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Welding stability assessment in the GMAW-S process based on fuzzy logic by acoustic sensing from arc emissions

E. Huanca Cayo*, S.C. Absi Alfaro
Mechanical / Mechatronic Engineering Department, University of Brasilia, Campus Universitário Darcy Ribeiro – Asa Norte 70.910-900, Brasilia - DF - Brazil
* Corresponding e-mail address: eber@unb.br

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ABSTRACT

Purpose: The present research work has as purpose detecting perturbations, measuring and assessing the welding stability in GMAW process in short circuit mode named hereafter as GMAW-S process.

Design/methodology/approach: Welding trials were performed with a set of optimal input welding parameters. During experiments were induced some perturbations on the welding trajectory. It causes alteration on the stability of welding resulting as consequence geometrical shape deformations. During each experiments, acoustic emission signal coming from electric arc as well as arc voltage and welding current were acquired aided by a card acquisition and virtual instrumentation software. A heuristic model was performed as knowledge base rules of a fuzzy logic system. This system has two inputs and one output. Some additional welding trials were performed for assessing its performance.

Findings: It was performed a welding stability assessment system based on fuzzy logic. As well as, this system is based on non-contact sensing what reduces the loading effects on the welding process.

Research limitations/implications: In the present work was monitored just the acoustic emissions coming from arc. Although that, the results were satisfactory, an approach on data fusion of sensors including electromagnetic emission sensors could improve the quality assessments system.

Originality/value: The non-contact welding stability assessment methods have reduces loading effects and a heuristic approach on the relations between arc emissions and welding stability allows quantifying nonlinear variables such as knowledge and experience of skilled welders, such that, it is possible to represent linguistic terms numerically what could be used as an on-line monitoring system of welding processes.

Keywords: Assessment; Welding stability; GMAW-S; Fuzzy logic; Arc emissions

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1. Introduction

Welding is the most used fabrication processes in metallic construction industry. As well as the welding applications reached industrial rates, its quality demand also became more rigorous. To ensure quality welding, some precautions are taken. It is usual applying quality assessment method simple such as visual inspections, more exigent such as NDT (non-destructive testing) till very rigorous methods as destructive tests. Usually, welding assessment tasks are performed after welding process and according requirements of the fabricated products, sometimes some sample are taken from total production and they are submitted to quality assessment tests and in other cases all products are submitted to quality assessment process. The last practice assures high quality of manufactured products but in counterpart, this method requires skilled and trained personal as well as long periods for performing assessment of welding quality what increases the production costs. An alternative for improving the quality assessments methods is the on-line monitoring of welding processes. Classically the arc voltage and welding current are monitored for assessing the welding quality. In more advanced monitoring methods, additional parameters such as welding speed, wire feed speed, gas flow are monitored [1-4]. Those practices demand using different kinds of sensors as well as acquisition data systems. The final results showed improvement in the quality assessment methods. Although this improvement, inserting sensors on the monitored process alters the monitored process due to *loading effects*. The inserted sensors extract some energy from welding parameters, thereby changing the value of the measured quantity from its undisturbed state and thus making perfect measurement theoretically impossible. In consequence the quality assessment method based on intrusive monitoring of welding parameters unavoidably alters the final welding quality.

The welding arc is a current flowing between two electrodes through an ionized column of gas called plasma. The space between the two electrodes can be divided into three areas of heat generation: the anode, the cathode and the arc plasma [5]. In the welding arc the electrons flow from cathode to anode and the positive ions flow from anode to cathode. These have been accelerated through the plasma by the arc voltage and they give up their energy as heat. The heat is generated in the cathode area mostly by the positive ions striking the surface of the cathode as well as the heat is generated at the anode mostly by the electrons. These electrons, atoms and ions that are flowing along the plasma column are in accelerated motion and constantly colliding. This chaotic flow together with the heat and the electromagnetic fields of the welding arc produces the arc emissions of electromagnetic nature such as the infrared emission. Besides electromagnetic emissions, the welding arc produces acoustic emissions principally due to changes of the electric power in the arc column [6]. These welding arc phenomena are perceived by skilled welders as sound and luminosity and just by extracting and combination of information coming from arc emissions, they can to monitor and to control the welding process. Sensing arc emissions constitutes a non-intrusive monitoring method and it avoids the *loading effect* over welding process.

