Short circuit GMA welding process quality assessment based on electric arc acoustic emissions

E. Huanca Cayo, S. C. Absi Alfaro
Automation and Control Group in Fabrication Processes - GRACO, Faculty of Technology,
Department of Mechanical/Mechatronic Engineering, University of Brasilia, Brazil
E-mail: eber@unb.br

Keywords

Short circuit GMA welding, quality assessment, electric arc acoustic emissions, sound level, ignition rate

1. Introduction

The gas metal arc welding - GMAW in short circuit mode process (hereafter named as GMAW-S), is the manufacture process most used in the metallic construction industry. Diverse advantages such as the high rate metallic transference, elevated penetration and facility to welding in diverse positions, does this process become the most requested. When the GMAW-S process demand grew at industrial rates, its quality requirements and exigencies also were multiplied. Welding quality assessment is subject at multiple investigations and discussions, due to its qualification involve diverse criteria such as their geometrical and metallurgical continuity. The confluence of the satisfactory assessment in each welding quality criteria permits to catalog 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 transfer; 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.

Expert welders use an acoustic and visual information combination that come from the electric arc for the monitoring and control the welding process aiming to achieve high stability and quality in welding [1]. Different researches showed that is possible to measure the arc voltage and its characteristics by acoustical methods [2]-[7]. The welding quality assessment using sensoring of the sound generated by the electric arc could allow detecting disturbances that originate the formation of defects in weld beads. This method could be an alternative against the classical on line methods of assessment and inspection used for detecting and finding disturbances that are based in direct measuring of parameters as arc voltage, welding current, wire feed speed, etc.

There are different characteristics of welding parameters to reach a high stability. It is reached in GMAW-S process during the welding principally when the pool fusion oscillation and short circuit frequency are same [8], when there is balance between wire feed speed and its melting rate [9]. 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 [10]-[12]. Based in these four conditions, the stability assessment criteria followed in this paper, is focused in the two first mentioned above. In this paper, stationary short circuits rate measured acoustically and the sound level pressure from electric arc will be used to assessing the welding quality.

2. Experimental Setup

Virtual instrumentation software, data acquisition card, energy source and an equipment set up as shown in the Figure 1 (a) was used for acquisition and processing data based on the voltage, current and sound signals. Those signals were sampled at 20 kHz. 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. In previous researches, the microphone was installed at different distances from weld pool fusion, for example: 85 mm [2], 35 mm [4]. Studies in psychoacoustic have determined that if the electric arc sound signal does not exceed 400 ms, this will be a good indicator of the behavior weld process [4]. Following these considerations, in this work the microphone

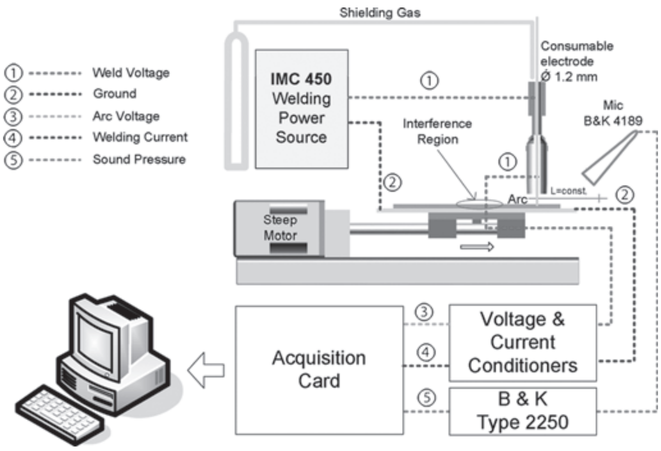

Figure 1. Experimental setup

was positioned at 150 mm from the pool fusion. 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 welds 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 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 stable 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. Welding parameters

AV [V]	WS [m/min]	SW [mm/s]	CTWD [mm]	SGF [l/min]
20	6	10	12	15

AV – ARC VOLTAGE
WS – WIRE SPEED
SW – SPEED WELDING
CTWD – CONTACT TIP TO WORK DISTANCE
SGF – SHIELD GAS FLOW

Secondly, four experiment sets of 10 bead-on-plate welds each and with 180mm 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 (Figure 1). 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 and Discussions

3.1. Monitored Signals from GMAW-S Process

Figure 2 shows a data window of welding parameter signals measured and computed simultaneously. Voltage and current (A), Sound (B), Power computed (C) Sound computed (D) Sound envelope (E) and Envelope computed (F).

