Process Behavior and Stability in Short Circuit Gas Metal Arc Welding

The stability of the short circuit gas metal arc welding process is directly related to weld pool oscillations

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ABSTRACT. In this paper, the results of an investigation dealing with short circuit gas metal arc welding with the emphasis on process stability are presented. Welding runs were made under different conditions and, during each run, the differprocess parameters continuously monitored. It was found that maximum process stability is reached under specific welding conditions. Outside this maximum, either irregular material transfer takes place with a tendency for open arc droplet transfer or stubbing of the welding wire in the weld pool starts to occur, accompanied by highly irregular melt-off behavior.

The results show that process stability is directly related to weld pool oscillation. More specifically, it appears that process stability is maximum when the short circuit frequency equals the oscillation frequency of the weld pool. Under these conditions, the weld pool touches the droplet at the end of the electrode at every oscillation, which results in regular droplet transfer and high stability of the overall welding process.

Introduction

In spite of the fact that over the years a considerable amount of information has been obtained about the short circuit gas metal arc welding (GMAW-S) process, a number of aspects of the process is still not well understood.

Short circuit gas metal arc welding is characterized by regular contact between the electrode and the weld pool. Droplet growth occurs in the arcing period, whereas, during the contact period, metal transfer from the electrode to the workpiece takes place. The cyclic be-

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havior of the process can be described in terms of the short circuit time, the arc time or the short circuit frequency.

As the arc does not burn during the short circuit period, the overall heat input is low compared to open arc welding. Therefore, GMAW-S always results in a small, fast-freezing weld pool, and, therefore, the process is especially suited for joining thin sections, for out-of-position welding and for bridging root openings.

Compared to open arc welding, GMAW-S is a very dynamic process. A major problem occurring during GMAW-S is unstable process behavior accompanied by the formation of spatter (Refs. 1–5). Three causes of instability can be distinguished:

- Instantaneous short circuits: the electrode touches the weld pool for a very short period of time, but no metal transport takes place (Refs. 6–12),
 - Failure of arc reignition (Ref. 13),
- Wire feed rate variations (Refs. 14–17).

This paper describes the results of an investigation aimed at obtaining insight in the fundamental aspects of the short circuit gas metal arc welding process with emphasis on process stability.

KEY WORDS

Short Circuit Gas Metal
Arc Welding (GMAW-S)
Process Behavior
Process Stability
Short Circuit Frequency
Weld Pool Oscillations
Weld Pool Oscillation
Frequency
Optimal Welding Conditions

Experimental Procedure

GMAW experiments were carried out under short circuiting welding conditions making use of a transistorized power source (The Welding Institute Transistor 500). Bead-on-plate welds were deposited on plates of mild steel (Fe360) having dimensions 250 x 200 x 10 mm, using 1.0-mm-thick mild steel (SG2) welding wire. The welding conditions used are listed in Table 1. During welding, current and voltage were measured with a sample frequency of 10 kHz by means of a transient recorder (Nicolet 410). The measured data were analyzed with the help of a computer program yielding values of arc time (t_a) and short circuit time (t_c). From these values, the short circuit frequency (f_s) was calculated using $f_s = 1/(t_a + t_c)$. The standard deviation of the short circuit frequency was taken as a measure of process stability.

To obtain additional information on the metal transport and the behavior of the weld pool, high-speed films (4000 frames/s) were made with a Hicam K20S4W camera.

After the welds were completed, cross sections were made and the weld geometry was determined with the help of optical microscopy (Leica CBA 8000).

Results and Discussion

Process Behavior

The most characteristic feature of the short circuit gas metal arc welding process is the short circuit frequency, f_s . Using the procedure outlined in the previous section, the value of f_s was measured under different welding conditions. It appears that f_s depends strongly on the welding parameters, in particular on the wire feed rate and the arc voltage.

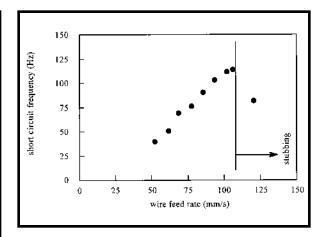


Fig. 1 — Short circuit frequency as function of the wire feed rate for a nominal voltage of 16 V.

Table 1 — Welding Conditions

voltage	14-22 V
current	50-250 A
wire feed rate	25-300 mm/s
travel speed	5 mm/s
slope power source	–1 V/100 A
electrode wire	1.0 mm SG2,
	mild steel
shielding gas	85% Ar-15%CO ₂
gas flow rate	16 L/min
contact tube-to-	20 mm
work distance	

Figure 1 depicts the influence of the wire feed rate on the short circuit frequency for a nominal voltage of 16 V. The figure shows that the short circuit frequency increases with increasing wire feed rate. After reaching a maximum, stubbing starts to occur and the welding process becomes irregular.

