Analysis of Gas Metal Arc Welding (GMAW) regime transition in Ar-CO₂/O₂ shielding gases

Quentin Castillon⁴, Maxime Wartel*, Nadia Pellerin², Stéphane Pellerin¹, François Faubert¹, Jean-Pierre Planckaert³, and Francis Briand³

¹ Groupe de Recherches sur l'Energétique des Milieux Ionisés (GREMI), UMR 7344 CNRS/Université d’Orléans, 63 avenue de Lattre de Tassigny, Bourges, France
² Conditions Extrêmes et Matériaux : Haute Température et Irradiation (CEMHTI), UPR 3079 CNRS, Orléans, 1D avenue de la recherche scientifique, Orléans, France
³ Air Liquide Research and Development, Paris-Saclay Research Center, Les Loges-En-Josas, France

* maxime.wartel@univ-orleans.fr

Abstract. An experimental study on MIG-MAG welding in reverse polarity (anode wire) has been implemented to analyse the influence of the active gas type and composition on the welding process. The analysis of the arc column using optical emission spectroscopy and high speed imaging completed by µ-structural study of the electrode wire by EDS/XRD and EPMA methods have provided helpful explanations on the globular/spray mode transition depending of the active gas in the shielding gas. These results highlight the existence of an oxide layer ("gangue") and the modification of the typology of this one in globular mode according to the active gas (Ar/CO₂ or Ar/O₂) probably responsible of the globular/spray mode transfer by modification of the electrical/thermal conductivities of the oxide layer. Spectroscopic analysis reveals modification by an arc constriction in Ar/O₂ mixtures and linked to a more prominent drop of the electronic temperature along the arc column axis. With this active gas, analysis of the Fe I / Ar I emissivity ratio show a higher metal vapours content responsible for the temperature drop by their strong radiative emission along the arc column.

1. Introduction
The Gas Metal Arc Welding (GMAW) in presence of pure Argon (MIG - Metal Inert Gas) and Ar/CO₂ or Ar/O₂ (MAG - Metal Active gas) mixture as shielding gas is a largely developed process allowing the transfer of the liquid metal from a consumable wire electrode to the metal workpiece according to various modes (short-arc, globular, spray-arc). This welding process remains currently misunderstood owing to the huge complexity of this multi-phase phenomenon depending on several parameters as the polarity, the chemical composition of the fuse wire [1-3], the current intensity or the composition and flow rate of the shielding gas for example [4, 5]. Among these factors, a particular attention has been paid on the influence of the active gas addition in the shielding gas during the process. Indeed, the active gas type and content in Ar induce a significant modification on the limit between the globular and spray modes, the latter commonly preferred in the industrial process because of this more homogeneous deposit, producing low fume level and molten metal projection [6, 7].
Previous studies [8] by high speed imaging and cinematography completed by electrical characteristic measurements have shown that the globular/spray mode transition is characterized by modification of the plasma shape, droplets frequency and diameter. Globular mode can be clearly identify owing the ‘bell’ shape of the arc column, noisy signals of the arc voltage and current intensity, low droplet frequency (lower than 150 Hz) and droplets diameters higher than the diameter of the wire. At contrary, spray mode is characterized by a ‘cone’ shape of the arc column, a higher droplet frequency (≈ 350 Hz), a droplet diameter narrower than the wire diameter, and smooth signals of the electrical characteristics. Thus, observations of these parameters allowed to identify globular/spray mode transition as a function of the current intensity and the active gas content in the shielding gases. Ar-CO$_2$ mixture is a commonly binary gas mixture allows to reduce the spatter and improves the weld beads appearance, particularly for carbon steel GMAW in short-circuiting transfer. The use of oxygen as active gas induces some drawbacks (e.g. higher price, danger associated to the use of oxidizer) limiting the industrial applications especially for high O$_2$ content. In small addition (1-5%) in argon, O$_2$ provides good arc stability and enhances weld beads appearance, but require the use of deoxidizers within the chemistry of filler alloys to avoid the oxygen oxidizing effect. Nevertheless, Ar-O$_2$ mixtures have been used in this study until high O$_2$ content for comparison with CO$_2$. A complete mapping of the results for CO$_2$ and O$_2$ addition (See table A.1. in Appendix) shows a shift of the globular/spray mode transition to higher current intensities as the active gas content increases. Indeed the spray mode is easier achieved at high current intensity and low active gas content. However, the spray mode transfer is more difficult to obtain in case of CO$_2$ addition compared to the use of O$_2$ which allows to extend the spray mode range. In order to define the origin of this phenomenon and his influence of the droplet detachment, μ-structural analysis by Scanning Electron Microscopy (SEM) of the wire surface have demonstrated the formation of an oxide layer in presence of oxidants in the shielding gas, surrounding the droplet, limiting the access to the spray mode transfer [9]. Presence of this oxide layer in globular mode, disappearing in spray mode transition, seems to be linked to modification of the plasma conductivity and viscosity with the active gas addition.

