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REAL TIME WELDING DEFECTS MONITORIMENT USING SPECTROMETRY

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Abstract. *This work presents an evaluation of a spectrometer for monitoring the arc electonic temperature (GTAW - Gas Tungsten Arc Welding). This electonic temperature is calculated measuring the relative intensity of chosen emission lines that can be found in the arc, like Argon, and other factors that come from quantic physics. It is known that the arc electronic temperature is related to the weld penetration depth and weld current. Therefore, monitoring arc eletronic temperature means depth monitoriment. The monitoration stablished a relation between the variation of the arc eletronic temperature (related to the tension produced by the sensor) and the variation of weld current. Some defects were simulated, like current variation, grease insertion and variation on the shielding gas flow. Their pertubation in the eletonic temperature were collected by the spectrometer as well. The data has been collected via a USB connection.*

Keywords*: Gas Tungsten Arc Welding, Welding Monitoring, Spectrometry.*

1. INTRODUCTION

One of the most manufacturing processes used in industry is arc welding. In ordering to guarantee the quality process, many studies have been made. They have begun with visual inspections, destructive and non-destructive testing techniques. But it was only made after the process and it raised the final cost.

This work proves that it is possible to improve a non-destructive and on-line weld defects monitoring system. It consists on monitoring the electronic temperature of chosen elements that are involved in the welding process. This property is taken from the arc weld region (plasma column) using an optic spectrometer sensor.

Some supposes are taken. The plasma is in local thermo dynamical equilibrium (LTE), i.e., there is no microscopic reversibility of collision and radioactive processes (Lacroix, 1999). It means that collision process should be greater than radioactive ones. Thus, based on (kinetic) electron temperature, atom and ion temperature can be calculated indirectly. This condition is not true near the electrode and plate. Thus, the arc area analyzed stands between these two pieces, but not including them.

1.1. Emission spetrometry and plasma characterisation

Spectrometry stands for a set of experimental techniques used for measuring the electromagnetic spectrum that results from phenomena such as absorption, emission or diffraction of electromagnetic radiation by atoms or molecules.

By the Quantum Theory, atoms and molecules can only exist in a steady energy states, which are characterized by discrete amounts of energy that are specific to each atom or molecule. When there is a change of this energy state, the electrons of atoms or molecules absorbs or emits a specific quantity of energy and light absorption or emission with a particular length related to the energy of both states. This theory is mathematically expressed as:

$$E_i - E_n = \frac{h \cdot c}{\lambda} \tag{1}$$

Where E_i is the energy in the lower state, E_n is the energy in the higher state, c is the light speed, h is the Planck Constant (6.6260755e-34 J.s) and λ is the wave length.

Two different kind of analysis can be made in the plasma: qualitative and quantitative. In the first, one can identify the elements that are present in the plasma. The second analysis corresponds in monitoring the intensities of chosen line spectrums. This can be used to calculate electronic temperature and plasma density.

1.2. Electronic temperature calculation

According to the LTE hypothesis, the plasma temperature is calculated from the temperature of the electrons. This theory means that the particles have an energy distribution given by the Maxwell equation and that the collision processes are dominant relative to the radiation processes, consequently the electrons temperature is similar to the temperature of the heavy particles (Griem, 1964). The LTE hypothesis is valid when

$$N_e \geq 1.6e12\sqrt{T_e}(\Delta E)^3 \tag{2}$$

In which N_e is the electronic density, T_e is the electron absolute temperature and ΔE is the difference of the transition energy intervals.

The method used to calculate the electronic temperature is the relative intensities of spectral lines (Griem, 1964). It considers two set of line transition, m→ r and j→ i, in the same ionization stage. Therefore, these transitions have the same ground state. A schematic figure can be seen below, in which N is the particle number, E is the Energy of the level, g is the statistical weight of the state, h is the Planck's constant and ν is the photon emission frequency:

