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New Approaches to Controlling Unstable Gas Metal Arc Welding

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New Approaches to Controlling Unstable Gas Metal Arc Welding

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Abstract

This paper describes recent developments at the University of Wollongong in the application of novel control strategies to improve the control of inherently unstable transfer in the GMAW process.

The paper reviews the problems involved in maintaining arc stability with CO_2 shielded arcs and proposes potential solutions based on the development of a new process control technique. Results of early investigations into the phenomena are reported.

Keywords

Short circuit CO_2 transfer, pulsed CO_2 transfer, controlled current waveform, reversing wire feed.

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1. INTRODUCTION

The gas metal arc welding (GMAW) process can be made to operate reliably over a wide range of deposition rates when used with solid mild steel wires and argon-based shielding gases. The behaviour of the process under these conditions has been widely investigated and reported since the 1950s [1, 2]. At low deposition (or wire feed) rates, current densities in the wire electrode are low, and the process operates in short-circuit transfer mode. In this mode, the molten droplet formed at the end of the wire/electrode regularly touches the weld pool, and metal transfer is achieved through a combination of surface tension and electromagnetic forces. This mode can be made to operate very stably with correct selection of key process parameters. In recent years, innovative application of current waveform control has increased the controllability and stability of this mode [3, 4, 5].

As the wire feed rate is increased, the current density must also increase so that the melting rate matches the feed rate. For mean currents of approximately 170A to 210A for 0.9mm diameter wire, the process operates in globular transfer mode. In this mode, the end of the electrode no longer touches the weld pool. Large droplets formed on the end of the electrode are detached by a combination of gravity and electromagnetic forces at irregular intervals. The irregular metal transfer results in poor bead appearance and low operator appeal. In these current ranges, the process is operated in pulsed spray transfer, an open-arc process where the metal transfer is regular and can be precisely controlled via the current waveform: A droplet of consistent size is propelled across the arc at regular intervals with minimal spatter [6] to produce a smooth weld bead of intermediate size.

Above approximately 220A for 0.9mm wire, the process transits to spray transfer mode. In this mode, fine droplets having a diameter less than that of the electrode are propelled from the electrode towards the weld pool at a high speed across the open arc. As current is increased, the droplets become finer and the electrode end becomes more tapered (see Figure 1). The constant metal transfer produces a smooth weld bead. The high current produces high heat input and a relatively wide bead. Large fusion areas and deep penetration can also be achieved if the travel speed is high enough to avoid “puddling”, but without producing undercut. Due to the large, highly liquid weld pool, the positional capability of this mode is mostly limited to downhand.

At very high currents (above 500A), and where the electrode stickout length is sufficiently long, rotating arc transfer can be produced [7]. Under these conditions, it is thought that the resistive preheating of the electrode is sufficiently high to soften it to a point where it is rotated irregularly by the non-axial arc forces [8]. An alternative explanation is that a kink instability of the molten electrode taper is created and perpetuated by a longitudinal magnetic field [7]. At the same time, tiny droplets are expelled from the end to the electrode towards the weld pool. The resulting weld bead is very wide, but the deposition rate is also very high. It should be noted that this mode is not widely used due to higher spatter and non-optimum bead quality. If very high deposition rates are required, then a larger electrode is used in spray mode at a lower wire feed rate.

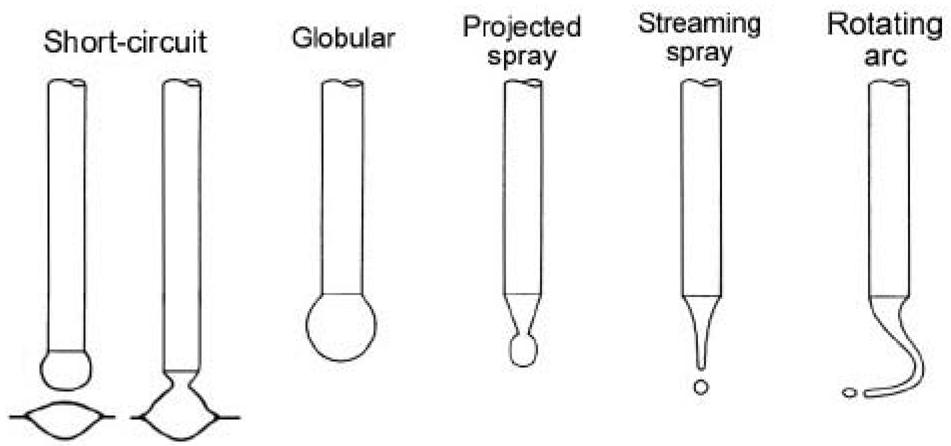

Figure 1. Diagrammatic representation of transfer modes in argon-based shielding gases

Due to the availability of a number of distinct operating modes, the argon-based GMAW process offers the ability to operate over a very wide range of deposition rates for a given electrode size. It has been widely studied, and is commonly used by the welding industry in “Western” countries for over four decades.

The major (arguably only) disadvantage of argon is its comparatively high cost of production, compared to carbon dioxide (CO_2). As CO_2 is a byproduct of processes such as brewing, it is relatively inexpensive since low temperature distillation equipment is not required. The Japanese welding industry has led in the application of CO_2-shielded GMAW for high-volume production. However, there are a number of fundamental and practical limitations which must be overcome, as described in the next section.