The frequency distribution of the short circuit frequency for different values of the wire feed rate is depicted in Fig. 2. For low wire feed rates, a low-frequency peak is observed. With increasing wire feed rate, this peak decreases in amplitude and broadens, while at the same time a second peak appears at higher frequency. This second peak gradually becomes more important and, finally, dominates the first one. When the wire feed rate is further increased, stubbing starts to occur and the process becomes highly irregular. This is accompanied by a wide distribution of the short circuit frequency. The presence of peaks in the frequency distributions is attributed to the occurrence of weld pool oscillations (see below).

The process stability of GMAW-S can be quantified in a number of ways (Refs.

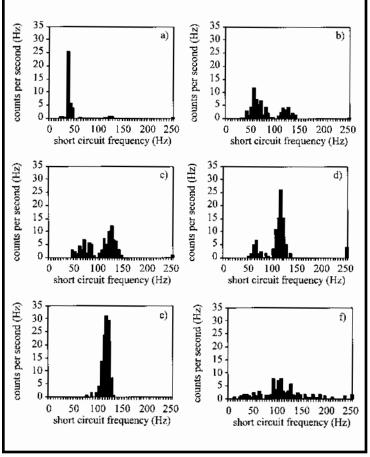


Fig. 2 — Distribution of the short circuit frequency for different wire feed rates at a constant voltage setting (U = 16 V). A — 52 mm/s; B — 68 mm/s; C — 85 mm/s; D — 93 mm/s; E — 106 mm/s; and F — 120 mm/s.

18–23). An appropriate measure of the process stability is the standard deviation of the short circuit frequency. As an illustration, the standard deviation of the short circuit frequency as function of the wire feed rate at constant voltage setting (U = 16 V) is given in Fig. 3. It can be seen that the standard deviation of the short circuit frequency reaches a minimum at a value of the wire feed rate for which the high frequency peak is most pronounced. At this minimum, the process stability is maximum.

Optimal Welding Conditions

Conditions of maximum process stability were also determined for other values of the voltage. This results in a locus of maximum process stability in the voltage-wire feed rate diagram, as illustrated in Fig. 4. The process conditions for which maximum process stability occurs are referred to as optimal welding conditions. It should be kept in mind that the position of the locus depends on the

other welding conditions, such as contact tube-to-workpiece distance, travel speed, shielding gas composition and the slope and the choke of the power source.

Weld Pool Oscillations

An important aspect of the process stability is its relation with the oscillation of the weld pool. Weld pool oscillations have been studied extensively in the case of autogenous gas tungsten arc (GTA) welding (Refs. 26-28). It appears that in the case of GTA welding, the weld pool can be brought into oscillation by applying short arc current pulses. The center of the weld pool is indented by the increase in arc pressure during the current pulse, which is counteracted by the surface tension of the liquid metal and by gravitational forces. Immediately after the current pulse, the weld pool surface tends to return to its original position, causing oscillation of the weld pool. The weld pool oscillation gives rise to voltage (arc length) variations. The oscillation fre-

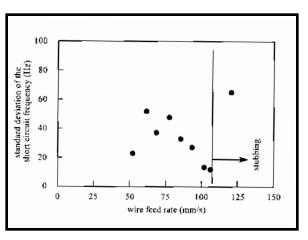


Fig. 3 — Standard deviation of the short circuit frequency as function of the wire feed rate (U = 16 V).

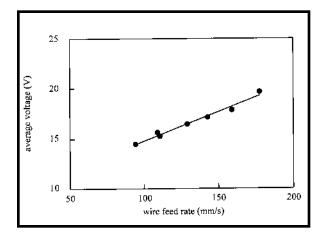


Fig. 4 — Locus of maximum process stability in the voltage-wire feed rate diagram.

quency can be extracted from these voltage variations using a Fast Fourier Transform algorithm.

Several modes of oscillation can be distinguished. The dominant oscillation mode in the case of partial penetration is schematically shown in Fig. 5.

The oscillation frequency in the case of a partially penetrated weld pool can be expressed by the following equation, assuming a flat weld pool surface (Ref. 27):

$$f_o = 5.84 \left(\frac{\gamma}{\rho_I}\right)^{1/2} D^{-3/2}$$
 (1)

in which fo represents the oscillation frequency of the weld pool, γ the surface tension of the liquid metal, ρ_l the density of the liquid metal and D the weld pool width.

Under certain conditions weld pool oscillations will also occur during GMAW-S (Refs. 5, 7, 19, 29-34). In the case of GMAW-S, oscillation of the weld pool is triggered by the sudden increase in arc pressure immediately following arc reignition and by the momentum of the liquid metal transferred to the weld pool at the moment of rupture of the liquid metal bridge.

It should be mentioned that measuring weld pool oscillations by monitoring the variation in arc voltage is practically impossible in GMAW due to a number of disturbing effects, in particular the impact of droplets entering the weld pool.

