedback control of the power source, so that the power source operates effectively in a perfectly constant voltage mode.

8. The voltage feedback control technique has also been used to adapt both the quadratic and linear power–current control units.

9. Both the quadratic and linear power–current control units have been adapted by an alternative technique of rescaling the output to provide 0–15 V, relevant to the input reference range of the thyristor power source.

10. The three control units have been shown to be capable of performing synergic operation. Thus, both steady DC open arc and short circuiting arc operations are not only simplified but also their range of application is extended.

11. The control units have been shown to be capable of making sound welds in a range of applications using both mechanised and manual welding techniques.

10.2. PENETRATION CONTROL IN TIG WELDING

Previous penetration control systems for TIG welding used a photodiode as a sensor. Essentially, the diode measures an average level of radiation from the weld bead penetration at the backface of the workpiece, and provides a signal to control process parameters so that uniform penetration is achieved. However, the penetration control is not reliable when changes occur in the radiation level because of changes in emissivity of the workpiece surface.

To overcome this problem. an alternative backface penetration control system, based on a fibre optic/video camera as a sensor and a microcomputer as a controller, has been developed at the University of Liverpool. Essentially the system controls the size of the weld pool, instead of an average level of radiation, by regulating pulse current period. The system has been evaluated at The Welding Institute and found to be capable of controlling penetration accurately, but it cannot be used with High

Frequency (HF) arc discharge, required for automatic arc initiation. This is because the electronic components malfunction and the software operation becomes corrupted because of HF interference.

A hard-wired control unit has been designed and developed at The Welding Institute to replace the microcomputer and interfacing unit. This system can be operated reliably with automatic HF arc initiation. The system is now being used for high quality industrial applications.

Conclusions

1. The backface penetration control based on fibre optics, video camera and microcomputer system has been found capable of controlling weld bead penetration in TIG welding, for a range of stainless steel plate thickness and joints.

2. The control system can control the penetration uniformly in plates with gradually varying as well as step variable thicknesses.

3. The system cannot be operated with an HF unit for automatic arc initiation because the electronic components and software become corrupted.

4. A hard-wired control unit has been developed to replace the microcomputer based controller.

5. The system can be operated reliably with automatic HF arc initiation.

6. The system has been found to be capable of controlling the weld bead penetration accurately in stainless steel plates and joints, for uniform as well as variable material thicknesses.

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APPENDIX A

A BRIEF REVIEW OF MIG WELDING

A.1. INTRODUCTION

This review sets out to give a perspective of advances in development of the MIG process. It complements the review in Chapter 2 which covered control methods of the one-knob MIG welding power sources developed previously to simplify the setting-up of welding conditions for both steady DC open arc and short circuiting arc operations.

MIG (Metal Inert Gas) welding was introduced in 1948 (A1). The process is now well established for welding a variety of ferrous and non-ferrous materials. Basically it has three operational modes:

— Steady DC open arc;

— Short circuiting arc;

— Pulsed arc operation.

For each mode, the physical processes taking place in the arc causing metal transfer, heat transfer, and weld pool stirring, determine weld quality. These processes, which are complex, have been studied by a number of investigators (A2-A7). However, in general, the development of these modes is described in the following sections.

A.2. ESSENTIAL REQUIREMENTS FOR ARC STABILITY

For successful operation of MIG welding, two essential requirements must be fulfilled. Firstly, the wire feed speed must match the burnoff rate, so that a constant arc length is maintained. Secondly, metal transfer from the wire electrode should be in the form of small droplets so that a uniform weld bead is formed. Otherwise, large droplet or globular type metal transfer would produce not only irregular weld beads but also cause lack of penetration and lack-of-fusion defects.

A.3. STEADY DC OPEN ARC OPERATION

MIG welding was first reported in 1948 (A1) for DC open arc operation, in which a nominally steady current is used to maintain an arc of constant length (say 3–10mm). In this mode, the requirement on arc length can be fulfilled over a wide current (or wire feed speed) range, ~ 50–500A. However, the requirement on metal transfer can only be fulfilled over a limited range, from a critical current (~ 250A) upwards at which a transition occurs from the unsuitable globular to the desirable small droplet (spray) type metal transfer, Fig. A–1 (A8–A14). Thus, applications requiring low current, such as joining thin sheet materials and positional welding, are not feasible.

