Metal Transfer Control in Gas Metal Arc Welding

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Abstract

Power input to the arc in gas metal arc welding controls both the metal transfer process and the base-plate heating process. It would be advantageous to decouple these processes. Methods to achieve this decoupling are discussed. Pulsed-power welding is widely used, but only partial decoupling can be achieved. More complete decoupling may be obtained by using independent power inputs to the system. Several techniques are reviewed, with emphasis on mechanical vibration of the electrode. The effects of mechanical vibration of the electrode are discussed along with a literature review of previous research. A new experiment at the MIT Welding Laboratory which implements electrode vibration, precision current control, and flexible real-time computer control is described.

1 Introduction

Gas metal arc welding (GMAW) is a widely used industrial process for joining metals. It accounts for approximately 30 to 40 percent of all welding in the United States, and the use of GMAW is increasing, primarily at the expense of shielded metal arc welding (SMAW) [1]. A better understanding of GMAW would be useful for improving and automating it. This paper reports on a program of research at MIT that will contribute to the understanding of droplet formation and control in gas metal arc welding.

The gas metal arc welding process is shown in Figure 1. An electric arc is established between the electrode and the base plates which are being welded together. The arc current is sustained by ionization of the shielding gas. The electrode, which is made of a similar material to the base plate, is rapidly melted by the heat of the arc. As the electrode melts, it is advanced downward in order to maintain a constant arc length. An inert gas blanket shields the electrode from the atmosphere.

The physics of the GMAW process is very complex. The shielding gas is only partially ionized by the arc and theories for either fully or weakly ionized gases may not be applied directly. Additionally, dynamic forces of multiple origins affect the detachment of molten metal from the electrode [2]. These dynamic forces act on the metal as it makes the phase transition from solid to liquid. The primary retaining force is the surface tension of the molten metal. The primary detaching forces are due to gravity, the drag of the shielding gas, and magnetic pinching caused by the large current flowing through the electrode and the arc. When studying the average metal deposition rate, the thermodynamic process is the most important, and a simple static force balance provides a reasonably accurate description of the metal transfer process. An instantaneous model of the metal transfer, which would be useful for designing a high-performance GMAW control system, requires the combined consideration of the thermodynamics, mechanics, and electromagnetics of the process.
2 Metal Transfer Control

A metal transfer control system should enforce a uniform stream of droplets coming off the welding electrode. There are many reasons such control is desirable. For example, a metal transfer control system could precisely monitor the amount of metal transferred. It could deliver small drops at any current so that spatter is minimized. It could regulate the amount of time the molten metal spends in the arc, thereby regulating its temperature.

2.1 Process Inputs

The electrode melting rate is intimately tied to the heat input to the base plate since both are a result of the electrical power ($VI$) supplied by the power source. There are times when the requirements for electrode melting rate and base-plate heating conflict. Additional control inputs are needed to achieve independent control of the electrode melting rate and the base-plate heating process.

A partial solution is to temporally shape the power input. This solution is based on a separation of time scales: while the weld pool responds only to the average power input (low frequencies), the melting electrode responds to both the average power and the higher input frequencies. The decoupling is not complete. It is relatively easy, however, to implement this solution and thus it is widely used. Typically, a square current waveform is imposed which has an average such that the $VI$ product is commensurate with the desired base-plate heating and the fundamental frequency is commensurate with the desired drop transfer rate. A square wave is used because its broadband frequency content readily incites pinch instabilities in the forming liquid drop on the end of the electrode. This type of welding is known as pulsed-current welding.

If feedback control is applied directly to current $I$, then the voltage $V$ must be indirectly controlled because the resistance of the arc is a function of the current. Most commercial pulsed-current welding systems measure the average voltage and regulate it by maintaining constant arc length with the electrode feed motor. Since the the resistance of the arc changes nonlinearly with current, controlling average voltage is only an approximate way to regulate power into the weld.