In the Figure 2 can be noticed that the arc voltage is characterized by ignitions and extinction arc sequence cycles (A) and that the arc sound fit the arc voltage cycles. In every ignition of the arc voltage there is a big sound peak, whereas in every arc voltage extinction there is a small peak of sound (B). Also is noticed that there is a delay in the sound compared with the arc voltage. This delay is produced by the airborne nature of the sound and when it does not exceed 400 ms, the arc sound will be feasible for to get information from behavior of the electric arc [4]. Such behavior of tension and sound (ignitions and extinctions) is called transfer cycle, and it is directly related to heat transfer. The power $P(t) = V(t) \bullet I(t)$ was computed from voltage $V(t)$ and current $I(t)$ and is showed in the figure 2-C. This resultant parameter also reflects clearly the behaviour of the transfer cycle. Researches on arc sound monitoring [2]-[4], describe that the relationship between the sound produced $S(t)$ and the arc power $P(t)$ can be expressed as:

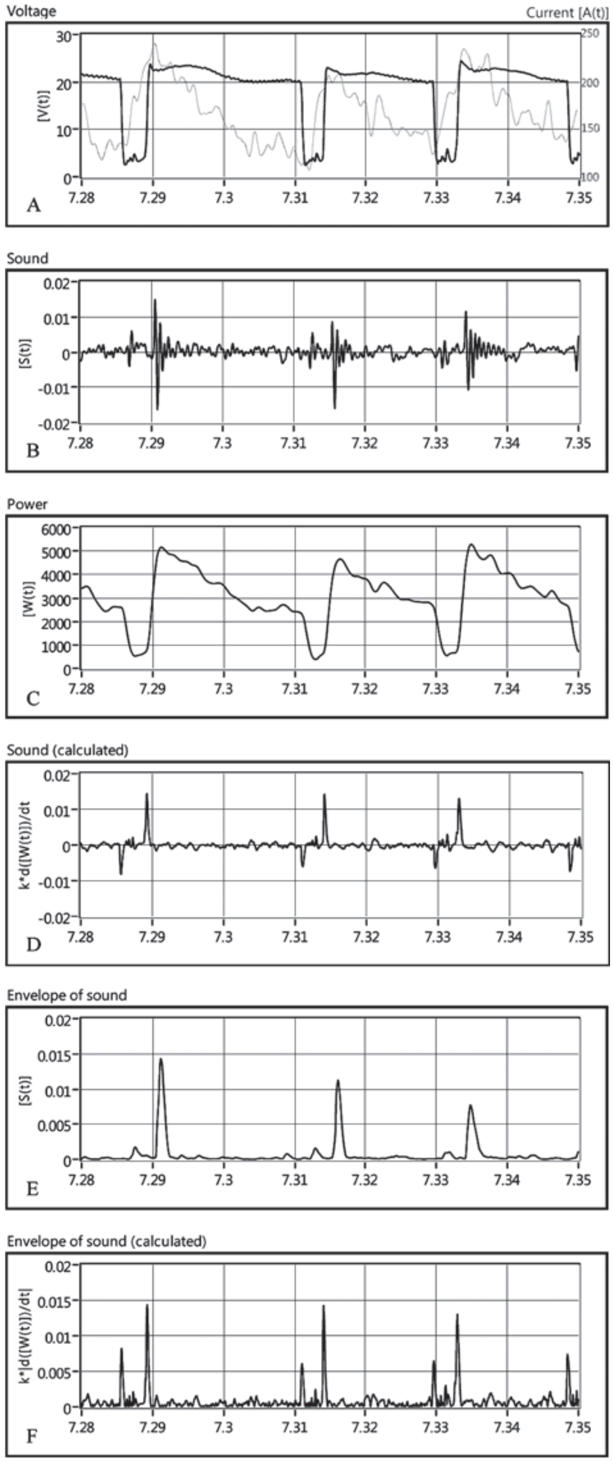

Figure 2. Monitored welding signals

$$S_c(t) = K\left[\frac{d(P(t))}{dt}\right] \tag{1}$$

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

Where: $S_c(t)$ is the computed sound, 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 computation of the previous equation is shown in the figure 2-D. A priori comparison between the acquired and calculated acoustic signals reflects differences in the behavior of the ignition and extinction peaks. These differences are mainly due to each peak of ignition and extinction is represented by more than one acoustic wave (2 to 3), while in the computed sound, each transfer cycle is represented only by a pulse. This result is mainly due to the calculation is based on an operator of differentiation. This operator accuses just the rising and falling of the computed signal (Arc power). Nevertheless, it is possible to notice differences in the magnitude of amplitude and polarity of each pulse. When there is an arc extinction cycle (short circuit), the pulse has small amplitude and negative polarity and in an ignition cycle, has big amplitude and its polarity is positive. By applying a quadratic amplitude demodulation operator $H[\square^2]$ at arc sound signal, is calculated its envelope (See Figure 2-E). And by applying an absolute value operator $|\square|$ at arc sound signal calculated, is obtained a signal similar to arc sound envelope calculated before (See Figure 2-F). This fact verifies the veracity of the equation 1, but worth to clear that in the case of