On the basis of these results, this article will present further investigations by optical emission spectroscopy and high speed interferential imaging of the arc column for several shielding gas composition (Ar/CO$_2$ and Ar/O$_2$) with different active gas contents. In parallel, more advanced researches have been carried out to characterize the influence of active gas composition and content on the physical and the chemical features of the oxide layer in the same welding conditions. Structural analysis performed by X-Ray Diffraction (XRD) and Electron Probe Micro-Analyser (EPMA) highlight significant discrepancies of the μ-structure (thickness, porosity…), chemical composition and iron oxide typology of these oxide layers, clearly depending of the active gas nature.

2. Experimental setup and diagnostic methods

The experimental device used for these experiments have already been described in details in previous articles [6, 7]. Briefly, the experiments consist to generate an electrical arc between a fuse wire and a workpiece using a programmable welding station (SAF FRO Digiwave 500). The program was set to supply a constant current intensity $I_{arc}$ in the range from 200 to 400 A. The wire feeding speed $S_{wire}$ have been adjusted for each current value to keep the arc length in a similar range for each condition. The arc voltage is automatically adjusted by the welding station, this value depending of the plasma parameters. All the experiments have been performed in reverse polarity for which the fuse wire is the anode, avoiding fast erosion of the nozzle and the contact tip by ions bombardment. Several mixtures of pure Ar, Ar/CO$_2$ and Ar/O$_2$ have been employed as shielding gases. The feeding gas composition have been adjusted by two mass flow controllers (BROOKS 5850S), calibrated for Ar and CO$_2$ respectively. Experiments with O$_2$ were conducted with the CO$_2$ mass flow meter taking into account a corrective factor given by the manufacturer. For all experiments, the gas flow was equal to $Q_{gas} = 20$ l.min$^{-1}$. The workpiece has been mounted on an X-axis linear translation plate to form a weld metal cord without movement of the welding torch. This mechanical arrangement has been selected to perform spectroscopic analysis requiring a fixed focus point. All experiments presented in this article have been
performed by using Nertalic 70S iron wire with a diameter of 1.2 mm. As shown on figure 1, the electrical characteristic of arc voltage and current intensity have been measured by current/voltage probes and observed on a high rate oscilloscope (LECROY Wave runner LT584L). The optical setup developed for this study is divided in two main part. The first system is composed of a high speed camera outfit with interferential filters and mounted in front of the arc column axis for observation of the plasma shape, presence of metal vapours and droplets fall. The second system is composed of two Optical Multichannel Analysers (OMA) for the implementation of the optical emission spectroscopy (OES). This optical device use two spectrometers (Acton SP2750i and SOPRA) and two ICCD camera (Princeton PIMAX II) in order to simultaneously collect Fe I and Ar I emission lines. This specific device has been developed to avoid potential disturbance between two welding test and collect simultaneously two emission lines in a different spectral range. A Dove’s prism has been placed along the optical device to rotate the plasma image at 90° enabling to collect the horizontal distribution of plasma radiation at a fixed height above the workpiece.

