IDENTIFICATION AND CONTROL OF METAL TRANSFER IN PULSED GMAW

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Abstract *The aim of this work was to design and develop an identification device for droplet detachments during pulsed GMAW and to assess the possibility of implementing a metal transfer control system. The developed identification device was based on a luminescence sensor and on an electronic interface, capable of sensing the arc light flux. A basic control system for the pulse parameters was implemented using an A/D – D/A board for receiving signals from the sensor and sending instructions to an electronic power source and a trained neural network for the metal transfer recognition. Alternatively, the signal from the electronic interface could be directed to a microcomputer with a dedicated monitoring program. Automated pulsed welding was carried out on plain aluminum plates in the flat position. The metal transfers were recorded using a high-speed camera, applying the shadowgraphy technique, to validate the device performance. The voltage and current welding signals, as well as the optical sensor and camera signals, were synchronized to guarantee suitable analysis. The results showed that the detachment device was efficient and consistent for aluminum welding. Moreover, the control system was capable of setting parameters that provided stable transfer at One Drop per Pulse (ODPP) rate, from welds starting at inadequate pulse parameter levels. Thus, it is possible to assert that this low cost developed device is a high flexibility tool, which can be applied in optimization of pulsed GMAW, through manual or automated parameters settings, without employing a high-speed camera.*

Keywords: *Metal transfer, Pulsed GMAW, Control, luminescence, neural networks.*

1. Introduction

Gas metal arc welding (GMAW) is commonly used to join pieces of metal in high throughput production, for example, in assembly lines employing robotic welders, such as in automotive manufacturing. An electric arc between one or more workpieces and a consumable electrode liquefies the electrode into metal droplets, which are shielded by an inert gas such as argon. These droplets form a weld by penetrating the metal of the workpieces before solidifying.

The mode that the droplet is transferred from the wire to the melting pool (known as metal transfer modes) is important in the GMAW process, since it determines the process stability and consequently the quality of the weld fillet (Norrish & Richardson, 1988). In a simple way, the current literature acknowledges three basic forms of metal transfer: short circuit, globular and spray (AWS, 1991).

A variation called pulsed GMAW, which is controlled by pulsing the current and/or voltage of the welding power supply, is particularly preferred in high throughput production because it produces low spattering and good bead finish while generating little heat. These characteristics are essential to avoid heat distortion and residual stress on relatively thin workpieces. The metal transfer that provides the best characteristics is the one with one drop per pulse (ODPP).

The ODPP condition can be obtained by the correct adjustment of the following variables: pulse current (Ip), base current (Ib), pulse time (tp), base time (tb), wire feed speed (WFS) and contact-tube to work distance (CTWD). However, the adjustment of these parameters is not easily reached due to this great number of variables for reaching a desired mean current and because of the dependence of these parameters on the shielding gas composition and on wire type and size (Ogunbiyi et al., 1999).

The greatest difficulty for accomplishing the appropriate adjustment of these parameters is the certification of the ODPP condition. This is so because, for pulsed welding, the signs of tension and current do not give a considerable indication of the moment of the application of the drop. In most situations, the adjustment is empirical, observing the stability of the arc and the superficial finish of the weld bead. However, this approach is very welder-feelings based and the ODPP condition is not always reached. A technique for more precise identification uses high-speed filming of the metal transfer, but as it presents very high costs and is of low flexibility, it is inaccessible for most welding users.

The alternatives are sensors based on sound, on the brightness of the electric arc and also on the statistical analysis of the arc voltage and welding current signals (Siewert et al., 1997). The sensors based on sound and the analysis technique for voltage and welding current, as well as having less sensitivity, are indirect methods that use statistical and numeric techniques to accomplish that identification. This implies a greater complexity of the analysis. Besides, one also has to add the high existent noise in welding areas that can interfere with the analysis through sound signals (Saini & Floyd, 1998).