the GMAW-S process, the sound that is calculated by applying of operators of differentiation and absolute value on arc power signal, really is just the envelope of the sound produced by the arc (Compare Figures 2 - E and F). Despite the similarity between the envelope signals calculated from the arc power and the sound of arc respectively and nevertheless the stochastic nature of the arc voltage and welding current [13], is necessary to show the stationarity of the arc sound signal, because the arc sound has not electric connections at welding process, its monitoring is just by mechanical propagation through surrounding air and it is subject at possible variations due to changes in the adiabatic expansion coefficient γ, variations in the sound speed by changes in the temperature of the air surround to arc welding pool c as well as due to noise of the environment. Determining of the stationarity of the arc sound will permit to use it as a reliable parameter to monitoring the transfer cycles in GMAW-S process. In the next section will be analyzed its stationarity.

3.2. Stationarity of arc sound

Stationarity is a statistical property of random nature processes what means that the statistical quantities are independent of the absolute time and dependant only on relative times, in other words a process is stationarity when its essential statistical properties are invariant over time. Two kinds of stationarity are distinguished: weak and strong stationarity. Weak stationarity is meant when the first and second moments are independent of time, that is, $\langle S_t\rangle = \mu$ and $\langle |S_t - \mu|^2\rangle = \sigma^2$, (where $\langle\square\rangle$ stands for the ensemble average) are constants. For finite process which is the case of the welding processes, the behavior of the mean value and variance cannot be enough estimators for stationarity. A stochastic process $\{S_t\}$ with t as an integer number, is denominated as strongly stationary if any set of times t_1, t_2 and any integer k the joint probability distributions of $\{S_{t_1}, \dots, S_{t_n}\}$ and $\{S_{t_{1+k}}, \dots, S_{t_{n+k}}\}$ coincide, in other words, when there is correlation between both distributions. Before to calculate the autocorrelation function is necessary obtain some statistical parameters considering the sound as a stochastic variable, $S(t, \beta)$.

Probability average

$$\langle S\rangle_j = \lim_{N\to\infty}\frac{1}{N}\left[\sum_{i=1}^{N} S(\beta_i, \tau_j)\right] \qquad j = 1, 2, \dots, M+1 \tag{3}$$

Where: N is the number of realizations of the process, M is the number of time steps and β is the random variable.