Welding quality assessment is subject at multiple investigations and discussions, due to that its qualification involves diverse criteria such as geometrical and metallurgical continuity of weld bead. The confluence of satisfactory assessment in each welding quality criteria permits to catalogue a weld bead as an acceptable quality weld. The welding quality is directly related to adequate setting welding parameters. In this conditions there is a stable metallic transference; this happens when the flow of the mass and heat from consumable electrode tip until fusion pool through arc, has uniform transference; possible discontinuities and/or upheavals in the transference could originate weld disturbances. Worth mentioning that although there is high stability in welding, this does not necessarily mean high quality. Welding quality in addition to stability, involves requirements as appropriate combination of metals to be joined and/or repair, adequate structural configurations of junction, among others, but certainly the stability is an essential condition.

There are different characteristics of welding parameters to reach a high stability. In GMAW-S process it is reached when during the welding the pool fusion oscillation and short circuit frequency are same, when there is balance between wire feed speed and its melting rate [2, 3]. In *On-line* welding quality monitoring systems for GMAW-S processes, there are four conditions for reach a high stability: maximum short circuits number, minimal standard deviation of the short circuits periods, minimal mass transfer in each short circuit and minimal spatter level [4]. In the present work we will to approach the welding quality assessment based on monitoring of the continuity of the acoustic arc emissions by a fuzzy logic system.

2. Experimental procedure

The experiments were performed using the set up shown in the Fig. 1. Signals of arc voltage, welding current and acoustic emissions were acquired at 10 kHz of sampling frequency. The arc voltage was acquired by a voltage shunt and optical insulator connected to acquisition card. The welding current was acquired by a Hall Effect sensor linked at acquisition card previously conditioned. The arc sound signal was acquired by the decibel meter B&K linked to acquisition card. The decibel meter uses a 4189 type microphone with -26±1.5 dB gain and sensitivity of 50 V/Pa.

The welding experiments were carried out using steel plates AISI 1020 (30 mm x 200 x 6.50 mm), electrode wire AWS A5.18 ER70S-6 with 1.2 mm of diameter, shield gas was the mixture of argon and carbonic anhydride M21 (ATAL 5A/Ar 82% + CO_2 18%).

First, were carried out welding runs with different parameter till reach a parameters combination balanced to obtain a steady state metal transference and an acceptable quality for GMAW-S process. This balanced set of welding parameters (Table 1) will be used in the next experiments.

Table 1.
Electrical parameters for tests on steady state of metallic transference

Welding Voltage (V)	Wire Feed Speed (m/min)	Speed Welding (mm/s)	Contact Tip to Work Distance (mm)	Protection Gas Flow (lt/min)
20	6	10	12	15

Secondly, four experiment sets of 10 bead-on-plate welds each and with 180 mm in rectilinear trajectory were carried out. The first set is constituted by weld run experiments without interferences and the rest by weld run experiments with disturbances induced in the interference region (Fig. 2).

