Time resolved Thomson scattering diagnostic of pulsed gas metal arc welding (GMAW) process

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Abstract. In this work a Thomson scattering diagnostic technique was applied to obtain time resolved electron temperature and density values during a gas metal arc welding (GMAW) process. The investigated GMAW process was run with aluminum wire (AlMg 4,5 Mn) with 1.2 mm diameter as a wire electrode, argon as a shielding gas and peak currents in the range of 400 A. Time resolved measurements could be achieved by triggering the laser pulse at shifted time positions with respect to the current pulse driving the process. Time evaluation of resulting electron temperatures and densities is used to investigate the state of the plasma in different phases of the current pulse and to determine the influence of the metal vapor and droplets on the plasma properties.

1. Introduction
Gas metal arc welding (GMAW) is one of the most common industrial welding processes. An electric arc ignited between the workpiece and the consumable wire electrode is used to heat and melt the wire. Metal droplets fall on the workpiece and form the join. In order to achieve a controlled metal transfer to the workpiece a pulsed current can 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 over past years there is still a need for experimental investigations in order to obtain a comprehensive model of the process [1].

Thomson scattering is a well-established diagnostic for simultaneous measurement of electron temperature and density without the assumption of LTE in pure argon plasmas [2]. 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 gas tungsten arc welding (GTAW) [3, 4] only few works investigated atmospheric discharges in presence of metal vapor by means of Thomson scattering [5, 6]. However it has not been used to investigate GMAW processes so far.

The plasmas containing metal vapor are often optically thick, which makes the application of optical diagnostic particularly difficult. The advantage of Thomson scattering is, that this technique requires an optically thin plasma only in a small spectral range. GMAW processes which use aluminum as the wire electrode are in general suitable for the Thomson scattering
diagnostic in the wavelength range of 532 nm. Since neither aluminum nor argon plasma emit strong lines in the spectral range of 532 ± 5 nm, the plasma can be considered as optically thin.

This work presents a Thomson scattering setup for time resolved measurements of pulsed GMAW processes. The goal of the investigation is to determine electron temperature and density in different current phases of the process.

2. Theory of Thomson Scattering

The radiation scattered 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 $k = |k_e - k_i| = \frac{4\pi}{\lambda_i} \sin (\theta/2)$. Here $k_i$ is the wave vector of the incident laser radiation and $k_e$ the wave vector of the scattered light, $\lambda_i$ is the laser wavelength and $\theta$ the scattering angle. $\omega = \omega_i - \omega_s$ indicates the frequency shift of the scattered light from the incident wavelength [7]. $S(k, \omega)$ is mainly influenced by the free electrons fluctuations and the electrostatic influence of the ions on the free electrons. These influences are described in the so called electron and ion feature of the scattered radiation spectrum.

In the case of plasmas present in welding arcs electron and ion velocity can be described by the Maxwellian distribution function $f(v) = \frac{1}{(\pi m k_B T)^{3/2}} \exp \left(-\frac{v^2}{2v_0^2}\right)$, with $v_0 = \sqrt{k_B T/m}$ the mean thermal speed, $T$ the particle temperature, $m$ the particle mass and $k_B$ the Boltzmann constant. Moreover the plasma is assumed to be collisionless. If in addition the ratio between the electron and ion temperature is $T_e/T_i \approx 1$, which is the case here, then the Salpeter approximation [8] can be used to calculate the spectral density function. In this case the electron contribution of $S(k, \omega)$ can be described as

$$S_e(k, \omega) \approx \frac{2\pi^{1/2}}{v_0} \frac{\sqrt{2}}{|\epsilon|^2}$$

where $\epsilon = (1 + \alpha^2) R_w(x_e)^2 + (\alpha^2 I_w(x_e))^2$ is the dielectric plasma function. For the real dimensionless frequency variable defined as $x_e = \omega/k_B v_0 e R_w(x_e)$ and $I_w(x_e)$ (the Landau damping term) are the given by

$$R_w(x_e) = 1 - 2x_e \exp \left(-x_e^2\right) \int_0^{x_e} \exp (p^2) dp, \quad I_w(x_e) = i\pi^{1/2} x_e \exp \left(-x_e^2\right)$$

Depending on the density and temperature of the investigated plasma one can distinguish between coherent and non coherent Thomson scattering, which is described by the parameter $\alpha$

$$\alpha = \frac{1}{k \lambda_D} = \frac{1}{4\pi \sin(\theta/2) \lambda_D}$$

with $\lambda_D$ the Debye length given as $\lambda_D \approx \sqrt{\frac{e^2 k_B T_e}{\epsilon_0 n_e}}$, electron density $n_e$, temperature $T_e$, permittivity of free space $\epsilon_0$ and the electron charge $e$. In plasmas investigated in this paper coherent Thomson scattering ($\alpha \geq 1$) is expected.