Time Average

$$\overline{S} = \lim_{T\to\infty}\frac{1}{2T}\int_0^T S(t)\,dt \tag{4}$$

Fluctuations

$$S'(t) = S(t) - \overline{S} \tag{5}$$

Since $\overline{S'(t)} = 0$, the variance is simply calculated as:

$$\sigma_{S'}^2 = \overline{S'^2} \tag{6}$$

The time average of the square of the fluctuations is evaluated by using the expression in equation (7).

$$\overline{S'^2} = \lim_{T\to\infty}\frac{1}{N}\int_0^T S'^2(t)\,dt \tag{7}$$

Finally the autocorrelation is defined as:

$$R_{S'}(\tau) = \langle S'(t+\tau)S'(t)\rangle = \overline{S'(t+\tau)S'(t)} \tag{8}$$

It is more convenient to work with the normalized autocorrelation function $C_{S'}$, defined in equation (9).

$$C_{S'}(\tau) = \frac{R_{S'}(\tau)}{\sqrt{\overline{S'^2(t)}}\sqrt{\overline{S'^2(t+\tau)}}} \tag{9}$$

Note that $C_{S'} = 1$ indicates weak stationarity and $C_{S'} = 0$ indicates strong stationarity. Figure 3 displays the plots of the normalized autocorrelation of the sound arc signal. Generally, the autocorrelation is expected to decay exponentially, and the fluctuations are expected to become uncorrelated after a sufficiently long-time.

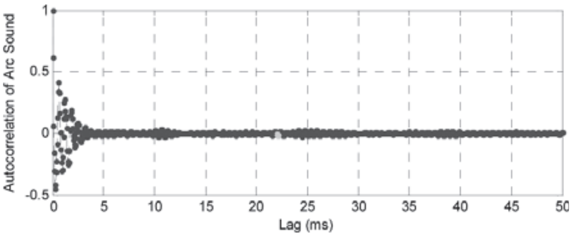

Figure 3. Arc sound correlation

From the graph in Figure 6, it can be observed that there is a high autocorrelation what means that the arc sound signal has a strong stationarity and it can be used to assessing as welding quality parameter. From arc sound signal, were computed two stability assessment parameters: ignition rate (IgR) and sound pressure level hereafter named just sound level (SL); will be treated the calculus of those parameters in the next two items.

3.3. Ignition Rate - IgR

The IgR was calculated from every 150 ms moving windows of sound pressure data. As the acoustic amplitude pulses produced by the arc ignitions are greater than acoustic amplitude pulse produced by the short circuits, consequently, the arc ignitions counting are easier than the short circuits counting. In the first place the envelopment sound pressure signal was determined using a quadratic demodulator. Squaring the signal effectively demodulates the input by using itself as the carrier wave. This means that half the energy of the signal is pushed up to higher frequencies and half is shifted towards DC. The envelope can then be extracted by keeping all the DC low-frequency energy and eliminating the high-frequency energy. It was done by a low pass filter. In the Figure 4 (a) is showed the 150 ms moving window data extracted from the arc sound signal and can also be observed the sound pressure signal and its envelopment sound pressure. From envelopment sound signal is calculated the arc ignitions for each moving window data. An ignition takes place whenever the envelopment sound pressure signal surpasses the ignition threshold established *(TH = 0,1)*.