2. LIMITATIONS OF THE CO_2 GMAW PROCESS

The most significant difference between GMAW processes using CO_2 and argon-based shielding gases is that the CO_2 process does not exhibit a spray transfer mode. For low currents (less than 170A for 0.9mm wire) the CO_2 process operates in dip transfer mode. The overall behaviour is similar to that for argon, but spatter levels tend to be higher and the bead finish is not as smooth. These differences are due to the lower surface tension of molten steel in CO_2, and the non-axial forces generated by the arc in CO_2. Research and development of the CO_2 short circuiting process has been ongoing since the early 1970’s [9, 3, 4, 10], resulting in advanced controlled-current waveform power sources that minimise the problems associated with CO_2 dip transfer.

As the current is increased, the CO_2 process enters the globular transfer mode, and continues to operate in this mode until very high currents (400 to 600A), where a form of rotating arc behaviour is exhibited [11]. While it is possible to deposit a weld bead using globular transfer in CO_2, the resulting weld bead has a poor appearance, arc stability is also poor, and spatter is very high. Observations of the process have shown that large droplets form at the tip of the electrode, and the arc force tends to push the droplet upwards and away from the weld pool, leading to the description of "repelled globular transfer". The large droplets are detached at low frequencies (<10Hz). The arc root is highly mobile, so the arc forces tend to move the droplet in an irregular manner. Also, a large amount of spatter in the form of fine particles on the workpiece is observed.

Detailed modelling and simulations of the welding process by Haidar and Lowke [12] have successfully modelled some of this behaviour. For currents between 325 and 400A, formation of both large and small droplets are predicted over a period of 250ms (see Figure 2). For currents below 325A, no small droplets are produced. Large droplets with a diameter greater than 3mm are produced at frequencies of 4 drops/sec or less. The small droplets are detached relatively quickly (approx 500 drops/s), but cannot account for the wire feed rate. The majority of the metal transfer occurs when the larger droplet falls from the electrode, as weight exceeds surface tension and other upward forces. The production of a large droplet (as opposed to fine droplets in an argon atmosphere at similar currents) is attributed to the high degree of arc constriction in CO_2 at the wire anode. The corresponding constriction of the current in the molten droplet at the arc attachment point causes an increase in the upward axial component of the magnetic force in the liquid (J_r X B). The rapid formation of very small droplets at the arc root is also due to the same constriction of current at that point, creating an electromagnetic pinch force. In contrast, the arc "root" in argon encompasses a much larger area of the droplet. The constriction of the current occurs at he top of the droplet, tending to pinch off the entire molten droplet rather than a small volume at the base.

Although asymmetry in the arc and droplet was not modelled by Haidar and Lowke, they suggest that the observed "repelled globular transfer" is due to the development of asymmetry in the alignment of the droplet. The resulting non-axial pinch forces cause the main droplet to be deflected, and also cause some of the smaller droplets to be propelled away from the weld area, producing the observed fine spatter.

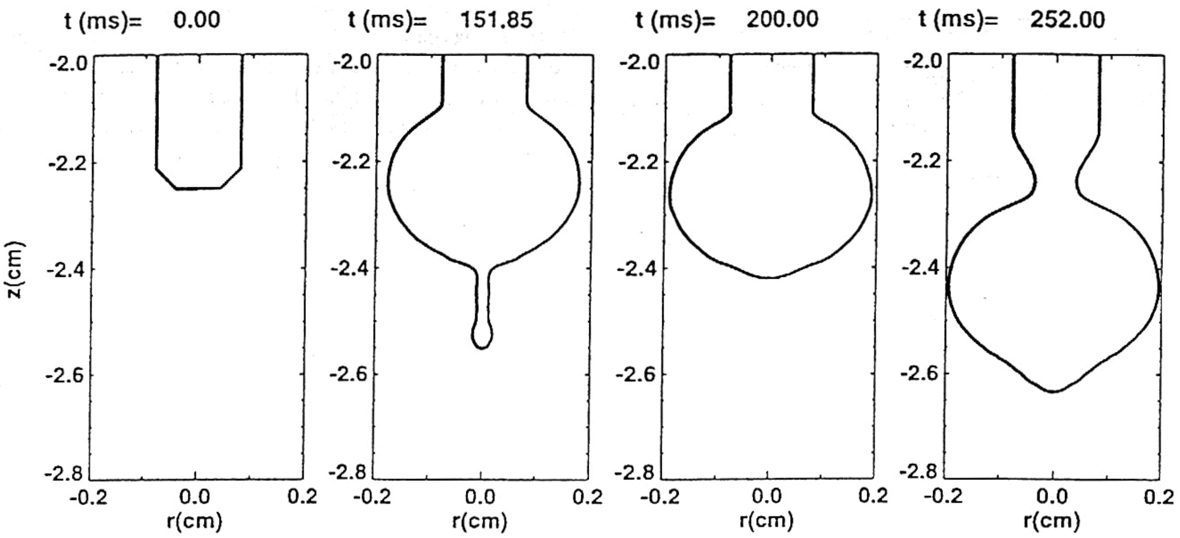

Figure 2 Simulated droplet growth in pure CO_2 at 325A, 1.6mm electrode (from [12])