Figure 1. Overview of the experimental setup.

Electron density and temperature have been determined simultaneously by Sola method [10-12] based on Stark width measurements of the Fe I lines at 538.3 nm and Ar I line at 696.5 nm. Indeed, the Stark width of these two particular emission lines have been expressed as a function of the electron temperature ($T_e$) and density ($N_e$) in previous works [13, 14] according to the following equations:

$$\Delta \lambda_e^{Fe} = 0.2648 \times \frac{N_e}{10^{22}} \left( \frac{T_e}{13000} \right)^{1.6700}$$

$$\Delta \lambda_e^{Ar} = 0.0814 \times \frac{N_e}{10^{22}} \left( \frac{T_e}{13000} \right)^{0.3645}$$

After an Abel inversion of the 1D spectral measurements, the cross checking of the equations (1) and (2) allows to determine radial profiles of electron density and temperature without hypothesis on the Local Thermodynamic Equilibrium (LTE). In addition, evaluations of metal vapour content inside the plasma have been provided by measurements of the emissivity $\varepsilon$ of these two emission lines, assuming an LTE, satisfying hypothesis for spatial position close to the arc column axis as demonstrated in a previous work [15]. Hence, the emissivity ratio is linked to the density ratio of iron $N_{FeI}(T_e)$ and argon $N_{ArI}(T_e)$ by the following equation:
\[
\mathcal{R} = \frac{N_{FeI}}{N_{ArI}} \left( \frac{T_e}{T} \right)^{\lambda_{FeI}} = \frac{\lambda_{FeI}}{\lambda_{ArI}} \cdot \frac{A_{FeI}}{A_{ArI}} \cdot \frac{U_{FeI}}{U_{ArI}} \cdot \frac{g_{FeI}}{g_{ArI}} \cdot \exp \left( -\frac{E_{FeI} - E_{ArI}}{kT_e} \right)
\]

(3)

where \(\lambda\) (nm), \(A\) (s\(^{-1}\)), \(g\) and \(U\) are respectively, the wavelength and the transition probability of the transition, the decay of the upper level, and the partition function of the considered atom. All these spectroscopic data have been extracted from the NIST atomic level database [16]. The partition function calculus take into account of the lowering of the potential ionization [17] and the results have been checked with databases from [18] and [19]. Based on this method, evaluation of the radial profile of the \(\mathcal{R}\) proportion of Fe I at a fixed height in the plasma \(h_{arc}\) can be achieved.

3. Plasma observations by high speed imaging

For a better understanding of the macroscopic modification of the plasma according to the current intensity and the active gas content in the shielding gas, measurements by high speed cinematography (Photron fastcam 1024PCI) using a laser diode backlight at 838 nm have been performed for the two mixture (Ar/CO\(_2\) and Ar/O\(_2\)). Different values of active gas content have been adjusted between 0\% and 15 \%\(_w\). Two parameters of the arc column (defined on the figure 2) have been evaluated on the basis of ten sequential images, each one corresponding to 5 ms in duration throughout the welding process: the arc height \(H_{arc}\) and the arc diameter \(D_{arc}\). The arc height is defined as the distance between the workpiece and the arc attachment on the fuse wire and the arc diameter as the diameter below the attached droplet on the wire. Because of the great influence of the wire feeding speed on the arc development, this parameter has been adjusted in pure Argon condition so that the arc height remains constant in any applied current intensity. In this condition, arc height modifications are clearly linked to the increase of melting rate of the fuse wire according to the active gas nature. Note that the arc height is voluntary greater than in common industrial process, to have an oversize the arc column which it facilitates the spectroscopic analysis. Overall, the arc height and diameter simultaneously increase with the current intensity irrespective of the active gas nature in the shielding gas (See figure 3).