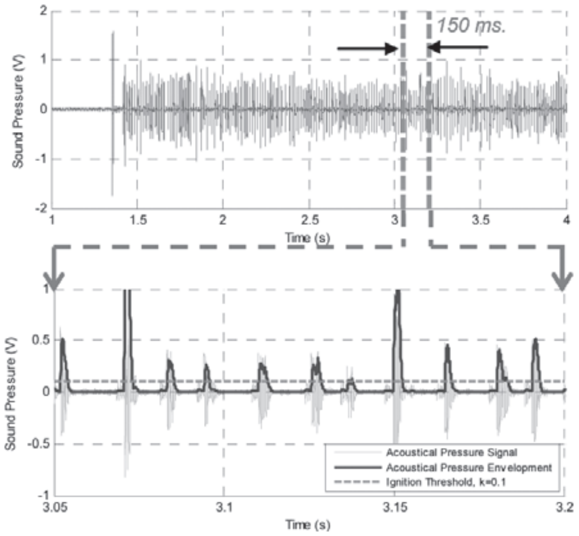

Figure 4. Arc sound envelope moving windows data

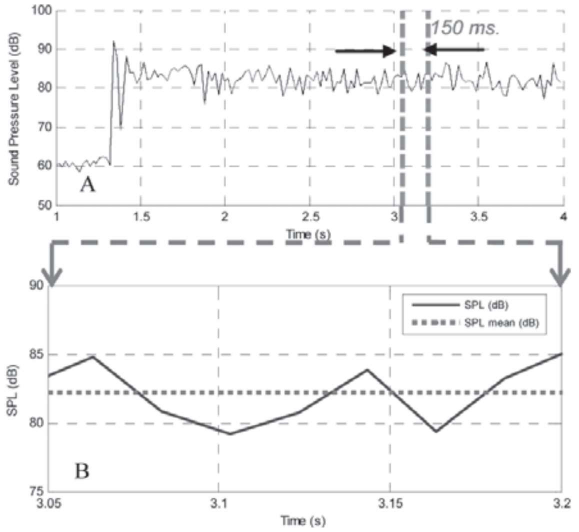

Figure 5. Sound level moving window data

3.4. Sound Level - SL

In first time, the sound level (SL) was computed by the equation 10 (See Figure 5-A).

$$SL = 20\log_{10}\left[\sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t}\left(\frac{s(t)}{s_m}\right)^2 dt}/p_o\right] \quad (10)$$

Where: SL is the sound level (dB), *Sm* 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).

Secondly the SL was calculated from 150ms windows data using the equation (11).

$$\overline{SL_\iota} = \frac{1}{n}\sum_{j=1}^{n} \mathrm{SL_i} = \frac{1}{n}\left(SL_1 + \cdots + SL_n\right) \quad (11)$$

Where $\overline{\mathrm{SL_ı}}$ is the SL average of each i data window and $\mathrm{SL_i}$ are SL data from i*th* until n*th* component in each moving window.

3.5. Welding Quality Assessing

Figure 6 shows the simultaneous stochastic behaviour of SL and IgR parameters and their individual statistic distributions (histogram). The Figures 6 [A], [B], [C] and [D] correspond at the weld run sets: free disturbances, CTWD variation, grease on plate and supply lack of shielding gas respectively.

In the weld run set correspondent at experimental welds without disturbances (Figure 6 [A]), is possible to notice that their statistical distributions have similarity with a uniform normal distributions and the parameters data are concentrated just in one region what implies that the welding set run has stationarity and so it is stable. This behaviour of both parameters corresponds at high quality welds reached with the welding parameters specified in the table 1. After computing SL and IgR parameters, their averages are 84.74 dB and 90.57 ignitions per second respectively. Their standard deviations are 0.7808 and 5.0897 respectively. On their respective graph, there is an elliptic region that indicates approximately the stability zone which means that just the welds with a high quality, will have similar distributions in their SL and IgR parameters. This ellipse is centred on the intersection of the averages of profile parameters. The proportion of its axes is a function of the equation (12) and this based on the third standard deviation method; this method is widely used in statistic quality control.

$$A_{P^x} = \overline{P^x} + 6 \times S_{P^x} \quad (12)$$

Where: $A_p x$ is the P^x*th* axis of the ellipse, $\overline{P^x}$ is the average of the *xth* parameter, $S_p x$ is the standard deviation of the P^x*th* 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.

Figure 6 (B) shows a considerable group of data parameters out from stability zone. This distribution corresponds to CTWD variations induced weld runs set. In this graph can be noticed that their individual histograms are corrupted in comparison with the profile expected. Also is possible to notice that there is more corrupted variation on IgR than SL parameter. Although this fact, the distances of the variations of the SL parameter are not too considerable but its incidence and dense concentration on the limit of the stability zone deserves a careful analysis. The IgR parameter has a chaotically data distribution, principally low rates. This behaviour implies definitely the presence of some perturbation on the process, in this case the CTWD variation that implies the length arc variation.