The arc constriction, which creates the undesired behaviour of the CO2 GMAW process, is caused by the non-monotonic variation in the thermal conductivity (K) of the gas with temperature. While monatomic gases like argon exhibit a thermal conductivity that rises steadily with temperature (T), the addition of a dissociative gas such as hydrogen, nitrogen or CO_2 creates a "kink" in the K vs T graph as shown in Figure 3a. The rise in K is due to dissociation of the gas (eg CO_2 -> CO + O) at that particular temperature. The higher K at lower temperatures causes heat to be drawn away from the outer sections of the arc, creating a change in the temperature distribution in the arc as represented in Figure 3b. The arc is concentrated, or constricted, to a smaller radius at a given current, since the electrical conductivity of most gases increases rapidly with temperature (Figure 3c).

The thermal conductivity variations of dissociative gases is intrinsic to CO_2, and the constriction of the arc is considered to be an inherent and unavoidable trait of the CO_2 GMAW process.

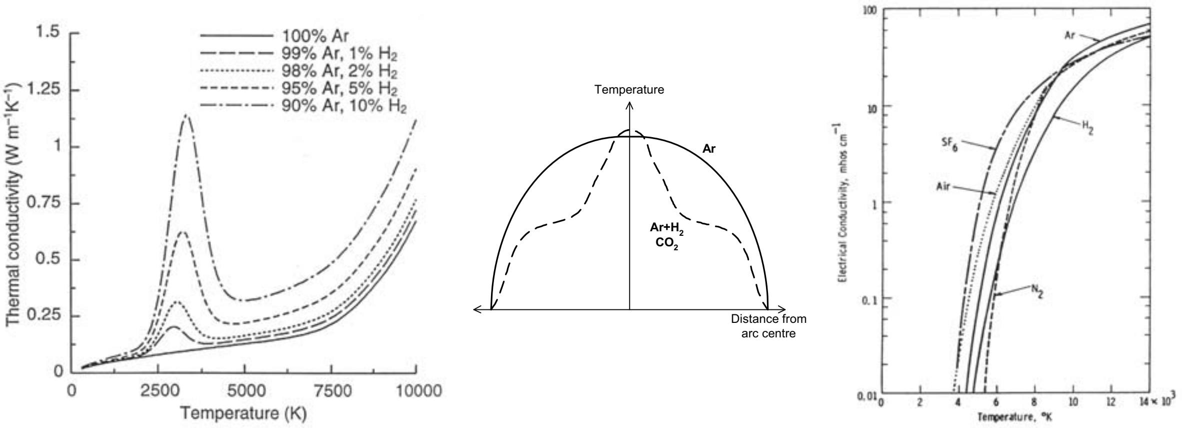

Figure 3 (a) K vs T for Ar and Ar-H_2 mixtures (b) Changes in arc temperature distribution (c) Electrical conductivity vs T of various gases (courtesy J.J. Lowke)

3. DEVELOPMENTS IN PULSED CO_2 GMAW PROCESSES

Although CO_2 has inherent properties which make its behaviour undesirable, the need to reduce welding costs have encouraged research for optimisation of the open arc (i.e. non short-circuiting) CO_2 GMAW process.

In the mid 1960's, attempts were made to apply the pulsed spray transfer method to CO_2 by Needham and Carter [13]. This was done in order to overcome the known limitations of using constant voltage/current, which produces "repelled globular transfer" as described earlier. Using the available technology, a power source was constructed having a selectable pulse frequency of 25 or 50Hz, an adjustable pulse current, independently adjustable background current, and a 150V 15A stabilising supply to avoid the arc extinguishing during long background periods at low current. Tests were carried out using 1.2mm steel electrodes at feed rates from 3.8 m/min to 13.5 m/min and corresponding mean currents of 150A to 380A. In the intermediate current range of 200 to 300A, welding could be carried out in the downhand position if the arc was kept very short, so the transfer just touched the weld pool to minimise spatter. At very low mean currents, the weld bead was grossly uneven, due to the low heat input, the fast-freezing nature of the weld pool, and the low frequency and irregularity of metal transfer. At very high mean currents, the correspondingly high pulse current produced excessive pool agitation, splashing at the bead edge, and consistent undercutting. The work of Needham and Carter showed that suitable operating conditions could be found for CO_2 pulsed spray transfer, which gave better results than globular transfer using a simple constant voltage (CV) power source operating in the same mean current range. However, better results could be obtained using argon-based gases with less expensive CV power sources. As a result, the pulsed spray CO_2 process was not widely used in the 1960s and 1970s.