In turn, the identification of metal transfer through optical sensor is quite viable due to the good sensitivity of the luminous variations and the facility for making analysis (Wang & Li, 1997). In welding, one attributes to the luminous variation of the arc is mainly the alteration of the welding current (the larger the current the larger the brightness) and modification of the arc length (the shorter the arc the less the brightness), in such a way that it may be possible to relate metal transfer with the brightness, because the detachment of a droplet provokes alterations in the arc length.

In this sense, it is supposed to be possible the use the optic sensors to identify the metal transfer and with that, to carry out the adjustments in the welding parameters so as to obtain the ODPP condition. This artifice does not need filming at high-speed (higher costs and less flexibility), but it would demand an electronic interface to be built for feeding the optical sensor and supplying a compatible signal to a display.

Once the identification system is developed and validated, it is possible to implement a metal transfer control system. The control system for this purpose would be important, specifically for pulsed GMAW, because it is necessary that the metal transfer frequency be conditioned to the modulation of the current signal, with the detachment of a metallic droplet at each current pulse, regardless the inconsistencies in the welding conditions. This conditioning, in turn, is not easy to be reached through simple adjustments to welding parameters and, usually, it is only reached through an effective control of the metal transfer.

Thus, the objective of this work is to use the principle of the arc luminescence to design and build a system for recognition and control of the metal transfer during pulsed GMAW, so that this process can be used at its maximum capability, i.e., always working at the ODPP condition, which is claimed to provide the best welds.

2. Experimental Methodology

An effective control of the detachment of the drop should be based on two main systems: a system for detection and recognition of the metal transfer and a system implementation. Essentially, the system for parameter setting (adjusting parameters along the welding) is not the main barrier to be overcome, because it is possible to use programming techniques based on relatively simple algorithms, provided that the detachment of the droplet is properly identified and recognized. In turn, the main obstacle to the implementation of an automatic control for the metal transfer is the "development of the identification system and recognition of the metal transfer", which should be composed of a sensor and "a computational interface" to associate the variations of the sensor signal with the instant and type of metal transfer. The computational interface can be developed by means of different tools, among which can be mentioned neural network, fuzzy logic and direct programming in C++. For classification problems, the probabilistic neural network seems to be a viable solution.

For identification of the metal transfer, an optical sensor and an electronic circuit were specifically developed, as illustrated by Figure 1. For more details see Miranda (2002).

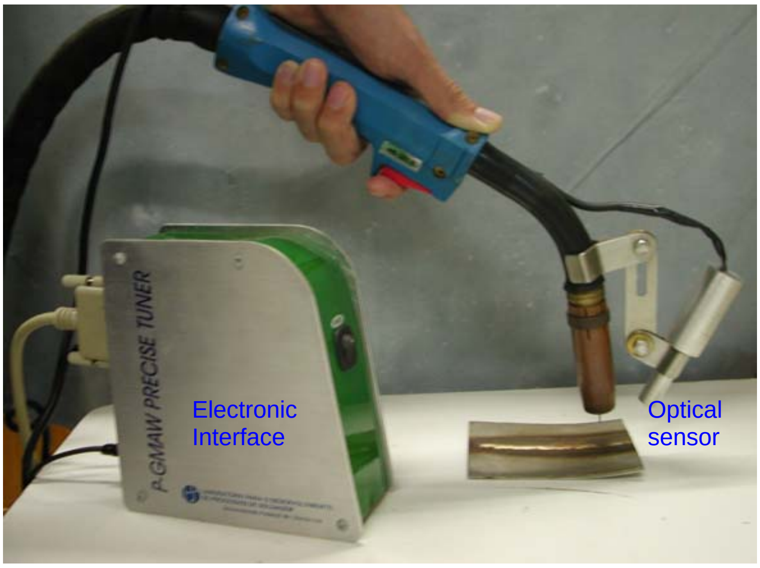


Figure 1. Identification device prototype

A proof of the efficiency of the identification system was accomplished through high-speed filming using a denominated technique of “shadowgraphy” (Balsamo et al., 2000). The filming methodology consists in using a He-Ne laser beam through the arc, so that by means of a band filter only the wavelength of the laser signal passes through the same, forming a type of shadow with the profile of the arc, the electrode, the droplet and the weld pool. In the rig developed in the lab, the images obtained were synchronized with the arc voltage and welding current signals. With high-speed filming, one is able to obtain information on metal transfer size, while the synchronization approach gives the idea of the detachment time (before, during and after current pulsation).