In the transitional range, a new type of metal transfer, called 'drop spray' has been discovered, Fig. A–2 (A8). It comprises medium sized regular spherical droplets giving reduced spatter and fumes (A8, A9, A12). For a given wire material and diameter, the transition current is dependent on shielding gas and wire extension used, Fig. A–3 (A14).

For steady DC arc MIG operation, with a required wire material/wire diameter/shielding gas combination, the operating variables include wire feed speed, current and arc voltage, for a given arc length and wire extension. These variables provide two relationships which could specify the operation entirely; the first, current

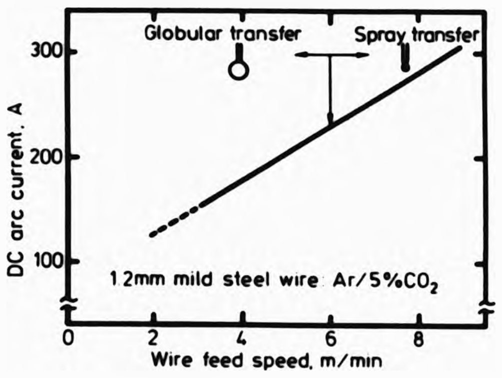


Fig. A–1. Typical burnoff characteristic for 1.2mm diameter mild steel wire in Ar + 5%CO_2 shielding gas.

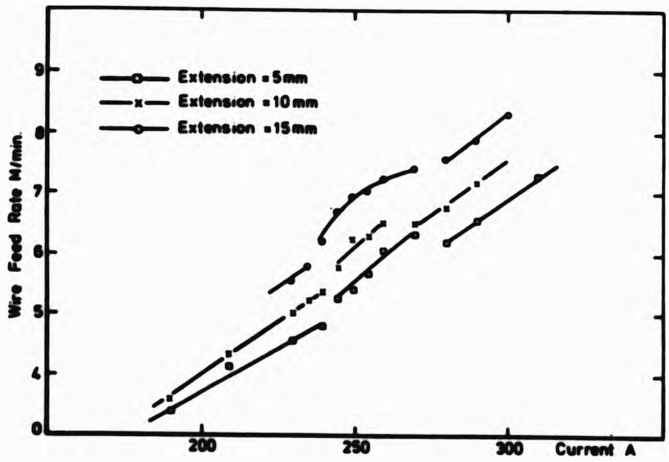
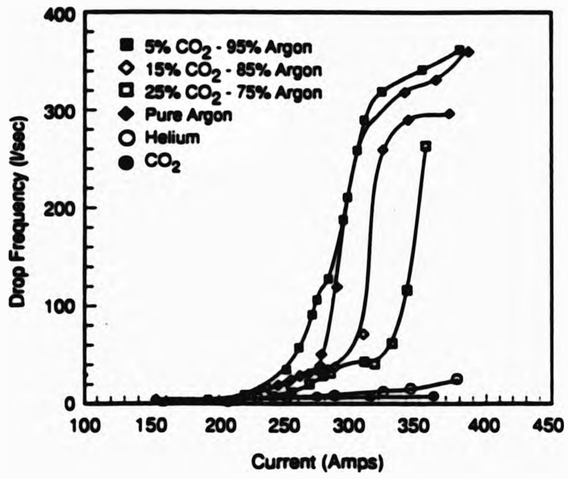


Fig. A–2. Burnoff characteristics for 1.2mm diameter mild steel wire in Ar + 5%CO_2 shielding gas, showing 'drop spray' metal transfer current range (A9).

a)



b)

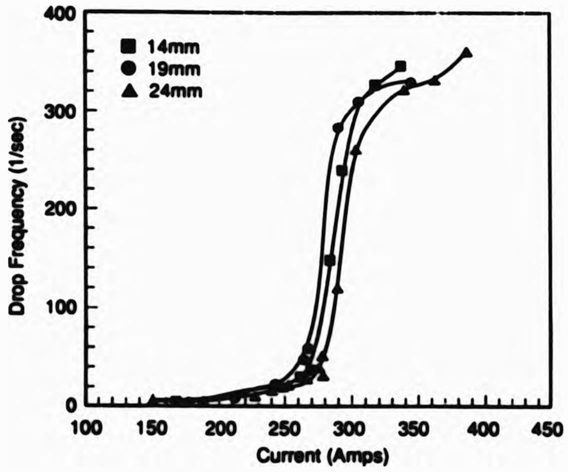


Fig. A–3. Effect on the droplet frequency and transition current due to:
a) shielding gas (A14) b) electrode extension (A14)

– wire feed speed (called burnoff), and the second, voltage – current relationship. These relationships and the effects of process parameters on the basic relationships have been described in Chapter 4 of this thesis.