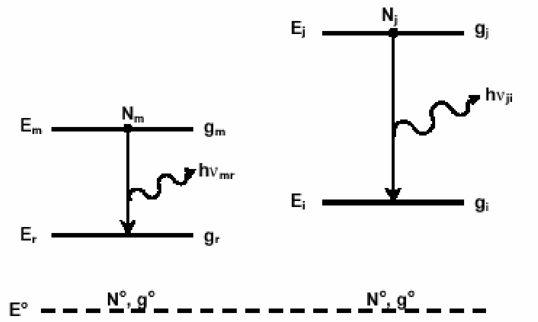

Figure1 - Spectra lines at the same ionization stage

The number of electron particles of the levels m and j is given from the Boltzmann's law (Chian,1979):

$$N_m = \frac{g_m}{g^0} \cdot N^0 \cdot \exp\left(\frac{E_m - E^0}{K_B \cdot T_e}\right) \tag{3}$$

$$N_j = \frac{g_j}{g^0} \cdot N^0 \cdot \exp\left(\frac{E_j - E^0}{K_B \cdot T_e}\right) \tag{4}$$

In which g_m and g_j are the statistical weight of states m and j, K_B is the Boltzmann's constant (1.380658e-23 J./K). These information about the elements can be found at the site of NIST (National Institute of Standards and Technology). The statistical weight is represented as a function of Z (Te), called partition function, given in Equation 5:

$$Z(T_e) = \sum g_s \cdot \exp\left(\frac{h \cdot \upsilon_{1s}}{k \cdot T_e}\right) = g_1 + g_2 \cdot \exp\left(\frac{h \cdot \upsilon_{12}}{k \cdot T_e}\right) + \ldots + g_s \cdot \exp\left(\frac{h \cdot \upsilon_{1s}}{k \cdot T_e}\right) \tag{5}$$

Equations 3 and 4 can be rewritten as:

$$N_m = \left(\frac{N^0}{Z \cdot T_e}\right) \cdot g_m \cdot \exp\left(\frac{-E_m}{K_B \cdot T_e}\right) \tag{6}$$

$$N_j = \left(\frac{N^0}{Z \cdot T_e}\right) \cdot g_j \cdot \exp\left(\frac{-E_j}{K_B \cdot T_e}\right) \tag{7}$$

The number of atoms that leaves an excited energetic level in a short period of time dt is proportional to the atom population in that stage at a time t. It can be written as:

$$\frac{dN_m}{dt} = -A_{mr} \cdot N_m \tag{8}$$

$$\frac{dN_j}{dt} = -A_{ji} \cdot N_j \tag{9}$$

Where A_{mr} and A_{ji} are the spontaneous transition probability, also found at the NIST site.
The emission line intensity for a transition from state m to state r and from state j to i are given as:

$$I_{mr} = N_m \cdot A_{mr} \cdot h\upsilon_{mr} \tag{10}$$

$$I_{ji} = N_j \cdot A_{ji} \cdot h\upsilon_{ji} \tag{11}$$

Substituting Equations 6 and 7 on Equations 10 and 11, it gives:

$$\frac{I_{mr}}{A_{mr} \cdot g_m \cdot \upsilon_{mr}} = \left(\frac{N^0 \cdot h}{Z \cdot T_e}\right) \exp\left(-\frac{E_m}{K_B \cdot T_e}\right) \tag{12}$$

$$\frac{I_{ji}}{A_{ji} \cdot g_j \cdot \upsilon_{ji}} = \left(\frac{N^0 \cdot h}{Z \cdot T_e}\right) \exp\left(-\frac{E_j}{K_B \cdot T_e}\right) \tag{13}$$

Applying logarithm on the both sides:

$$\ln\left(\frac{I_{mr}}{A_{mr} \cdot g_m \cdot \upsilon_{mr}}\right) = \ln\left(\frac{N^0 \cdot h}{Z \cdot T_e}\right) - \frac{E_m}{K_B \cdot T_e} \tag{14}$$

$$\ln\left(\frac{I_{ji}}{A_{ji} \cdot g_j \cdot \upsilon_{ji}}\right) = \ln\left(\frac{N^0 \cdot h}{Z \cdot T_e}\right) - \frac{E_j}{K_B \cdot T_e} \tag{15}$$

The electronic temperature is calculated by the relation between the relative intensities of a pair of one line spectral of a single element at the same ionization state. It is obtained dividing equations 14 and 15:

$$\frac{E_m - E_j}{K_B \cdot T_e} = \ln\left(\frac{I_{ji} \cdot A_{mr} \cdot g_m \cdot \upsilon_{mr}}{I_{mr} \cdot A_{ji} \cdot g_j \cdot \upsilon_{ji}}\right) \tag{16}$$

