Temporally and spatially resolved electron density measurements in a pulsed GMAW process by means of Stark broadening of H_α line

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Stark broadening of H_α line was used for spatially resolved electron density and temperature determination in a pulsed gas metal arc welding (GMAW) process. The process was operated with aluminum wire (AlMg 4,5 Mn) with 1.2 mm diameter as a wire electrode, argon with traces of hydrogen as a shielding gas and peak currents in the range of 400 A. Time resolved measurements were performed along different positions with respect to the process current. The resulting temporal electron density and temperature profiles are used to investigate the state of the plasma in different phases of the current pulse and to discuss the influence of the metal vapor and droplets on the plasma properties.

1. Introduction

Gas metal arc welding (GMAW) is one of the most frequently used industrial process for joining a wide range of materials. Here an electric arc ignited between the work piece and the consumable wire electrode is used to heat and melt the wire and to create a weld pool. The molten metal droplets fall on the work piece and thus form the join. In order to achieve a controlled metal transfer to the work piece a pulsed current can be used, which allows to obtain a so called one-droplet-per-pulse mode. Due to better control possibilities and reproducibility pulsed GMAW processes in particular are interesting for automatization purposes.

Although GMAW processes have been widely studied over past years, there is still a need for experimental investigations in order to obtain a comprehensive model of the process [1]. So far mostly pulsed GMAW processes operated with iron as the wire electrode were investigated (e.g. [2]). Electron density and temperature measurements in a process operated with aluminum were conducted by means of Thomson scattering [3]. Yet no comparable time resolved measurements were conducted until now.

Stark broadening is a widely used passive spectroscopic technique, which can be applied for the evaluation of electron density and temperature. Evaluation of the line width of different resonance lines was successfully applied for investigation of GMAW processes with iron [2],[4],[5].

This work presents a spectroscopic setup for time and spatially resolved measurements in pulsed GMAW process. The goal of the investigation is to simultaneously determine electron temperature and density in different current phases of the process using the Stark broadening of the H_α line.

2. Plasma diagnostic using Stark broadening of H_α line

The spectral lines emitted by a plasma are in general broadened by several mechanisms like Doppler broadening, van-der-Waals broadening or the Stark effect. Besides the broadening effects depending on the state of the plasma, the line width is also influenced by the instrumental profile of the spectrometer. If several broadening effects take place, the final line shape can be calculated by convoluting the separate line profiles resulting from particular effects. However in welding plasmas, the Stark effect is predominant [6]. Hence the final line shape can be treated as a convolution of the line profile determined by the Stark effect and the instrumental function of the spectrometer.

Since the broadening of the H_α line due to the Stark effect is temperature and density dependent, it can be used as a diagnostic technique for estimation of these plasma parameters. Gigosos at al. [7] provide calculated full emission profiles of this line based on a molecular dynamics approach. This calculation method delivers profiles for different electron densities and electron temperatures in a plasma. Moreover, it allows to consider different ion and electron temperatures.

Figure 3 shows an example of the temperature-electron density curve evaluated for a fixed measured line width using the theoretical profiles provided in [7]. It is clearly visible, that the line width of H_α line is more sensitive to electron density than to temperature. This allows electron density determination without any further information. Yet in order to simultaneously obtain electron density and temperature additional assumptions are necessary. For this purpose local thermal equilibrium (LTE) conditions are taken into account. This restriction appears reasonable, as was

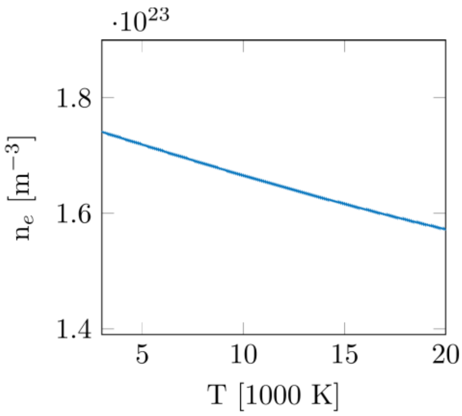

Figure 3: Example of the evaluation of H_α line width (w=1.38 nm) using temperature and density depended line profile data (μ=1, T_e=T_i).

shown in [3] at least inside the bulk plasma. Here the Saha equation for an assumed Ar-Al gas mixture – where Ar is the process gas with Al metal vapor contamination - is solved under consideration of the ideal gas law for different Ar-Al concentration pairs. This dataset is used to restrict the temperature-density curves to the values possible under LTE. Thus the mean electron density and temperature values can be determined from the resulting restricted dataset.

3. Experimental setup

The experimental setup is shown in figure 1. It mainly consists of three parts: the welding torch, generating the plasma, the optical system and the trigger logic. The gas metal plasma of the GMAW process was generated at atmospheric pressure as shown in figure 2. The arc was ignited between an aluminum wire (AlMg 4,5 Mn, Ø 1.2 mm) serving as an anode and a water cooled donut shaped copper cathode with a 100 mm outer diameter. On the central axis the copper cathode was provided with a hole of 7 mm in diameter, assuring that the metal droplets do not accumulate on the cathode surface.

