25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

WELDING POWER SOURCES WAVEFORMS ANALYSIS

Alberto Bonamigo Viviani
Rodrigo Rodrigues Nogueira
Universidade Federal de Santa Catarina
alberto.bonamigo@labsolda.ufsc.br
rodrigo.nogueira@posgrad.ufsc.br

Luciano Machado Cirino
Instituto Federal do Rio Grande do Sul – Campus Ibirubá
luciano.cirino@ibiruba.ifrs.edu.br

Régis Henrique Gonçalves e Silva
Universidade Federal de Santa Catarina
regis.silva@labsolda.ufsc.br

Gustavo Luis de Sousa
Universidade Federal de Santa Catarina
gustavo.sousa@posgrad.ufsc.br

Abstract. *The pulsed GMAW welding process is a controlled method of metal transfer, whose main objective is to produce a metallic transfer of the spray type in values of average current below the transition current, where a short-circuit or globular transference would be conventional. The most widespread current waveform is commonly called rectangular, although the actual current signal is not fully rectangular. The main objective of this work was to characterize the waveforms of four different welding machines, as well as the metallic transfer in each of these and to analyze the effects of the different waveforms on the geometric characteristics (penetration, width, height of the reinforcement, dilution and contact angle) of weld beads generated in welding with these machines. The results showed different wave characteristics for each manufacturer, implying different forms of metallic transfer, thus influencing parameters such as wettability, penetration, reinforcement width. Different forms of metal drop detachment were also identified, such as frequency and period of detachment.*

Keywords: *Welding, Pulsed GMAW, Metallic transfer, ODPP, Waveforms analysis.*

1. INTRODUCTION

The most diffused current waveform is illustrated in Figure 1, commonly called the rectangular, although the actual current signal is not fully rectangular, defined by four basic parameters: pulses time (*tp*), pulse current (*Ip*), base time (*tb*), base current (*Ib*) and average current (*Im*). Conventionally, it is understood that the pulse time (*tp*) starts at the instant when the current begins to increase and ends at the instant the current begins to decrease (ESSERS and VAN GOMPEL, 1984). Acting together, the pair *Ip* (pulse current) and *tp* must provide enough energy to ensure the formation and detachment of a metallic drop per pulse (*ODPP* condition, "one droplet per pulse") (VILARINHO and SCOTTI, 2001) established in the literature as a condition stable.

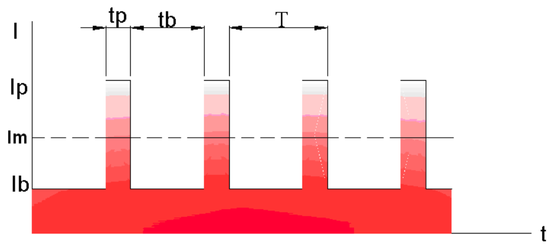

Figure 1. Rectangular waveforms type and main parameters.

The base current (*Ib*) is smaller than the pulse current and should be sufficient to maintain arc stability, while *tb* is the base time. It is commonly said that the base parameters (*Ib* and *tb*) have little effect on detachment, however they influence the final dimensions of the metallic droplet (SCOTTI and PONOMAREV, 2008).

Although the rectangular waveform is satisfactory to achieve these characteristics, manufacturers of welding sources have presented complex waveforms that introduce parameters different from those considered basic. For example, the waveform employed in the synergistic system of the Fronius CMT Advanced 4000R welding source, shown in Figure 2, differs from the rectangular one mainly by the current ramps. Was included in it a phase of detachment (*td*), with drop detachment current (*Id*) of value less than *Ip*, but greater than *Ib*. Ueguri et al. (1985) already recommended, that detachment of droplet did not occur during the pulse. In fact, Praveen et al. (2006) report that detachment during the base provides smoother metal transfer. Scotti and Ponomarev (2008) show some concern about the detachment at the base, as there is the possibility that the metallic drop can't be detached due to the electromagnetic force being smaller during the base and not enough to overcome the surface tension that acts to retain the drop. In this way, some waveforms, such as that of Fronius CMT (Fig. 2), incorporate an additional phase to ensure the detachment of droplet.

