Plasma diagnostics of arc welding

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The gas metal arc welding process is a fairly sensitive complex system involving plasma and material interaction. Here diagnostic systems for material transfer, plasma characterization and energy transfer are described to determine transient phenomena using pyrometry, laser scattering and magnetic field measurements. The droplet temperature during the trajectory from the electrode to the workpiece is measured to ~ 2500 K, the electron temperature during the high current phase approaches 15000 K and a new non-intrusive method for current density distribution measurements in the workpiece is introduced.

1. Introduction

Diagnostics of arc welding processes has a significant commercial importance. With innovations in material science, the development of new processes that reduce the energy input into the material treated and the urge to produce with less energy consumption and lower costs has put an enormous pressure on welding technology. In order to comply with the demands a better understanding of the welding process is necessary allowing to develop or improve new processes fast and efficiently.

In arc welding this task is somewhat challenging. Essentially in gas metal arc welding (GMAW) numerous interactions take place and require significant diagnostic effort to be able to understand the physical processes taking place. For once the arc is ignited between a consumable anode – the wire electrode – and a constantly changing cathode – the workpiece –. Droplets are produced, during droplet production metal vapour entrains into the plasma. The droplet travels through and interacts with the plasma before it enters the molten surface. In figure 1 an image of some of this process is shown.

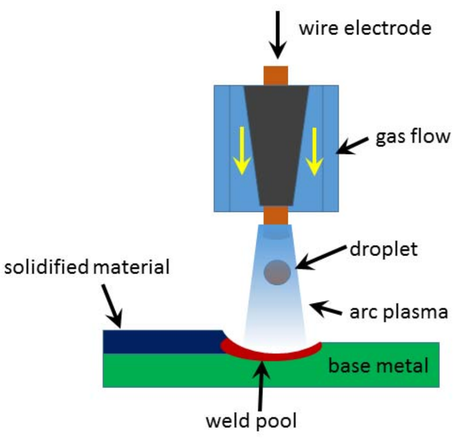

Fig. 1: Schematic of GMAW process

This fairly complex system requires a significant diagnostic effort to be properly understood. In this paper we will focus on methods to analyse the material transport, the arc plasma properties and the energy input into the workpiece. Here a pulsed process is investigated.

2. Material transfer characterization

The droplets that are produced from the tip of the wire electrode enter the weld pool and add significantly to the heat into the workpiece, which in turn influences the join. How the mixing takes place is to large extend determined by the droplet temperature as a molecular dynamics (MD) analysis demonstrates. If the droplet has a higher temperature than the weld pool the incoming material stays on the surface and does not mix very well with the base material (figure 2), thus it is important to determine droplet temperature in dependence on operating parameters.

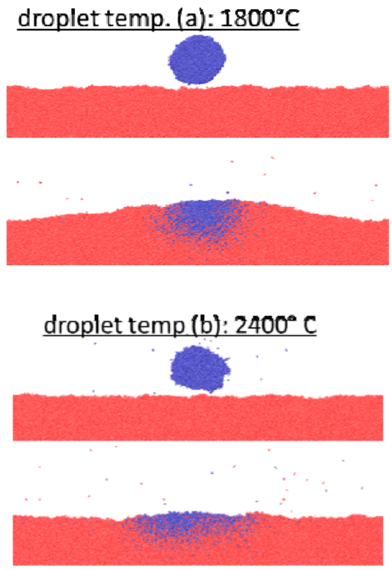

Fig. 2: Results of an MD model simulating droplet entrainment into a weld pool: material Fe, 70000 atoms used for calculation, v_{fall}: 1.4 m/s

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In order to be able to investigate the droplet temperature a two colour pyrometry [1] setup using a high-speed camera is used (figure 3).