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1 The plasma acts as a distributed-parameter, nonlinear resistor with little parasitic capacitance or inductance.
Recently, new systems have been designed which use more sophisticated techniques for arc length control. In [3, 4], the power source behaves like a constant-current supply during the base-current portion of the waveform, and like a constant-voltage supply during the peak current portion. The peak time and peak voltage are preset according to the electrode type while the base current is set according to the desired heat input to the base plate. The base time (and thus the pulsing frequency) is allowed to vary depending on the measured voltage. This adaptability of the pulsing frequency improves the stability of the arc. The electrode feed motor is regulated by measuring the voltage only during the base-current portion of the waveform. By measuring an instantaneous voltage rather than a smoothed voltage, the frequency response and stability of the controller are improved. The tradeoff however, is that heat input to the base plate is strongly coupled to the electrode feed speed. The faster the feed speed, the greater the heat input to the base plate. Conversely, welding thin plate will take longer than necessary.

In [5] the electrode feed speed is held constant and a constant-current power source is used. Base- and peak-current amplitudes are preselected and arc length is regulated by controlling the base and peak periods. The current is switched between the peak and base currents according to the measured instantaneous voltage. This adaptability of the pulsing frequency and base/peak duty ratio results is a very stable arc, independent of the electrode feed speed. However, as with the previous system, heat input to the base plate is strongly coupled to the electrode feed speed.

The limitations in the above schemes illustrate the need for an additional control input. This input could inject power into the base plate or the electrode, independent of the other. In most cases, it is preferrable to increase the melting rate of the electrode with respect to the base plate, thereby increasing the productivity of the process. Injecting power into the base plate might take the form of a secondary preheat/postheat arc. Injecting power in the electrode could be achieved in a number of ways. For example, thermal power could be injected with a secondary arc within the torch. This technique, which requires two power supplies, is described in [6]. Mechanical power could be injected electromagnetically with a solenoid around the electrode or by pulsing the gas flow rate. These methods have been investigated and found to be inefficient [7-9]. Finally, mechanical power could be injected into the electrode by vibrating it. This method has been investigated and found to be very effective [10-17].

The vibration of the electrode will not inject enough mechanical energy to directly melt additional metal. The question then arises as to why electrode vibration can change the melting rate. The answer is that in common DC-current welding, the metal drops are greatly overheated. By vibrating the electrode, the energy previously used to overheat the drops is available to melt additional metal.

The average temperature of molten steel drops coming off the electrode has been measured to be approximately 2400°C [18]. During pulsed-current welding, it has been shown analytically [19] and experimentally [20] that the drop temperature is several hundred degrees lower. This result corresponds to the earlier drop detachment effected by pulsing the current. Additionally, the central axis of the arc has been experimentally measured to be cooler than the surrounding region [21], which is a result of metal vapor from the falling drops cooling the plasma. Using heat flow modeling, it has been demonstrated that when using steel electrodes and carbon dioxide or helium shielding gas, the electrode melting rate is controlled by the heat conduction across the liquid drop from the arc to the solid electrode [22]. Therefore, early removal of the drop enhances the transfer of arc heat to the solid electrode.

In addition to improved process control, electrode vibration offers opportunities to study the GMAW process. This input can effect changes in the mechanical system directly rather than as a consequence of changes in the thermal system. Therefore, the thermal system may be studied by observing its response to these mechanical changes. For example, the electrode vibration could allow the heat flow modeling results in [22] to be experimentally verified.
2.2 Process Outputs

The quantity and rate of metal transferred from the electrode to the weld pool, and the stability with which it is transferred, are the primary process outputs. If DC current is used, stable transfer means the constant frequency transfer of uniform size drops. If pulsed-current, or vibrated-electrode welding is used, stable transfer means the transfer of a single uniform size drop per pulse cycle, preferrably at a constant frequency. The parameters in a pulsed system are typically chosen such that stable transfer occurs most of the time. In the face of disturbances or operating extremes, none of the control systems described in Section 2.1 can guarantee these stable transfer conditions.

A technique is needed to detect the separation of individual drops from the electrode. The arc voltage (which is measured to control the electrode feed motor in constant-current welding) contains the desired information due to the impedance change of the arc when a drop separates. However, due to noise and the fact that the current supply regulation is not ideal, the information is difficult to extract. Therefore, it is necessary to examine both the measured arc current and voltage. Successful techniques to do this have not been reported. They need to be developed and are part of our research efforts.

2.3 Closed-Loop Controller

With a method for drop separation detection and semi-complete decoupling of the electrode melting and base-plate heating processes, a metal transfer controller can be developed that can operate in conjunction with a base-plate heating controller. An obvious goal of this metal transfer controller would be to maximize the stable transfer of metal for a given base-plate heating.

