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Abstract

The control strategies that have been developed over the past four decades to control the inherently unstable metal transfer in the CO2-shielded GMAW process are described. The fundamental reasons for poor arc stability with CO2 as a shielding gas are discussed. From an understanding of the process behaviour, a new process control technique is proposed, and the future direction of research in this area is discussed.

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. This mode is characterised by large droplets being 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 GMAW process is preferably 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.

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

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 sub-optimal bead quality. If very high deposition rates are required, then a larger electrode is used in spray mode at a lower wire feed rate.

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 (CO₂). As CO₂ 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 CO₂-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.

**Limitations of the CO₂ GMAW process**

The most significant difference between GMAW processes using CO₂ and argon-based shielding gases is that the CO₂ process does not exhibit a spray transfer mode. For low currents (less than 170A for 0.9mm wire) the CO₂ 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 CO₂, and the non-axial forces generated by the arc in CO₂. Research and development of the CO₂ short circuiting process has been ongoing since the early 1970’s [3, 4, 9, 10], resulting in advanced controlled-current waveform power sources that minimise the problems associated with CO₂ dip transfer.

As the current is increased, the CO₂ 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 CO₂, 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 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 CO₂ at 325A, 1.6mm electrode [12]](image)

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 CO₂ creates “kinks” in the K vs T graph as shown in Figure 3a. The rise in K is due to dissociation of the gas (ie. CO₂ -> CO + O and CO -> C+O) at those particular temperatures. 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 gases increases rapidly with temperature, as shown in Figure 3c. The electrical conductivity of CO₂ is markedly higher than argon above 20 000K, further concentrating the current to the centre of the CO₂ arc, where the temperatures reach 27 000K [12].

![Figure 3(a) K vs T for Ar and CO₂ [26]](image)

![Figure 3(b) Changes in arc temperature distribution](image)
The thermal conductivity variations of dissociative gases is intrinsic to CO₂, and the constriction of the arc is considered to be an inherent and unavoidable trait of the CO₂ GMAW process.

Developments in pulsed CO₂ GMAW processes

Although CO₂ has inherent properties which make its behaviour undesirable, the need to reduce welding costs has encouraged research for optimisation of the open arc (i.e. non short-circuiting) CO₂ GMAW process.

In the mid 1960’s, attempts were made to apply the pulsed spray transfer method to CO₂ 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 to 13.5 m/min (150 to 530 in/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 CO₂ pulsed 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 CO₂ 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 CO₂ 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 (8 m/min or 315 in/min wire feed speed) 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 CO₂ 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 CO₂ 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 CO₂ 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].

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 CO₂ may contribute to increased spatter levels over those observed in argon.
Figure 6 Observed spatter production mechanisms in pulsed CO₂ welding [15]

Due to the inherent operation of the CO₂ 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 bead appearance, high stability and post-weld spatter removal.

Developments in CO₂ 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 CO₂ 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 a complete weld cycle.

An alternative approach to generating similar current waveforms for the short-circuiting CO₂ 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 so far have concentrated on manipulating the power source output 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 stepped feeding to dictate the dipping frequency of the process.

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

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 wire feeding 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. The operating cycle is shown in Figure 8.

Although tests were conducted by Huismann at relatively low wire feed rate and current (150A) with a 1.6mm steel electrode in Ar-3%O₂, 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 CO₂ process.

A new approach to controlling the CO₂ 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 (these have not yet been observed). 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 future research, we propose to investigate the possibility of extending the operation of the short-circuiting CO₂ shielded GMAW process. The objective is to avoid free-flight transfer of the metal from electrode to workpiece, due to the inherent problems associated with this mode of transfer. If the short-circuiting mode can be made to operate at wire speeds higher than those currently achieved with more conventional methods, then it will be possible to increase the deposition rate in CO₂ without incurring the negative aspects of open-arc transfer in this shielding gas. It is planned to use a reversing wire feed system of high dynamic response, in conjunction with an advanced welding power source having a programmable waveform and high current turnoff capability. The operation of this equipment will be coordinated from a central DSP-based control system. The system will be programmable in high level language, so that a variety of control techniques can be tested and evaluated.

Conclusion

This paper has discussed the fundamental physical reasons for the instabilities in the CO₂ shielded 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 proposed. Future experimentation will aim to increase the productivity of the short-circuiting process, ideally to make it comparable to the open-arc process, whilst avoiding the undesirable aspects associated with free flight metal transfer.

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