ELECTRON TEMPERATURE AND DENSITY MEASUREMENTS IN GTAW AND GMAW PROCESSES BY THOMSON SCATTERING

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ABSTRACT

In this work coherent Thomson scattering (TS) is used to investigate thermal plasmas composed of single inert gas species and a mixture of inert gas and metal vapor species, since this technique allows electron temperature and density measurements independent from the heavy plasma particles (ions and neutrals). The experimental setup is adapted to perform measurements on stationary as well as transient processes. Therefore thermal plasmas generated by a DC gas Tungsten arc welding (GTAW) process using Argon as a shielding gas and pulsed gas metal arc welding (GMAW) process using Aluminum welding wire and Argon as a shielding gas can be investigated. The results of the measurements are used to estimate the concentration of the metal vapor in the plasma arc.

1. INTRODUCTION

GMAW is one of the most common industrial welding processes. Here an electric arc ignited between the workpiece and the welding wire is used to melt the wire. The resulting metal droplets fall on the workpiece and form the join. In order to achieve a controlled metal transfer to the workpiece pulsed current may be used, which allows to obtain a so called one droplet per pulse mode. Due to their reproducibility pulsed GMAW processes are interesting for industrial application. Although GMAW processes have been widely studied the over past years there is still a need for experimental investigations in order to obtain a comprehensive model of the process and improve the quality of the welding join [3].

So far GMAW has mainly been investigated spectroscopically measuring the radiation of the plasma which is formed between the wire and the workpiece. Due to presence of metal and shielding gas species in the plasma spectroscopic measurements of GMAW processes are more difficult especially with regard to possible absorption of radiation. Pulsed processes moreover present an additional challenge due to their transient nature.

Thomson scattering is a well-established diagnostic for simultaneous measurement of electron temperature and density without the assumption of local thermal equilibrium (LTE) in pure Argon plasmas [3]. This technique does not require the knowledge of the gas composition, so it can be applied for diagnostics of gas mixtures. Although widely applied to GTAW [3, 6], Thomson scattering has not been used to investigate GMAW processes so far. In this work the electron temperature and density of pulsed GMAW process and a stationary GTAW process are investigated by means of Thomson scattering. The measurement results of the two processes allow to discuss the influence of the metal vapor on the electron temperature and density in the atmospheric pressure arcs.

2. THEORY

The scattering of laser light by free non relativistic electrons in a plasma is proportional to the spectral density function $S(k, \omega)$, which indicates the fluctuation of the electron density along the scattering wave vector k. ω indicates the frequency shift of the scattered light from the incident wavelength. $S(k, \omega)$ has two components:

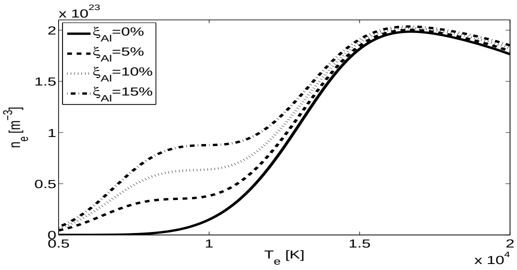

Fig. 1: Dependence of T_e and n_e on concentration of Aluminum species ξ_{Al} in a plasma composed of Argon and Aluminum species under assumption of LTE

the so called electron feature due to density fluctuation of the free electrons and the ion feature due to electrostatic influence of the density fluctuation of the ions on the free electrons. In the case of atmospheric pressure arcs the Salpeter approximation [5] can be used to calculate the spectral density function. The detailed description of the fitting procedure for determination of electron temperature and density from the scattered spectra, as used in this work is given in [2].
Electron density n_e and temperature T_e obtained from the TS measurement can be used for the estimation of plasma composition. Under the assumption of LTE the Saha equation is valid. When combined with the ideal gas law and the quasi neutrality condition, assuming a single temperature for all gas species the plasma composition can be calculated as a function of n_e and T_e [2]. Figure 1 shows the dependence of plasma parameters on the relative molar concentration of Aluminum species ξ_{Al} (ions and atoms) in a plasma composed from Argon and Aluminum species. It can be seen that already a relatively low ξ_{Al} the electron density considerably increases at a relatively low temperature compared to pure Argon plasma. This makes it possible to perform plasma composition reconstruction for this case.

3. EXPERIMENTAL SETUP

The general principle of the TS measurement setup is shown in figure 2. As the laser light source a pulsed Nd:YAG laser with a central wavelength of $532nm$ was used (ML II, Continuum).The laser energy was set to $25mJ$ per pulse with the pulse duration of $3-5ns$. The laser beam was focused on the arc column. The beam waist within the plasma was approximately $500\mu m$. The scattering light was detected at an angle of 90°. The scattering image was projected on to the slit of