A.4. SELF–ADJUSTMENT OF ARC LENGTH

Initially, the process was operated using a power source giving a nominally constant current or drooping mode of output characteristic, Fig. A–4 (A15). As this mode does not provide any self–adjustment of the arc length, the current has to be carefully adjusted so that the burnoff rate matches the wire feed speed for any required arc length. Otherwise, even a small mismatch between the current and wire feed speed produces arc length instability, and causes either short circuiting or an excessively long arc and possibly burnback. Therefore, arc voltage control was incorporated, whereby a reference voltage representative of the required arc voltage is compared with actual arc voltage and the difference between the two values, called the error signal, is used to regulate the wire feed speed. Although this method works well for stable arc operation, it provides inadequate response to fast voltage fluctuations which occur in some welding situations.

Use of a power source with a nominally constant voltage or flat output characteristics, Fig. A–5 (A15), removed the difficulties caused by excessive arc length instability (A16). This is because the flat characteristic provides a degree of self–adjustment in arc length, as a consequence of relatively large changes in current for a given change in arc voltage (or length). Arc length fluctuations are thus restricted within narrow limits and arc operation remains largely stable. Consequently, the process became more popular in industry.

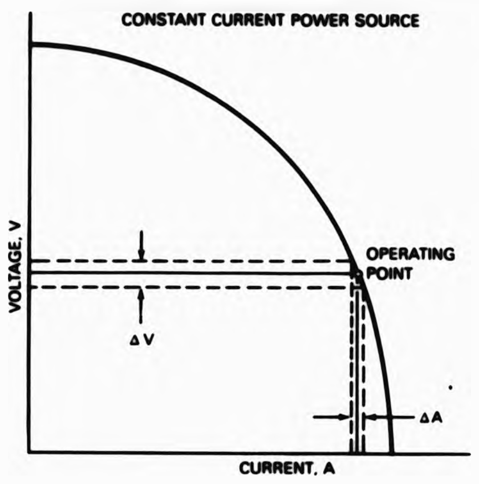


Fig. A–4. Typical static output characteristic for a constant current or 'drooping' characteristics power source (A15).

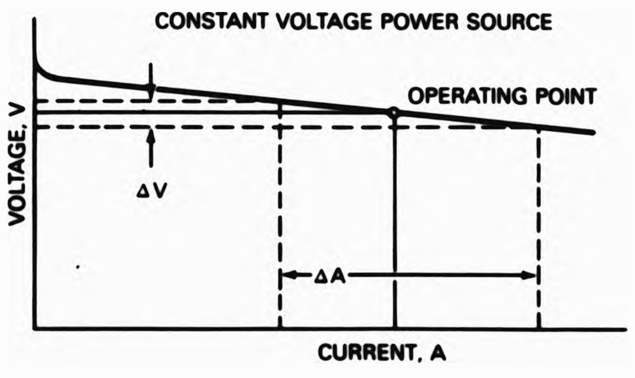


Fig. A–5. Typical static output characteristic for a constant voltage or 'flat' characteristics power source (A15).

A.5. SHORT CIRCUITING ARC OPERATION

For steel wires, the limitation imposed by globular metal transfer at lower current could be removed by using the short circuiting arc technique (A17–A20). In this technique, a power source with flat output characteristics is used and the arc voltage (arc length) is reduced for a given wire feed speed, such that the arc operation comprises arcing and short circuiting intervals alternating at approximately 50–200Hz, Fig. A–6 (A21). Consequently, both the arc voltage and current fluctuate consistently. Therefore these parameters in general are described by the mean values. With this type of arc operation, not only can the balance between the wire feed speed and burnoff rate be maintained, but also small droplet type metal transfer is achieved by the short circuits.

The slope of the output characteristics of the power source is an important parameter in the short circuiting arc operation. This is because it controls the magnitude of the short circuit current, which in turn causes detachment of the molten droplets from the electrode wire due to the well known electromagnetic pinch effect. That is, short circuit current (and therefore pinch effect) is a function of the slope of the output characteristics of the power source, Fig. A–7 (A15, A22). For a smaller slope, the short circuit current will rise more rapidly to a higher level. The pinch effect will also be high and molten droplets will be detached explosively, creating excessive spatter.

