Optical emission spectroscopic diagnostic of a GMAW plasma column

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Abstract: The diagnosis of a plasma column in gas metal arc welding (GMAW) has been made using optical emission spectroscopy. Data have been acquired for different gas mixtures with a vertical resolution of 0.5 mm and a radial resolution of 0.06 mm using Boltzmann plot method and a method based on two lines stark width measurement. Plasma parameters are compared to arc imaging with high speed camera.

Keywords: Welding, plasma, spectroscopy.

1. Introduction

The GMAW process is a widely used joining process. During welding, metal from a consumable anode is transferred to the workpiece under various modes, mainly depending on arc current and shielding gas composition. The most common are called short-arc, globular transfer and spray-arc [1]. The transition from the second mode to the third is reached by increasing current. The common explanation is based on the modification of the forces acting on the molten droplet at the end of the consumable electrode. In particular, the magnetic force depends on the current lines path inside the droplet and in the plasma. Then the plasma parameters are an important element in understanding arc behavior and the transition condition.

The plasma created by a GMAW torch has been studied using optical emission spectroscopy in order to get a map of the plasma parameters. The electron temperature and density have been measured using a method developed by Sola et al. [2, 3] based on the stark width measurement of two different lines. This method does not need any hypothesis on the Local Thermodynamical Equilibrium (LTE) state of the plasma. Then the temperature has been calculated from the Boltzmann plot method [4] using three iron lines. When the two temperature match the LTE hypothesis can be assessed. This allows calculating the other plasma parameters, in particular the iron vapor concentration. This parameter is particularly important as the iron increases the thermal and electrical conductivity of the plasma. The data obtained can be used as a reference for plasma modeling and arc study.

2. Experimental setup

The welding experiments have been performed in the most common configuration, with the consumable electrode acting as anode. A 1.2 mm diameter mild steel (AWS A5.17) wire has been used, with a wire feed speed of 9 mm/s. The arc current was set at 330 amperes and various shielding gases were used: pure argon and mixtures of argon with 5%, 10% or 20% of CO₂. The CO₂ concentra-
For the spectroscopic study, the argon 696.5 nm and the iron 5383 Å lines have been used to get electron density and temperature with the first method, as presented in [5]. For the Boltzmann plot method, the iron lines at 538.3 nm, 539.3 nm and 539.7 nm have been used, using spectroscopic data from the NIST [6]. These iron lines can be recorded simultaneously and the argon line is recorded during another experiment under similar conditions. All acquisition were performed with an exposure time of 50 ms. Each time a dozen of spectra are acquired and the results are calculated after checking on the electric signals that the welding conditions are actually similar. The reproducibility of the results is checked to assess this two steps method.

For high speed imaging of the plasma a camera fitted with an interferential filter, center at 468.8 nm (3 nm fwhm), is used. In this wavelength window only metallic lines, mainly iron, can be seen but only the argon continuum is visible. Then the recorded pictures show the repartition of iron vapor and the shape of current lines, as at this wavelength the argon continuum is almost only dependant of square electron density. Images are acquired with a speed up to 3000 frames per second.

3. Results and discussion

Under pure argon and argon with 5% CO$_2$, the welding operates under spray-arc, for argon with 10 and 20% of CO$_2$ globular transfer occur. The second mode is unstable and occurs at low current or high CO$_2$ concentration. The transition current to get spray transfer increases with CO$_2$ concentration. A current of 330 amperes corresponds to the transition from globular to spray transfer mode with 10% of CO$_2$ in the shielding gas. The detailed analysis of arc shape evolution is presented in [5] and the study of temperature and electron density, for three different positions in the plasma column, is presented in [7]. In the case of spray arc transfer, the recorded image of the plasma show a conical bright central part of the plasma as shown on Fig.2. The liquid end of the anode streams inside this area which iron vapor content is high. As the weld bead can rise above the cathode, the spectroscopic measurements have been made from 2 mm to 6.5 mm above the cathode with a vertical step of 0.5 mm. The total length of the arc is about 7 mm.

In the case of the globular transfer mode, the total length of the plasma increases up to 12 mm and the metal vapors are more homogenously mixed as shown on Fig.3. There is no liquid metal vein inside the plasma but the droplets detach just at the end of the non-melted anode and the plasma wraps the droplet and the lower part of the anode.