![Figure 2. Imaging by high speed camera of the arc column for 5\%\(_w\) active gas \((Q_{gas} = 20 \text{ L.min}^{-1})\); Spray mode. On the left: Ar/CO\(_2\) mixture, on the right: Ar/O\(_2\) mixture.](image1)

![Figure 3. Evolution of the arc height \(H_{arc}\) and the arc diameter \(D_{arc}\) depending on the current intensity for 5\%\(_w\) active gas - \(Q_{gas} = 20 \text{ L.min}^{-1}\); Spray mode.](image2)
7500 K (cf. section 4), calculus indicate that the electrical conductivity is higher in case of oxygen addition as active gas in comparison with CO$_2$ addition.

4. Arc column analysis by optical emission spectroscopy

With these results on plasma observations, optical emission spectroscopy measurements have been carried out in these condition at an arc height close to 9 mm, this value have been specially selected to be close to the anode wire. The large scale emission spectrum (not presented) along the arc column axis reveals the prominence of Fe I emission lines with the presence of some weak Ar I and Fe II emission lines. For the tested arc height, no iron oxide FeO broadband emission, CO or other molecular structure have been observed owing to the huge Fe I lines over dominate the emission spectrum.

Based on Sola method described in a previous section, the radial profiles of the electronic temperatures and densities have been simultaneously determined for different active CO$_2$ and O$_2$ contents. Results for 1%$_w$ of active gas in Ar/CO$_2$ and Ar/O$_2$ are presented on figure 4. The maximal values of electronic temperature are relatively similar in view of the uncertainties, 7500 K for Ar/CO$_2$ and 7800 K for Ar/O$_2$. The same applies for the electronic density close to 1.75×10$^{23}$ m$^{-3}$ for the two active gas tested. However, different shapes of these radial profiles have been observed depending of the active gas, a more pronounced drop of the electronic temperature is noted in case of oxygen addition. A reasonable explanation of this temperature drop is a cooling effect along the arc column due to radiation of important metal vapours. Note that these results on radial profile also confirm the arc constriction in Ar/O$_2$ mixture confirming the observation by high speed imaging.

![Figure 4](image)

**Figure 4.** Radial profiles of electronic temperature and density at $h_{arc} = 9$ mm, $I_{arc} = 330$ A, 1%$_w$ active gas, $S_{wire} = 9$m.min$^{-1}$, $D_{gas} = 20$ L.min$^{-1}$; Spray mode. On the left: Ar/CO$_2$ mixture, on the right: Ar/O$_2$ mixture.

Evaluation of the Fe I vapours content within the plasma have been realised on the base of the emissivity ratio Fe I / Ar I as explained in the previous section. An example of the obtained results for 1%$_w$ and 8%$_w$ active gas is shown on figure 5. The arrow at the top of the graphs represents the maximal value of electronic temperature obtained by the Sola method. These results highlight a more important ratio of iron vapour in case of oxygen addition compare to Ar/CO$_2$ mixture for the two different %$_w$ of active gas. Then it exists a more effective accumulation of iron vapours within the plasma with the use of oxygen as active gas in the same area as the drop of electronic temperature. However, as already observed by Valensi et al. [7], this accumulation is preferentially off-axis of the arc column beyond the area of molten metal passage. To conclude on the spectroscopic analysis of the plasma, all these results indicate that the presence of maximal iron vapours content inside the plasma comes from the vaporisation of the metal during the droplet detachment leading to an increase of energy loss by metal vapours radiations. The more pronounced drop of the electronic temperature with O$_2$ addition seems to be related to a more effective metal vapours production within the plasma using this active gas.
Figure 5. Radial profiles of electronic temperature and density at $h_{\text{arc}} = 9 \text{ mm}$, $i_{\text{arc}} = 330 \text{ A}$, 1\%\_w active gas, $S_{\text{wire}} = 9 \text{ m.min}^{-1}$, $D_{\text{gas}} = 20 \text{ L.min}^{-1}$; Spray mode. On the left: Ar/CO$_2$ mixture, on the right: Ar/O$_2$ mixture.