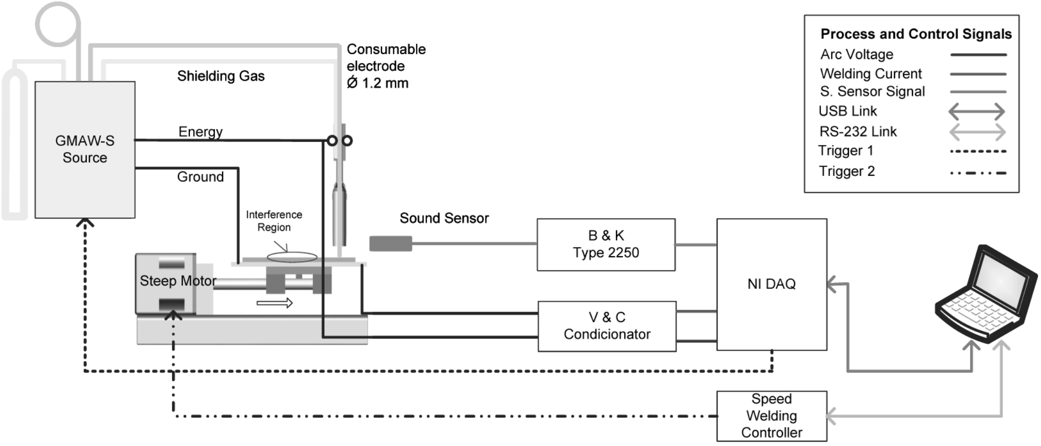
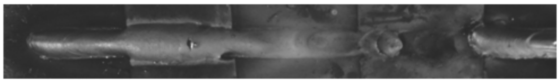
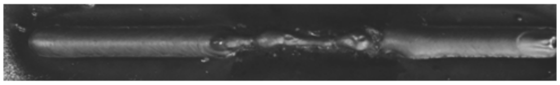


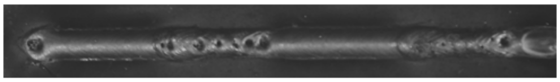
Fig. 1. Experimental setup



Disturbance 1



Disturbance 2



Disturbance 3

Fig. 2. Weld runs experiments with induced disturbances

The induced disturbances are: sudden variation of CTWD, grease presence and shielding gas fall respectively. For to simulate the disturbance induced by CTWD variation was made placing a small steel plate (50 mm x 20 mm x 2 mm) on the interference region. In the case of second induced disturbance, a grease layer was placed on the interference region. And finally the third disturbance induced was simulated interrupting the shield gas flow closing and opening the source shield gas valve when the weld run to cross the interference region. In each experiment voltage, current and sound pressure signals from electrical arc were acquired simultaneously.

3. Results

In GMAW-S process the metal is transferred to the welding pool when the molten tip of the consumable electrode contacts the molten puddle. This generates sudden changes in the power of the welding arc. The metal transference mode is characterized by ignitions and extinction sequences and the welding arc sound fits this welding arc behaviour. In each arc ignition there is a sound peak as well as when the arc has been extinct, a small sound peak is produced (see Fig. 3).

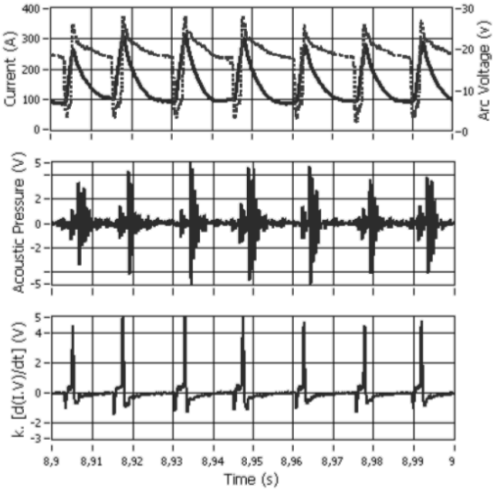


Fig. 3. Monitored and modelled waveforms

The correspondence between the welding arc sound emission $S_e(t)$ and the welding arc power $P(t)=V(t)I(t)$ could be expressed by the model describes in the Eq. 2.

$$S_e(t) = K\frac{d(P(t))}{dt} \tag{1}$$

$$K = \alpha(\gamma - 1)/c^2 \tag{2}$$

where: K is a proportionality factor, α is a geometrical factor, γ the adiabatic expansion coefficient of air and c the velocity of sound in the arc. The variable values are determined experimentally [7].

Comparing the monitored and modelled waveforms of acoustic emission of welding arc, it is noticed that there are a lag time among them. This delay is produced by the airborne nature of the sound and when this value is not great than 400 ms (See Fig. 4) the welding arc sound, is feasible for getting reliable information from welding arc [8].

