The Effect of Out-of-Phase Pulsing on Metal Transfer in Twin-Wire GMA Welding at High Current Level

An investigation into deposit transfer and arc characteristics revealed conventional nonpulsing machines are capable of providing quality weldments

BY A. SCOTTI, C. O. MORAIS, AND L. O. VILARINHO

ABSTRACT. Out-of-phase current pulsing has been commercially claimed to be indispensable for minimizing magnetic interaction between arcs in the twin-wire gas metal arc welding (GMAW) process and reaching stable operations. This paper presents an investigation about the use of out-of-phase current pulse technology as applied to the twin-wire GMAW process. High-speed digital images were recorded with the objective of evaluating the metal transfer and the behavior of the voltaic arcs under the influence of out-of-phase current pulsing at different current levels. Conditions of in-phase and out-of-phase pulsing were evaluated and compared to no pulsed settings. A relationship between pulsing and pool oscillation was investigated, but it seems the natural frequency of the pool is the governing phenomena. Weldments were deposited on overlap joints in the flat position in order to study the resulting geometric characteristics. The results showed no evidence that out-of-phase current pulses can impose any reduction of arc and droplet attractions at a high current level, which is an attractive advantage of the twin-wire GMAW process. Concerning bead profiles, no remarkable influences were found. In summary, the results indicate that the need for out-of-phase pulsing machines is overstated and that conventional machines are totally capable of conducting quality weldments.

Introduction

The twin-wire gas metal arc welding (GMAW) process is becoming widely popular due to its high deposition rate. This technology was used initially in the welding of thick plates (Ref. 1). However, its great application has been mainly in the welding of thin plates with high welding speed, which may reach more than 2 m/min (Refs. 2–4). The more popular version of the twin-wire GMAW process uses two electrically isolated electrodes, which are melted together in a single molten pool.

Michie et al. (Ref. 4) cite that the use of twin wires to increase the productivity of GMAW was attempted as early as 1955. However, limitations in the power source technology prevented the process from reaching its full potential. In recent years, modern electronically controlled inverter power source technology has been applied to twin-wire GMAW. The result has been improved stability and performance, thus making the process commercially feasible.

The use of pulsed current has been the tonic of the modern systems for twin-wire GMA welding: two power supplies linked to each other (master and slave) and commanded by the master power supply in such a way that an out-of-phase current pulsing is established. In this case, while the current from the master power source is at the pulse period, the one from the slave power source is at the base period, reducing the magnetic attraction between the arcs (and vice-versa). Michie et al. (Ref. 4) quoted other authors to suggest that greater stability is obtained when the pulses are staggered, because the magnetic field of the low background current of one arc is not strong enough to interfere with the other arc.

However, the objective of getting high productivity conflicts with the philosophy of the use of the pulsed current in GMAW. Pulsed current was developed to control the transfer in such a way to imitate the spray transfer yet at low current (below transition current). Increasing productivity by raising current would be simpler by using spray transfer or even buried short-circuiting. However, in several papers in the literature (Refs. 3–6), the pulsed current, with mean levels above the transition current, has been cited as the most important mean for reaching the high melting rates with twin-wire GMAW, mainly in industrial applications.

Despite the real sense of the pulsed current application, it has been claimed, mainly by the makers of equipment, that the use of pulsed current improves the performance of the twin-wire GMAW process with isolated potentials, regardless of the greater complexity of the equipment (high cost) and difficulties for parameter settings, when compared to no-pulse welding.

One could think that to reach a high mean current as industrially applied, the background current should assume high values too, high enough to cause strong electromagnetic interactions with the other arc current at the pulse period. In addition, the background current must be of very short duration. Thus, the one drop per pulse condition is difficult to sustain (actually, the so-called pulsed twin-wire GMAW should be named high-frequency pulsing twin-wire GMAW).

Another aspect that should be considered is that, in many practical cases, to guarantee sound weld beads with the twin wires at high welding travel speed, one should weld with short arcs. In those circumstances, the question raised is would it not be easier and cheaper to work with steady DC current, since the arcs are short anyway and the electromagnetic effect is minimized?