5. µ-structural analysis of the fuse wire and the oxide layer

The distribution of the globular regime and the spray regime was globally similar for the two active gases (See table A.1. in Appendix). The spray mode is reached using high current intensity and low active gas content while the globular mode is obtained with relatively low current intensity or high active gas content. The shift of the globular/spray mode transfer is related to the disappearance of an oxide layer surrounding the droplet. Analysis of the droplet by SEM (See example presented on figure 6) highlights significant differences on the oxide layer structure according to the active gas nature. Indeed, in case of O$_2$ addition, a brittle, voluminous and porous oxide layer is observed while the oxide layer remains very thin for carbon dioxide addition in the shielding gas. Then, we have concluded that the modification of the oxide layer macrostructure with the active gas seems to generate shift of the globular/spray transition with oxygen addition. Energy Dispersive X-ray Spectroscopy (EDS) analysis completing SEM measurements reveals a great oxygen content inside the oxide layer. Then the oxygen seems to be the major chemical specie responsible for the formation of an iron oxide surrounding the droplet at the wire tip.

Figure 6. Imaging of the fuse wire and the surrounding oxide layer by SEM. $i_{\text{arc}} = 280 \text{ A}$, $S_{\text{wire}} = 7.4 \text{ m.min}^{-1}$, gas, $D_{\text{gas}} = 20 \text{ L.min}^{-1}$, 50\%w of active gas; Globular mode. On the left: Ar/O$_2$ mixture, on the right: Ar/CO$_2$ mixture.
However, cross checking of these results with mapping of the globular/spray mode transfer do not explain the more favored changeover under Ar/O<sub>2</sub> mixture despite a more voluminous and porous oxide layer than in Ar/CO<sub>2</sub> mixture. Therefore extended µ-structural study on fuse wire samples for several condition in globular mode have been performed combining X-Ray Diffraction (XRD) and Electron Probe Micro-Analyzer (EPMA) in order to reveal potential discrepancies of the oxide layer composition according to the active gas used in the shielding gas. Processing of the samples have been carried out at the end of a welding test by cutting the metal droplet at the tip of the fuse wire. Note that cooling effect by a high flow pure Ar shielding gas has been operated to freeze the possible reactivity at the end of the welding test. Previous studies by F. Valensi and S. Zielinska [1, 9] have confirmed that this sampling is representative of the droplet during normal operation. After that, the samples have been polished by some grit paper until 0.25 µm grain size. All these sample have been cleaned by ultrasound bath and dried in a desiccator (at 80 °C) to avoid surface oxidation. Then, the prepared samples have been analysed: an example of EPMA analysis is present on the figure 7. The EPMA analyses confirm the strong oxygen contents in the oxide layer regardless of the active gas. At the same time, a huge decrease of the iron content in the oxide layer is observed (∼30% in mass unit) and confirms the iron oxide formation surrounding the fuse wire. No particular modification of the minor elements (as Si, Mn, or Cu) content has been observed in the oxide layer despite a huge decrease of the iron content for all the experiments. In case of Ar/CO<sub>2</sub> conditions, no significant amount of carbon atoms have been detected, hence there is no specific inclusion of carbon inside the oxide layer during the welding operation.

![Figure 7](image_url)

**Figure 7.** Cartography of the major chemical element by EPMA for Ar-CO<sub>2</sub> mixture (Results in ppm). \(I_{arc} = 240\ A,\ Ar + 30\%\ CO_2;\ Q_{gas} = 20 \text{l.min}^{-1};\) Globular mode.

The combined analysis using EDS/EPMA completed by XRD studies on electrode tip after working in Ar/CO<sub>2</sub> or Ar/O<sub>2</sub> mixture (See example on figure 8) allowed to determine O/Fe atomic ratios for several samples. Two iron oxide major typology are finally distinguished depending of the active gas: phases of magnetite (Fe<sub>3</sub>O<sub>4</sub>) and phases of hematite (Fe<sub>2</sub>O<sub>3</sub>), corresponding to O/Fe atomic ratios of 1.33 and 1.50, respectively. All the samples obtained under Ar/CO<sub>2</sub> mixtures in globular mode are characterised by hematite iron oxide, despite the oxygen addition leads to formation of magnetite as major iron oxide. The results on the µ-structural study and his comparison with the shift of the globular/spray mode transfer suggest that the magnetite seems to have a higher electrical and thermal conductivity than the hematite [22]. Therefore, according to this hypothesis, the magnetite seems to be an oxide more favourable to the passage of electrical current which may explain the shift of the globular/spay mode transition for lower current intensity in Ar/O<sub>2</sub> mixture. The addition of oxygen in the shielding gas therefore seems to be a good way to favour a spray mode operation.
6. Conclusion