It is better to express the photon emission frequency (ν) in terms of wave length (λ). This can be done with the Equation 17:

$$\upsilon = \frac{c}{\lambda} \tag{17}$$

Substituting this on the Equation 16 for both lines and isolating the electronic temperature:

$$T_e = \frac{E_m - E_j}{K_B \cdot \ln\left(\frac{I_{ji} \cdot A_{mr} \cdot g_m \cdot \upsilon_{mr}}{I_{mr} \cdot A_{ji} \cdot g_j \cdot \upsilon_{ji}}\right)} \tag{18}$$

For the particular case of arc welding plasmas, where only the temperature of the plasma axis is needed, Te can be determined as:

$$T_e = \frac{E_m - E_j}{K_B \cdot \ln\left(\frac{E_m \cdot I_{ji} \cdot A_{mr} \cdot g_m \cdot \upsilon_{mr}}{E_j \cdot I_{mr} \cdot A_{ji} \cdot g_j \cdot \upsilon_{ji}}\right)} \tag{19}$$

The difference between Equations 19 and 18 can be seen by the inclusion of the ratio of the excitation energies of the selected lines in the logarithm. This consideration allows the approximate calculation of the local axial temperature in axisymmetric plasmas without using the more complex Abel inversion method (Mirapeix *et al.*, 2006).

With this simple method it is possible to monitor in real-time because the processing time is short. But the lines must respect the following condition:

$$E_m - E_j > K_B \cdot T_e \tag{20}$$

2. EXPERIMENTAL PROCEDURE

The experimental scheme can be seen below:

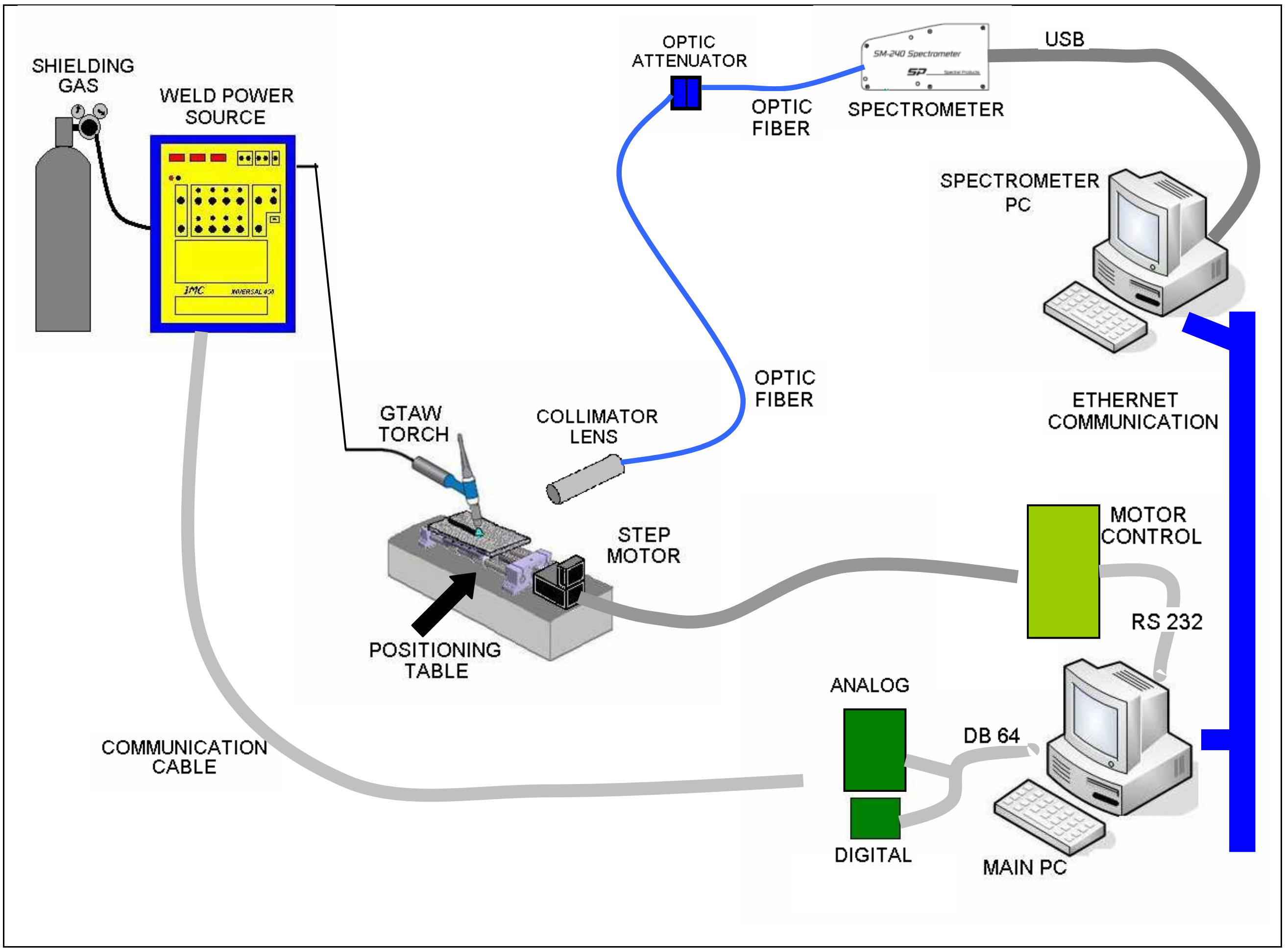

Figure 2 – Experimental scheme

The equipments seen above are:

- Weld power source: IMC Inversal 450. It is an inverse power supply that can provide 450 A. It works with many kinds of welding. For this work, it only used the GTAW continuous current type. The communication is made by one cable with analog and digital commands.

- Welding torch: an ordinary type. In the experiments it used a tungsten electrode with 2 % Thorium and a diameter of 1.6 mm. The stand-off was 5 mm for all experiments.
- Gas: Argon shielding gas at 10 l/min.
- Motor control system: Based on a PIC. It sends two different signals to control the motor. One corresponds to speed (frequency pulse) and the other is responsible for the direction.
- Step motor: Berger Lahr IDS91.
- Positioning table: In these experiments, there is a fixed holder for the welding torch. It is the table that moves the system with the plates.
- Acquisition board: Eagle Technologies 703S. It has two connectors, one for analog communication and the other for digital. Both are DB 37.
- Main PC: Responsible for sending and collecting information to the power supply via the acquisition system. In the experiments, the program developed in LabVIEW sends the value of the current (analog) for the welding machine and receives to analog signals corresponding to current and voltage. The digital communication is responsible for the ignition and shield gas flow (on-off).
- Spectrometer PC: Responsible for receiving the data that comes from the spectrometer by USB cable. It runs a LabVIEW program that is started by one command of the main PC via Ethernet communication.
- Spectrometer: Spectral Products model SM 240-USB. It is a polychromatic type with 0.3 to 400 nm of resolution. This device converts the light that comes from an optic fiber to a vector of 2048 positions. This conversion is made by the Sony ILX511 CCD. In this vector, the position corresponds to the wavelength (to be calibrated) and position value is the relative intensity of that wave length.
- Collimator lens: The lens focuses the measured region at the arc. Focal distance: 80 mm.
- Optic fiber: Ocean Optics code P200-5-UV/VIS.
- Optic attenuator: There are some factors that are related to the intensity measured by the CCD. One is the light that comes from the welding arc. Another is the integration time of the spectrometer. The fist factor depends on the welding current: the greater the current, greater the intensity. The second factor is related to the acquisition time: the greater the time, the greater the intensity measured. Depending on these two parameters, the intensity measured saturates at the maximum value. To avoid that, this optic attenuator goes between those two optic fibers. It only attenuates, not modifies the light nor the wavelength.

3. RESULTS AND DISCUSSION

First was made an experiment to observe only the welding arc and analyze its components. It was made standing the weld torch on a cooled copper plate, so the material could not be consumed. The spectrum only indicates the presence of Argon. The next figure demonstrates the result of two experiments, with 90 A and 130 A.