By the mid 1980s, major improvements in power source technology created renewed interest in the pulsed CO_2 process. Japanese researchers [14, 15] employed an adjustable square-wave current waveform to optimise behaviour of the process. Using a 1.2mm steel electrode at mean currents of around 250A and pulse frequencies of around 38Hz, the metal transfer behaviour was observed using high speed cinematography, and is represented in Figure 4. The transfer of the large droplet occurs approximately mid way through the pulse period. The replacement droplet is developed during the remainder of the pulse period, and during the background period. The distortion of the transferred droplet at the high current is clearly visible in the photographic frames of Figure 5. As discussed previously, the constricted CO_2 arc at high currents produces large upward asymmetrical forces on the droplet at the same time that electromagnetic pinch forces create necking of the droplet. In contrast to CO_2 pulsed transfer, the pulsed transfer in argon occurs at the end of a relatively short pulse period (1.5 to 5 ms typically [16]), and the droplet is propelled directionally to the weld pool during the background period under low current. The CO_2 transfer exhibits a much high spatter rate, and this characteristic is unavoidable due to the operation of the transfer. Similar behaviour has been reported by other researchers employing similar techniques [17].

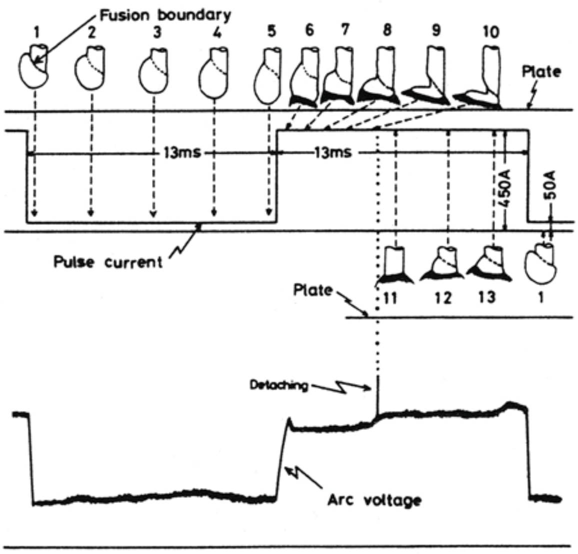

Figure 4 Example of droplet behaviour and waveforms in pulsed CO_2 (from [15])

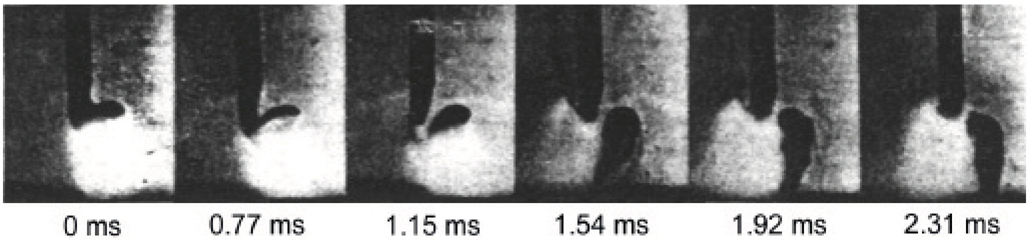

Figure 5 High speed cinematography of droplet transfer (from [15])

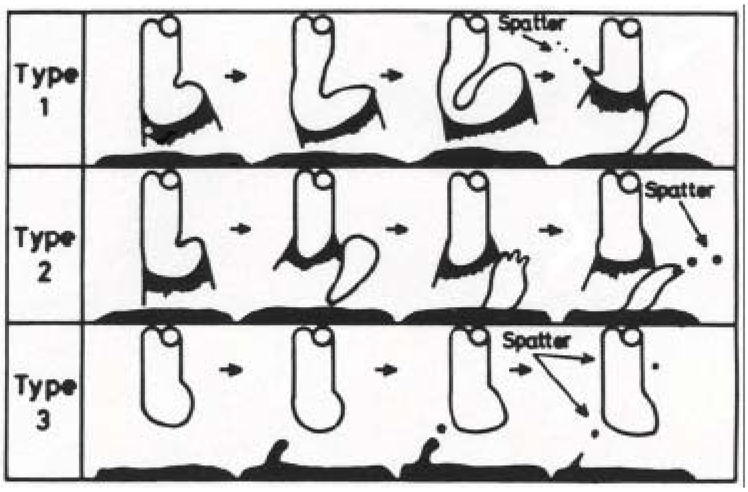

Figure 6 Observed spatter production mechanisms in pulsed CO_2 welding (from [15])

In additional observations, three mechanisms of spatter production have been observed, and are represented in Figure 6. “Type 1” is produced from the kink instability in the droplet neck at the moment of droplet detachment during the pulse period. This was found to be the most common, and produces fine spatter. “Type 2” spatter is blown off from the detached droplet by arc blow, before the droplet is immersed into the weld pool. “Type 3” spatter is caused by expulsion of chemically reacted gas from the weld pool. The reduced surface tension in CO_2 may contribute to increased spatter levels over those observed in argon.

Due to the inherent operation of the CO_2 process, improvements in behaviour over those described in these papers has not been forthcoming over the past decade. Further advances in power source technology and process modelling have not generated a solution to the problems. Yet despite the limitations imposed by a constricted arc and droplet repulsion, the open arc process is used in production applications where low cost outweighs other considerations such as excellent bead appearances and very stable running.