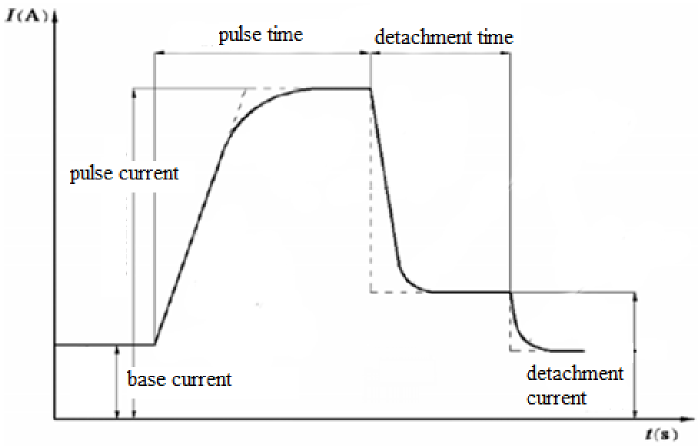

Figure 2. Advanced waveform for Pulsed GMAW. Adapted from Wu et al. (2006).

2. METODOLOGY AND RESULTS

2.1 Metodology

The welding power sources tested in this work were Fronius CMT Advanced 4000R, OTC DW300, Lincoln Power Wave 455M and IMC Digitec 600 (Fig. 3), which present synergistic systems that characterize each manufacturer's approach to Pulsed MIG/MAG. It should be noted that the Lincoln manufacturer's source features two synergic systems ("Pulse *Crisp*" and "Pulse *Soft*"), so that five different waveforms were tested. For ease of understanding, these systems will be referred to as Lincoln *Crisp* and Lincoln *Soft* throughout the text.

Figure 3. Welding power sources evaluated

For the evaluation of the geometric characteristics of the weld beads, three samples of bead on plate type were realized for each synergic system making a total of 15 samples. The dimensions of the carbon steel samples (SAE 1020) were 200 x 60 x 9 mm. Macrographic tests were carried out to determine the weld bead width, penetration, reinforcement height, dilution and contact angle in each sample. The contact tip distance and torch angle were respectively 12 mm and 90 ° relative to the workpiece surface. The wire used was the ER70S-6 with a diameter of 1.2 mm and a wire feed rate (Va) of 5 m/min. The protection gas was 95% Ar + 5% CO_2 with a flow rate of 12 l/min.

The length of the arc was monitored through filming conducted with a HEMA Model Selector ICAM-HD4 camera. In this way, it was possible to maintain the arc length between 4 and 5 mm, minimizing the influence of this variable on the characteristics of the weld bead. Subsequently the filming was analyzed and arc length was measured for each trial in a software for image processing.

As a movement system, the YASKAWA MOTOMAN anthropomorphic robot model YR-UP6-A02 was used. The welding torch was installed on a stand while the robot moved the workpiece, the most suitable situation for filming. The welding speed (Vs) was 45 cm/min.

For reading and characterization of the waveforms of each welding source, the Portable Acquisition System (SAP) was used. The voltage reading was performed between the welding torch connector and the grounding clamp. A Hall effect sensor to the current measurement was installed on the ground cable, as a wire speed measurement system (developed in LABSOLDA-UFSC) was installed directly on the wire tractor. The SAP also allows the calculation of the average current, average voltage and wire feed rate, pulse frequency and droplet diameter.

Finally, high-speed filming was performed to evaluate the metal transfer for each process pulsed with a Y4-S2 camera, from the manufacturer IDT. Table 1 summarizes the conditions observed in all the tests, in addition to the experimental apparatus employed.