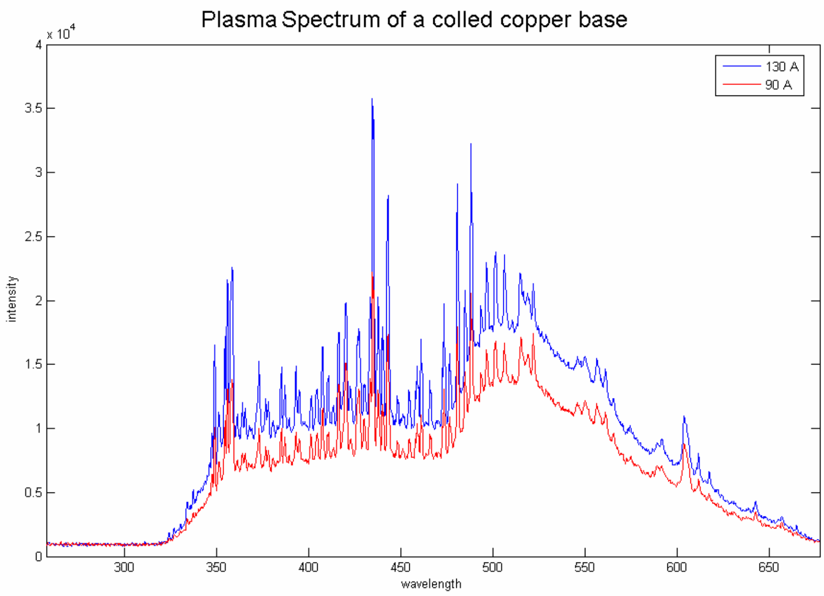

Figure 3 – GTAW spectrum on a cooled cooper plate

The others experiments were made on a steel plate. And the next figure shows its spectrum.

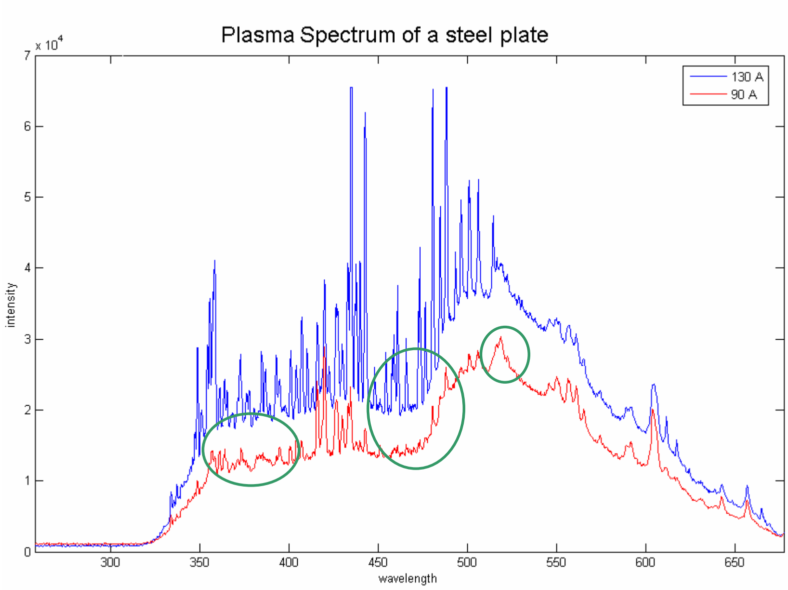

Figure 4 – GTAW spectrum on a steel plate.

One can notice some differences between Figure 3 and 4. These are because some elements present in the steel, like Ion and Manganese.

For the following experiments, they were done bead on plate.

The next experiment was made to observe the electronic temperature on a plate without defects. The answer expected was a constant value with smooth fluctuations. It is important to know that the absolute electronic temperature is not important, but its fluctuations.