These questions have not yet been well discussed in the literature, although the technology of out-of-phase current pulsing is already recommended for the twin-wire systems available in the market, and it is being used in applications without question. In a recent work (Ref. 7), the use

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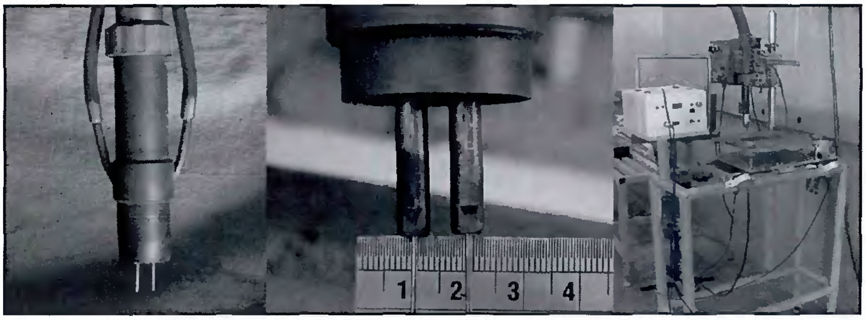

Fig. 1 — Illustration of the welding head and experimental rig.

of out-of-phase current pulsing technology was studied for twin-wire GMAW application on claddings. The results showed that, with the electrodes positioned side by side and mean currents below the transition current, the out-of-phase current pulsing reduced the deviations of the arcs and had an influence on the penetration profile of the weld beads, but they are not necessarily beneficial for the bead formation. Having as evaluation criteria the surface finish of the deposits and the amount of spatter and porosity present, these authors did not find significant differences between the deposits carried out with or without out-of-phase technology in current pulsing.

However, no other publication with this focus was found. Considering that Motta's work was developed with the electrode side by side and with average current below the transition current, it seems there is a lacuna in the literature about the real effect of the out-of-phase technology. Therefore, this work studied what effect out-of-phase current pulsing had on arc configuration, metallic transfer, and geometric profile of the deposits. It also discusses the benefits of that technology for welding applications.

Experimental Procedure

All the weldments in this study were carried out using two microprocessor-based power sources. An electronic circuit to link them was implemented in such a way that the beginning of the current pulsation of one of the sources (slave power source) was commanded by the other one (master power source). The lag time between the current pulses (lt — the time that the slave power source delays the beginning of its pulsation in relation to the beginning of the master power source pulses) could be freely set by the user. If not connected to each other, the power sources could work alone in a conventional way (constant voltage mode).

A welding head (isolated potential, manufactured by TBI), as illustrated in Fig. 1, was placed perpendicularly to plain carbon steel plates (12.7 × 50.8 × 300 mm) in such a way that the two electrodes were positioned one after the other in relation to the welding direction. The advantages of using this welding head in this study, besides the good performance for this process, are the wires come out parallel and they are a reasonable distance from each other (10 mm away). A nonparallelism of the wires might enhance the possible attraction of the droplets due to the directions of the impulses during the detachment. The farther away the wires, the less intense would be the magnetic interaction. Thus, if the phenomenon happens under this condition, it would be stronger in a welding head in which the wires are closer to parallel than when not.

The welds were bead-on-plate deposited at a travel speed of 11.67 mm/s. Shadowgraphy technique and CCD high-speed filming was employed to visualize the arcs and metal transfers during actual welding. When the objective was to see metal transfer, a more intense filter (optical density = 3) was placed between the arc and the camera. No filter was used to emphasize the arc. The signals of arc voltage and welding current of both arcs were acquired by means of a data-log system at a reading frequency of 4 kHz for each signal and with resolution of 12 bit. The filming, at a rate of 2000 frames per second, was synchronized with the electrical signals (Ref. 8).