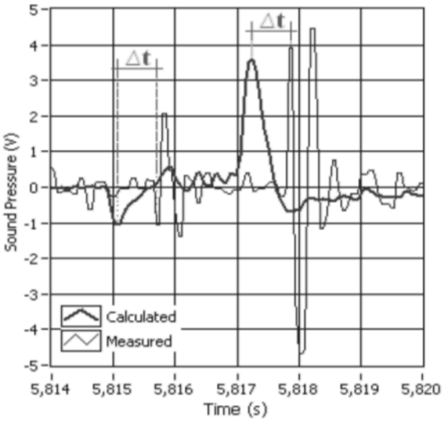


Fig. 4. Delay among acoustic emission signals measured and modelled

Certainly the expert welders have capacity to inferring and reaching the stability conditions mentioned before just by to perceive the emissions coming from arc (hearing and seeing). But, how can they do it? The knowledge and experience are the answer. Different researches showed that is possible to measure the arc voltage and its characteristics by acoustical methods [6-11]. But, more than monitoring the arc voltage by non-intrusive methods, it is necessary understanding and quantify the relation among the acoustic emission and the welding quality. The fuzzy logic permits to quantify nonlinear functions such as the knowledge and experience of welders. In the present work the welding stability assessment is performed by sensing the acoustic emissions coming from electric arc in GMAW-S process. Two parameters are extracted from acoustic emission and after their fuzzification they are assessed by an inference engine that relates the relations between acoustic emissions from arc and the welding quality. Finally an output that represents the quality level is defuzzified allowing detecting disturbances and perturbations due to lack of stability on metal transference. This method could be an alternative against the classical on line methods of welding.

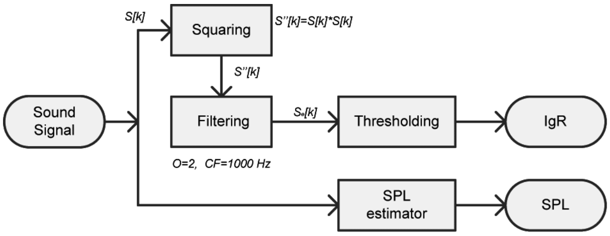


Fig. 5. Diagram blocks of acoustic emission signals processing

From arc sound signal, were computed two stability assessment parameters: ignition rate (IgR) and sound pressure level (SPL). Fig. 5 shows the data flow to extracting parameters from acoustic emissions. Each block will be treated in the next two items.

3.1. Ignition Rate — IgR

The short-circuiting frequency behavior indicates the stability on GMAW-S process and this characteristic can be represented by the acoustic emissions peaks. When the welding process reaches a steady state (stationarity) all parameters involved also reaches a steady state. Then the acoustic emission waveform also reaches a steady state. The information about short-circuiting contained on acoustic emission signal is present on the envelopment of this signal. The envelope signal was determined by squaring itself $[S_e(t)]^2$. This means that half the energy of the signal is pushed up to higher frequencies and half is shifted towards DC. The envelope signal can then extracted by keeping all the DC low-frequency energy and eliminating the high-frequency energy using some filter. It was performed by a low pass filter of second order $F(s) = a/(\tau s + 1)$.

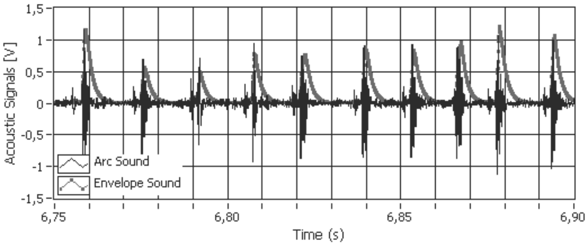


Fig. 6. Acoustic emission and envelope signal

The acoustic emission signal and its envelope waveforms are represented in the Fig. 6. The acoustic emission peaks produced by ignition rate are greater than acoustic emissions peaks produced by short-circuiting. Thus, ignition rate measuring is easier than short circuits rate measuring. From envelope signal the ignitions rate is measured by thresholding ($Th = 0.1$).