When the short circuit current is excessively low due to a steeper slope, the pinch effect will be inadequate to transfer the droplet and re–establish the arc. Under these conditions the wire would tend to freeze to the weld pool. When the short circuit current is at the optimum level, the metal transfer is smooth with very little

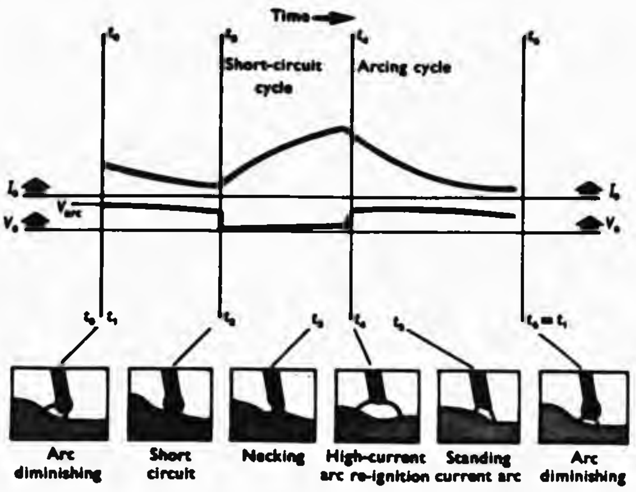


Fig. A–6. The short circuiting arc process showing typical current and voltage waveforms, and high speed cine record for 1.2mm diameter mild steel wire at 42mm/s wire feed speed in CO_2 shielding gas (A21).

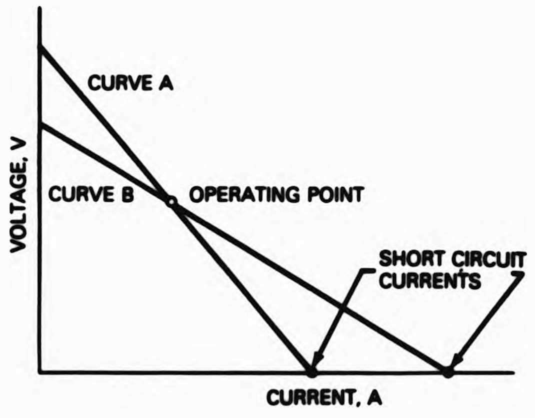


Fig. A–7. Effect of changing slope of output characteristic of a power source on short circuit current (A15).

spatter. Many constant voltage power sources are provided with slope adjustment, either in steps or continuous to provide desirable operating conditions. Some power sources have a fixed slope which has been preset for most common welding conditions.

Another essential requirement, relevant only to the short circuiting arc operation, is that the rate of rise of current during a short circuit must be restricted between two limits, Fig. A-8 (A23). This is achieved by varying the inductance (or some other device) contained in the arc circuit. Otherwise, an excessively high rate of rise of current would cause spatter, or an insufficient rate of rise a sluggish arc performance, Fig. A-9 (A15). Between these limits, the rate of rise of current can be adjusted further to provide optimum arc performance.

The effects of both the slope of the output characteristic and the inductance are shown in Fig. A-9 (A15). The maximum level of the output current is determined by the slope of the characteristic, whereas the rate of rise of current is controlled by the combined effect of the inductance and resistance.

A measure of arc stability has been related to maximum short circuit frequency, Fig. A-10 (A21), minimum standard deviation of current peaks Fig. A-11 (A24, A25) and a ratio of arc time to short circuit time (A26). A reduction in spatter has been achieved by controlling the short circuit current level and waveform (A27-A29).