Table 1 — Parameter Settings Used in the Experiments and Monitored Output Signals

Run	Wires	WFS (m/min)	Pulsation Settings				lt (ms)	Uref (V)	Monitored	
			Ip (A)	tp (ms)	Ib (A)	tb (ms)			Im (A)	Um (V)
1	leader	8	430	4	50	5	—	—	203.9	34.4
	trailing	8	430	4	50	5	0	—	212.1	—
2	leader	8	430	4	50	5	—	—	211.5	29.8
	trailing	8	430	4	50	5	4.5	—	212.0	—
3	leader	14	430	4	340	5	—	—	371.5	37.8
	trailing	8	430	4	50	5	0	—	212.3	—
4	leader	14	430	4	340	5	—	—	369.8	38.3
	trailing	8	430	4	50	5	4.5	—	207.2	—
5	leader	14	430	4	340	5	—	—	368.9	38.6
	trailing	14	430	4	340	5	0	—	374.6	—
6	leader	14	430	4	340	5	—	—	371.3	38.3
	trailing	14	430	4	340	5	4.5	—	375.6	—
7	leader	8	—	—	—	—	—	32	246.6	31.7
	trailing	8	—	—	—	—	—	32	265.1	—
8	leader	14	—	—	—	—	—	39	374.6	38.5
	trailing	8	—	—	—	—	—	32	258.4	—
9	leader	14	—	—	—	—	—	39	335.7	34.8
	trailing	14	—	—	—	—	—	39	345.0	—

Note: WFS — Wire feed speed; Ip — pulse current; tp — pulse time; Ib — background current; tb — background time; lt — lag time; Uref = voltage setting when the power source was used in a non pulsing mode; Im = mean current; Um = mean voltage (not measured for the trailing arc, because the data-acquisition channel was used for synchronization).

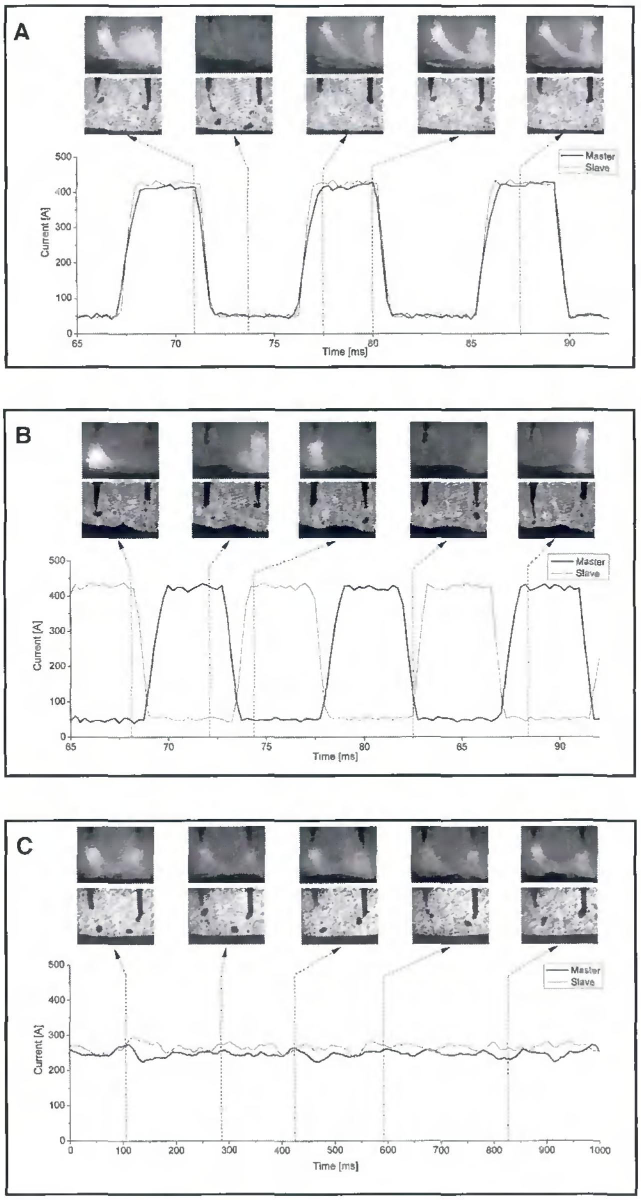

Fig. 2 — Sequential pictures of arcs and metal transfer and respective current oscillograms from Runs 1, 2, and 7. The leader wire is on the right. A — In-phase configuration, WFS_{leader} = $WFS_{trailing}$ = 8 m/min (Run 1); B — out-of-phase configuration, WFS_{leader} = $WFS_{trailing}$ = 8 m/min (Run 2); C — No pulse configuration, WFS_{leader} = $WFS_{trailing}$ = 8 m/min (Run 7).