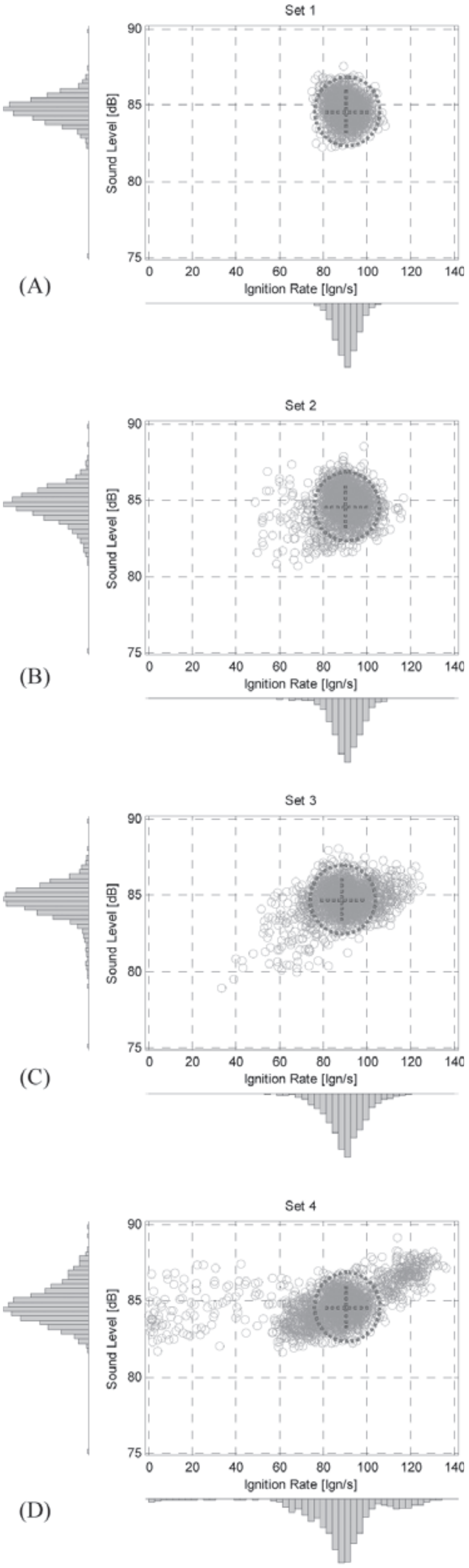

Figure 6. Quality welding assessment parameters

In the figure 6 (C) is shown a chaotic data distribution out from stability zone correspondent to welding set with perturbation induced: grease on plate. Their individual histograms have unexpected components in comparison with the reference profile. It is possible to notice that there are bigger variations on SL and especially on IgR parameter.

The SL and IgR parameters in the welding set with the third induced perturbation (absence of shielding gas) also have a chaotic data distribution out from stability zone (Figure 6 (D)). It is possible to notice that there are bigger variations on SL and especially on IgR parameter; it has the most chaotic behaviour than in other cases.

4. Conclusions

Arc voltage and welding current were used to estimating the arc power and a comparative analysis with the arc sound demonstrates that there is a close relation between the arc sound and the arc power. Also it was noticed that there is a delay between both signals due to the airborne nature of the sound propagation.

After processing the sound and power signals, it was found that the differentiated and conditioned power signal is equivalent at envelope conditioned sound signal. And a second analysis demonstrates that the arc sound reach a stationary state what means that this signal can be used as a quality welding parameter.

From arc sound were calculated two parameters: IgR and SL. Both parameters are stationary for welding without induced interferences and from them were estimated their average and standard deviation which were used for establishing the stability zone. This region was delimited by an elliptical region on the both parameter distributions. The axes of this elliptical region were calculated following the third standard deviation criteria. This representation was used to assessing the welding quality. The IgR and SL data distributions were represented for the three weld run sets with induced disturbances. In every distribution data was observed data parameters out from stability region. In some experiments just one parameter had changes in its distribution, but it was enough to consider the quality welding as unsatisfactory. For example it was noticed that in experiments with CTWD variations and shielding gas fall induced disturbances, the SL parameter has not pronounced variations and just in experiments with grease on the plate disturbance there is notable changes that can indicate anomalous behaviour on the weld and consequently a low welding quality. In counterpart the IgR parameter was very expressive for all different kinds of perturbations. This parameter measures the short circuits frequency which means that it is measuring the regularity of the transfer cycles. So any changes in the frequency will alter the welding quality and it is noticed by the IgR, but the SL parameter is based in the RMS of the sound data window, and sometimes the eventual irregularities of the short circuit frequency cannot be expressed with clarity. In other words, the SL parameter measures changes in the amplitude of the arc sound and the IgR measures changes in the frequency of the arc sound (sequence of acoustic peaks). The SL parameter has a disadvantage that depends of the amplitude of the arc sound, and it cannot be constant because in first time its amplitude gain changes according of the distance between the poll fusion and the microphone. Secondly the arc sound amplitude can be corrupted by the ambient noise, generating false responses. For GMAW-S acoustic monitoring the IgR parameter was highly effective. It could detect changes in all welding experiment with disturbances. Although those disadvantages the SL parameter, it could be used in other welding processes that their arcs welding does not generate peaks of sound (GTAW, LASER), but definitely is critical to take care with the acoustic noise of environment.