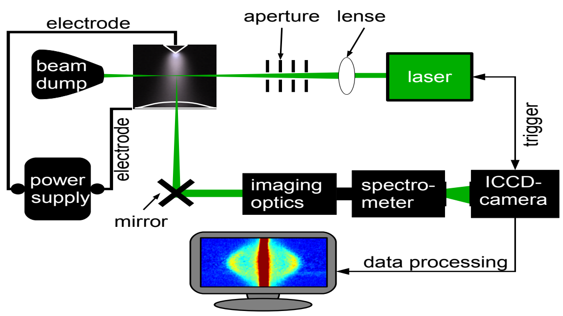

Fig. 2: Schematic of the TS setup for measurements in a welding process

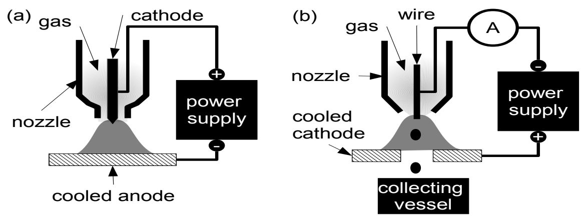

Fig. 3: Schematic of the (a) GTAW and (b) GMAW process inversitgated by Thomson scattering

a Jobin Yvon Spectrometer (Fastier-Ebert design) with a focal length of $250mm$ and a diffraction grating with $1500g/mm$ using two mirrors for image rotation and an imaging optics. The scattering spectrum was recorded by an ICCD camera.
The measurements were performed on GTAW and GMAW processes. The schematic of the GTAW process setup is shown in figure 3a. Here the arc was generated between a Tungsten cathode with 1.5% La_2O_3 ($3.2mm$ diameter and 60° tip angle) and a water-cooled copper anode with a diameter of $100mm$ under atmospheric pressure ($P = 10^5 Pa$). The cathode-to-anode gap was adjusted to $7mm$. The shielding gas inserted into the welding torch was Argon 4.6 (99,9 % purity) with a gas flow rate of $14slpm$. As a power supply the EWM Tetrix 230 was used in the DC mode with the current set to $150A$. Melting of the anode was not observed in these experimental conditions, so the entrainment of the metal vapor can be neglected.
The TS measurement was performed at a height of $5mm$ above the anode surface. The spectral signal in the GTAW process could be accumulated over 250 laser pulses at a repetition rate of $12.5Hz$ since the process is considered to be stable over time. Here the scattering spectrum was recorded by an ICCD camera 4Picos (Stanford Computer Optics, GEN II image intensifier). The camera chip was exposed for $10ns$. The chip resolution yields a spatial resolution of $0.23mm$.
The plasma in the GMAW process was generated at atmospheric pressure by a welding gun as shown in figure 3b. The arc was ignited between an Aluminum wire (AlMg 4,5 Mn) serving as an anode and a water cooled cylindrical copper cathode with a $100mm$ diameter. The wire had a diameter of $1.2mm$ and was fed at a velocity of $3m/min$. On the central axis the copper cathode was obtained with a hole of $7mm$ in diameter. The metal droplets could fall through the hole into a collecting vessel and so prevent metal accumulation on the cathode surface. Hence the cathode

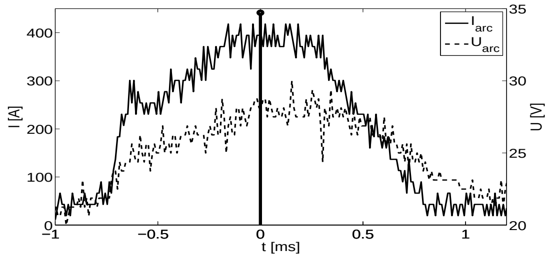

Fig. 4: Typical current pulse during GMAW process using Al wire. $t = 0ms$ marks the trigger position for the TS measurement

did not have to be moved during the process. As a shielding gas Argon 4.6 (99,9 % purity) at a flow rate of $25slpm$ was used. The anode stickout was set to $17.5mm$ and was kept constant during the whole process. OTC DW 300 was used as power supply in the pulsed DC mode.

In the case of the pulsed GMAW process each TS measurement was triggered at predefined position in the current pulse. The trigger was generated by a micro-controller which evaluated the pulse current measured by a hall sensor SS94A1F. Figure 4 shows a typical current pulse and the trigger position at which the TS measurement was performed. The region investigated by TS method was located $5.5mm$ above the cathode surface. The GMAW process is in general less stable than the GTAW process. Hence the number of laser pulses during which the signal was integrated had to be reduced to 5 laser pulses at the repetition rate of $15Hz$ at a fixed trigger position. The TS spectrum was recorded by an ICCD camera Pi-MAX (Princeton Instruments, GEN III image intensifier), which uses an image intensifier with a higher quantum efficiency than the one used for the GTAW process. The camera chip was exposed for $5ns$ in order to minimize the plasma background radiation. Here the spatial resolution of $0.4mm$ was obtained.

4. RESULTS AND DISCUSSION

TS method was applied to a GTAW and a GMAW process as described in section 3. Figure 5 shows an example of measured TS spectra of the processes. In both investigated cases a plasma background measurement was performed in order to obtain an acceptable signal to noise ratio. However the plasma radiation was at least an order of magnitude lower than the laser signal, so that effects such as absorption could be neglected.