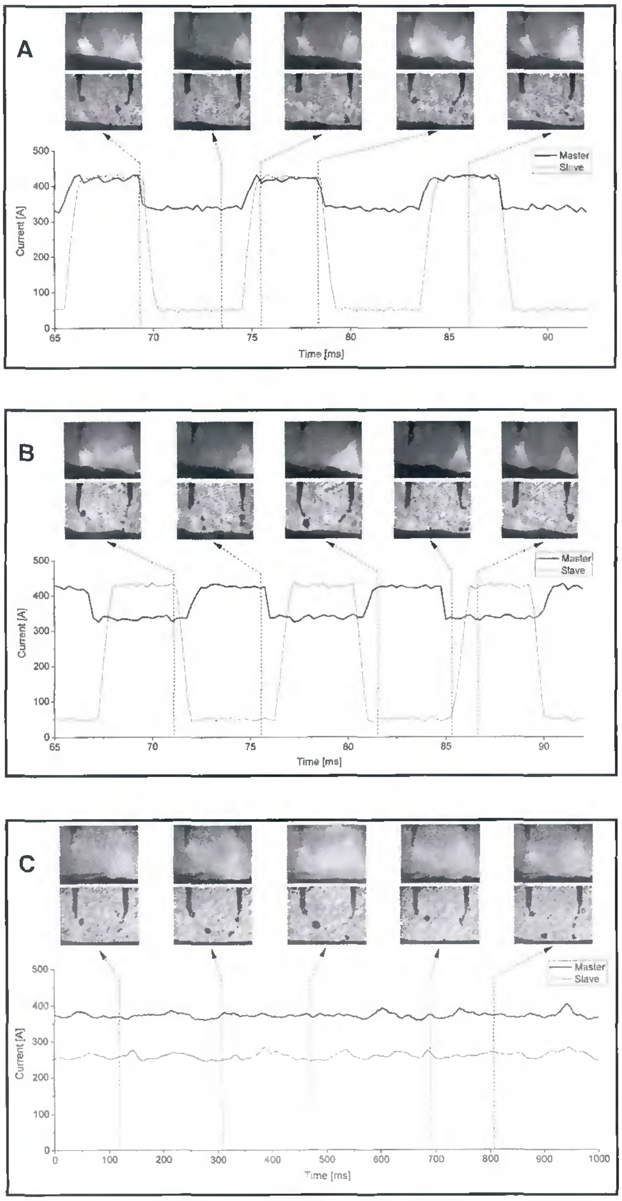

Fig. 3 — Sequential pictures of arcs and metal transfer and respective current oscillograms from Runs 3, 4, and 8. The leader wire is on the right. A — In-phase configuration, WFS_{leader} = 14 and $WFS_{trailing}$ = 8m/min (Run 3); B — out-of-phase configuration, WFS_{leader} = 14 and $WFS_{trailing}$ = 8 m/min (Run 4); C — No pulse configuration, WFS_{leader} = 14 and $WFS_{trailing}$ = 8 m/min (Run 8).

The electrodes used were 1.2-mm-diameter AWS ER70S-6, and the contact-tip distance to the surface of the plates was 22 mm. The shielding gas was a mixture of 92% Ar and 8% CO_2 with a flow of 40 L/min. The pulsing parameters were chosen to provide one droplet per pulse by using a luminescence sensing system dedicated to recognize droplet detachments in pulsed GMAW (Ref. 9).

Three combinations of wire feed speeds for each wire (8/8 m/min, 14/8 m/min, and 14/14 m/min) were evaluated with three different power source configurations: 1) in-phase pulses, 2) out-of-phase pulses, and 3) no pulse. Similar arc lengths for all welds were established as a criterion. As a consequence, the mean currents for each power source configuration were not exactly the same even at the same wire feed speed combination. However, the wire feed speeds were chosen to give three levels of mean current (one below the transition current and the others above it). Table 1 presents the parameters used in the nine experiments and the mean values of current and voltage resulting from the signal screening during 1 s of welding.