3 Soviet Research

A great amount of welding research has been performed in the Soviet Union and Eastern Europe over the last four decades. It would seem that researchers in the West have, for the most part, overlooked these efforts. In addition to a number of papers on the use of electrode vibration for droplet control, we have encountered numerous other interesting papers in the Soviet literature on the welding process and its control. Virtually all of the Soviet papers in our reference list have never been cited outside the Soviet Union. A number of Soviet papers are recommended as secondary references in [23], however the most recent appeared in 1971. We have found numerous more recent papers of interest and we would like to encourage welding researchers to not overlook the Soviet efforts as they contain much information and many ideas.

Much effort was expended to develop suitable electrode vibration mechanisms. These devices were used to demonstrate the benefits of electrode vibration. One of the earliest accounts dates from 1965 [10]. Over the next few years, many intricate electrode vibration mechanisms were developed, some of astonishing complexity [11, 12]. The development of vibration mechanisms through 1969 is summarized in [13]. A more elegant method of vibration is first described in 1977 [14–16]. The electrode is grabbed by unidirectional clamps and pulsed forward by a solenoid mechanism built into the welding head. Vibration frequencies of up to approximately 150 Hz were achieved. A review of current modulation efforts prior to 1983, including electrode vibration, is found in [17].

The impetus for electrode vibration techniques was welding thin (1–2 mm) sheet metal. By shaking droplets off the electrode, a much lower welding current could be used. Mechanical vibration is a much more efficient way to effect premature drop detachment compared to using an external magnetic field [7] or pulsations of the gas flow [8, 9]. It is also more effective than pulsed-current

[2] It is pointed out in [17] that periodic alteration of the power of the welding arc first appeared in a Soviet patent [24] in 1953. This predates the concept of pulsed-power welding in the West by almost a decade.
### Transition Currents (A) for Different Electrode Diameters

<table>
<thead>
<tr>
<th>Electrode Wire</th>
<th>Shielding Gas</th>
<th>0.8 mm</th>
<th>1.2 mm</th>
<th>1.6 mm</th>
<th>2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Mg Alloy</td>
<td>Ar</td>
<td>25–30</td>
<td>35–45</td>
<td>50–60</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Ar</td>
<td>25–30</td>
<td>35–45</td>
<td>50–60</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Ar + 15% CO₂</td>
<td>45–55</td>
<td>55–65</td>
<td>70–80</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: DC currents required to transition from globular to spray transfer reported in [14]. Upper values are for welds made using electrode vibration. Lower values are for welds made without using electrode vibration.

Welding. It is reported in [14] that when using electrode vibration, the minimum current required for welding thin sheets is 10–20% lower than with pulsed-current welding. When DC current welding is performed with and without electrode vibration, the results are impressive. Table 1, reproduced from [14], shows the currents required to transition from globular to spray transfer.

Further benefits of electrode vibration are cited in [14]. It was observed that when aluminum-magnesium alloys were welded, less dust was precipitated in the heat affected zone. It was also found experimentally that when using electrode vibration, less high vapor pressure constituent metals were lost to metal vapor. For example, when AlMg6 alloy was welded in argon with a similar composition wire, it was found that the magnesium content of the deposited metal was 5.6% when electrode vibration was used and 5.2% when electrode vibration was not used.

## 4 The MIT Experiment

The unique capabilities that electrode vibration imparts to the welding process have prompted us to construct a new experiment at the MIT Welding Laboratory. A diagram of the system is shown in Figure 2. We have implemented electrode vibration, precise current control, complete parameter monitoring, real-time floating point computation, and high-speed video of the arc.

Unique to this experiment is the electrode feed system, a detail of which is shown in Figure 3. This mechanism is designed to vibrate the electrode at frequencies up to 500 Hz with accelerations of 50 G. This capability will allow vibration and control experiments to be performed well into the range of spray metal transfer. Also unique to this experiment is the use of a digital signal processor for high-bandwidth control. Algorithms execute on the processor under the SPOX real-time operating system and are written entirely in C using floating-point arithmetic.

With this system, unprecedented flexible control of the welding arc is achieved. Experimental results using this new system will appear in forthcoming papers.

## 5 Acknowledgements

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References