Table 1. Equipment and welding conditions

Welding conditions: Samples: Carbon steel; 200 x 60 x 9 mm Wire: ER70S-6; Ø1,2 mm Feeding speed: 5 m/min Gas: 95%Ar + 5%CO_2 Flow rate: 12 l/min Welding speed: 45 cm/min Contact tip distance = 12 mm Arc lenght: 4-5 mm
Experimental equipment: HEMA Seelector ICAM-HD4 Model Camera Y4-S2 High speed camera YR-UP6-A02 model YASKAWA MOTOMAN robot Sistema de Aquisição Portátil (SAP)

2.2 Results

2.2.1 WAVEFORM AND METALLIC TRANSFERENCE CHARACTERIZATION

Waveform analysis of welding machines, Fig. 4, shows that, with the exception of IMC, welding manufacturers employ high pulse currents (from 451 to 556 A) and short pulse times (from 1.5 to 2.4 ms) as presented in Table 1. The conventional understanding of Pulsed MIG/MAG only suggests the use of pulse currents above the transition value (AMIN, 1983). However, Ueguri *et al*. (1985) recommend the use of pulse currents of at least 380 A, for welding conditions similar to those employed in this work. According to these authors, for a steel wire (ER70S-G, Ø 1.2 mm) at values below 380 A, the metallic drop tends to oscillate at the end of the electrode and no detachment occurs during the pulse or later, regardless of the time of pulse. As a result, the gout becomes larger and causes instability of the arc accompanied by occasional short circuits.

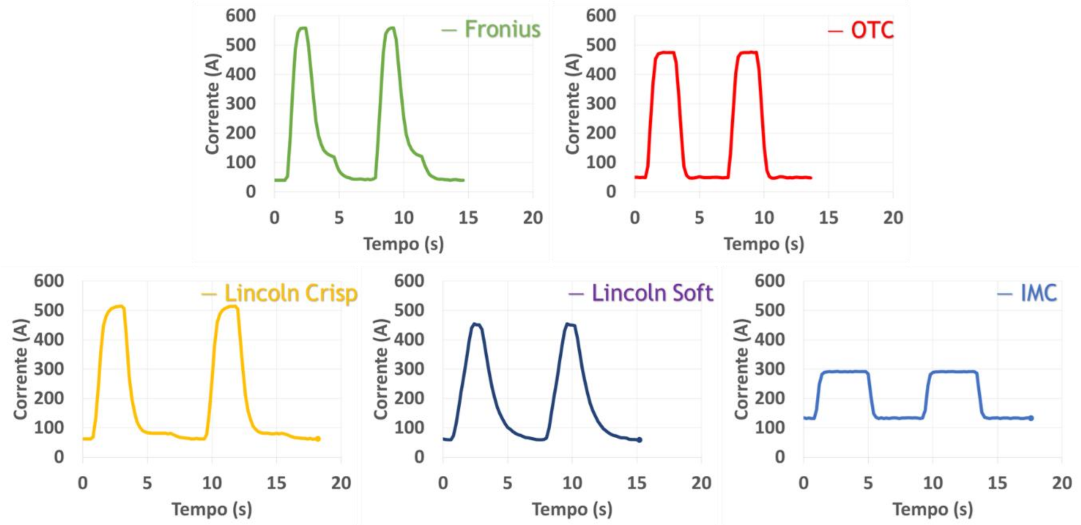

Figure 4. Waveforms of the weld machines analyzed.

Table 2. Values of the parameters for the waveforms of the evaluated weld machines.

	Fronius	OTC	Lincoln *Crisp*	Lincoln *Soft*	IMC
Frequency (Hz)	140,0	156,3	117,7	138,5	118,9
***Tp* (ms)**	1,5	2,2	2,4	2,2	4,1
***Td* (ms)**	2,1	-	3,6	-	-
***Tb* (ms)**	3,5	4,2	2,4	5,0	4,3
***Ip* (A)**	556	474	515	451	291
***Id* (A)**	125	-	80	-	-
***Ib* (A)**	38	49	62	59	133

Although the waveforms of the Fronius and Lincoln *Crisp* synergetic systems incorporate a drop detachment phase, characterized by t_d and I_d, only in the first system did drop detachment actually occur in the detachment phase as shown in the illustration of Figure 5 , which shows high-speed footage synchronized with the acquisition of voltage and current signals. In addition, the Fronius system obeyed the ODPP condition, a fact that did not occur in the Lincoln *Crisp* system, as shown in Figure 6.