4. DEVELOPMENTS IN THE CO_2 SHORT-CIRCUITING GMAW PROCESSES

Unlike the open arc process, the short-circuiting process has been greatly improved since its initial implementation in the late 1950s [18]. In the early 1970s, research by Boughton and MacGregor [9] demonstrated techniques for reducing weld pool disturbances and spatter. The first involves reduction of current for 0.5 to 1.5ms after the start of the short-circuiting period, allowing the droplet formed at the tip of the electrode to "wet in" to the weld pool, This minimises repulsion forces which would cause the short to blow apart and generate spatter. After the wetting-in time is complete, the current is increased to promote normal metal transfer to the weld pool. The second involves reducing the current in the short-circuit, just prior to the rupture of the neck connecting the electrode to the weld pool. This step avoids generation of spatter and pool disturbance when the neck ruptures like a fuse at high current. Although the equipment functioned well in a laboratory using a mechanised welding rig, it was not possible to accurately predict the point of short-circuit rupture as conditions changed; particularly contact tip to workpiece distance (CTWD).

In the mid 1980s, Ogasawara et al [3] devised a reliable means of predicting the short-circuit rupture. Improvements to the arcing period waveform were also devised, namely, applying a current pulse of suitable magnitude and duration to produce an adequate arc length to avoid premature short-circuiting. Along with improvements in power source technology, these improvements were packaged into a commercial CO_2 robotic welding system.

In 1989, Stava [4] reported another commercially available power source which further improved the prediction of the short-circuit rupture, and also incorporated circuitry designed specifically to turn off the welding current very rapidly (within 50 microseconds) when such an event is predicted. The waveforms are illustrated in Figure 7, for later reference.

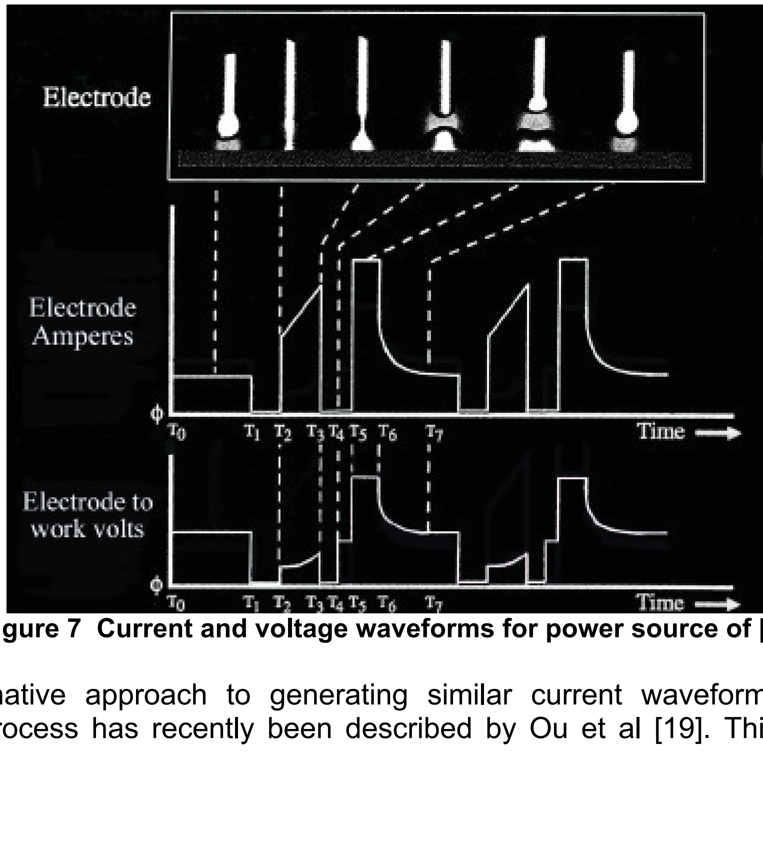

Figure 7 Current and voltage waveforms for power source of [4]

An alternative approach to generating similar current waveforms for the short-circuiting CO_2 process has recently been described by Ou et al [19]. This approach uses programmable voltage-current characteristics rather than time-oriented wave shapes. This results in a power source that is more self-adaptive to the process, and is more conducive to the implementation of a “one knob control” facility.

The developments described above have concentrated on manipulating the current to achieve the desired process behaviour, while feeding the electrode at a constant rate. Researchers have also used mechanical means of rapidly adjusting the wire feed rate to improve the process, without resorting to complex power sources. Earlier attempts involved the unidirectional stepped feeding of wire [20, 21, 22]. This approach used the step feeding to dictate the dipping frequency of the process. More recently, Huismann [23, 24] has described in detail the operation of a dynamic wire feeding system which rapidly reverses the direction of the electrode at the start of the short circuit. In this system, the dipping frequency is not enforced. Instead, the control system merely responds to the incidence of a short circuiting event. The withdrawal of the electrode away from the weld pool guarantees that the rupture of the short circuit can successfully occur even at low currents for large electrodes, with minimal disturbance to the weld pool. Once the arc is re-established after the short circuit, the wire is fed forward at the desired feed rate. Although tests were conducted at relatively low wire feed rate and current (150A) with a 1.6mm steel electrode in Ar-3%O_2, this development is considered worthy of mention here. The dynamic reversing is a significant departure from prior art, and there is no apparent barrier to its use with the CO_2 process.