3.2. Sound Pressure Level — SPL

The sound pressure level *SPL* is a measuring that compares sensitivity of the acoustic emissions $S(t)$ with a reference value S_m during an interval time $[t_0 - t_0 + \Delta t]$. This relation is expressed in decibels as is shown in the Eq. 3.

$$\mathrm{SPL} = 20\log_{10}\left[\sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\left(\frac{S(t)}{S_m}\right)^2 dt / p_0}\,\right] \tag{3}$$

where: S_m is the microphone Sensibility (50x10-3 mV/Pa), p_0 acoustical standard pressure (20 µPa), t_0 initial time of integration (s) and Δt interval time of integration (s).

The SPL was computed to by Eq. 3. The waveforms of the acoustic emission $S(t)$ and SPL are shown in the Figure 7.

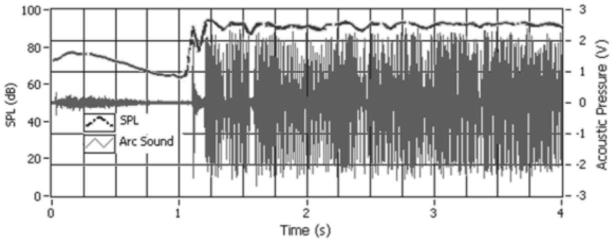


Fig. 7. Acoustic emission and SPL

3.3. Relation among IgR and SPL

As well as the welding parameters, the emissions arc has a stochastic nature [12]. This fact is depicted in the following XY graphs. Figure 8 shows the simultaneous stochastic behaviour of IgR and SPL parameters and their individual statistic distributions (probability density distribution – PDD) correspondent to experiments: free disturbances (Fig. 8a), CTWD variation (Fig. 8b), grease on plate (Fig. 8c) and supply lack of shielding gas (Fig. 8d). On each XY graph, there is an elliptic region that indicates approximately the stability zone which means that the welding has a high quality while IgR and SPL parameters are inside this zone. This ellipse is centred on the intersection of the averages of profile parameters. The proportion of the axes of ellipse defines the stability zone and they are determined by the Eq. 4; this equation is based on the third standard deviation method.

$$A_{p^x} = \overline{P^x} + 6 \times S_{p^x} \qquad (4)$$

where: A_{p^x} is the P^xth axis of the ellipse, $\overline{P^x}$ is the average of the xth parameter, S_{p^x} is the standard deviation of the P^xth parameter.

Oscillations inside of elliptical zone are considered as normal fluctuations in a high quality welding. But sometimes there is data spurious out from stability zone and it could be considered also as normal when their distance from the limits of the control zone and its quantity are trifling.

In the first case the average and standard deviations of the SPL and IgR parameters are 84.74±0.7808 dB and 90.57±5.0897 Ig/s respectively; these quantities represents a welding on steady state (profile parameter). In the last three XY graphs represent experiments where the steady state has been broken. Notice that the average and standard deviation of each parameter were altered.

The XY graphs are two-dimensional indicators which permit to determine if a welding is stable or not and from this fact assessing the welding quality. A one-dimensional indicator will be performed on the next section addressing the fuzzy logic.

Figures 9-10 show the differences between the disturbed and the undisturbed experiments, but there are obvious differences between both types of experiments. Expert knowledge and skill are required to reliably recognize and distinguish the IgR and SPL of the GMAW-S experiments. For a stability prediction without an expert, especially for stability prediction in production lines, automatic evaluation methods have to be developed. A possible solution for this is the implementation of neural networks, fuzzy logic or combinations of both. This paper concentrates on a fuzzy logic system.