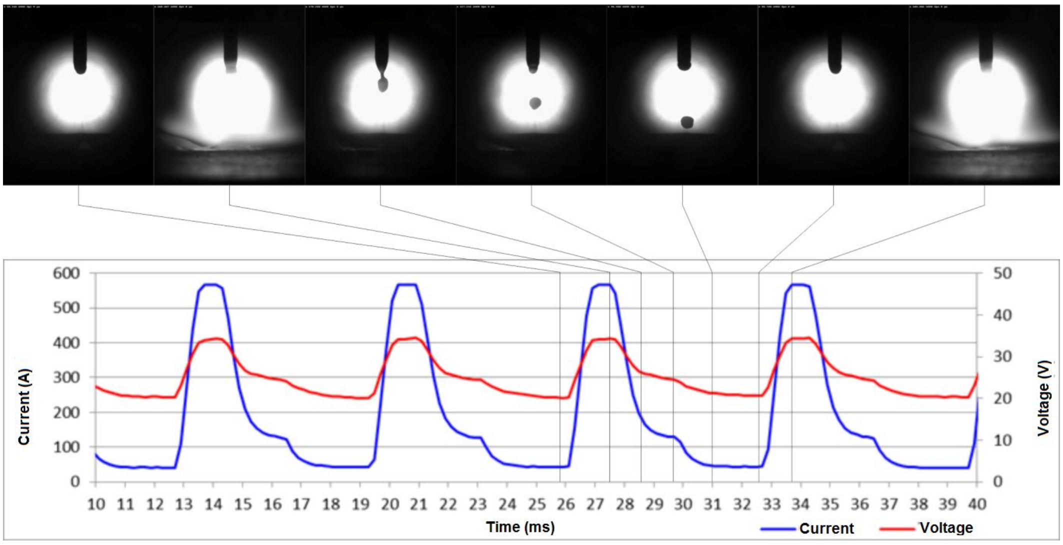

Figure 5. Metallic transfer in the Fronius synergetic system that produces the detachment of one drop per pulse. The detachment of the drop occurs at the beginning of the detachment phase.

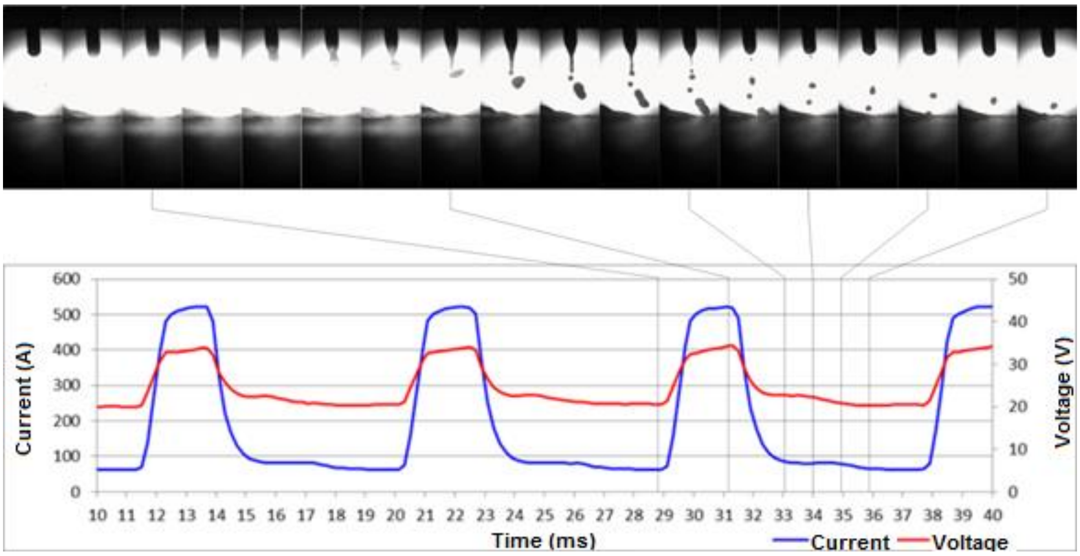

Figure 6. Metal transfer in the Lincoln *Crisp* synergistic system, which produces the detachment of a main drop and secondary drops per pulse. Detachment occurs at the end of the pulse phase.