2.1. Validation trials of the identification system

Automatic Pulsed GMA welding, flat position, were carried out in a bead-on-plate fashion using an electronic power supply. Three different materials and wire were used for, namely, plain carbon steel, stainless steel and aluminum alloy. The objective was to adequately explore the application extent of the metal transfer identification system, including the recognition of the detachment conditions of One Drop (ODPP), more than One Drop (+ ODPP) and less than One Drop per Pulse (- ODPP).

For the aluminum alloy (AA 5052), AWS ER 4043 wires of 1.0 mm (Run 2) and 1.2 mm (in other runs) of diameter, shielded by commercially pure argon at 12 l/min, were used. The CTWD was set in 18 mm, the travel speed (TS) in 25 cm/min and the distance (L) from the tip of the sensor to the arc in 40 mm. The other welding conditions are present in Table 1.

Table 1. Parameter setting for the validation tests of the identification system

Run	Ip (A)	tp (ms)	Ib (A)	tb (ms)	WFS (m/min)
1	210	3.0	40	10.0	3.7
2	165	4.0	70	13.0	5.7
3	255	0.7	40	6.0	3.2
4	250	3.0	40	10	4.0
5	210	5.5	60	8.0	5.3

Where: Ip - pulse current; tp – pulse time; Ib - base current; tb – base time; WFS – wire feed speed

2.2. Implementation of metal transfer control system

The implementation of the control system obeyed two basic phases: development of a computational interface through PNN – “Probabilistic Neural Network”, for recognition of the metal transfer, and the implementation of the logic control.

Depending on the metal transfer mode, the luminescence signal presented different patterns. The first step in the creation of the neural network was the association of these patterns with the metal transfer modes. The signals of the welding identification device was arranged in seven categories (Figure 2): One Drop Per Pulse (ODPP), referred as patterns 3 and 4; less than One Drop Per Pulse (-ODPP), referred as patterns 1 and 2; and more than One Drop Per Pulse (+ODPP), referred as patterns 5, 6 and 7. For evaluation and training of the net, 600 pulses (units) of signals coming from different welding conditions (covering each pattern shown in Figure 2) were selected at random, totaling 4200 pulses.

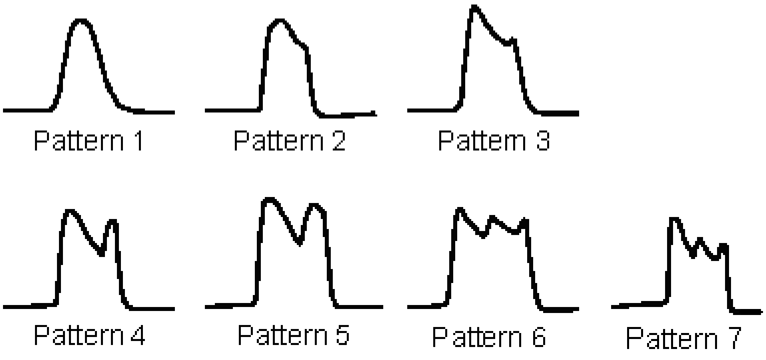


Figure 2. Characteristic patterns established for different metal transfer modes.

The second step was the choice of the mathematical treatment of the signal from the identification device, so that it can represent qualitatively the format of each pattern. Basically, the procedure adopted for the mathematical treatment was that of dividing each pulse collected in 5 parts, followed by the calculation of different mathematical indexes. For this work, the index calculated for each interval was the average and the inclination.