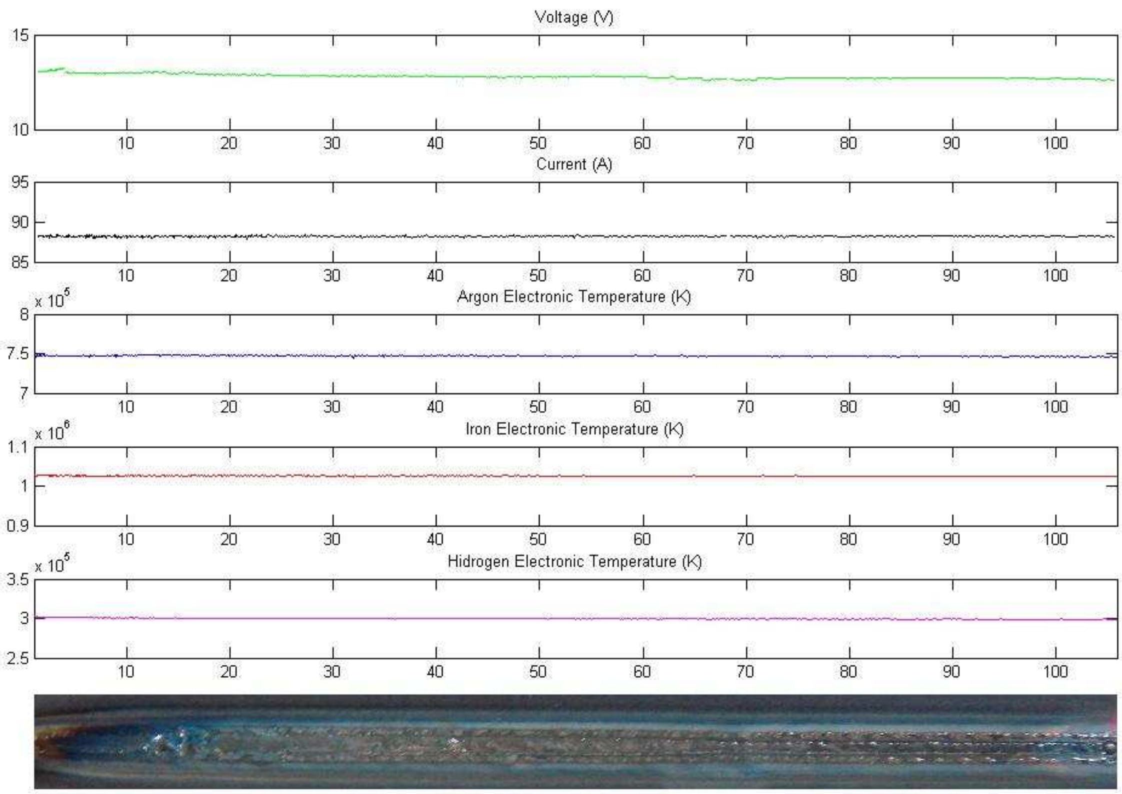

Figure 5 – Electronic Temperature in a plate without defects.

Figure 6 illustrates a test with a simulated defect in varying the shield gas flux during the weld.

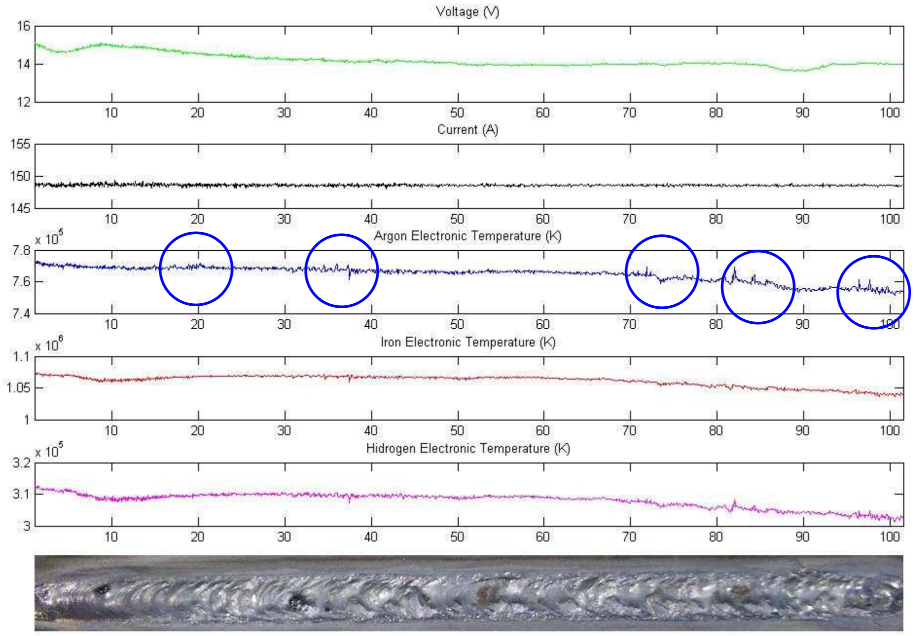

Figure 6 - Defect on shielding gas flow rate

One can notice that a perturbation like this caused variation in both current and voltage. But, in voltage, one can notice that it presented a great variation – between 15 and close to 13.5 V. And for current, it presented a noise and its mean remains basically the same.