Electron behavior in a plasma can be influenced by collisions with heavy particles. In this case the composition of the plasma becomes relevant. However as shown by [9], in a TIG arc plasma, the electron heavy particles collision frequency is several orders of magnitude lower than the plasma frequency. In the GMAW process similar conditions are expected. Consequently in this case the electron feature of the scattering spectrum does not depend on plasma composition.

In general laser radiation may influence initial conditions of the plasma and heat up the free electrons [10]. However as was previously shown [11] this effect can be neglected under the experimental conditions which were chosen for this work.
3. Experimental setup

The gas metal plasma of the GMAW process was generated at atmospheric pressure by a welding gun as shown in figure 1. The arc was ignited between an aluminum wire (AlMg 4.5 Mn) serving as an anode and a water cooled donut shaped copper cathode with a 100\textit{mm} outer diameter. On the central axis the copper cathode was provided with a hole of 7\textit{mm} in diameter. The wire had a diameter of 1.2\textit{mm} and was fed at a velocity of 3\textit{m/min}. The metal droplets fall through the hole into a collecting vessel and so prevent metal accumulation on the cathode surface. Hence the cathode did not have to be moved during the process. As a shielding gas argon 4.6 (99.9 \% purity) at a flow rate of 25\textit{slm} was used. The anode stickout was set to 17.5\textit{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. The region investigated by the Thomson scattering method was located 5.5\textit{mm} above the cathode surface.

The principle of the Thomson scattering measurement setup is shown in figure 2. As the radiation source a pulsed Nd:YAG laser with a central wavelength of 532\textit{nm} was used (ML II, Continuum). The laser energy was set to 25\textit{mJ} per pulse with the pulse duration of 3 – 5\textit{ns} and the repetition rate of maximum 15\textit{Hz}. The radiation beam was focused on the arc column. The beam waist within the plasma was approximately 500\textit{µm}. The scattering light was detected at...
an angle of $\theta = 90^\circ$. The image of the measurement volume was projected on to the slit of 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 resulting spectrum was recorded by the ICCD camera Pi-MAX (Princeton Instruments, GEN III image intensifier). The camera was synchronized with the laser using the Q-switch output of the laser. The spatial resolution of the setup in the radial direction of the arc was 0.4mm.

The OTC power supply ensures a constant welding quality by regulating the voltage, current level and frequency of the arc in order to obtain a constant arc length. Since the current pulse frequency varies during the welding process, an additional trigger logic is needed in order to implement time resolution. Therefore a combination of a hall sensor (SS94A1F) for current pulse tracking and a micro-controller (Arduino Due board with Atmel SAM3X8E ARM Cortex-M3 MCU processor) are used. The analog digital converter of the micro-controller board is used to detect a predefined level of the current pulse. With a sampling rate of 1 MHz and a 12 bit resolution it is fast and precise enough to deliver reproducible trigger points for the GMAW process. The counter functionality of the micro controller allows to implement a temporal delay with a precision of 25 ns. The delay function is used to temporally shift the outgoing laser trigger impulse, which initiates the Thomson scattering measurement.

In general it is possible to obtain measurements from a single laser pulse using the described setup. However in order to improve the signal to noise ratio the scattering signal generated by several laser shots is accumulated on the CCD chip of the camera. On the short time range the GMAW process is sufficiently reproducible. However on the long time range the behavior of the arc may change. Hence in order to ensure comparable results the signal was integrated over 5 laser pulses during the high current phase and 20 laser pulse during the low current phase data acquisition. The image intensifier was activated for 5ns per pulse in order to minimize the plasma background radiation. In order to minimize the CCD readout noise the on-chip accumulation function of the ICCD camera was used. Additionally the background radiation is recorded by keeping the experimental conditions and the trigger time of the GMAW pulse but by blocking the path of the laser radiation.

A supplementary high speed camera was installed for imaging of the arc. The images were use for the arc shape visualization. Thus it was possible to optically verify that the arc shape did not considerably change during the signal integration procedure.