The neural network was implemented. The architecture of the chosen net has 10 units in the Entrance Layer (5 divisions x 2 mathematical parameters “medium and inclination”), 70 in the Standard Layer (10 representative pulses for each detachment standard), 7 in the Total Layer (1 for each category) and 1 in the Exit Layer (classified pulse). Therefore, there are a total of 88 units used to carry out the classification of one pulse.

The logic control was divided into three main blocks: a routine to acquire and treat the signals of the optical sensor; a routine to classify the type of metal transfer and a routine for sending signals to the welding power source: pulse current - Ip; pulse time - tp; base current - Ib; base time - tb and wire feed speed - WFS.

The control routine acts on the pulse time (tp) and on the feeding speed (WFS), as from the information on the types of metal transfer, correcting, when needed, the transfer mode and the arc length so that the signal from the optical sensor keeps between patterns 3 and 4. The feeding of the pulsation parameters (Ip, tp, Ib, tb and WFS) was made using a computer with a control board connected to the analogical input connector of the power supply.

The experiments were planned so that they provided as much the initial condition of +ODPP as -ODPP, due to different setting pulsation conditions. The welding condition used for the bead-on-plate flat position welds were an AWS ER 4043 wire of 1.2 mm, shielded by argon at 12 l/min, CTWD set in 18 mm and travel speed (TS) in 27 cm/min.

3. Results And Discussion

The main analysis of this work concentrates on the identification system validation, thus the most important results will be presented so as to prove the success of the objectives. In other words, the results comparing the signals of the optical sensor with the images of the metal transfer.

Figure 3 (a) shows a signal of the optical sensor with the respective images of the metal transfer related to Run 1. It is observed that only one drop for each pulse was transferred and that the signal of the sensor suffered significant alterations during the detachment (being characterized by a “V” format in most of the pulses). The analysis of the whole acquired signal showed that the detachment of the drop provoked an oscillation in the signal of the optical sensor, i.e., a small fall followed by a sudden increase, immediately before the detachment of the drop. This result indicated that the signal of the optical sensor had good sensibility to detect the metal transfer in the aluminum, which is in agreement with what was obtained by Wang & Li (1997) and Waszink & Piena (1986). Analyzing only the luminescence signal (ignoring the images), it would be possible to affirm that the predominant condition of the detachment is of ODPP in virtue of the characteristic profile presented (“V” profile).