Observing the electronic temperatures, when measured with Iron emission lines, there was no great noise, but smooth fluctuations. However, when measured with Argon, the noise was greater as well its fluctuations. This result was expected because the variations were on the shield gas flux, which was the Argon. The test picture indicates weld failures along the piece, but the noise obtained by the Argon electronic temperature were related to big shield gas flow rate variation.

The next figure presents an experiment that consisted in varying the weld current from 150 to 75 A. It was made three times along the experiment with an interval of two seconds. This simulates a current defect that could be happened.

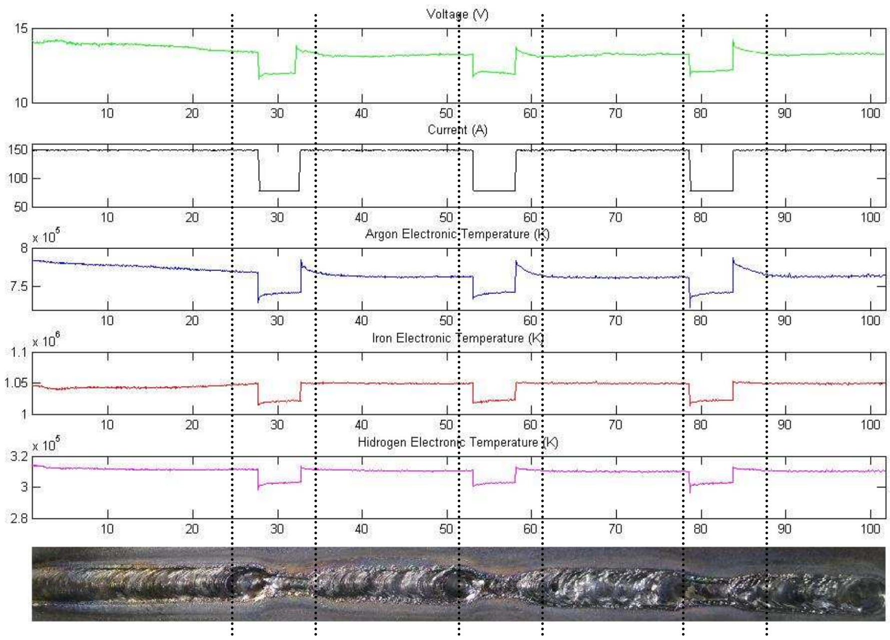

Figure 7 - Experiment with current defect of 2 seconds

A similar situation is seen in the figure below. But the variation in current is from 120 to 70 A. The interval of the defect in this experiment was 1 second.

