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Cladding welding of CA6M with pulsed FCAW and results analysis through the L9 TAGUCHI and ANOVA

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***Abstract*— *The cladding welding analysis with pulsed flux cored arc welding (FCAW) process, were carried over a AISI 1020 base metal (thickness 12,7 mm, width 63,5 and length 185mm) with an CA6NM steel wire with diameter of 1.2mm. Was performed only one weld cord in the flat position. For experimental design was used the method of Taguchi L9 to determinate the parameter to be analyzed through the application of the analysis of variance (ANOVA) method. The response signals in RMS (Root Mean Square) analyzed were the voltage, current and acceleration. The procedure is based on a non-parametric domain-selective ANOVA for functional data, which results in the selection of the intervals of the domain presenting the most statistically significant effects of each factor over the selected response signals. The statistical results presented by ANOVA show that not all the selected variables have influenced the results. The best results for the cladding welding were obtained from the current average of230amperes, and statistically the average current was the variable that significantly affected the results, however, the welding speed only affected the yield of the process.*

Keywords*— *FCAW Pulsed, Martensitic steel cladding, RMS current, ANOVA.

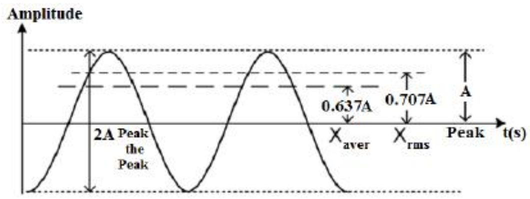
I. INTRODUCTION

The cladding welding of carbon steel with stainless steel is defined by PALANI & MURUNGAN (2007) as the deposition of a layer of stainless steel on surfaces of carbon steel or low alloy steels with the purpose of obtaining coatings with good properties of corrosion resistance. Even though the stainless steel offers some huge advantages over the common carbon steel, the price of using stainless steel can be ten times greater. In that way, the cladding welding process main advantage is related to the fact that the produced layers are less expensive but still benefits from some of the properties of the stainless steel if compared with the carbon steel.

The arc welding with FCAW (Flux Cored Arc Welding) is a process that produces coalescence of metals by heating them with an arc established between a continuous consumable tubular electrode and the work piece (MARQUES et al., 2005 andRODRIGUES et al, 2008). The protection of the arc and the weld bead is provided by a welding flux contained within the electrode, which can be supplemented by a gas flow supplied from an external source. For stainless steels literature recommends using argon mixture with 2% oxygen which has a slightly oxidizing behavior.

The monitoring technique used in this work was based in sensors that could acquire simultaneously signals such as, current, voltage and acceleration. The vibration signal that provides interesting results in Predictive Maintenance Programs, and also in the analysis of welding stability, as the spectral analysis of vibration frequencies can show different defects characteristics during a welding process.

In the Figure 1a, it is possible to observe the correlation between the average, peak, peak-to-peak, RMS value and the amplitude of a sinusoidal signal. The Figure 1b shows a generic vibrational signal. In a signal of this nature, the choice of the numerical value to be used to determinate its characteristics can imply in great differences.



(a) Main characteristics of a vibration signal Average, RMS and peak.

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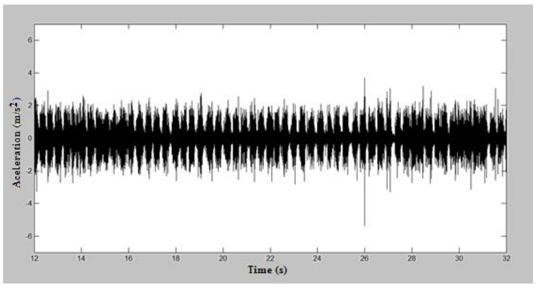

(b) Example of a vibration signal in the time domain.