Although the OTC synergist has a simple rectangular waveform, detachment also occurs at the base. However, filming shows a condition far removed from the ODPP. Figure 7 shows the detachment of a major droplet shortly after the end of the pulse, with posterior detachment of minor droplets of secondary diameter which generally complete its transfer into the pulse phase.

The so-called Lincoln *Soft* waveform uses a different strategy, and just after the pulse there is a tail-out ramp. This system also produces the detachment of one drop per pulse, as shown in Figure 8. Drop detachment occurs a few moments before the end of tail-out.

The synergistic IMC system has an I_p of 291 A and a t_p of 4.1 ms. This conservative approach may be due to the fact that it is the least recent manufacturing machine. For the IMC synergist, there is a tendency for droplet not to be detached with the action of only one pulse, but only after one second and in some cases a third or fourth pulse (Figure 9). In the frames ranging from 44 ms to 48 ms it suggests that the electromagnetic forces were not enough to overcome the action of surface tension. As a result, drop is not detached in either this pulse or the next pulse. Even with this abnormality, there were no major instabilities such as short circuits.

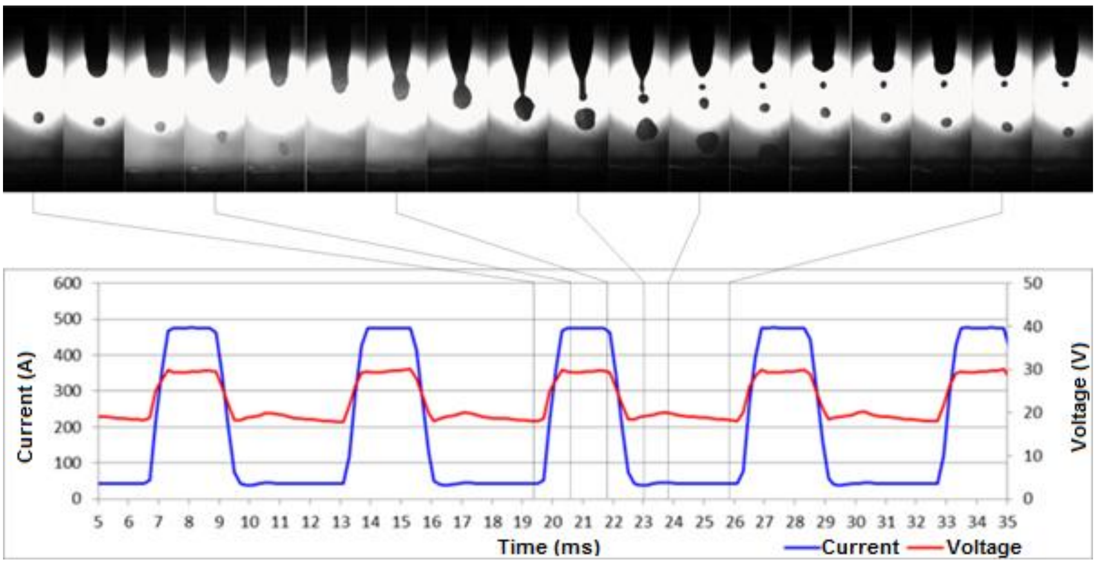

Figure 7. Metal transfer in the OTC synergistic system that produces detachment of a main droplet pulse followed by secondary droplets. The drop stands out at the beginning of the base phase.