The combination of data parameter was interesting because is better to has different data sources to has more certainly about some irregular data distributions, and the monitoring of other arc parameters including the arc sound could give a mayor certainly at the moment of assessing the welding quality and also the knowledge of some characteristic in the parameter behaviour associated with some disturbance could enable the detection of disturbances.

Acknowledgements

The authors gratefully acknowledge support for this Project from The Brasilia University, the CNPq (Brazilian Research Council) and Finatec (Private Research Foundation).

References

[1]. Kralj, V.: "Biocybernetic investigations of hand movements of human operator in hand welding". *IIW/IIS Doc. 212-140-68, 1968*.

[2]. Drouet, M., Nadeau, F.: "Pressure waves due to arcing faults in a substation", *IEEE Trans. Power App. Sys., 5*, pp. 98, 1979.

[3]. Arata, Y., Inoue, K., Futamata, M. and Toh, T.: "Investigation of welding arc sound (report 1) - effect of welding method and welding condition on welding arc sound". *Trans. Join Weld Res. Inst. Osaka Univ., 8,* pp.25-38, 1979.

[4]. Tam, J., Huissoon, J.: "Developing psycho-acoustic experiments in gas metal arc welding", *International Conference on Mechatronics & Automation, Niagara Falls, ON, Canada*, pp. 1112-1117, Jul 2005.

[5]. Grad, L., Grum, J., Polajnar, I., and Slabe, J.M.: "Feasibility study of acoustic signals for on-line monitoring in short circuit gas metal arc welding", *International Journal of Machine Tools and Manufacture, Volume 44, Issue 5*, pp.555-561, 2004.

[6]. Čudina, M., Prezelj, J., Polojnar, I.: "Use of audible sound for on-line monitoring of gas metal arc welding process", *Croatian Metallurgical Society, Metalurgija 47 2*, pp.81-85, 2008.

[7]. Cayo, E.H.: "Monitoring, detection and localization system for welding defects based on the acoustic pressure of the GMAW-S process electric arc". *Master Dissertation in Mechatronics Systems, FT University of Brasilia, DF, Brazil*, pp. 108, Set 2008.

[8]. Hermans, M.J.M., Den, O.G.: "Process behavior and stability in short circuit gas metal arc welding". *Weld. J., 78*, pp.137-141, 1999.

[9]. Bingul, Z., Cook, G. E.: "A real - time prediction model of electrode extension for GMAW", *IEEE/ASME Transactions on Mechatronics, vol 11, no 1., 2006*.

[10]. Adolfsson, S., Bahrami, A., Bolmsjö, G., Claesson, I.: "On-line quality monitoring in short-circuit gas metal arc welding", *Welding Journal, p. no2* pp.59-73 Feb. 1999.

[11]. Cook, G.E., Maxwell, J.E., Barnett, R.J. and Strauss, A.M.: "Statistical process control application to weld process". *IEEE Trans. Ind. Appl., 33*, pp.454-463, 1997.

[12]. Wu, C.S., Gao, J.Q. and Hu J. K.: "Real-time sensing and monitoring in robotic gas metal arc welding", *Measurement Science and Technology, Institute for Materials joining, Shandong University, Jinan, 250061, People's Republic of China,* 18 pp.303-310, 2007.

[13]. Absi, S.C., Carbalho, G.C., Da, Cunha, F.R.: "A statistical approach for monitoring stochastic welding processes", *Journal of Materials Processing Technology, 175*, pp.4-14, 2006.