Fig.1: Examples of vibration signals (RAO, 2009)

The method that involves vibration measurements are subdivided into: techniques based on the time domain, frequency domain and time/frequency domain. The graphics of the signal in the time domain registers the amplitude as a function of the time but when analyzed through the frequency domain, the amplitude is presented as a function of the frequency. As can be observed in the Figure 2, the identification of the frequency components of complex signals by using the time domain is very difficult, so the signal is transported to the frequency domain to make it simpler to find erratic behaviors that could represent some failure or another point of interest in the signal. The effective value or Root Mean Square (RMS) is the mean quadratic level of a sinusoidal signal, being an extremely important measure of the amplitude, as it shows the average energy contained in a vibratory movement.

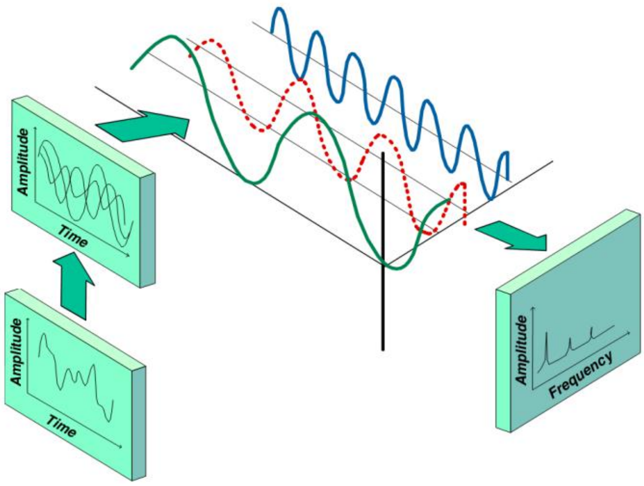

Fig.2: Comparison of the analysis of a signal through the time and frequency domains (RAO, 2009)

Based on the simultaneous acquisition of signals, a variety of studies has been developed, such as the research of (ARATA et al; 1981) that used an accelerometer and a microphone to identify possible defects in a GMAW welding process, where (GRAD et al; 2004) also conducted an extensive research of this process through the analysis of the current signals with a noise signal acquired with a microphone. In a more advanced research, JOHNSON et al (1991) coupled the current, voltage and noise signals together to produce a more reliable analysis system.

For the FCAW process, (WANG et al, 1995) wrote about the prediction of the metal transfer modes through the analysis of simultaneously acquired signals. As well as LIMA & FERRARESI (2006) that developed a research on the analysis of current and voltage signals in a way to determinate the metal transfer mode.

The statistical analysis in this work is based on the analysis of variance (ANOVA), that is primary used to verify which parameters are more intensively correlated to the results obtained during the tests (THAKUR & NANDEDKAR, 2010).

The main parameters analyzed through this method are the average current, pulse frequency, welding speed and contact tip to work distance, which were correlated to the geometrical parameters of the weld cord. ANOOP & KUMAR (2013), KUMAR (2014) at optimization in tungsten gas arc welding with aluminum and stainless steel, respectively using Taguchi and ANOVA. PINI et al (2015) studied the analysis of a laser welding process through the ANOVA software method (ANIL KUMAR et al, 2015) studied the parameters of welding with ANOVA.

II. MATERIALS AND METHODS

Materials:

The base metal used was an AISI 1020 steel plate with the following dimensions (185 × 63.5 × 12.7 mm) and for the cladding was used the EC410NiMo MC 1.2 mm in diameter electrode wire with the shield gas a mixture of argon with oxygen 2%. The chemical composition of the base metal and filler is show in Table 1.

Table.1: Chemical composition data for the base metal and the filler metal

Materials	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**
AISI 1020	0.18/0.23	0.30/0.60	0.03	0.035	0.10/0.30	0.15	0.15	…
EC410NiMo	0.027	0.590	0.024	0.006	0.44	4.86	12.50	0.43

Methods:

To perform the welding, a test bench consisting of a welding machine, a displacement system for the welding torch and a modular data acquisition system, compose by an ammeter, a voltmeter and an accelerometer. A diagram of this test setup can be seen in the Figure 3 at where the main features and components are described.The welding process is usually limited by the diameter of the wire used for deposition.