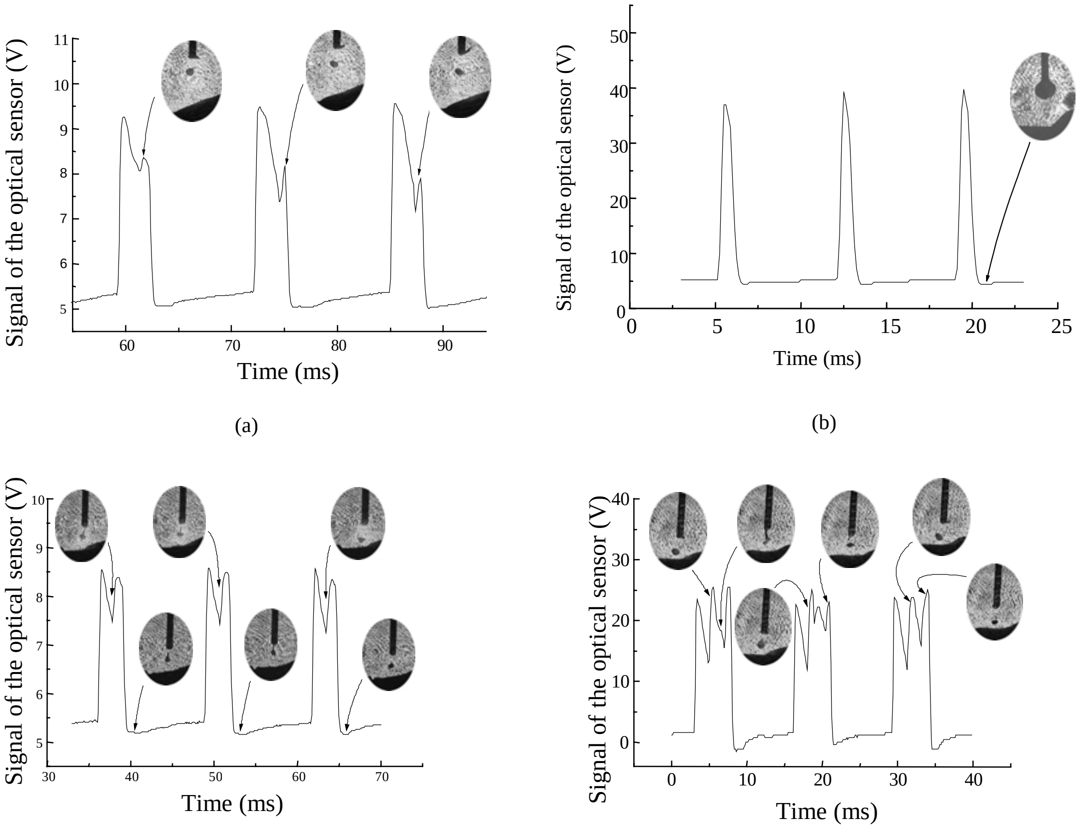
Figure 3 (b) displays a section of the optical sensor signal with images of the metal transfer for Run 3. The droplet detaches after the pulse and sometimes there will be more than one pulse to have a detachment (–ODPP category). The metal droplet grows during the pulses (reaching larger large diameter). This occurred due to a short pulse time, which did not provide enough energy for the droplet detachment.

Figure 3 (c) represents a section of the optical sensor signal from Run 4, in which a transfer with +ODPP was obtained. The profile of the optical sensor signal for this run (+ODPP) is similar to the signal of Run 1 (ODPP), however with a displacement of the “V” format towards the middle of the pulse. A considerable waste of energy happens after the droplet detachment, and a second droplet can form at the end of the pulse.

For the second drop, the sensor signal does not present a significant variation in its profile because the formation and detachment of this drop occurs during the transition of the pulse to base. The metal transfer that occurs in the transition pulse/base is difficult to identify because of the fact that, when the drop is about to be detached, the influence of the current level swift on the arc brightness hides the effect of the arc length oscillation due to metal transferring.

Run 5 provided a +ODPP condition with the transfer of the second drop occurring totally during the pulse phase (pulse time too long). Figure 3 (d) illustrates the profile of the optical sensor signal from this run, in which the form of a double “V” is characterized.

One model to explain the gradual reduction in the signal of the optical sensor followed by an abrupt increase is based on an alteration of arc length. Basically, at the beginning of the pulse, the drop is in formation, the length of the arc is long (Figure 4-a). The arc brightness is proportional to its length. During the pulse, when the drop is about to be released, a decrease of the arc length takes place due to the growth of the drop and/or lengthening of the electrode (Figure 4-b). Immediately before the transfer, the arc jumps from the lower surface of the drop to the transition area droplet/electrode, increasing the arc length again (Figure 4-c).



(a)

(b)

(c)

(d)

Figure 3. Trace of the optical sensor signal for a transfer with: (a) ODPP (Run 1); (b) –ODPP (Run 3); (c) +ODPP (one droplet at the pulse and one droplet after the pulse) (Run 4) and (d) +ODPP (two droplets at the pulse) (Run 5)

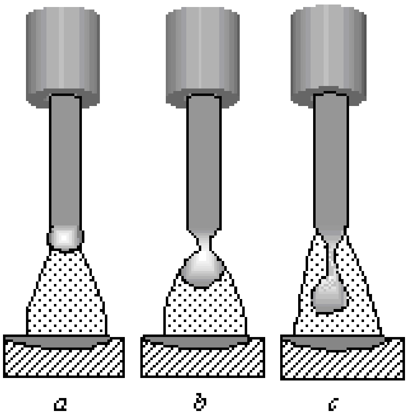


Figure 4. Illustration of the effect of the droplet detachment on the arc length and consequent brightness.