The influence active gas nature and content has been clearly identified both from the point of view of arc plasma analysis and the electrode wire properties. Thus, the use of oxygen in the active gas extends the spray regime range and this fact has been correlated with changes in arc plasma characterized by constriction of the arc diameter and length. This phenomenon has been linked to a more pronounced drop of the electronic temperature along the arc column axis in Ar/O\textsubscript{2} mixture. It has also been demonstrated that Ar/O\textsubscript{2} plasma has a higher metal vapours content favouring radiation cooling in the centre of the arc.

The analysis of the fuse wire tip clearly shows structural changes and composition of the oxide layer surrounding the droplet according to the active gas: a thinner gangue consisting mainly of hematite having a more insulating nature is observed for the Ar/CO\textsubscript{2} mixtures. In the case of Ar/O\textsubscript{2} mixtures, a thicker, more porous oxide layer predominantly in magnetite having a higher thermal/electrical conductivity is identified. These physical properties of the magnetite would therefore allow a better passage of the electric current and thus the axial spraying regime more easily achieved. It can therefore be concluded that the use of oxygen seems to promote stable operation of the MIG-MAG process by extend the operating range of the spray mode. Nevertheless, the understanding of the oxide layer formation is far to be fully resolved. In particular, the formation of hematite is observed in Ar/CO\textsubscript{2} mixtures despite a reduction to magnetite oxide for temperature above 1500 K and some wire sample collected in Ar/O\textsubscript{2} welding conditions seems to present a thin layer of hematite surrounding the magnetite.

Further investigations have to be performed to provide clear explanations of these observations. In this context, it would be therefore interesting to develop two colour pyrometry using high speed camera to determine the metal droplet temperature during the welding process; but this remains difficult owing to the presence of welding fume, parasitic plasma radiation and the lack of knowledge about droplet emissivity. In addition, a more extended spectroscopic analysis is needed especially concerning the iron vapours content within the plasma, experimental data showing an unexpected off-axis maximal value in numerical simulations.

Figure 8. XRD analysis of the oxide layer for Ar-O\textsubscript{2} mixture. \(I_{\text{arc}} = 220\) A, Ar \(+ x\%\text{O}_2\); \(Q_{\text{gas}} = 20\) l.min\(^{-1}\); Globular mode (Theta angle in °).

8
Acknowledgments
This work was supported by the CTAS-Air Liquide Welding in the frame of a CIFRE agreement. Special thanks to A.B. Murphy from the CSIRO Materials Science and Engineering for his helpful calculus on thermodynamic properties of Ar/CO\(_2\)-O\(_2\)/Fe plasmas.

Appendix

Table A.1. Mapping of the globular/spray mode transition as a function of the current intensity and the active gas content for Ar/CO\(_2\) and Ar/O\(_2\) mixtures. (Reverse polarity, 70S iron wire, \(S_{\text{wire}} = 1.2\) mm, \(Q_{\text{gas}} = 20\) l.min\(^{-1}\)).
References

[1] F. Valensi et al., ‘Influence of Wire Initial Composition on Anode Microstructure and on Metal Transfer Mode in GMAW: Noteworthy Role of Alkali Elements’, *Plasma Chem. and Plasma Proc.*, 2018, 38, 177-205.

[2] A. Lesnewich, ‘Electrode activation for inert gas shielding metal arc welding’, *Welding Journal*, 1955, 1167-1178.