Being possible to use large diameter wires to weld in the flat surfaces in the horizontal position, the use of small diameters wires makes possible to weld in almost any position.

After the welding process, a layer of slag that covers the weld bead must be removed to be able to visualize clearly the bead and its defects. Figure 4 shows a schematic view of the flux-cored arc welding process.

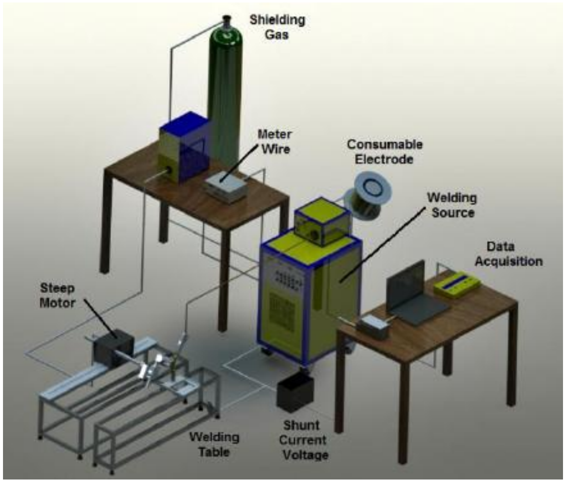

Fig.3: Diagram showing the layout of the test equipment

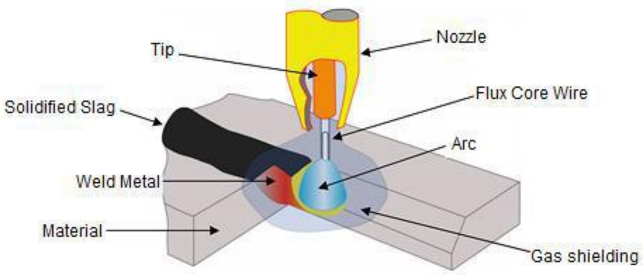

Fig.4: Schematic view of the flux cored arc welding process

The FCAW parameters of interest for this work are the welding speed, current, the distance between the wire and the work-piece or Arc Length, and the pulse frequency.

The welding parameters were defined through an extensive bibliographical consultation and preliminary tests. Through the analysis of those acquired data and taking into account the main goals of this study, the limits of each variable were prefixed. The Table 2 shows those parameters and their values that were used during the tests.

Before the welding process, all the specimens surface were treated through an abrasive blasting process with steel grit G-25 S-280 with hardness D, this process were produced in accordance to the SAE J444 (1993) standard, to provide a surface free of contaminants. The equipment used were a CMV blaster, model GS-9075X.

After that, all samples were pre-heated to a temperature of 200ºC in a muffle furnace NT-380 before they were brought to the test bench, then, an infrared gauge were used to monitor the work piece temperature, in the moment that it reached 150ºC, the welding process were started.

Table.2: Optimal parameters obtained for the FCAW process and their respective values

Parameters	Values
Polarity of the Electrode	DCEP
Shielding Gas	O_2 + 2% Ar
Gas Flow	18 L/min.
Torch Angle	90^O
Welding Position	Flat
Inter-pass Temperature	150^O C
Number of Cords	01
Peak Current (Ip)	350 A
Peak Time	10 ms

The signals provided by different sensors (ammeter, voltmeter and accelerometer) were acquired simultaneously as well as the welding vibration that was detected with a piezoelectric accelerometer model KSD-80D, with a sensibility of 100 mV/g and response frequency in the range of 0,13 ~ 22000 Hz.

The accelerometer was installed in the central part of the specimen below the welding table, in such a way that its operating temperature would not be exceeded, where the initials tests to verify the accelerometer responsiveness and was possible to verify that its location did not affected the results.