In general, analyzing all the profiles of the luminescence signal for the welding, the following was verified:

- the behavior of the optical sensor signal for transfers with less than one drop per pulse (-ODPP) is characterized by not presenting a defined pulse profile concerning amplitude and shape of the signal;
- the behavior of the optical sensor signal for transfers with one drop per pulse (ODPP) is characterized by presenting a defined pattern of a “V” during the pulse, allowing the identification of the detachment moment;
- the behavior of the optical sensor signal for transfer with more than one drop per pulse (+ODPP) is characterized by the defined signal profile with more than one “V” pattern during the pulse;
- the sensitivity of the luminescence signal was greater for aluminum welding and smallest for plain carbon steel.

4. Implementation of the Control System

The results of the experiments are shown in Table 2. It can be observed that the directly controlled parameters are pulse time (tp) and wire feed speed (WFS). The trials set out from an initial condition of +ODPP to reach ODPP (Runs 13 and 14) and -ODPP to ODPP (Runs 15 and 16).

Table 2. Aluminum welding parameters settings and after correction during the control system evaluation

Run	Ip (A)	tp (ms)		Ib (A)	tb (ms)	WFS (m/min)		Im (A)		Detachment	
		Start	End			Start	End	Start	End	Start	End
13	210	5.5	2.1	60	8.0	5.3	3.8	121.1	91.2	+ODPP	ODPP
14	180	5.5	2.5	40	10.0	4.0	1.8	89.7	68.0	+ODPP	ODPP
15	255	0.7	1.2	40	6.0	3.2	2.8	62.5	75.8	-ODPP	ODPP
16	210	0.9	1.8	60	8.0	3.4	3.8	75.2	87.6	-ODPP	ODPP

Figure 5 shows the action of the control over the welding parameters for Run 13. It is noticed that the detachment presents at the beginning a Standard 7 classification (+ODPP) and at the end reaches the Standard 3 (ODPP). The tp and WFS are altered according to the relationship previously defined (WFS is correct according to tp in virtue of changes in arc length and occurrence of short-circuits).