Figure 6 shows the measured electron temperature and density in the GMAW process,

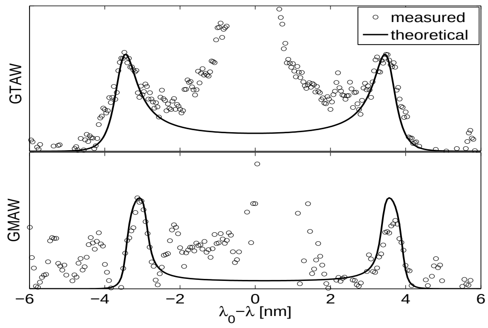

Fig. 5: Example of a TS spectrum of the GTAW process (top) and GMAW process (bottom)

displaying a radial decrease of the electron temperature and density from the hot dense region in the center of the arc column. The maximal electron temperature lies about $18000K$ and the electron density at $14 \times 10^{22} m^{-3}$ respectively.

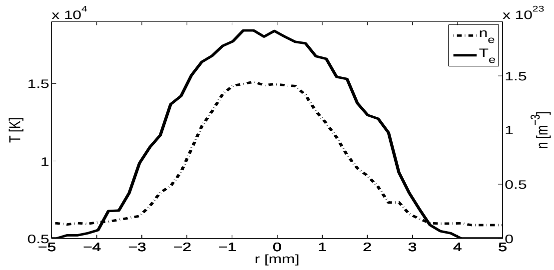

Fig. 6: Radial electron temperature and density measured in the GTAW process at $5mm$ above the anode surface

Figure 7 shows the measured electron temperatures and densities obtained in the GMAW process. Here as well a radial decrease of electron temperature and density from the hot dense region in the center of the arc column is observed. Although the current during the measurement exceeded $400A$ the maximal measured electron temperature was in the range of $14000K$ whereas the electron density was higher than it was the case in the GTAW process. Its maximum value lies about $16 \times 10^{22} m^{-3}$.

The electron temperatures measured in the GMAW process are slightly higher than spectroscopically measured temperatures presented by Goecke [1] There the temperatures in the center of the arc of a comparable GMAW process run with Aluminum as the welding wire and Argon as a shielding gas lay in the range of $11000K$. Maximum temperatures in the center of an Aluminum GMAW arc with a DC current of $95A$ obtained from a simulation model by Murphy [4] reach $9800K$ when considering the influence of the metal vapor.

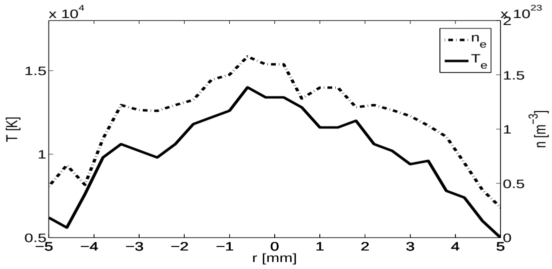

Fig. 7: Radial electron temperature and density measured in the GMAW process at $5.5mm$ above cathode surface

The decreased T_e and increased n_e clearly suggest that the gas metal arc plasma contains an increased concentration of metal species. Since the copper cathode was cooled during the measurement, the supply of metal species mainly comes from the melting anode-wire. When assuming that the plasma is mainly composed from Argon and Aluminum species, Aluminum concentration can be calculated as sketched in section 2. Figure 8 shows the resulting relative molar Aluminum concentration calculated using the electron temperature and density obtained from the TS measurement. The estimation yields metal concentrations in the range of $10 - 30\%$ in the inner region of the arc. Similar metal concentrations were reported by [1]. The Aluminum vapor concentration given in [4] however lays with up to 80% much higher. In the outer regions however the estimated concentration drastically rises. This may be explained by the entrainment of metal vapor in the outer region of the plasma arc, which density the initial phase of the arc ignition has not yet been able to diffuse inwards. However higher relative error of the TS method for lower T_e and n_e and the lower sensitivity of the estimation method for a temperature in the range of $5000K$ should be taken into account.

5. CONCLUSIONS AND OUTLOOK

In this work TS method was successfully used to measure electron temperature and density in stationary and transient gas welding arcs plasmas. The investigated plasmas were generated by a GTAW process run with pure Argon as a shielding gas and a GMAW process with Aluminum as the melting wire and Argon as a shielding gas. The measurements of the two processes were used to estimate the plasma composition. In a next step GMAW processes will be investigated using the method of Stark measurements obtained by TS.

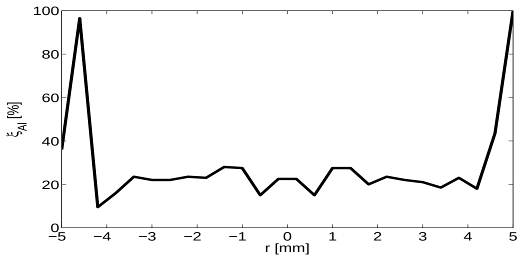

Fig. 8: Molar Aluminum species concentration in a Aluminum-Argon GMAW plasma estimated using parameters T_e and n_e obtained by Thomson scattering

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