A Criterion for Maximum Process Stability

Considering the course of events taking place during the short circuit gas metal arc welding process in combination with the oscillation of the weld pool, it must be expected that maximum process stability occurs at a specific value of the wire feed rate for which the short circuit frequency f_s equals the oscillation frequency fo of the weld pool, i.e., when $f_s = f_o$. When this is the case, the oscillating surface of the weld pool touches the metal droplet formed at the end of the welding wire once every

oscillation cycle. It is evident that under these conditions the stability of the process is maximum, the short circuit cycle being dictated by the weld pool oscillation.

At a lower wire feed rate the short circuit frequency is smaller than the oscillation frequency of the weld pool ($f_s < f_o$). Under these conditions the oscillating weld pool surface will miss the growing droplet at the end of the electrode one or more times before contact is established (low-frequency peak in the short circuit frequency distribution). This will result in a more random course of events (less constant values of arc time, short circuit frequency and hence transferred droplet mass), i.e., in lower process stability.

At higher wire feed rate the arc length becomes so small that stubbing of the welding wire in the weld pool becomes a real possibility, distorting the weld pool oscillation and resulting in irregularities and instabilities of the welding process.

The sequence of events taking place during the GMAW-S process, as described previously, were found to be consistent with the results of high-speed filming.

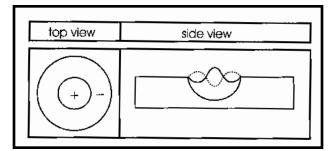


Fig. 5 — The dominant mode of oscillation in a partially penetrated weld pool.

Verification of the Criterion

To test the validity of the hypothesis that maximum process stability occurs when the short circuit frequency and the oscillation frequency of the weld pool are synchronized, welding experiments were carried out in which partially penetrated weld pools of different sizes were produced. For each situation, the short circuit frequency was measured and the oscillation frequency of the weld pool was calculated from the width of the weld pool with the help of Equation 1. The values of γ and ρ_{l} used for the calculations of the oscillation frequency were taken to be 0.9 N/m and 7.0 x 10^3 (kg/m³), respectively (Ref. 35).

In the first series of experiments the voltage was kept constant while the wire feed rate was increased. Figure 6 shows the short circuit frequency and the calculated oscillation frequency as function of the wire feed rate for a voltage setting of 16 V. The figure shows that for low wire feed rates, the calculated oscillation frequency is much larger than the measured short circuit frequency due to the fact that under these conditions the oscillating weld pool surface misses the ap-

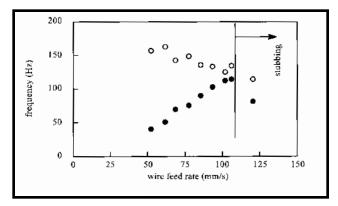


Fig. 6 — The measured short circuit frequency (\bullet) and the calculated oscillation frequency of the weld pool (\circ) as function of the wire feed rate (U = 16 V).

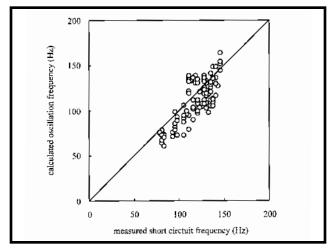


Fig. 7 — The calculated oscillation frequency vs. the measured short circuit frequency for conditions of maximum process stability.

proaching droplet one or more times before contact is established. With increasing wire feed rate the difference between both frequencies decreases until, under optimal conditions, they become equal. When the wire feed rate is further increased, no stationary situation is reached anymore and stubbing occurs (melting rate < wire feed rate). This results in random weld pool movements and a short circuit frequency that is not physically related to the calculated oscillation frequency.

To further evaluate the criterion for maximum process stability as formulated above, a second series of experiments was carried out under conditions of maximum process stability, *i.e.*, under conditions for which the average short circuit frequency is maximum. Weld pool dimensions were changed by varying the current and the voltage simultaneously along the locus of maximum process stability or by changing the travel speed. For each situation the short circuit frequency was measured, while the oscillation frequency was calculated from the width of the weld pool.

In Fig. 7 the calculated oscillation frequency of the weld pool is plotted vs. the measured short circuit frequency for conditions of maximum process stability.

The figure shows that relatively good agreement exists between the measured short circuit frequency and the calculated oscillation frequency of the weld pool over a wide range of welding conditions. The observed difference between f_s and f_o can be understood by taking the influence of the weld pool temperature on the surface tension into account (Ref. 24).

Conclusions

On the basis of the results presented, the following conclusions can be drawn:

- 1) Short circuit gas metal arc welding is possible in a relatively small voltagewire feed rate window. Within this window, a locus of maximum process stability can be assigned. The position of this locus depends on the welding conditions.
- 2) Maximum process stability occurs when the standard deviation of the short circuit frequency is minimum. Under these conditions, a single peak in the short circuit frequency spectrum is observed.
- 3) In the case of GMAW-S, weld pool oscillations are triggered by the reignition of the arc after the rupture of the liquid bridge and by the momentum of liquid metal transferred. These oscillations play a decisive role as regards the stability of the process.
- 4) In the case of partially penetrated weld pools, maximum process stability occurs when the short circuit frequency and the oscillation frequency of the weld pool are equal.

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