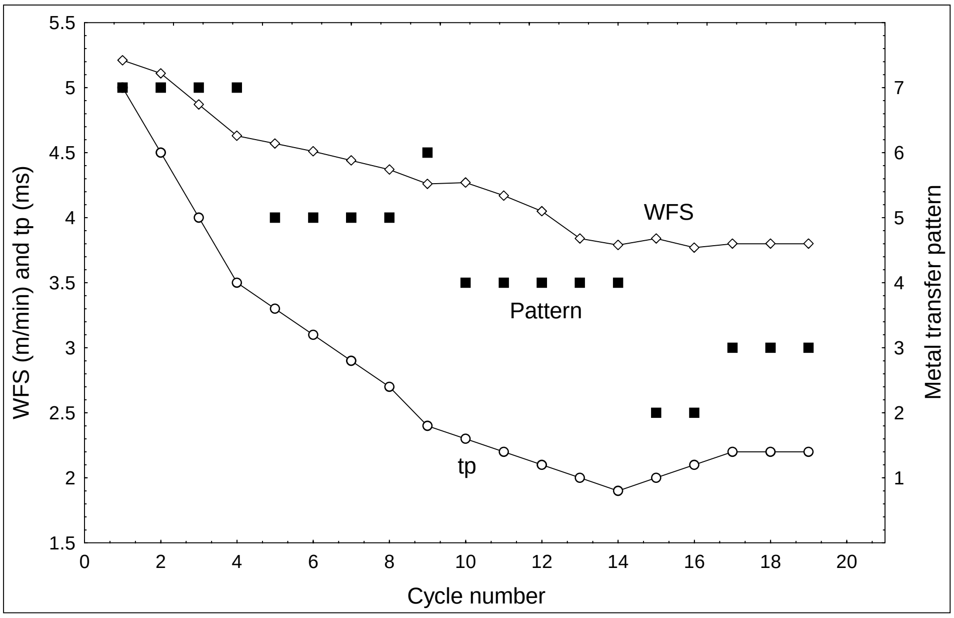
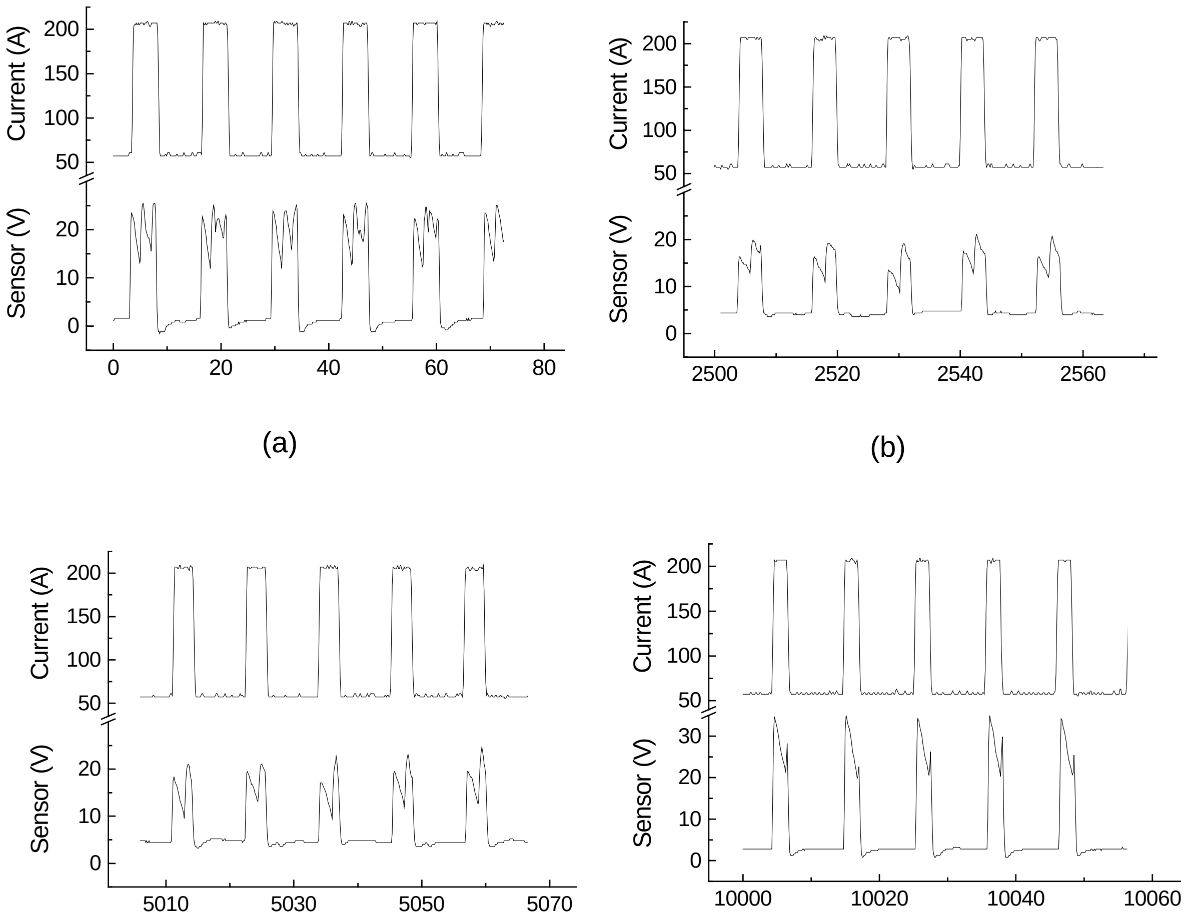


Figure 5. Parameters adjustments along the control action (Run 13)

In Figure 6 illustrate the changes in the luminescence and current signals during the control action. One can verify that Standard 3 was reached in approximately 18 cycles (10 s). The number of cycles necessary for implementation will depend on how far is the droplet detachment condition in relation to the ODPP condition, which, in turn, depends on how much from the previous state the welding condition (welding position CTWD, etc.) changed. This time is dependable as well from the increment selected in the control program so as to adjust tp and WFS, but it is small for the welding quality point of view.