Bead-on-plate welds do not represent real situations. Thus, to evaluate the influence of the out-of-phase current pulses on bead geometry, similar parameters from experiments 1 to 4 were used to make welds on overlap joints composed of two 3-mm-thick plain carbon steel sheets (400 × 35 mm). The main parameter differences were the travel speed and the position of the welding head was 10 deg forward and pointing to the joint corner at 45 deg. As the equilibrium to get the same arc length in a much faster weld is dependent on other parameters (such as pool volume), some

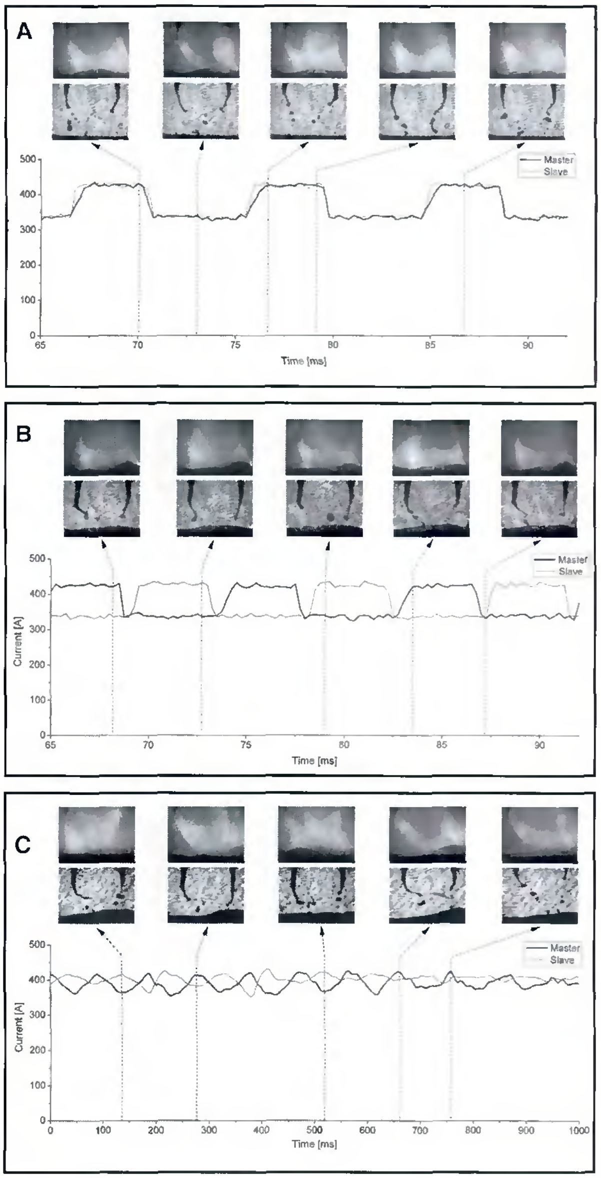

Fig. 4 — Sequential pictures of the arcs and the metal transferences and respective current oscillograms from Runs 5, 6 and 9. The leader wire is on the right. A — In-phase configuration, WFS_{leader} = WFS-trailing = 14 m/min (Run 5); B - Out-of-phase configuration, WFSleader = $WFS_{trailing}$ = 14 m/min (Run 6); C — No pulse configuration, WFS_{leader} = $WFS_{trailing}$ = 14 m/min (Run 9)

changes in pulsing parameters were imposed to get stable arcs. The travel speed was higher to make the parameters more compatible to the joint geometry. It was adjusted accordingly to both wire feed speeds to keep the same weld volume in all runs. In this way, the comparison became between two different power source configurations (no pulse vs. out-of-phase pulses) at two combinations of wire feed speed at each wire (8/8 m/min and 14/8 m/min). Table 2 presents the parameters used and the mean values of current and voltage resulting from the signal screening.

Results and Discussions

Behavior Characterization

Figure 2 shows a sequence of frames representing the arc profile and metal transfer behavior during the welds with the lowest mean current (Runs 1, 2, and 7). The oscillograms under the pictures show the respective output current and voltage signals. The one drop per pulse condition was confirmed in both pulsed configurations. As seen in the pictures for the out-of-phase configuration, while a droplet is detaching from one wire during the brighter pulsing period, the other droplet is growing during the base period. For the no pulse condition, the transfer resembles spray mode. One can also see that there was a strong attraction of the arcs in both no pulse and in-phase configurations, but with the out-of-phase configuration, there is no arc attraction. The same behavior was observed for the droplets, which made their path along the arc core (less pressure).