5. A NEW APPROACH TO CONTROLLING THE CO_2 GMAW PROCESS

The greater improvement in performance of the short-circuiting process compared to that of the open-arc process has been possible because the metal transfer mechanism of the short-circuiting process is inherently more stable. In the open arc process, the droplet must be detached from the electrode at high current, while it is being simultaneously acted on by a non-axial repulsion force which tends to push it away from the centreline of the weld pool. As shown in Figure 6, spatter types 1 and 2 are more readily produced at the higher pulse currents. In the short circuiting process, the droplet is allowed to come into contact with the weld pool at low current, where the repulsion forces are lower. The material is transferred quite close to the centreline of the pool. There is less opportunity to produce spatter types 1 and 2, although type 3 is likely to be produced during the arcing period. According to simulations by Haidar and Lowke, another form of spatter similar to type 1 may also be produced during the arcing period, since small droplets may be expelled from the main droplet during arcing. But since there is no pinch-off of the droplet at high current, the overall level of type 1 spatter is expected to be lower.

In this project it is proposed that the operating range of the short-circuiting CO_2 process be significantly extended to cover a higher range of currents which would normally be associated with the use of either pulse or globular transfer. The objective is to provide a means of increasing the deposition rate in CO_2 without incurring the negative aspects of open-arc transfer in this shielding gas. It is planned to operate a 0.9mm electrode at mean currents in the range of 200A to 350A (i.e. well above the spray transition current in argon-based shielding gases) using “normal” values of CTWD (12 to 20mm).

We intend to use a reversing wire feed system in conjunction with an advanced welding power source having a programmable waveform and high current turnoff capability. The primary function of the reversing wire feed system is to prevent stubbing of the electrode tip into the weld pool at high wire feed (deposition) rates. To ensure correct operation, it must also have a high dynamic response of better than 5 milliseconds. The power source is capable of rapid current turnoff just prior to short-circuit rupture (to avoid fine spatter and pool disturbance). The power source is also programmable in high level language, so that a variety of control techniques can be tested and evaluated.

6. EXPERIMENTAL EQUIPMENT

The reversing wire feed unit (Figure 8) has been constructed and tested. The mechanical design minimises wire feeding friction both upstream and downstream of the feed rolls. The distance between feed rolls and contact tip has been minimised. This avoids wire “springing” effects and ensures than any movement at the tip of the electrode corresponds to controlled motion at the feed roll. The time taken to stop 0.9mm diameter wire from full speed (40 m/min) has been measured at approximately 2.1ms, while the time taken to accelerate the wire from rest to 40m/min is approximately 3.8ms.

Figure 9 is a photograph of the experimental power source. This power source has been constructed and used for previous research [5]. It incorporates all the circuit features required for optimised control of the short-circuiting GMAW process. It has a peak current output capacity of 600A, and a current turnoff capability of 20,000 A/ms. The mean current output is thermally restricted to 330A at 60% duty cycle. For experiments having a lower duty cycle, higher mean currents can be supplied for short periods.

Figure 8 Reversing wire feed unit

Figure 9 Advanced experimental power source

7. CONTROL METHODOLOGY

The control method to be initially tested will use a controlled current waveform to regulate the instantaneous melting rate of the electrode. The instantaneous wire feed rate is adjusted in response to events in the process, as signalled by the voltage feedback.

Typical reference waveforms for current and wire feed rate, as well as welding voltage, are shown in Figure 10. The shape of the voltage waveform is based on observed behaviour in preliminary tests. The figure depicts one complete metal transfer cycle in the process. The process is considered to proceed in several distinct stages. Stages 2, 3 and 4 constitute the short-circuiting period, when the droplet forms a bridge connecting the electrode tip to the weld pool. Stages 5, 6 and 1 constitute the arcing period, when the droplet is formed at the tip of the electrode, and the arc contributes to workpiece heating. The short circuit period is typically 3 to 5 milliseconds in duration, while the arcing period lasts typically 10 to 50 milliseconds. The typical range of dipping frequency is 20 to 75Hz. The similarities with the current waveform of Figure 7 are evident.