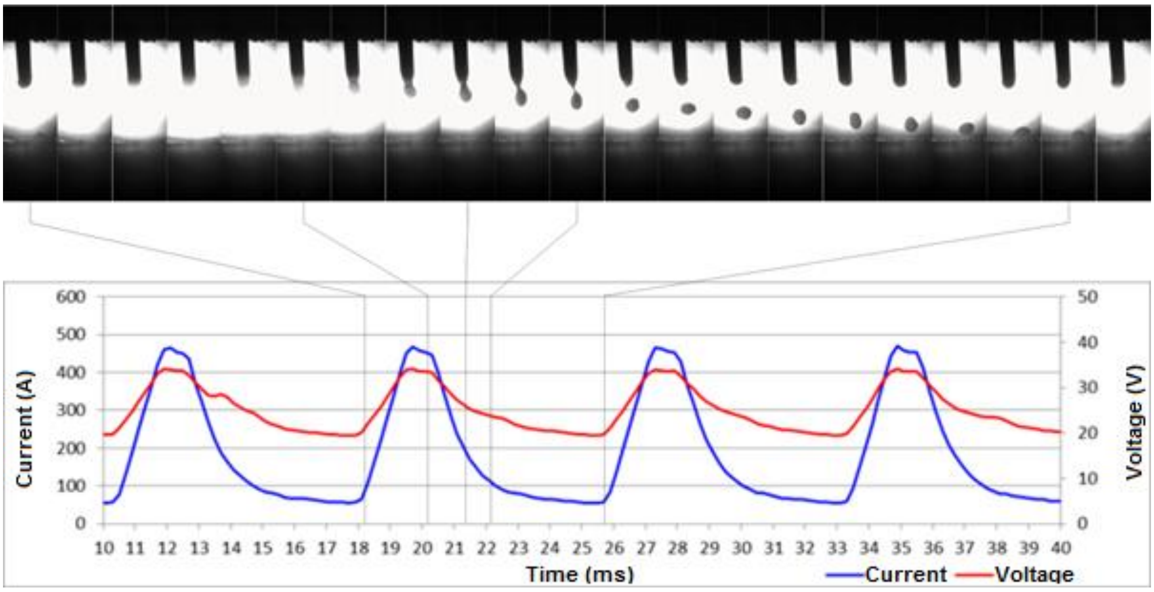

Figure 8. Metal transfer in the Lincoln *Soft* synergetic system that produces the detachment of one drop per pulse. Droplet completes his detachment in the final moments of tail-out.

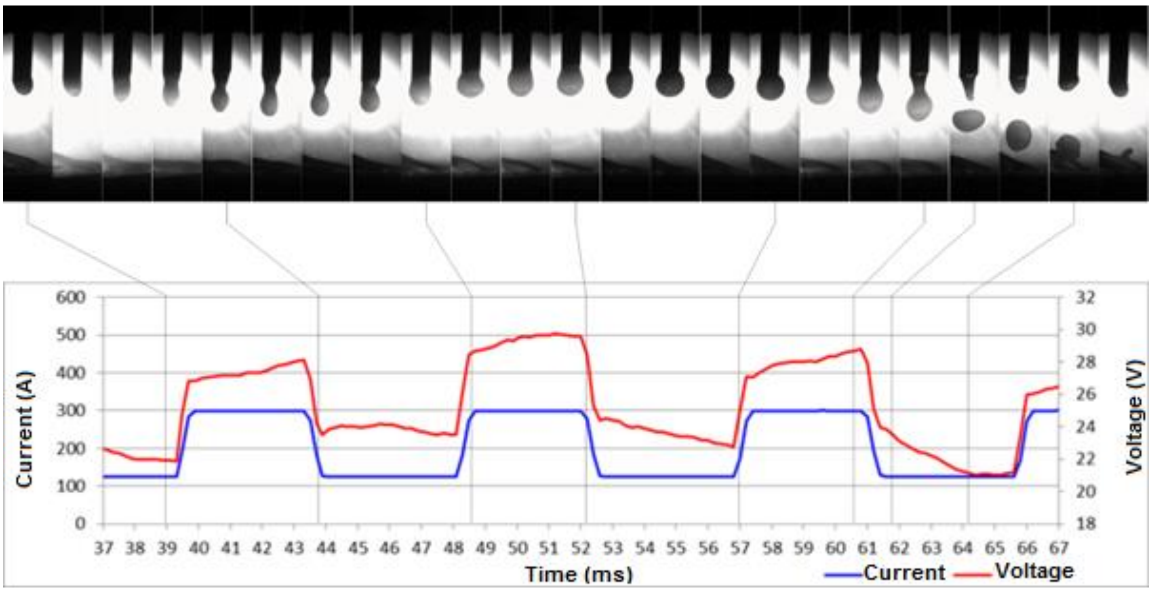

Figure 9. Metal transfer in the synergistic IMC system. The metallic droplet is only detached after the occurrence of three pulses.