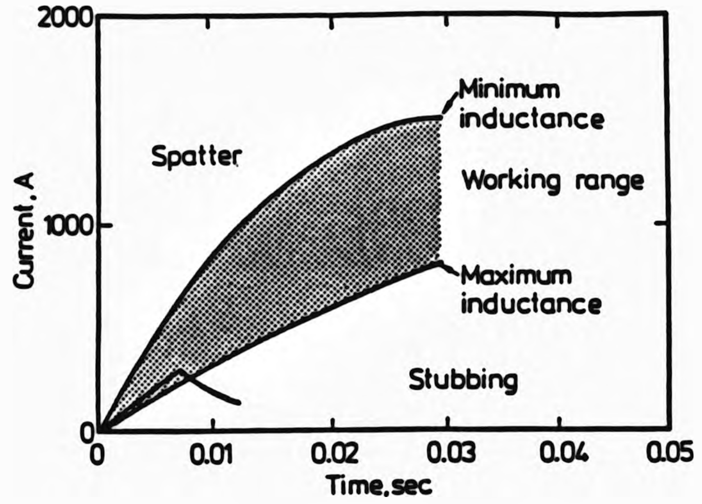


Fig. A–8. Optimum working range of rate of rise of current, controlled by inductance during the short circuit, for 1.2mm diameter mild steel wire (A23).

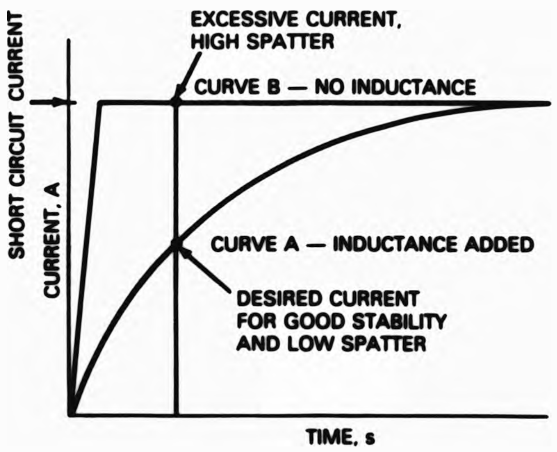


Fig. A–9. Change in rate of current rise due to added inductance (A15).

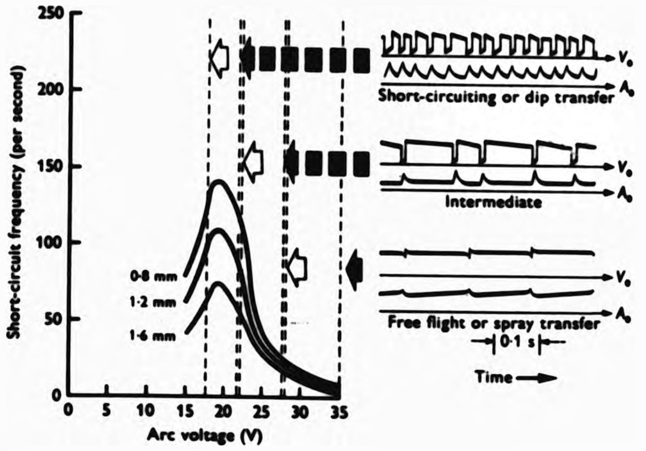


Fig. A–10. Dependence of short circuit frequency on both, voltage and wire diameter for steel in CO_2 (A21).

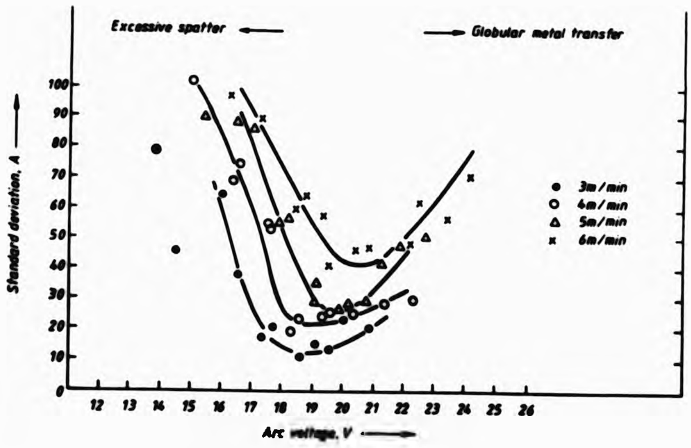


Fig. A–11. Effect of arc voltage on standard deviation values of short circuit current levels. Minimum standard deviation indicates the most stable arc (A24).

A.6. PULSED OPERATION

Pulsed MIG is another method developed to remove the limitation imposed by globular metal transfer, in which the current is periodically modulated between a low background level and high pulse level (A30, A8). The pulse parameters are shown schematically in fig. A-12. While the overall mean current falls within the range normally associated with globular transfer, the pulse level exceeds the critical value to transfer a small droplet. Thus droplet type (spray) transfer is produced by repeated application of a current pulse.