Figure 5 shows a schematic view of the accelerometer assembly used in the work piece, and is important to observe that the torch displacement systems was not mounted in the same structure as the welding table in a way to isolate the noises that could be picked during its motion.

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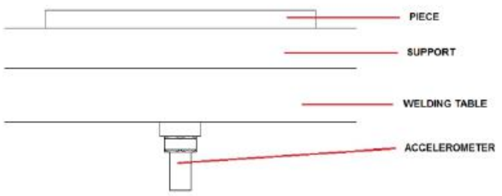

Fig.5: Schematic arrangement of the accelerometer

Development of L9 Taguchi

The method developed by Taguchi objective: Project products or processes that are robust with respect to the environmental, design and develop products that are robust to the variability of its components and minimize variability around a nominal value.

The methods Taguchi (MONTGOMERY & RUNGER, 2012) typically use three or more levels in the welding process parameters that aim at estimating potential non-linear interactions thereof.

To relate the combination of four variables and three levels of each was used the test by Minitab software and the relationships are presented in Table 3.

The Taguchi method has been optimized for many studies of welded joints by various processeswhere delineating experimental matrix with their levels.

Experiments based on the Taguchi technique was used to get the data by analysis of variance (ANOVA) were used to investigate the welding characteristics for deposition of EC410NiMo MC in AISI 1020 steel and optimize welding parameters (SAPAKALet al 2012)

III. RESULTS AND DISCUSSIONS

For a better uniformity of the results, the signals were all analyzed between the times of 20 and 30 seconds. In that way, the results obtained were most probably found in a zone were the arc was fully developed. The results shown as RMS (Root Mean Square) values can be seen in the Table 4 for the 9 samples. It is possible to observe that the highest RMS current and voltage values were obtained for an Average Current of 230 A.

In the FCAW welding process as in the GMAW, the metal transfer through short circuit occurs at low currents and low voltages levels, then, possibly at voltages up to 20 V this was the predominant type of metal transfer. While at voltages above 20 volts there was probably occurred globular transfer with the presence of elongation, causing the drop to touch the workpiece without being transferred.

Table.3: Design of Experimental Matrix

Sample	Average Current (A)	Pulse Frequency (Hz)	Welding Speed (mm/min.)	Tip to Work-piece Distance (mm)
1	170	18.18	300	30
2	170	22.22	350	33
3	170	20.00	400	36
4	200	20.00	300	33
5	200	18.18	350	36
6	200	22.22	400	30
7	230	22.22	300	36
8	230	20.00	350	30
9	230	18.18	400	33

Table.4: Results for current, voltage and acceleration of the pulsed current in RMS

Sample	Welding Parameters				Results		
	Average Current (A)	Pulse Frequency (Hz)	Welding Speed (mm/min)	Contact Tip Work Distance (mm)	Current RMS (A)	Voltage RMS (V)	Acceleration RMS (m/s^2)
1	170	18.18	300	30	193.2465	15.2346	0.3779
2		22.22	350	33	185.4450	16.9629	0.3147
3		20.00	400	36	160.5643	17.7862	0.2945
4	200	20.00	300	33	191.3539	25.4825	0.2009
5		18.18	350	36	182.2212	26.3488	0.1854
6		22.22	400	30	178.3370	22.1801	0.2065
7	230	22.22	300	36	209.9335	27.8447	0.1810
8		20.00	350	30	215.3948	25.3854	0.1700
9		18.18	400	33	195.2679	25.3066	0.1665

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The best welding current during all the tests was 230 A, this result could be probably related to the fact that it could be above the transitional current and that it could have a greater heat input that increases the wire tip temperature due to the Joule Effect, which facilitate the transfer process.

Using shadowgraph KIM & EAGAR (1993) mention what the fact that the transition between metal transference modes (globular with elongation and rotational transfer) are more likely to occur when the base material is steel and the shielding gas is argon.