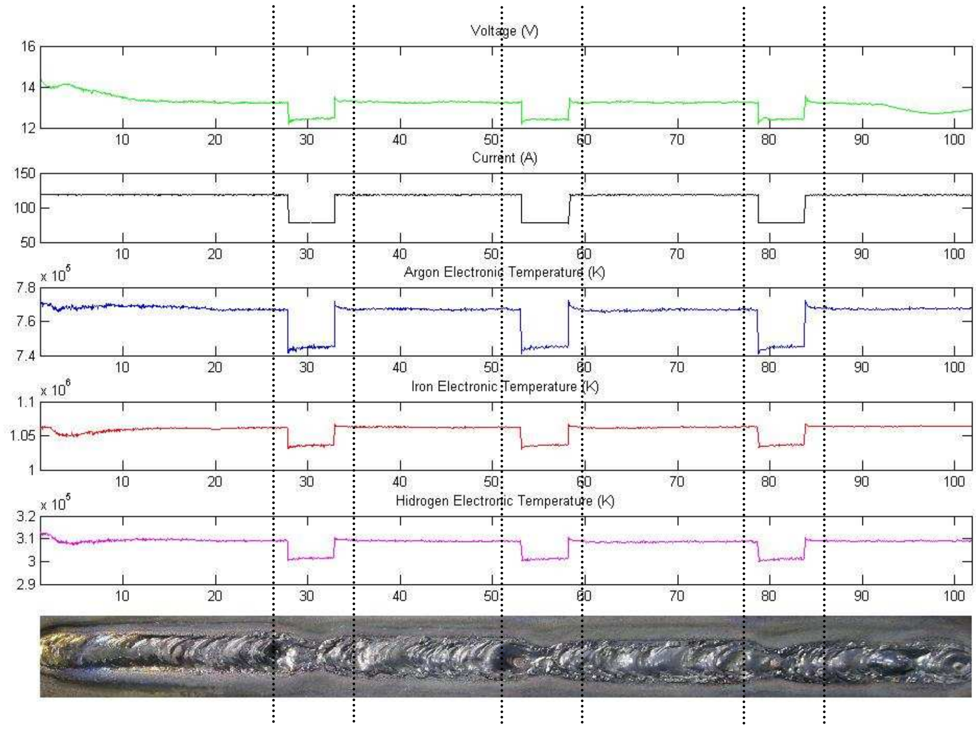

Figure 8 - Experiment with current defect of 1 second

In Figure 6 one can notice that the weld parameters and electronic temperatures were stables (no great fluctuations) as expected. It is known that the light emitted by the arc is proportional to the energy in that arc. This energy is related to welding parameters: current and voltage. The voltage was quite constant because the distance between the electrode and the plate was constant. Thus, the energy is associated to the current.

That is why can be seen in Figures 7 and 8 that both Argon and Iron electronic temperatures varied when current varied in proportional way. The intensity off all the lines in the weld increased when current increased.

The following figure illustrates a different experiment from the others. The defects were grease and small wire pieces.

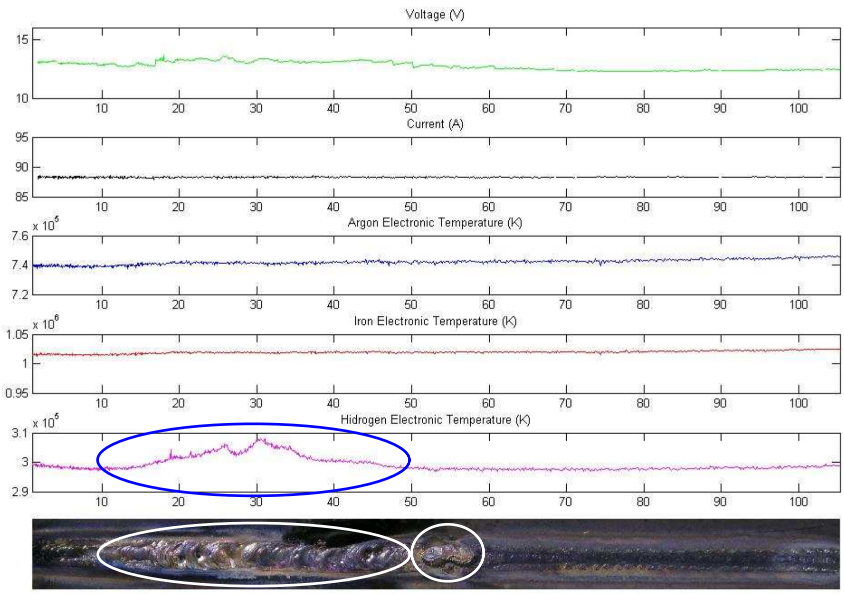

Figure 9 – Grease and wire insertion.

The result shows that for the wire insertion, the electronic temperature has not changed. The amount of Iron in the wire was not sufficient to vary the relative intensity of the chosen wave lengths. It has to be remembered that the plate also has Iron, thus it can masqueraded the result. But, for the grease, the electronic temperature of the Hydrogen varied along the defect extension. It is known that grease has Carbon, Hydrogen, Nitrogen and other components. But previous observations showed that the Hydrogen line emission presented a great variation. This very emission line can be used as a qualitative monitoring system to indicate the presence of components with Hydrogen, such as water, oil, grease, lubricant and others. These components may cause porosity, bad depth penetration, weld contamination.

Thus, it is possible to monitor the quality in a quantitative way by the calculation of the electronic temperature. As well it can be in a qualitative way, if the interest is the presence or not of one or more elements. The tests proved that a problem in current affects the electronic temperature. Other defect could be variation of the shielding gas flow. Some other experiments will be done to evaluate more defects detection.

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