A wire feed rate of 3 m/min was used. As a shielding gas argon 4.6 (99,9 % purity) fully mixed with a trace of molecular hydrogen, which concentration did not exceed 0,5 %, was used. The flow rate was set to of 25 slm. The anode standoff was adjusted to 17.5 mm and was kept constant during the whole process. OTC DW 300 was used as power supply in the pulsed DC mode. The process current was monitored by a hall sensor and the arc voltage by a voltage probe. The region investigated by the Stark broadening method was located 5.5 mm above the cathode surface.

The OTC power supply ensures a constant welding quality by regulating the voltage, current level and pulse frequency of the arc in order to obtain approximately constant arc length.

The plasma radiation was imaged onto the slit of a Jobin Yvon Spectrometer (Fastier-Ebert design) using an imaging optics consisting of two plane mirrors and two lenses. The spectrometer has a focal length of 250 mm and is equipped with a diffraction grating with 1500 g/mm. The resulting spectrum was recorded by an ICCD camera 4Picos (Stanford Computer Optics, GEN II image intensifier). The camera chip was exposed for 140 ns. The instrumental full width half maximum of the apparatus profile was 0.275 nm. The spatial resolution in the radial direction of the arc was 0.28 mm. Moreover a supplementary high speed camera was installed for the monitoring of the arc.

A trigger logic was needed in order achieve temporal resolution of the measurements. Therefore a combination of a hall sensor (SS94A1F) for current pulse tracking and a micro-controller (Arduino Due board with Atmel SAM3X8E ARM CortexM3 MCU processor) was used. The analog digital converter of the micro-controller board was applied to detect a predefined level of the current pulse. The counter functionality of the micro

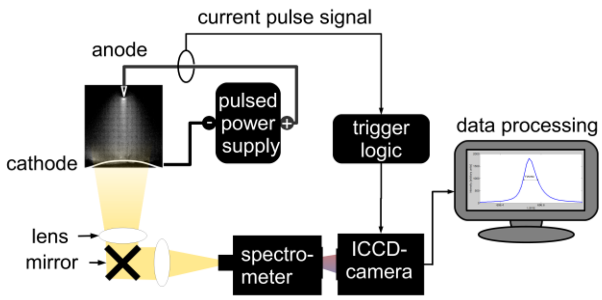

Figure 1: Schematic setup for Stark width measurement in the GMAW process.

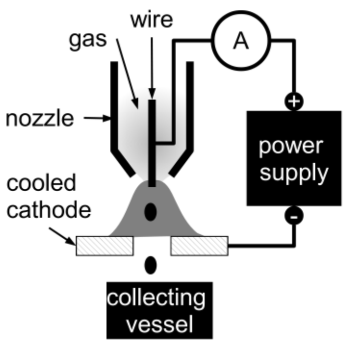

Figure 2: Schematic setup of the GMAW process.

controller allowed implementing a temporal delay with respect to the detected current level. Thus the signal generated by the microcontroller triggered the image intensifier of the ICCD camera and an additional plasma imaging camera at a desired time with respect to the current pulse.

The recorded spectroscopic data was deconvoluted using the approximation formula proposed in [8]. It was assumed that the measured line shape can be approximated by the Voigt profile. Thereafter the Abel inversion was performed using the analytical method applied in [9]. Finally the full width half maximum of the resulting line shapes was further processed for the plasma parameter evaluation as sketched in section 2.

4. Results and discussion

Figure 4 shows the evaluation of spatial electron density and temperature distributions at the beginning of the high current phase under consideration of LTE (μ=1). The resulting peak electron density lies in the range 11×10^{22} m^{-3} in the arc center. It steadily drops down towards the edges up to around 3×10^{22} m^{-3}. The methodical uncertainty varies between 2-4 %. The resulting peak temperature lies at 9700 K in the arc center. The temperature falls off to around 8000 K at the arc edge region. The methodical uncertainty is in the range 32-34 %.

The temporal investigation was performed with a resolution of at least 250 μs. In order to clearly present temporal evolution of the electron densities and temperatures along the current pulse only the maximal values of each measurement are presented in figure 5 (bottom). Besides the evaluated plasma parameters the process current and voltage together with the trigger time represented by the vertical bars