Although the technique is attractive in that it extends open arc operation to low current, it is not easy to set up a working welding condition. For a given wire feed speed (or mean current), the pulse amplitude and duration together must be adjusted so that at least one droplet is detached with each pulse. In addition, the mean current, determined by a combination of four pulse parameters, must be that giving a burnoff rate equal to the wire feed speed to maintain a constant arc length. To accomplish such adjustment in practice is difficult. Furthermore, even minor changes in wire feed speed, which can frequently occur with commercial equipment, lead to degeneration of the established welding condition, causing arc and metal transfer instability, burnbacks or stubbing-in.

A.7. TRANSISTOR POWER SOURCE

The advent of the transistor power source (A31) was a major step forward in the research and control of the MIG process. This is because the power source can provide voltage or current output of any waveform and level with accuracy.

The power source comprised a three phase transformer rectifier unit with the addition of a feedback controlled linear transistor series regulator. The transformer rectifier provided steady DC which was then controlled by the regulator to supply the arc with the desired current waveform (e.g. smooth DC or modulated waveform). The range of the current extended from 0–500A. As the frequency response of the transistor regulator extended from DC to about 10kHz, the power source could provide a square wave modulated current with a range of frequencies up to 1kHz.

The regulator could be operated in either constant current or constant voltage mode. It was driven from an instruction or reference signal, on the basis that 0–5V reference input gave 0–500A regulator output to the arc for constant current mode and 0–50V output for the constant voltage mode. The calibrated reference signal of the desired level was provided by the associated electronic control unit.

A.7. SYNERGIC CONTROL IN MIG WELDING — pulsed operation

Synergic control has transformed conventional 'MIG welding — pulsed operation' which was impractical because of the difficulties in setting up stable welding conditions, into a usable process (A32). It is capable not only of setting up stable welding conditions automatically at constant wire feed speed, but also provides stable arc operation even when the wire feed speed is changing, Fig. A-13. Control is based on a relationship between the mean current (or wire feed speed) and parameters of the pulse waveform. Although the relationship is very simple, it expresses all possible modes in which the pulse parameters can be varied relevant to the wire feed speed (or mean current).

In practice, an electronic control unit or a microcomputer (A33) computes the relationship, according to wire feed speed (or its dependent parameters), and drives

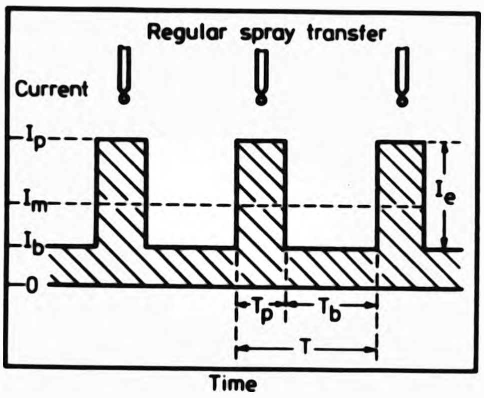


Fig. A-12. Schematic square pulsed current waveform showing pulse parameters.
I_p, T_p — pulse current and duration;
I_b, T_b — background current and duration;
I_m — mean current; T — total cycle duration.

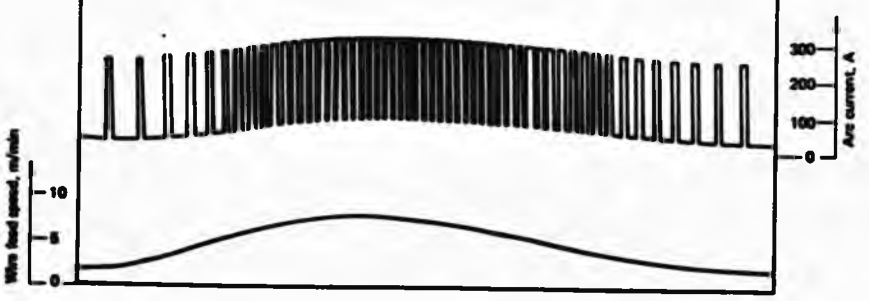


Fig. A-13. Synergic control in pulsed operation of MIG process showing the variation in current parameters with variation of wire feed speed (A31).

a transistor power source, such that suitable pulse parameters are adjusted automatically providing stable arc operation even for square wave modulated wire feed speed. All that is needed from the operator is to select the wire feed speed for the required application. In addition, the feed speed can be programmed as desired for robotic applications. Another important feature of the control is that it enables modulated wire feed speed to be operated for thermal pulsing, at any frequency and with as much difference as desired between low and high feed speed levels of modulation. As these advantages have made synergic control attractive to industry, it has already been incorporated in many commercial power sources the world over.