[3] E. Cushman, ‘Electrode for spatter-free welding of steel in carbon dioxide’, *Welding Journal*, 1961, 14-21.

[4] A. T. Zimer et al., ‘The influence of operating parameters on number-weighted aerosol size distribution generated from a gas metal arc welding process’, *Aerosol Sci.*, 2001, 33, 519-531.

[5] D. Iordachescu et al., ‘Influence of shielding gases and process parameters on metal transfer and bead shape in MIG brazed joints of the thin zinc coated steel plates’, *Mat. and Design*, 2004, 27, 381-390.

[6] F. Valensi, S. Pellerin, A. Boutaghane, K. Dzierzega, S. Zielinska, N. Pellerin and F. Briand, ‘Plasma diagnostics in gas metal arc welding by optical emission spectroscopy’, *J. Phys. D: Applied Physics*, 2010, 43, 434002.

[7] F. Valensi, S. Pellerin, Q. Castillon, A. Boutaghane, K. Dzierzega, S. Zielinska, N. Pellerin and F. Briand, ‘Study of the spray to globular transition in gas metal arc welding: a spectroscopic investigation’, *J. Phys. D: Applied Physics*, 2013, 46, 224005.

[8] S. Zielinska et al., ‘Gas influence on the arc shape in MIG-MAG welding’, *Eur. Phys. J. Appl. Phys.*, 2008, 43, 111-122.

[9] S. Zielinska, F. Valensi, N. Pellerin, S. Pellerin S, K. Musiol, ‘Microstructural analysis of the anode in gas metal arc welding’, *J Mat Process Tech*, 2009, 209, 3581–3591.

[10] A. Sola, A. Gamero, J. Cortino, M. Saez, C. Lao, M.-D. Calzada, M.-C. Quintero and Ballesteros, Book of Contributed Papers ICPiG XX (Barga), 1991, p.1147

[11] J. Torres et al., ‘An easy way to determine simultaneously the electron density and temperature in high-pressure plasmas by using Stark broadening’, *J. Phys. D: App. Phys.*, 2003,36,55-59.

[12] J. Torres et al., ‘The Stark-crossing method for the simultaneous determination of the electron temperature and density in plasmas’, *J. of Phys.: Conf. Ser.*, 2006,179,219-224.

[13] S. Pellerin et al., ‘Stark width of the 696.5 nm argon I line’, *J. Phys. B:At. Mol. and Opt. Phys.*, 1996,29,3911-3924.

[14] S Zielinska, K Musiol, K Dzierzega, S Pellerin, F Valensi, Ch de Izarra and F Briand, ‘Investigations of GMAW plasma by optical emission spectroscopy’, Plasma Sources Sci. Technol., 2007, 16, 832-838.

[15] F. Valensi et al., ‘LTE Experimental Validation in a Gas Metal Arc Welding Plasma Column’, *Contrib. Plasma Phys.*, 2011, 51, 293-296.

[16] https://physics.nist.gov/PhysRefData/ASD/lines_form.html

[17] H. R. Griem, ‘Plasma Spectroscopy’, *McGraw-Hill Book Compagny*, 1964

[18] J. Halenka and J. Madej, ‘Tables of the partition function for iron, Fe I – Fe X’, *Acta Astronimca*, 2002, 52, 195-202.

[19] A. W. Irwin, ‘Polynomial partition function approximations of 344 atomic and molecular species’, *The Astrophysical journal supplement Series*, 1981, 45, 621-633.

[20] A. B. Murphy and C. J. Arundell, ‘Transport coefficients of argon, nitrogen, oxygen, argon-nitrogen and argon-oxygen plasma’, *Plasma Chemistry and Plasma Processing*, 1994, 14, 451-490.

[21] A. B. Murphy, ‘The effects of metal vapour in arc welding’, *Journal of Physics D: Applied Physics*, 2010, 43, 434001.

[22] T. Akiyamah, ‘Measurement and modeling of thermal conductivity for dense iron oxide’, *ISIJ*, 1992, 32, 829-837.