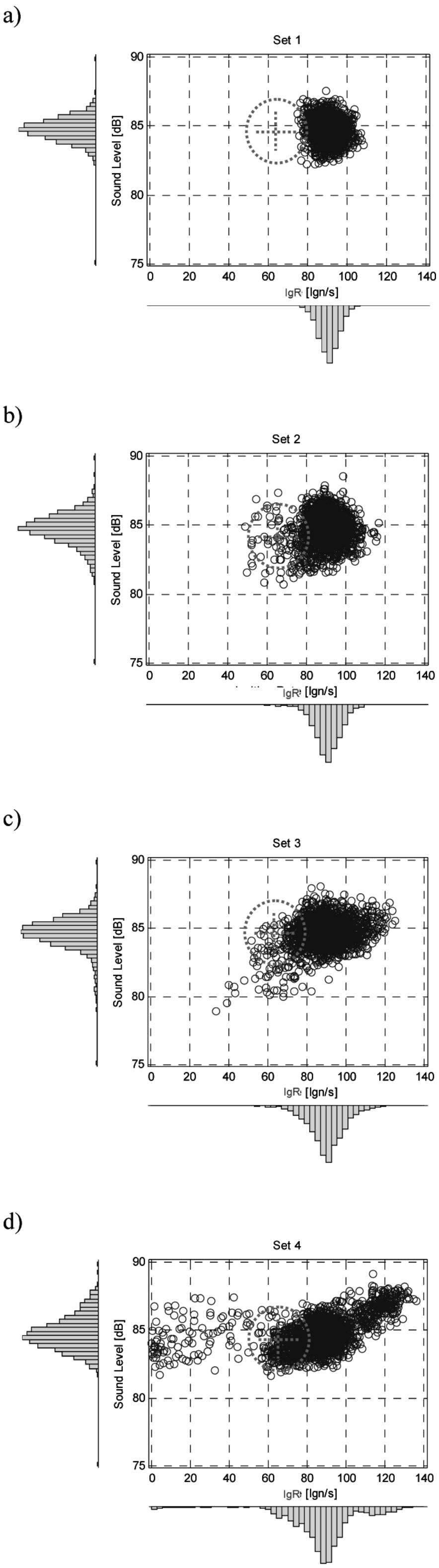


Fig. 8. Quality welding assessment parameters

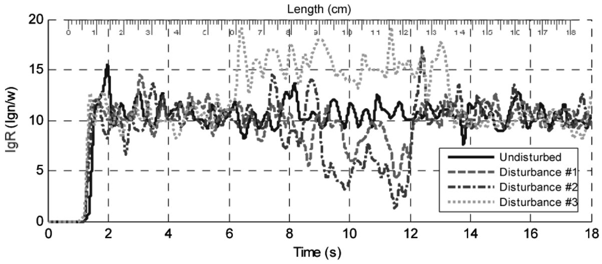


Fig. 9. IgR response for different welding experiments

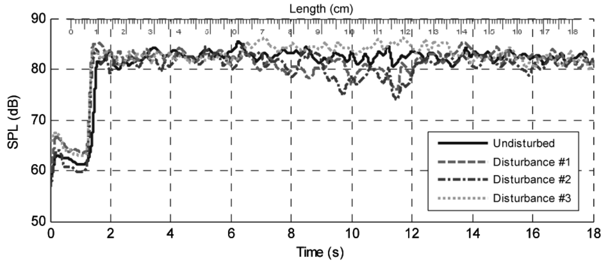


Fig. 10. SPL response for different welding experiments

3.4. Fuzzy system

To solve a problem based on uncertain or fuzzy observations or correlations, it is necessary to describe, map and process the influencing factors in fuzzy terms and to provide the result of this processing in a usable form. These requirements result in the basic elements of a knowledge-based fuzzy system. The numeric values of the input variables (Ignition rate and sound pressure level) are transformed into memberships of fuzzy sets by fuzzifying. This information, together with the declared rules, is given to the inference engine, the results again being a set of memberships of fuzzy sets (terms for the output variables). The last step is to transform these membership values into the required scalar variables output (welding quality) by defuzzifying.