2.2.2 GEOMETRIC CHARACTERISTICS

Table 3 shows the results for average voltage (*Um*), average current (*Im*), Power (*P*), and another parameters, calculated through the *SAP* (*Sistema de Aquisição Portátil*).

Films executed with the HEMA camera allowed a satisfactory control of the arc length that was maintained in values that varied between 4 and 5 mm (average during the tests) as shown in Figure 10, in order to minimize the effect of the arc length on the result of welding. The mean current was higher for the IMC weld machine (209 A), which also had the largest arc amplitude, remembering that all experiments were performed with the same *Va*. In contrast to IMC, a mean Fronius current was lower (*Im* = 184 A) as well as the measurement of the arc (4.1 mm).

The regulation of the arc length of the IMC acts on decreasing the *Va* of 0.1 m/min and vice versa. If on the one hand this strategy modifies *Va*, on the other hand it keeps the average current constant. This particularity became more difficult for an arc length within the desired range. A fixed, non-over-moving pulse source that can be used to switch the average current. In other power sources the regulation of arc length occurs by acting on the pulse frequency, without changing the wire speed, which results in alteration of the average current.

Table 3. Average voltage (Um), average current (Im), Power (P) and among parameters calculated

	Fronius	**OTC**	**Lincoln** ***Crisp***	**Lincoln** ***Soft***	**IMC**
Um **(V)**	22,1	23,5	24,2	22,6	27,2
Im **(A)**	184	198	194	190	209
Va **(m/min)**	5,0	5,0	5,0	5,0	5,0
P**(kW)**	4,9	5,5	5,5	4,8	5,9
U_{ef} **(V)**	22,6	24,0	24,7	22,9	27,3
I_{ef} **(A)**	260	272	260	236	223
Frequency (Hz)	140,0	156,3	117,7	138,5	118,9
Droplet diameter (mm)	1,08	1,05	1,15	1,09	1,15
Arc length (mm)	4,1	4,7	4,8	4,3	5,0
Droplet velocity (m/s)	1,6	1,5	1,7	0,7	0,6

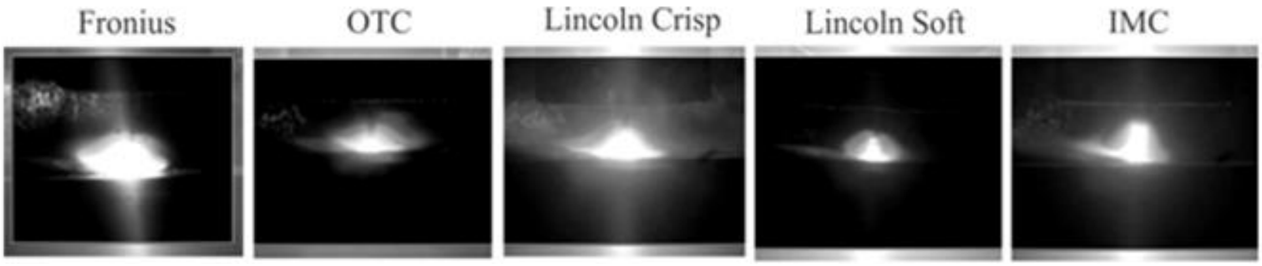

Figure 10. Images taken with the HEMA camera to control the length of the arc.

The macrographs are shown in Figure 11 while the results of the measurements are shown in the graphs of Figure 12. For convenience, the term pulse frequency will be used for all cases, since in the case of the second group the secondary metal drops are deployed. The values for the geometric characteristics are average values of the three samples collected for each welding source.

Figure 11. Macrographical samples corresponding to each welding source tested.

Figure 12. Macrocraphics measurements results

The Fronius synergist had a pulse frequency of 140 Hz, with an average current of 184 A (the lowest of all analyzed systems) and a power of 4.9 kW. The average penetration of the weld beads was 2.3 mm with a 37% dilution. The Lincoln *Soft* system produced weld beads with the same penetration and slightly lower dilution (35%) with an average current of 190 A and a power of 4.8 kW. With respect to penetration and dilution, the weld beads are practically equivalent. The differences are in the width, height of the reinforcement and contact angle. The most significant difference is at the contact angle, which is 41 ° for Lincoln *Soft* versus 49° for CMT Fronius.