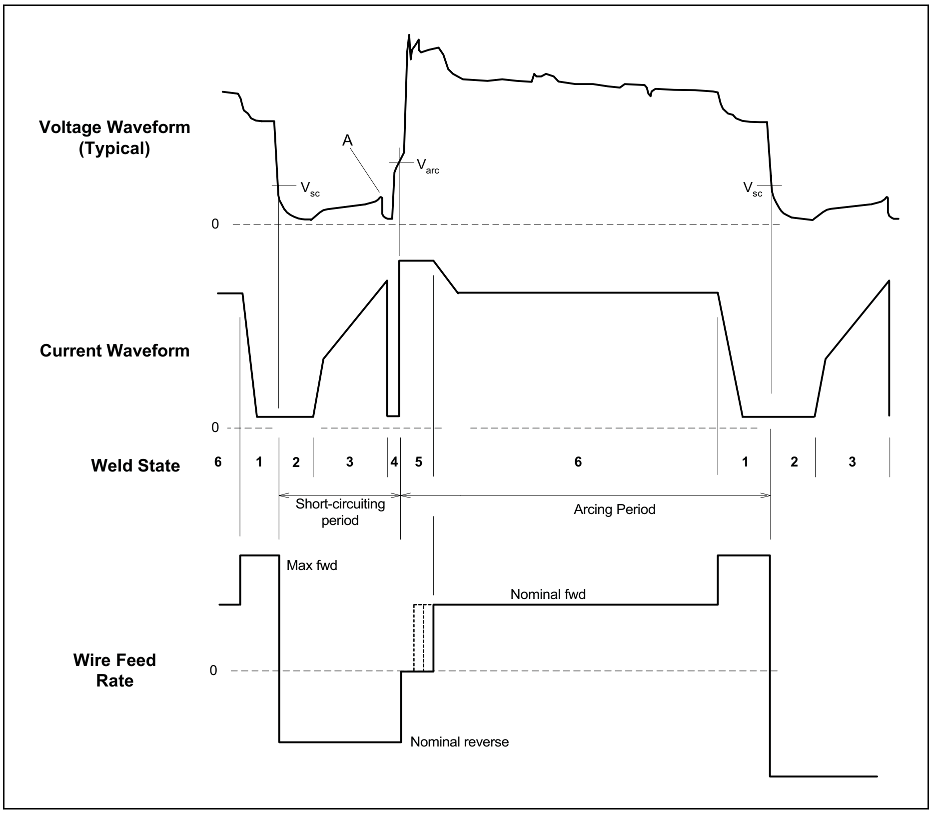

Figure 10 Typical waveforms for current, wire feed speed, and welding voltage

Stage 6 has the longest duration, and contributes the greatest amount of heat input to the workpiece. The wire is fed forwards into the process at the nominal rate. The current is chosen to balance the feeding rate with the melting rate, so that as the droplet is formed on the tip of the electrode, the arc length decreases slowly but is sufficient to avoid an accidental short circuit. For a 0.9mm electrode feeding at 20 m/min with a CTWD of 12mm, the balance current is around 325A. This current is maintained for the desired time, and this approximately determines the droplet size and dipping frequency. For controlling purposes, the process is then considered to enter stage 1, although the process continues to arc.

In stage 1, the current is rapidly reduced to a background level (25A, say), and the wire feed rate is increased to a higher level. These steps are intended to promote the onset of the next short circuit. The reduction in arc force should also removes weld pool depression, which should assist in reducing the duration of this stage. It is desirable to minimise the duration of this stage, because there is very little contribution to heat input at the background current. It is also desirable to make the short circuit occur at low current, to minimise ball repulsion spatter. Regular short circuiting at 300A would produce unacceptably high spatter levels.

When the short circuit is detected (voltage drops below V_{sc} in Figure 10), the stage 2 period begins. For a fixed duration of 0.5ms, the current is maintained at background level to promote wetting of the droplet into the weld pool, avoiding repulsion. At the beginning of this stage, the wire feeding is reversed. As stated previously, the mechanism requires 2ms to stop the electrode, so there is no chance of the short circuit being broken by taking this action.

In stage 3, the current is allowed to increase, producing an electromagnetic pinch force which pumps the molten metal into the weld pool. Simultaneously, the tip of the electrode comes to a halt and then begins to reverse away from the weld pool. This is vital to avoiding stubbing at high wire feed rates. The combination of wire reversal and electromagnetic pinch forces guarantees the formation of a thin neck on the short circuit that bridges the pool and wire tip. The imminent rupture is detected by the dV/dt of the feedback voltage exceeding a certain value (point “A” in Figure 10). At this instant, the current is rapidly reduced to the background level, and stage 4 begins. During stage 4, the short circuit rupture occurs at reduced current. The reverse motion of the wire guarantees this event.

When the voltage feedback exceeds Varc, the short circuit neck has ruptured and arcing has commenced.

The control parameters of stage 5 produce the initial conditions for the arcing period. The electrode is brought to a standstill, and the current can be increased to a level higher than the nominal arcing current of stage 6. This establishes the initial arc length, which must be long enough to avoid premature short circuiting due to motion in the weld pool. The ability to hold the electrode stationary while extending the arc length means that the stage 5 current does not need to be much greater than the nominal arcing current. This avoids excessive weld pool depression, disturbance, spatter and possible excessive arc gouging of the workpiece which would otherwise occur for systems using constant wire feed speed. Note that the electrode does not need to be stationary for the entire duration of stage 5.

8. PRELIMINARY RESULTS

Prior to completion of the reversing wire feed system, tests were conducted using constant wire feed speed and the advanced experimental power source described previously. The tests used 0.9mm diameter steel wire (AWS A5.18 ER70S-6) in CO_2 at a CTWD of 12mm. Stable welds using short-circuiting transfer were achieved at wire feed rates of 12, 15 and 18 m/min, corresponding to mean currents of 190, 230 and 260A, respectively. These tests demonstrate that the short-circuiting CO_2 process can be extended well beyond the spray transition current in argon-based shielding gases. Several other observations were made:

1) The tendency for the wire to stub into the weld pool increases with wire feed rate, and it becomes progressively more difficult to find welding parameters that will avoid the stubbing condition.
2) At high feed rates, very high values of initial arcing current (>400A) are required to establish a suitable arc length to avoid premature short circuiting. The shape of the recorded voltage waveforms during stage 5 indicate that excessive weld pool disturbance is generated by these current levels.
3) Spatter levels become greater as the wire feed rate increases, particularly for welds where premature short circuits occur at the nominal arcing current.