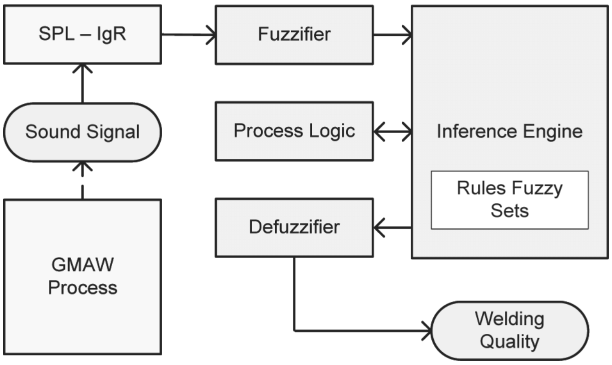


Fig. 11. Fuzzy system

The Figure 11 shows the block diagram of the assessment system for welding quality based on fuzzy logic proposed in this work. This system works with the IgR and SPL as input signals. The range of each input signals were divided in five fuzzy sets (membership functions). A membership degree between 0 and 1 were performed following the PDDs equalization method [13] using triangle membership functions. Welding experiments free of disturbances as well as with induced disturbances were performed. From their PDDs were identified abnormal variations (Figs. 12a and 13a) and according this variations were adjusted the limits (specifications of these limits are shown in the Tables 2 and 3) of each of the five triangle membership functions (Figs. 12b and 13b). This operations set is called fuzzifying. The next step was to develop the inference engine for indentifying abnormal variations or discontinuities on the inputs aiming to measure the welding stability. The inference engine is composed by twenty-five rules. They interact with the inputs and the output sets, taking into account rules of aggregation, implication and accumulation. In the present work were employed the minimum aggregation operator, algebraic product as the implication operator and the "or" operator as accumulation operator. Finally the defuzzifying based on the mean of maxima method was performed. The output of this fuzzy system was divided into three triangle membership functions which represent the stability level St level in percentage terms (Table 4). When the acoustic arc emissions of the GMA welding have uniform distributions on the PDD of IgR and SPL, it means that the metal and heat have a uniform transference; unexpected variations could be related to interferences.

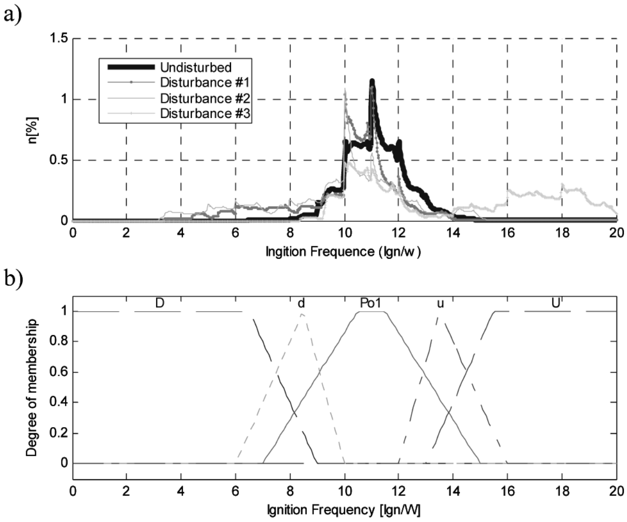


Fig. 12. IgR fuzzification

Table 2.
IgR fuzzy sets

Linguistic Variable	Symbol	Range
Very down	D	[6, 0, 6.5, 9]
Down	d	[6, 8, 10]
Optimal	Po1	[7, 10.5, 11.5, 15]
Up	u	[12, 13.5, 16]
Very up	U	[13, 15.5, 20]