It is also possible to observe in the Table 4 that the average RMS acceleration for the pulsed current was 0.3290 m/s^2 for 170 A, 0.1976 m/s^2 for 200 A and 0.1725 m/s^2 for a 230 A current, which shows that the acceleration decreases substantially with the increase of the average current, meaning that less vibration was captured, leading to a more stable arc during the welding process.

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested. Tables 5, 6 and 7 present the RMS ANOVA of current, voltage and acceleration respectively. Table 8 shows these compiled results.

The software MINITAB in its version 16 was used to produce the statistical results for this work. Statistically when the significance level (α) of an output parameter, provided by ANOVA results for a given factor, were less than 5%, we can say that this factor must directly affect the response of the result.

However if the significance level (α) values are greater than 5% there is a weak correlation between the factor analysis and the output signal (PATEL & PATEL, 2014).

It is also possible to observe in the same table, the factors that affect the output signals are the average current, which was directly correlated with all three results, but on the other hand, the welding speed was the only affecting RMS Current (α = 0.000344%).

On the other hand, the Contact Tip to Work Distance were more likely to have close correlation with the RMS Current and Voltage (α = 0.028926% and 0.004418, respectively), but with less intensity if compared to the other situations.

The Root Mean Square showed that the effects of the quadratic regression, was better than linear regression in a given range.

However, quadratic regression could not directly perceive the relationship between the welding parameters and weld geometry. Hence, this research considered the establishment of the exponential regression.

This exponential regression showed that with the increasing of welding average current, notice that the weld width and reinforcement increase and also if welding voltage increases, the weld width increases, reinforcement decreases a bit.

Table.5: ANOVA to RMS Current

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	4	3315.20	3315.20	828.80	17.0582	0.000043
Average Current (A)	1	1894.73	1894.73	1894.73	38.9969	0.000030
Pulse Frequency (Hz)	1	6.00	6.00	6.00	0.1235	0.730870
Welding Speed (mm/min)	1	1121.58	1121.58	1121.58	23.0841	0.000344
Contact Tip to Work Distance (mm)	1	292.89	292.89	292.89	6.0283	0.028926
Error	13	631.63	631.63	48.59		
Total	17	3946.82				

P.S.*Adjusted squared sum (Adj SS) is a measure of the variation for the different components of the model.*
Adjusted mean squares (Adj MS) measure how much variation a term or model explains.
Sums sequential squares (Seq SS) are measures of the variation of different components of the model.
Degree of Freedom (DF)

Table.6: ANOVA to RMS Voltage

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	4	297.701	297.701	74.425	24.7937	0.000006
Average Current (A)	1	257.553	257.553	257.553	85.8003	0.000000
Pulse Frequency (Hz)	1	0.037	0.037	0.037	0.0122	0.913739
Welding Speed (mm/min)	1	4.654	4.654	4.654	1.5504	0.235061
Contact Tip to Work Distance (mm)	1	35.457	35.457	35.457	11.8121	0.004418

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Error	13	39.023	39.023	3.002		
Total	17	336.724				

Table.7: ANOVA to RMS Acceleration

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	0.086599	0.0965991	0.0216498	15.5975	0.000070
AverageCurrent (A)	1	0.081593	0.0815925	0.0815925	58.7829	0.000004
Pulse Frequency (Hz)	1	0.000033	0.0000332	0.0000332	0.0239	0.879474
Welding Speed (mm/min)	1	0.000758	0.0007584	0.0007584	0.5464	0.472926
Contact Tip to Work Distance(mm)	1	0.004215	0.0420150	0.0420150	3.0367	0.104992
Error	13	0.018044	0.0180444	0.0013880		
Total	17	0.0104644				

Table.8: Level of Significance (P) obtained through the ANOVA method

Factor	RMS Current (A)	RMS Voltage (V)	RMS Acceleration (m/s^2)
1 – Average Current (A)	0.000030	0.000000	0.000004
2 – Pulse Frequency (Hz)	0.730870	0.913739	0.879474
3 – Welding Speed (mm/min)	0.000344	0.235061	0.472926
4 – CTWD (mm)	0.028926	0.004418	0.104992

Figures 6, 7 and 8 shows the effects and influence of the factors for each response variable and the higher the slope of the curves, the bigger the influence of the factors over the output variables. Those graphics can provide a quick and interesting perspective of the data provided in the Table 4.