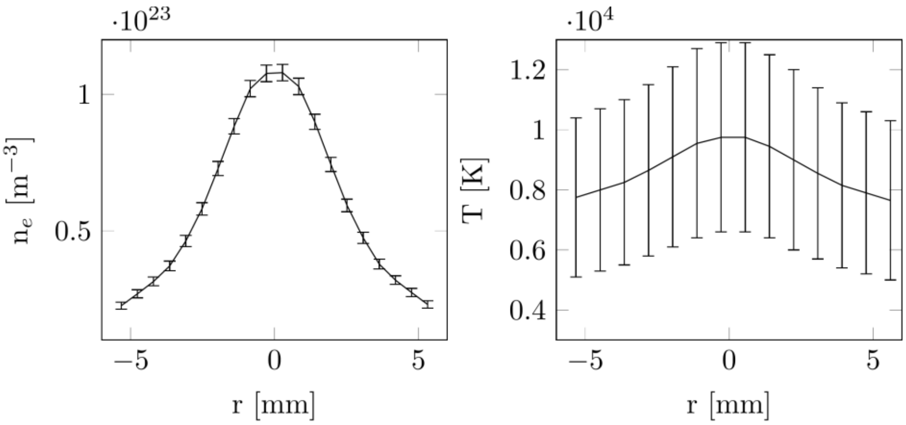

Figure 4: Evaluation of electron density and temperature at t_{trig}=0.25 ms under consideration of LTE from the H_α line for μ=1.

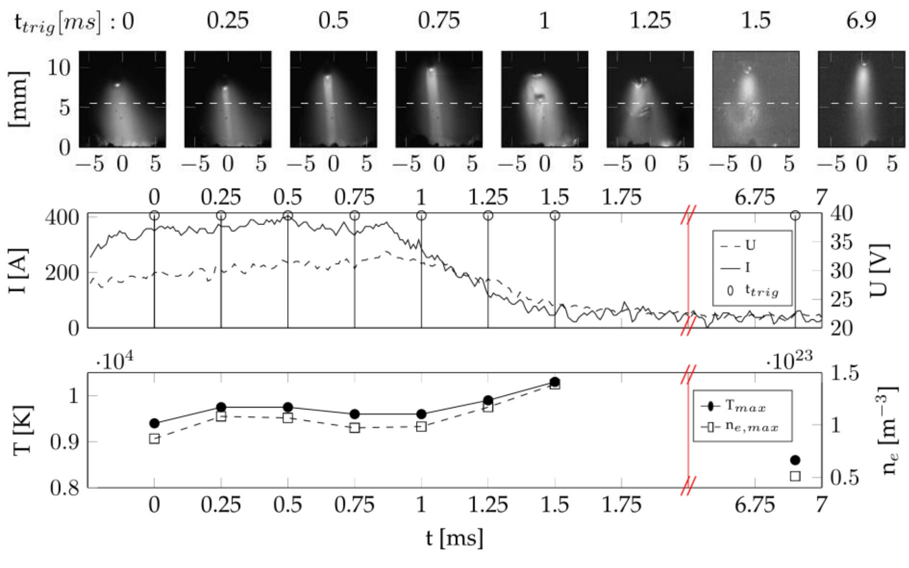

Figure 5: Temporal development of the maximal electron density and temperature evaluated at a particular trigger time (bottom) along the arc current and voltage signal (center). The arc images illustrate the position of droplets relative to the measurement volume (top). The white dashed line in the images marks the position of the measurement volume.

are shown (center). Additionally the images of the arc are depicted for each trigger point (top). The white dashed line indicates the position of the investigated plasma volume. The relative intensities in the images are scaled in order to visualize the shape of the arc without saturation.

In the high current phase the resulting electron densities and temperatures approximately follow the shape of the pulse. The values obtained on the descending slope however unexpectedly rise. An explanation for this result can be found, when taking a closer look on the arc images. In the first 5 measurements (t_{trig}=0-1 ms) no droplets are present below the measurement volume. For t_{trig}=1.25-1.5 ms the situation is different. In both cases a metal droplet is visible below the measurement volume, which may lead to increased metal vapor concentration in the plasma. In the low current phase and in the absence of metal droplets (t_{trig}=6.9 ms) the values of the electron densities and temperatures lower considerably.

Since the H_α line is very sensitive to ion dynamics, the increased metal vapor concentration may lead to self-absorption of the line and hence to apparently higher density and temperature values. Moreover the different metal vapor concentration during the high current pulse and the falling edge might require different theoretical parameters (e.g. different μ) in order to correctly describe the line shape. Hence a more precise modeling of the line shape for the particular welding plasma conditions is necessary.

The Thomson scattering measurement presented in [3] was conducted under equivalent process conditions. Yet the electron densities yielded by this method are higher ($16x10^{22}$ m^{-3}) than the values obtained from Stark broadening measurement. Still the resulting temperatures are in comparable range, when considering the experimental error of both methods.

The shapes of the temporal development of the results of both methods are comparable in the high current phase. However the electron densities and temperatures obtained by Thomson scattering decrease with the decreasing arc current. This reinforces the assumption, that absorption phenomena influence the line shape.

5. Conclusions

In this work Stark broadening of H_α line was applied to obtain time and space resolved electron densities and temperatures in the GMAW process operated with aluminum. For the simultaneous evaluation of both plasma parameters assumption of LTE was necessary. The results of the measurement indicated, that the increased metal vapor concentration arising from metal droplets strongly influence the shape of the H_α line.

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