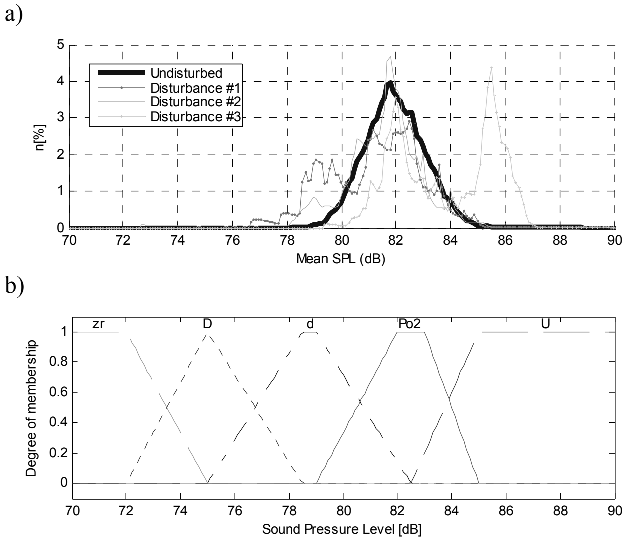


Fig. 13. SPL fuzzification

Table 3.
SPL fuzzy sets

Linguistic Variable	Symbol	Range
Null	Zr	[70, 70, 72, 75]
Very down	D	[6, 8, 10]
Down	d	[72, 75, 78.5]
Optimal	Po2	[79, 81.5, 83, 85]
Very up	U	[83 – 85 – 90 - 90]

Table 4.
Stability fuzzy sets

Linguistic Variable	Symbol	Range
Null	Nl	[0, 0, 5]
Average	Av	[85, 95, 98]
High	Hg	[95, 98, 100, 100]

4. Discussions

Figures from 14 to 16 show the fuzzy assessment performance for welding experiments with induced disturbances (variation of arc length, grease presence and absence of gas respectively). In those can be noted that for the three cases, the stability level St has an expressive variation when the welding pool pass through the induced disturbances region.

The stability level St drops to 0% in all cases. In steady sate and without perturbations the stability level St varies around approximately 90%. In effect, reaching 100% of stability is a theoretical concept.

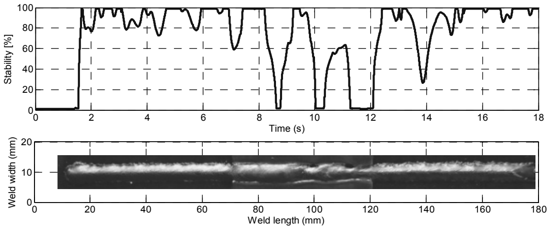


Fig. 14. Level of stability in presence disturbances 1

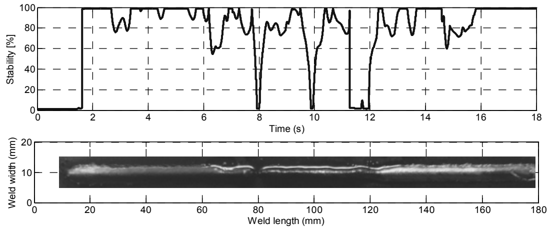


Fig. 15. Level of stability in presence of disturbances 2

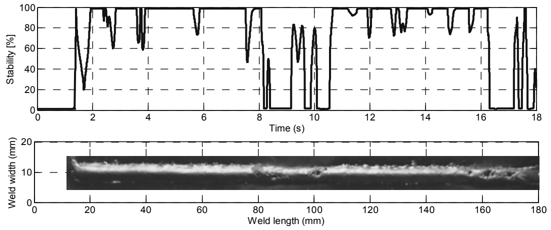


Fig. 16. Level of stability in presence of disturbances 3

By visual inspection of the welding experiments and contrasting the stability waveforms, could be consider two situations of definite instability. In first place when the magnitude of amplitude variations is too considerable (more than 60%). It is clear that when the amplitude variation increases, the presence of instabilities is more probable. But if this amplitude variation surpasses the 50%, definitely there is some considerable disturbance. In second place, the instability time duration should be considerate. If the stability level amplitude is less than 60% and that value remains during long time, definitely there is some welding disturbance. If the stability level reaches 0%, absolutely there is a considerable welding disturbance, what implies a meticulous inspection in the detected area.

5. Conclusions

In the present research work was carried out a non-contact welding stability assessment system based on fuzzy logic. Heuristic base rules were performed according the PDDs histogram equalization.

The fuzzy logic allowed to quantize the knowledge and experience in welding and became it possible performing a system that can be used in monitoring of stability in welding. Certainly a high acoustic stability coming from welding process indicates a high stability in metal transference. But although the acoustic and the metal transference reach a high stability, that state is not enough condition for guarantying the quality in welding.

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