For the four studied gases, the temperature has been calculated using the two methods in order to study the regions of the plasma were the LTE hypothesis was available. The criteria to determine if the two temperature match takes into account the uncertainties for the two curves as shown on Fig.4 at 3.5 mm above the cathode, under pure argon. The LTE validity extends up to 5 mm from the axis but becomes narrower near the anode, as the

![Fig.2 Arc shape in spray transfer (Argon, I = 330A)](image1)

![Fig.3 Arc shape in globular mode (Ar+20%CO$_2$, I = 330A)](image2)

![Fig.4 Validity assessment of LTE hypothesis](image3)
The temperature has been calculated for all studied position and represented on a diagram giving its repartition compared to the position of the brighter part of the plasma. The position of the cathode and the liquid metal vein from the anode are also shown. As the plasma is supposed to be symmetric, only one half has been represented. Results for experiments under pure argon are shown on Fig. 5. The main results are that the temperature does not exceed 12500 K and this value is not observed on the central part of the plasma column. On the contrary, there is a temperature drop of 4000 K in the center of the column. The position of the maximum depends of the position in the arc: it gets closer to the axis near the anode and is more distant close to the cathode. It can be seen that the limit of the brightest part of the plasma follows the maximal temperature position in the arc, especially on its upper part. The thermal gradient is also stronger near the anode, the lowest studied slices of the plasma showing similar behavior and low plasma parameters evolution. The temperature drop could be linked to the presence of the liquid metal vein and the droplets falling to the cathode. They cool down the plasma and provide metal vapors that increase the plasma emissivity [8,9] and thus energy losses.

The electron density is also non-homogeneous in the vertical as well as in the radial directions. The highest values, up to \(2.2 \times 10^{23} \text{ m}^{-3}\), are observed near the anode. This represents almost twice the density observed near the cathode. The density gradient is also stronger on the upper part of the arc. On the radial direction, the main behavior is a density increase towards the axis of the arc. A small decrease is only observed at the half height of the arc, but in that region the radial gradient remain low and the relative evolution is small. The highest density areas still seem close to brighter part of the plasma, indicated by the dark line on Fig. 6, but the correlation is not so strong as in the case of the temperature repartition.

In the area where the LTE hypothesis can been assessed, the iron ratio on argon has been calculated. The strongest values correspond to the central part of the arc indicated by the dark line on Fig. 5 and Fig. 6, but the concentration is important mainly near the anode, where it becomes greater than 0.01%. This corresponds to the region where the temperature drop is stronger.

When a small amount of CO\(_2\) is added to the shielding gas, the arc shape and length is not strongly modified. The temperature slightly increases but higher values are observed for greater radial position compared to pure argon shielding. For CO\(_2\) concentration above 10%, arc length increases noticeably as transfer becomes globular. The temperature is higher, with 20% CO\(_2\) it reaches 14500 K and there is no strong temperature drop on the axis. Even for the lowest CO\(_2\) concentration, the electron density is lower than under pure argon. The density still reaches its
maximum value on the arc axis but plasma extension is greater. The electron density is almost twice lower, at comparable distance from the anode. This supports the hypothesis of the plasma conductivity reduction when CO\textsubscript{2} is added. The iron ratio on argon is also higher when welding under argon/CO\textsubscript{2} mixtures and in the case of the globular transfer the concentration is more homogeneous.

The comparison of metal vapors, calculated at 6.5 mm above the cathode, is shown on Fig.7 for the four used shielding gases. There is a strong increase of concentration with 5% of CO\textsubscript{2}. The lower values observed for 10% and 20% of CO\textsubscript{2} are due to the greater arc length which places the anode end higher.

4. Conclusion

The plasma diagnosis has been made for the entire arc column for various experimental conditions. The results showed a modification of arc behaviour according to welding conditions. The adjunction of CO\textsubscript{2} leads to a temperature increase but an electron density decrease. The electron temperature and arc shape is slightly modified when a small amount of CO\textsubscript{2} is added, when the arc still operates in spray transfer. Arc temperature does not exceed 12500 K in this mode and, there is a temperature drop down to 8000 K on the axis of the arc. In globular mode, the temperature is higher as it reaches 14500 K and there is no such temperature drop.

Comparison between results obtained by the methods of Sola and the Boltzmann plot, we have determined the regions in the column where the LTE hypothesis could be available. In these regions, we can try to determine locally the Fe/Ar proportions in the plasma column. Then, the metallic vapors seem also more homogenously mixed in globular transfer mode than in spray arc transfer.

We must note that the method give just indications on the excitation equilibrium in the plasma. To be sure of the total LTE existence, it would be necessary to verify the Saha equilibrium.

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References