4. Results and discussion

Figure 3 shows an image of the spatially resolved Thomson scattering spectrum of the GMAW processes recorded by the ICCD camera. Here the aluminum plasma background radiation, the electron feature of the Thomson scattering spectrum (white dotted line) and the central laser wavelength are visible. The intensity of the latter depends on the ion feature of the Thomson scattering spectrum, the Rayleigh scattering on the neutral atoms and reflection of the laser beam on the cathode and anode surface.

A theoretical Thomson scattering spectrum, which was fitted to the measured spectrum at a specific spatial position is shown in figure 4. For the fitting procedure the background radiation was subtracted from the original signal. As previously described in [11] lookup tables which correlate the shape parameters of theoretical Thomson scattering spectra under consideration of the instrumental function of the spectrometer with the corresponding electron temperatures and densities were used to assign temperatures and densities to the measured spectral profiles.

An example of a typical temperature and density profile evaluated from the Thomson scattering measurement in the high current phase is depicted in figure 5. In figure 6 the trigger time and typical current and voltage characteristic of the arc are plotted. At the a current value of 400A the maximum temperatures in the range of 14000K and maximum density in the range of $1.6 \times 10^{23} m^{-3}$ are reached in the center of the arc. Both electron temperature and density...
diminish with an increasing distance to the arc center. Temperatures under 5000 K and densities under $1 \times 10^{22} m^{-3}$ could not be resolved by the used setup. For temperatures and densities under the given limit the expected spectral shift of the scattered radiation would lie below the order of magnitude of the instrumental width of the spectrometer.

In order to clearly arrange the evaluation of the time-resolved results only the temperatures and densities in the central region of the arc are plotted. A typical temperature and density evolution along the current pulse can be seen in figure 7(c). Figure 7(b) shows the measurement time relative to the current pulse whereas in figure 7(a) the images of the arc shape at the time of the measurement are depicted. The relative intensities in the images are scaled in order to visualize the shape of the arc in an optimal way. Hence the image intensities at different $t_{\text{meas}}$ are not comparable. The white horizontal bar in the images indicates the position of the incident laser beam.

In first approximation it can be concluded that the electron temperature and density are
clearly related to the arc current. The highest values are reached by the end of the high current phase, whereas temperature as well as density fall with the decreasing current.

The last two measurements at $t_{\text{meas}} = 2.21\, \text{ms}$ and $t_{\text{meas}} = 4.29\, \text{ms}$ are made in the low current phase, where arc current was in the range of 10A to 30A. As already seen on the images of the arc, almost no plasma is visible in this phase. The lighter spots positioned above the laser beam at $t_{\text{meas}} = 2.21\, \text{ms}$ and under the beam at $t_{\text{meas}} = 4.29\, \text{ms}$ are aluminum metal droplets detached from the wire anode. The scattering signal in these two measurements was considerably lower than in the preceding ones. Thus only signals close to the center of the arc could be evaluated. Nevertheless it can be concluded that the electron temperature in this phase does not exceed 5000K. The maximal electron density lies in the range of $1.5 - 2 \times 10^{22}\, \text{m}^{-3}$.

In these two measurements almost no difference between the measured plasma parameters can be seen before and after the metal droplet has passed the measurement volume. However it has to be considered that those values lay in the lower resolution limit of the applied setup. Moreover due to the weak signal the relative error increases in comparison to the measurements in the high current phase.

When assuming local thermal equilibrium (LTE), Saha equation and the ideal gas law [11] can be applied to estimate the ionization rate. It is further assumed that plasma is composed from argon and aluminum atoms and ions. For the conditions measured in the low current phase the estimation delivers an ionization rate, which does not exceed 1.5%. In contrast ionization rate reaches from 5% at the edge of the plasma column up to 50% on the central arc axis in the high current phase. This explains a relatively weak scattering signal in the low current phase. In order to be able to investigate the influence of the droplets more in detail either the Thomson
scattering has to be adapted to resolve lower temperatures and densities or different methods such as emission spectroscopy should be used.

5. Conclusions and Outlook
In this work time resolved Thomson scattering was successfully performed to determine electron temperature and density in the GMAW process run with aluminum wire and pure argon as a shielding gas. It was shown that the setup is suitable to investigate electron temperatures and densities in the high current phase of the process. As a next step validation of the measurement using spectroscopic methods such as Stark broadening will be performed for the GMAW process.

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