A.8. EFFECT OF PROCESS PARAMETERS ON SYNERGIC RELATIONSHIP

The synergic equation (A33) has been based on proportionality of burnoff relationship regardless of wire material, wire diameter, wire extension, shielding gas or arc voltage. Therefore the effects of these parameters on the burnoff behaviour would determine how the synergic control should be modified to accommodate changes in these parameters.

A specific synergic relationship has been derived (A34, A35) including the effect of wire extension with any wire material and diameter. Furthermore, burnoff relationships obtained empirically for various wire material/wire diameter/shielding gas combinations have been obtained (A34–A41). All these relationships are again linear and pass through the origin, whether the wire material is mild steel, stainless steel, nickel chrome alloy, aluminium or aluminium alloy. Similarly, proportionality is not affected whether the wire diameter is 1mm, 1.2mm (A34–A41) or 1.6mm, whether the shielding gas is Ar (A38), Ar+2%O_2 (A37) or Ar+5%CO_2 (A34–A36); and whether the wire extension is 11mm or 15mm (A34–A37). Therefore for a wide range of wire materials, wire diameters, shielding gases and for a relatively limited but nevertheless, working range (11 to 15mm) of wire extension, all of which are normally used in practice, the proportionality of burnoff relationship is maintained.

A.9. MAIN ADVANTAGES OF SYNERGIC OPERATION

The potential advantages of synergic pulsed MIG operation are described below.

One–knob operation

A synergic system provides one knob operation for a given wire material /wire diameter/shielding gas combination. The mean current can be adjusted for a required application simply from the one–knob 'current' control. A further 'trim' control is also provided for adjusting arc length to optimise control of the weld pool. These controls virtually eliminate the need for the operator to set up suitable pulse parameters.

Wide range of operating current

For a given wire diameter, the current can be varied continuously over the entire range from as low as 50A to the rated value of the power source, say 500A. This range provides great flexibility of welding a wide range of material thickness, from thin sheet to thick sections. In contrast, conventional MIG power sources require re-adjustment of the controls as the current (wire feed speed) is changed to suit specific applications.

Profile control

Synergic operation provides profile control, for example, in crater filling at the end of the weld seam, whereby the wire feed speed can be steadily reduced from normal running level with the arc length remaining constant throughout. Similarly, the profile at the weld start can be altered to avoid excessive build up which normally occurs in MIG welding.

Modulated wire feed speed

Because pulse parameters are related to the wire feed speed, stable arc and metal transfer can be maintained even with the modulated wire feed speed, i.e. thermal pulsing. While the wire feed speed modulates between low and high levels, the intensity and width of the arc column also modulate, fusing the joint uniformly as well as stirring the weld pool to give better wetting on to the joint walls and producing good penetration.

Reduced spatter and fume

Compared with short circuiting, synergic operation is virtually free from spatter. In addition, fume level is reduced with synergic operation (A9, A10), because metal transfer is controlled and occurs in the form of regular spherical droplets.

Range of materials

Synergic pulsed MIG can operate with a wide range of wire materials, including those which cannot be operated with a short circuiting mode of metal transfer e.g. stainless steel, aluminium alloys and nickel alloys.

A.10. FLUX-CORED WIRES

Gas-shielded flux-cored wires first gained acceptance for welding stainless steel and non-ferrous materials, but in the mid 1950s they began to be promoted to weld mild steel and low alloy steels (A42, A43). The electrodes and relevant equipment were refined and introduced in essentially the present form in 1957 (A15). The process is still being developed. Wire and flux compositions are being improved continuously to provide a stable arc and metal transfer, together with improved weld properties. Alloy wires and small diameter wires have been developed more recently (A42, A43).

The benefits of welding with flux-cored wires are achieved mainly from a combination of the following three factors:

1. Greater productivity due to continuous wire feeding.
2. Metallurgical benefits provided by the flux.
3. Improvement in the weld bead shape provided by the slag.