In turn, Fig. 3 shows the sequence of frames for the intermediate mean current Runs 3, 4, and 8. One can see that the attraction of both arc and droplets got stronger either in no pulse or in in-phase configurations, and some attraction can be seen in the out-of-phase configuration. Finally, Fig. 4 shows the sequence of frames for the highest mean current, well above the transition current (Runs 5, 6, and 9). One can see that the attraction of both arc and droplets got even stronger at any case. No differences are noticed among the three configurations. The condition of one drop per pulse cannot be sustained anymore at this current level (even the base current is higher than the transition current for this wire). In any case, the transfer is spray like. This results suggest that at high current (in which the twin-wire process present better performance based on production), pulsation does not make any change in the arc performance.

It is important to point out that a magnetic attraction between parallel welding arcs is expected due to a magnetic field gradient resultant of the arc interactions, and the higher the carrying current in each arc, the stronger the attraction. Thus if the currents in both arcs are staggered in such a way that while one is high (pulse current) the other is low (base current), the interaction would be much smaller than in the case in which the currents are in-phase and at high levels (pulse current periods). On the other hand, even though the welding currents are staggered, but always assuming high values at both pulse and base periods, the expected interaction would be significant. The outcomes from the experiments confirm there theoretical expectances.

Table 2 — Parameter Settings Used in the Experiments and Monitored Output Signals

Run	Wires	WFS (m/min)	Pulsation Settings				lt (ms)	Uref (V)	TS (mm/s)	Monitored	
			Ip (A)	tp (ms)	Ib (A)	tb (ms)				Im (A)	Um (V)
10	leader	8	—	—	—	—	—	30.2	24.24	236.5	30.0
	trailing	8	—	—	—	—	—	30.2		264.7	30.1
11	leader	14	—	—	—	—	—	32.5	33.33	329.0	32.1
	trailing	8	—	—	—	—	—	30.5		259.4	30.4
12	leader	8	430	4	40	5	—	—	24.24	199.0	31.0
	trailing	8	430	4	50	5	4.5	—		214.7	32.3
13	leader	14	430	4	261	5	—	—	33.33	327.6	30.6
	trailing	8	430	4	79	5	4.5	—		232.9	31.7

Note: WFS — Wire feed speed; Ip — pulse current; tp — pulse time; Ib — background current; tb — background time; lt — lag time; Uref = voltage setting when the power source was used in a non pulsing mode; TS — travel speed; Im = mean current; Um = mean voltage.

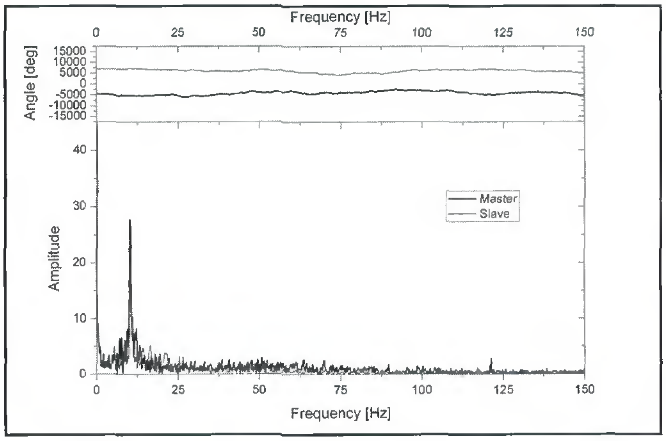

Fig. 5 — FFT of the current signals resulting from run 9 (no pulse configuration, WFS_{leader} = $WFS_{trailing}$ = 14 m/min).