(a)

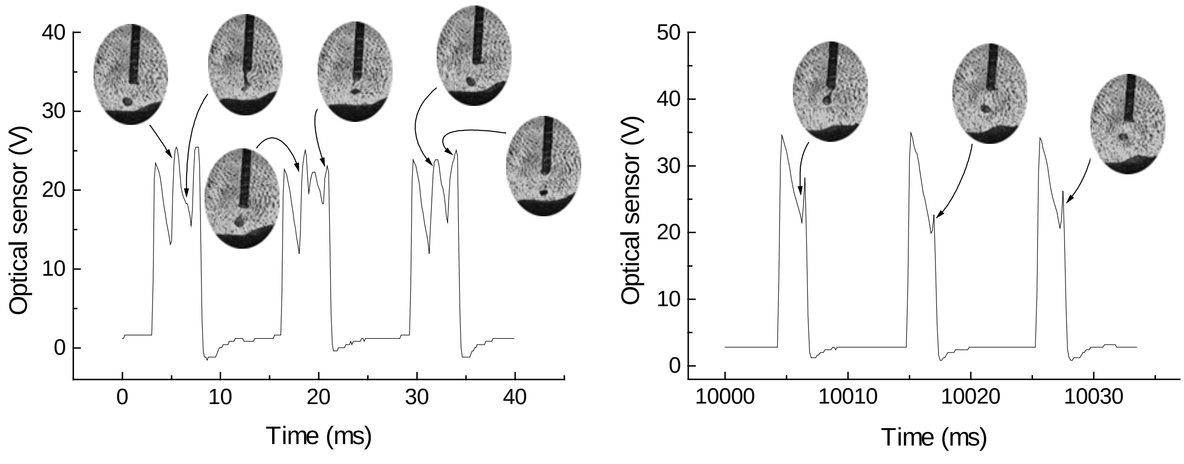
(b)

(c)

(d)

Figure 6. Modifications of the optical sensor and welding current signals over time under control action (Run 13).

The proof of the efficiency of the control was carried out through filming at high-speed. Figure 7(a) shows the images of the metal transfer for Figure 6(a), corresponding to the beginning of the welding, and for Figure 6(d), related to the welding with corrected parameters (Figure 7(b)). A similar control situation occurred for Run 14 (replicated run).



(a)

(b)

Figure 7. Images of the metal transfer corresponding to the periods shown in Figure 6(a) and (d), respectively (Run 13).

In all cases, the recognition efficiency of the metal transfer, using the trained neural network, was more than 90%. As a consequence of the results, the method and devices were patented (Miranda et al., 2004). It is important to mention that it is also possible to manually set the pulse parameters for Pulsed GMAW process, so as to obtain the ODPP condition, using only the developed detection system.

5. Conclusions

The proposed identification and control system for metal transfer in Pulsed GMAW showed to be possible an efficient. This system, made up of a luminescence-based sensor and an electronic interface, presented the following points:

- The sensing and recognition system was able to characterize different conditions of metal transfer in Pulsed GMAW related to pulse parameter settings for materials studied: One Drop Per Pulse (ODPP), less than One Drop Per Pulse (-ODPP) and more than One Drop Per Pulse (+ODPP);
- Only seven different patterns of luminescence signals (traces) were observed so that the conditions ODPP, -ODPP and +ODPP can be visually recognized;
- The use of an artificial neural network (PNN) for metal transfer recognition presented high efficiency;

6. Acknowledgments

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