Although solid MIG wires can achieve high deposition rates, practical problems are minimised by use of flux-cored wires. For any given wire diameter, the same current will produce higher current density, and hence greater I^2R heating in the wire extension, and a higher deposition rate with tubular wires than solid wires, Fig. A-14 (A42). The slag formers and readily ionised compounds in the core can cause a stable arc, good control of bead shape, greater weld metal toughness, reduced spatter, all positional welding and high deposition rates (A42, A44, A45, A46).

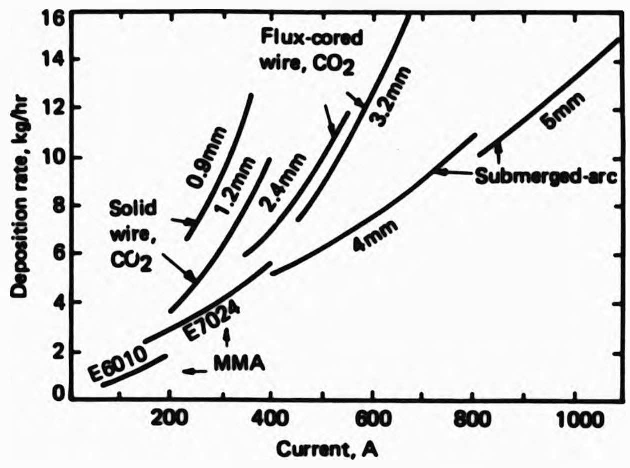


Fig. A-14. Deposition rates for solid and flux-cored wire CO_2 welding compared with those for MMA and submerged-arc welding (A42).

A.11. CONCLUDING REMARKS

Since introduction of the MIG process in 1948, great progress has been made in its development. At present the process is used extensively, mainly in three equally important modes. For successful operation, the basic requirements of each mode are essentially the same, that is, balance between the wire feed speed and the burnoff rate, specified by the burnoff relationship, and small droplet type metal transfer from the wire electrode. The main difference between the three modes is that their operating ranges are different. The original mode, steady DC open arc operation, fulfils the basic requirements at relatively high currents. Therefore this mode is used for applications requiring high currents, for example, welding relatively thick materials in the down hand position. The other two modes can fulfil the basic requirements at low currents. Therefore both modes are used for applications requiring low currents, for example, welding of thin materials and positional welding.

For each mode, the weld quality depends on the arc and the metal transfer stability. For steady DC open arc operation, the required type of metal transfer occurs naturally for currents greater than the critical value. Therefore no special control of the parameters is required to assist metal transfer. However, for arc stability, self-adjustment of arc length is essential, otherwise arc length will fluctuate. This adjustment, in the conventional process operation, is achieved simply by using a nominally constant voltage or flat output characteristic. In this method, arc voltage must be adjusted for a given wire feed speed. Therefore the method is inadequate for modulated wire feed speed operations, for example, those required to achieve thermal pulsing.

To achieve stable arc and metal transfer with short circuiting arc operation is more complex. This is because, in addition to the requirement of a flat output characteristic of the power source, the rate of rise of current during the short circuits must also be optimised to avoid spatter. In practice, this is achieved by adjusting an inductance included in the welding circuit. Furthermore the arc voltage must be adjusted accurately to obtain regular and high short circuiting frequency, which results in consistent bead deposits.

The pulsed MIG, where the current is periodically modulated between a low background level and a high pulse level, produces regular and spatter-free metal transfer. In principle, droplets of different sizes can be detached by adjusting the pulse parameters, but the droplet sizes corresponding to 'Drop-spray' (A10) have been recommended for reduced spatter and fumes.

Although the pulse technique is attractive, it is not easy to set up a stable welding condition in practice. This requires accurate adjustment of the relevant combinations of operating pulse parameters. However, this difficulty has already been removed by developing synergic control which relates all the relevant parameters to the wire feed speed. Essentially, an electronic control unit or a microcomputer executes the synergic relationship automatically and controls the power source, so that the required pulse parameters for any given wire feed speed are supplied to the arc. All that is needed from the operator is to select the wire feed speed for the required application. As the synergic system greatly simplifies pulsed operation, it has already been incorporated in commercial power sources.

Similarly, the difficulty in setting up welding conditions would be removed if 'synergic' type control systems could be developed for steady DC open arc and short circuiting arc operations. Such systems would also make possible thermal pulsing where the wire feed speed is modulated to make welds with preferable characteristics. Development of synergic controls for both the modes was the objective of the work described in Part 1 of this thesis.

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