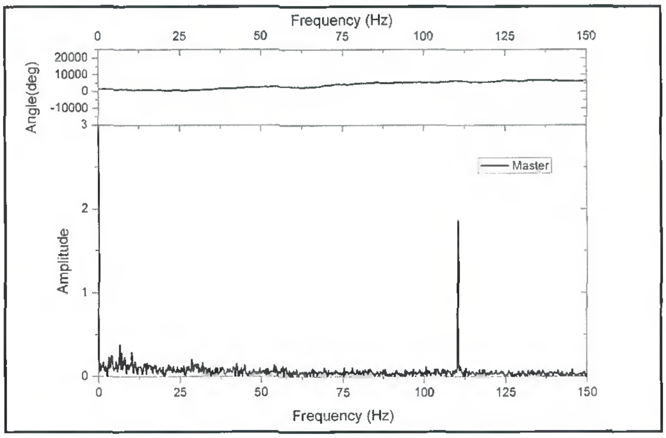

Fig. 6 — FFT of the voltage signals resulting from run 6 (out-of-phase pulses, WFS_{leader} = $WFS_{trailing}$ = 14 m/min).

Weld Pool Oscillation

During the analyses of the high-speed films from the no pulse configuration with the highest current (WFS = 14/14 m/min), it was verified that the weld pool oscillates back and forth in a coherent way, regardless of the metal transfer frequency. By applying fast-Fourier transform (FFT) algorithm to the current signals of both lead and trailing wires, as shown in Fig. 5, it was determined that the two current signals had a frequency component around 10 Hz (replications showed that there was a range from 9 to 11 Hz) and that the signals were 180 deg apart.

By observing the traces related to run 9, presented in Fig. 4, one can also observe the signs in reverse phase angles, i.e., while one current is at a higher level, the other one is at a lower level. It must be pointed out that the analysis was carried out on the current signals since the power sources in run 9 are in constant voltage mode. From an image sample presented in Fig. 4, it is possible to observe that the arc deviates according to the pool oscillation, i.e., when the pool went forward, the trailing arc deviated onward; when the pool went backward, the trailing arc deviation was lesser. The lead arc did not deviate as much as the trailing one. In other words, the trailing arc deviation is more significant.

In the other two configurations with no pulse (WFS at 8/8 and 14/8 m/min), the molten pool oscillation was not as easily seen