As it is possible to observe on the Figure 6, the average current are much more likely to interfere with the RMS current, specifically at higher current levels, on the other way, the welding speed is more likely to interfere at lower speed, the same is also true for the contact tip to work distance (CTWD).

On the Figure 7, the same behavior can be observed for the RMS voltage, being the average current the most correlated factor, on the other hand, the effect of the contact tip to work distance (CTWD) is the complete opposite, being more correlated for bigger distances. With respect to the acceleration, the results are totally opposite to the ones shown above, as the average current influence appeared at low accelerations, this result, as already discussed, demonstrate the higher level of stability of the arc for higher average currents, probably this happens due to a change of the metal transfer mechanism (from short circuit to globular).

For all the situations, it is possible to visualize the low influence of the pulse frequency in the results, the same result is possible to observe in the Table 4, as for this factor, the Level of Significance were the highest above all other factors. The welding speed, as well, did not show a high interference in all situations.

From the Table 4 as for the Figures 6 and 7, it is possible to note that statistically the CTWD affect more the RMS voltage than the RMS current and makes almost no effect over the RMS Acceleration.

This could be related to the fact that the CTWD will influence directly the amount of heat generated due to the Joule effect that can change the melting of the wire and its internal heating, which facilitates the metal transference.

If the distance is too big, there will be a lot of spills and the formation of a convex bead, but, if the distance is too small there will be more arc instability.

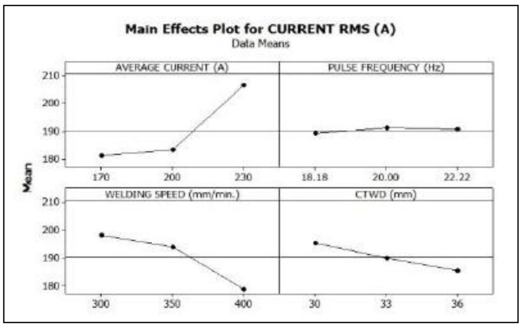

Fig.6: Effect of the main factors over the RMS Current

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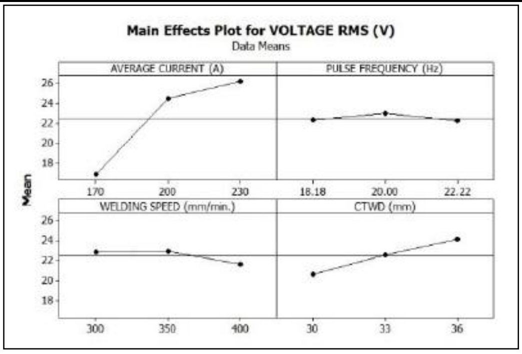