The OTC system produced weld beads with greater penetration than the other sources (2.5 mm) and 40% dilution with an average current of 198 A, power of 5.5 kW and pulse frequency of 156 Hz. The Lincoln *Crisp* system had a slightly smaller penetration (2.4 mm) and a 38% dilution with equal power, practically equal average current (194 A) and pulse frequency of 117 Hz, much lower than that of OTC. Reinforcement height and contact angle are practically the same in both strands. The strands differ in width, being 9.1 mm for OTC and 8.6 mm for Lincoln *Crisp*.

The differences between the geometric characteristics between the weld beads are quite subtle. For example, among the sources analyzed in the previous items, the difference between the highest and lowest penetration is, on average, 0.2 mm.

The formation of the weld bead in the MIG/MAG process is the consequence of a set of factors. Essers and Walter (1981) estimate that the smallest amount of heat transferred to the region of the weld is due to the metal droplets transferred (25%). The heat transferred by radiation, convection and conduction combined and by the current flow represent 34% and 41%, respectively. The penetration results with mean current, power and pulse frequency demonstrate that, in fact, penetration is higher for systems that use higher average current and higher power.

The Lincoln *Crisp* system, even with a lower pulse rate, with the exception of IMC, had the second highest penetration. Essers and Walter (1981), through high-speed shooting, found that the impact of each drop with the weldpool severely formed a cavity in the center of this. When the frequency of detachment is high and after the impact of a metallic drop, there is no time for a cavity to close. The subsequent drops contact the bottom of the weld pool producing greater penetration. The frequency of detachment, but also the velocity and mass of the droplets impacting the weld pool influence the penetration of welding.

The fact that the Lincoln *Crisp* system produced the detachment of one main droplet during the pulse, not during the base like the others, produced a higher displacement velocity so that the impact of the droplet against the fusion pool is larger, producing a cavity higher and, consequently, higher penetration of weld. It should also be considered that secondary droplets were detached shortly after the main, which also transfer energy as they came into contact with the bottom of the pool. Possibly these factors combined with the high power, compensated the lower pulse frequency of this system.

The Fronius *CMT* had the lowest contact angle (49°), which could be attributed to a shorter arc length (4.1 mm) and the lower average current. However, the wettability of Lincoln *Soft* was 41° and the arc length was only 0.2 mm smaller. Thus, it is difficult to assign the results to one parameter or another, because in the Pulsed MIG/MAG process, the geometry of the weld bead depends on the interaction of several factors.

The case of the IMC synergist was treated as a particular case, since the detachment of a drop can occur only after several pulses. Thus, even with the highest average current (209 A) and higher power (5.9 kW) the resulting strings show the lowest penetration between all sources tested (1.9 mm). However, the results concerning weld bead wettability were satisfactory, evidenced mainly by the lower contact angle (31°).

3. CONCLUSIONS

- All tested synergistic systems promote detachment of drop out of the pulse (some on the base other in the detachment or tail-out phase), with the exception of the Lincoln *Crisp* system.
- Synergy systems from Fronius and Lincoln *Soft* promote regular dropping of one drop per pulse while the OTC and Lincoln *Crisp* systems highlight a major drop and subsequent secondary drops.
- The surface appearance of weld beads was satisfactory, even in cases where there is no detachment of one drop per pulse (ODPP condition).
- With the exception of IMC, there was no significant difference with respect to weld penetration, the lowest penetration being Fronius (2.3 mm) and the highest was OTC (2.5 mm). This difference, however small, was attributed to the greater current and power developed by the OTC system over other systems.
- The synergistic system of IMC was analyzed separately, since detachment of gout occurs after the occurrence of two or three pulses, which probably resulted in damage to the penetration of the weld bead. However, the results with regard to the wettability of the weld bead (width, reinforcement height and contact angle) were quite satisfactory.

4. ACKNOWLEDGEMENTS

The authors thank the entire LABSOLDA team, the Post-Graduation Program in Mechanical Engineering of the UFSC (POSMEC) and the CNPq for making this work possible.

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