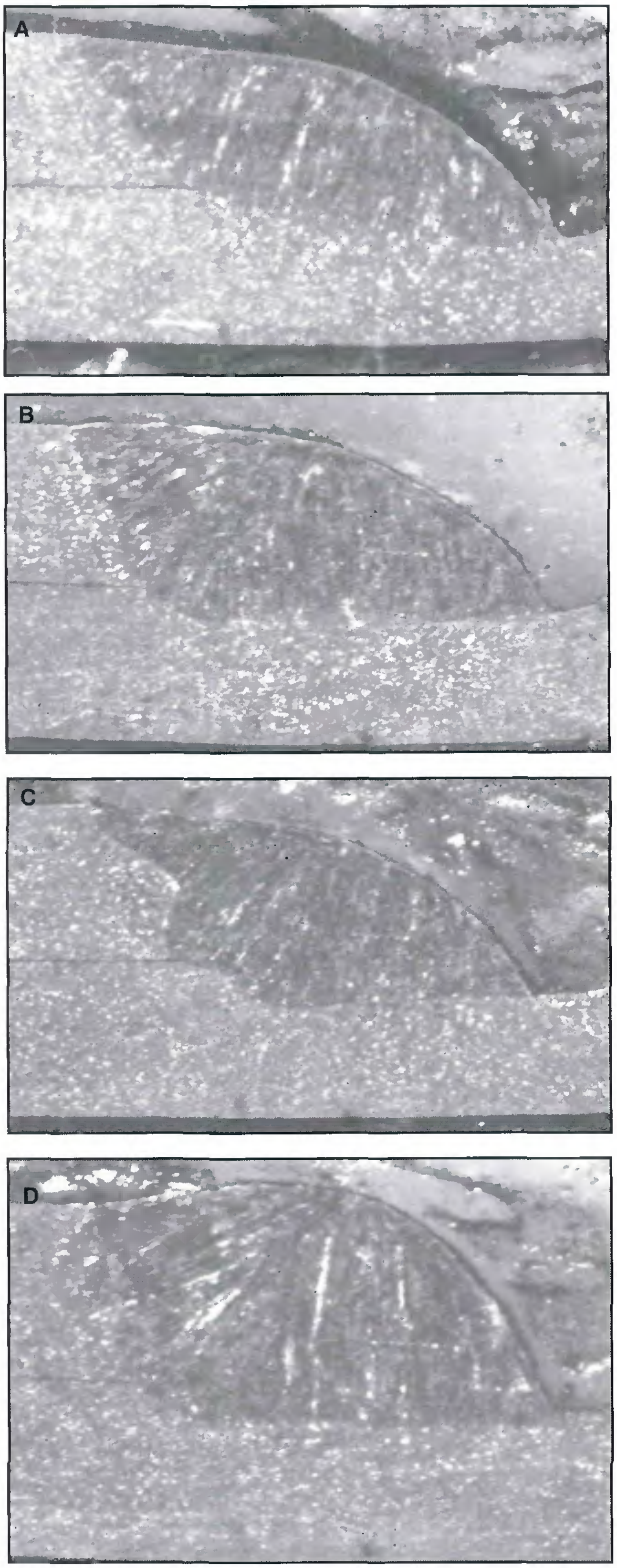

Fig. 7 — Cross sections of the beads (3-mm-thick plate overlap joints). A — Run 10, no-pulse configuration, WFS_{leader} = $WFS_{trailing}$ = 8 m/min; B — run 11, no-pulse configuration, WFS_{leader} = 14 /min and $WFS_{trailing}$ = 8 m/min; C — run 12, out-of-phase configuration, WFS_{leader} = $WFS_{trailing}$ = 8 m/min; D — run 13, out-of-phase configuration, WFS_{leader} = 14 /min and $WFS_{trailing}$ = 8 m/min.

as in the 14/14 case, but the FFT of the current signal presented a frequency component in the range of 9 to 11 Hz, yet not as well defined as in Fig. 5. This can be explained by the fact that the arc pressure and oscillation in the 14/14 case were higher than in the other two cases.

When the power source was in the constant current mode, no molten pool oscillation was seen in the high-speed filming. Fast-Fourier transform was performed on the voltage signals, as exemplified in Fig. 6. In this figure, the pulse frequency of 110 Hz (the inverse of the pulse period of 9 ms) is easily identified. There is also a small frequency band around 10 Hz, though not as distinguishable, presented in Fig. 5. One could argue that a "push-push" effect acting on the molten pool by the arc pressure due to out-of-phase pulses should be expected, and that this effect could lead to a much higher pool oscillation frequency than the one observed in the no-pulse configuration. However, in either in-phase or out-of-phase configurations, the FFT results were very similar. High-speed filming was able to show pool oscillation even at 110 Hz. Thus, one can conclude that the natural frequency of those pools (they have approximately the same volume) was around 10 Hz and that such "push-push" effect was not a governing factor.

Two more questions arise in this section though. The first one is about the origin of the oscillation. In the no-pulse configuration, for instance, was it instability in the weld pool that started the current oscillation or did the current oscillation start the weld pool oscillation? The second one is about thermal effects that might result from the current oscillation in the no-pulse configuration. This oscillation could lead to a breakage of the solidification front, which is favored for materials such as aluminum and stainless steel (one must remember that thermal pulsing applied to GTAW or GMAW lies in this frequency range). In fact, thermal effect is not expected, because the current signals have a phase angle of ~180 deg, i.e., when one current is in a higher level, the other one is in a lower level. Thus, the average of the two currents remains approximately constant.

However, these are speculations only, and since the molten pools presented here have a higher volume than those found in more practical situations, further work should be carried out to clarify the phenomenon of weld pool oscillation in twin-wire GMAW.

Bead Profiles

So far, unless there is an effect of the pulsing (either out-of-phase or in-phase condition) on the bead geometry, there would be no sense in using such sophisticated and more expensive technology. That was the reason of carrying out the welds accordingly (Table 2). Figure 7 exhibits the typical profiles of the beads of each run. There was no significant changes in the geometry.

Conclusions

At least for the conditions of this work (plain carbon steel wires positioned one behind the other, mean current below and above the transition current), the following can be concluded:

- The out-of-phase pulses really reduced the deviations of the arcs at current levels below the transition current, but this characteristic does not reproduce itself if it exceeds mean currents above that of transition.
- There is no difference whatsoever in bead shape whether or not out-of-phase pulsing is used.
- Conventional power sources can be used to replace sophisticated integrated pulsing power sources in twin-wire GMA welding operations, with reduced costs.

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