Fig.7: Effect of the main factors over the RMS Voltage

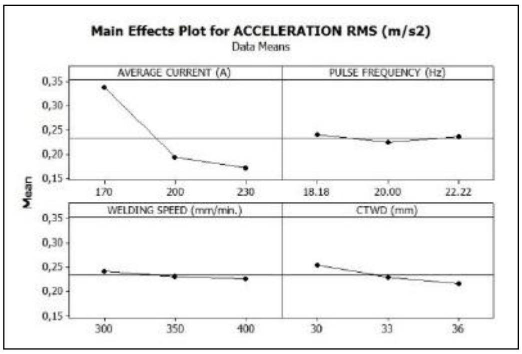


Fig.8: Effect of the main factors over the RMS Acceleration

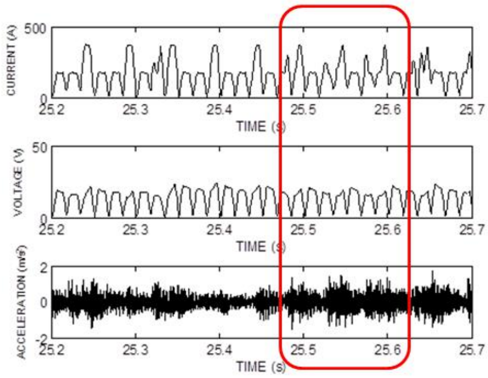
To provide a better view of the results obtained from the signals, the Figure 9 presents the simultaneous signals for the current, voltage and acceleration as a function of the average current in 0.5 seconds of interval.

For the average current welding at 170 A and 200 A, as shown in Figure 9a and 9b, respectively, there is an instability evidenced arc in the current graphics and acceleration, which showed abnormal behavior with series of current peaks with different amplitudes and lot of noise in the acceleration graphics.

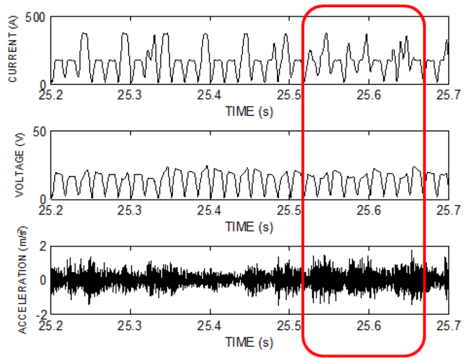
Therefore, the results show that the metal transfer mechanism is not occurring as expected, with a behavior which characterizes the metal transfer short circuit.

Those characteristics were found as well by (LUZ et al; 2005), (LIMA & FERRARESI, 2006) (STARLING & MODENESI, 2005) that observed a behavior very similar with the one found here.

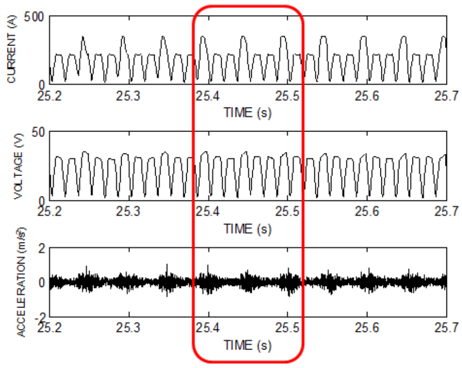
The better condition of droplet detachment was to current average of 230 A as in the Figure 9c,where you can observe a arc stability with current and acceleration and stable metal globular transfer (WANG, et al 1995, KIM & EAGAR 1993), which was observed in other studies in more detail by a high speed camera system (LOPERA et al 2011, DUTRA et al 2012).



(a) Currentof 170 amperes.



(b) Current of 200 amperes.



(c) Current of 230 amperes.

Fig.9: Simultaneous signals acquired in a total range of 0.5s.

IV. CONCLUSIONS

The analysis of the cladding welding through the FCAW pulsed process by applying the ANOVA method presented some very interesting results on respect to the weld quality and arc stability, mainly by high correlation between the average current and the arc stability.

The fact that the welding speed is not a big factor influences the arc stability and consequently to the quality of the weld cord, shows that cladding process could be faster without to drop the quality.

Which respect to the pulse frequency, was found that it does not imposes great differences over the process, not interfering so much over the metal transfer process or arc stability.

As the acceleration showed very well the stability of the arc, it is possible to say that the use of an industrial accelerometer as a non-intrusive and easy to install method to verify the stability of the arc during the welding process, making it possible even to correct the parameters directly.

Therefore we observed that statistically analyzedthe best results for the cladding welding were obtained from thecurrentaverage of230amperes, with the average currentbeing that more likely to interfere with the RMS current, specifically at higher current levels.

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