The major limiting factor to further increases in deposition rate is the tendency for stubbing. This is thought to be caused by reduction in the length of the short-circuit bridge during the short circuiting time, due to the high feed rate. For example, at 18 m/min (300 mm/sec), the average dipping frequency was measured at 33Hz. This corresponds to the typical droplet consisting of 9.1mm of electrode length. If the droplet is modelled as a truncated sphere attached to a solid cylindrical electrode, it would have a diameter of 2.23mm and a length of 2.14mm along the electrode axis. The latter is expected to be the initial bridge length of the short circuit. Assuming no movement of the weld pool during the average short-circuiting time of 4ms, then the forward movement of the electrode during the short circuit will reduce the bridge length by 1.2mm to 0.94mm. Weld pool movement towards the electrode can will this further. Calculations by Kiyohara et al [25] show that as the bridge length becomes less than the electrode diameter, the bridge requires increasing current to successfully pinched off.

From these tests, the benefits of using a reversing wire feed system become apparent. At the time of preparing this document, the reversing wire feeding system has been recently installed, and only a limited number of tests have been performed. Very stable welds have been produced at average wire feed rates of 11.8, 14.2 and 15.6 m/min, corresponding to mean currents of 185, 200 and 240A, respectively. It should be noted that the average wire feed rate is less than the nominal forward feed rate, since the process control involves periodic reversal of the electrode. In the 240A weld, the nominal forward rate is 22 m/min, and the nominal arcing current is 325A. The average dipping frequency is 30Hz. The spatter levels are impressively low, since the chosen welding parameters allow almost all short circuits to occur at the background current level. With a reverse feed rate of 20 m/min, a suitable arc length is established at the beginning of the arcing period with only

325A of initial current. The short-circuit metal transfers occur at very regular intervals, and result in a stability index of better than 0.80 as calculated by:

$$Stability\ Index = 1 - \frac{Std\ Deviation\ of\ weld\ cycle\ duration}{Mean\ Value\ of\ weld\ cycle\ duration}$$

Using this criterion, a perfectly regular weld would have a stability index of 1.00. The recorded current and voltage waveforms for the described weld are shown in Figure 11.

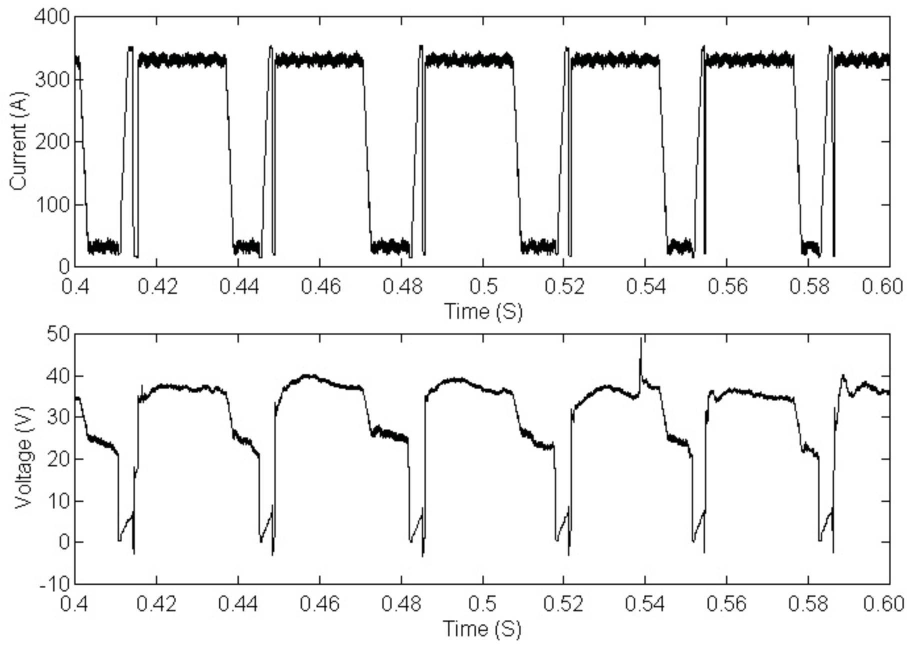

Figure 11 Voltage and current waveforms for weld at I_{mean}=240A

9. CONCLUSIONS AND FUTURE WORK

This paper has discussed the fundamental physical reasons for the instabilities in the CO_2 GMAW process, and has reviewed the history of improvements to the control of the process. Building on these developments, a new approach to improved metal transfer has been described. The experimental equipment has been recently completed, and preliminary tests have shown promising results. Further experiments will be conducted at higher wire feeding rates, to establish the limitations of the process. Behaviour with larger electrodes will also be investigated.

10. ACKNOWLEDGEMENTS

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