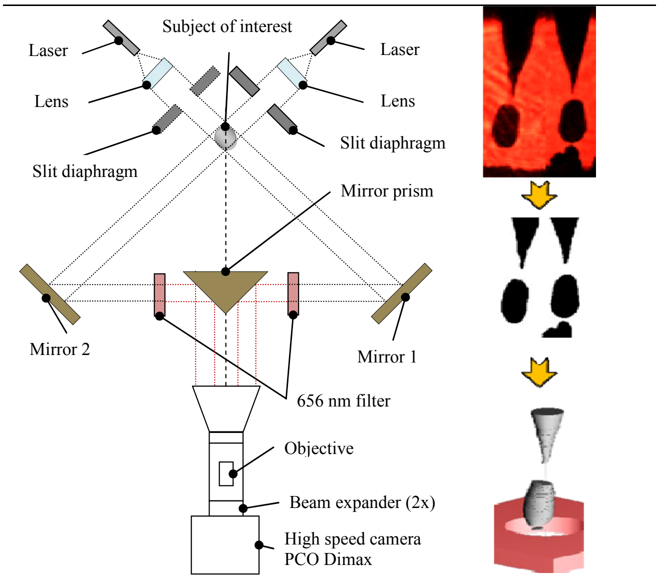

Fig. 3: Principle setup of dual imaging using a single camera. Either 3D information or two-wavelength information can be obtained

The object of interest is observed through an objective. The collected light is divided into two beams by a mirror prism. Both beams are projected onto a low light performance CMOS image sensor of a high-speed camera by two mirrors. In both beam paths an interference filter of different wavelengths is placed, producing a single image on the sensor chip displaying two images of the same droplet. The surface temperature of the observed object is determined by ratio generation of the intensity at both wavelengths.

The results of the temperature measurement are demonstrated in figure 4, showing a decrease in surface temperature during the trajectory from the wire tip to the weld pool.

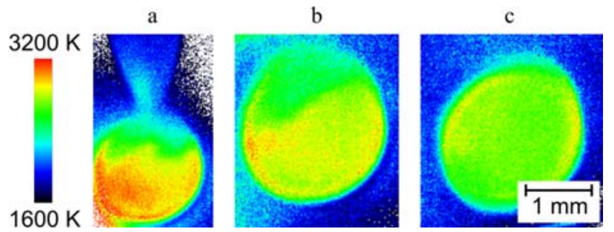

Fig. 4: Temperature distribution of the droplet surface while traveling to the workpiece, before detachment (a), after detachment (b), at height of cathode (workpiece) (c)

The same kind of setup can be used to analyse the droplet shape and the plasma composition identifying Ar radiation as well as metal vapour radiation synchronized with current and voltage (figure 5).

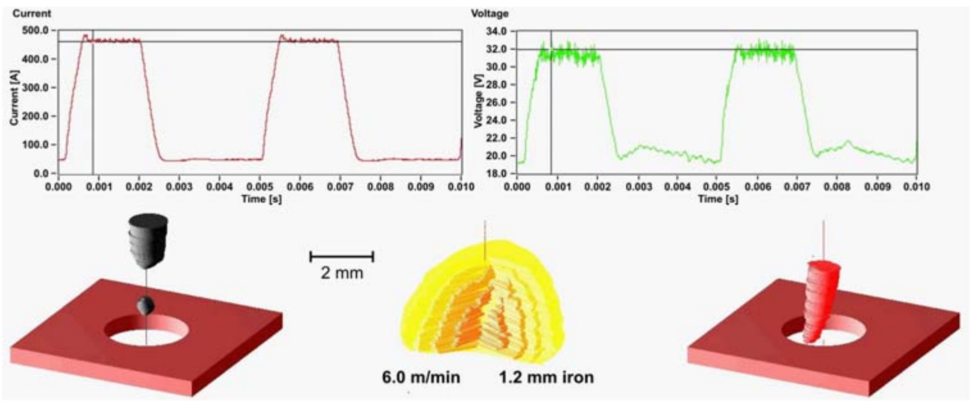

Fig. 5: Synchronized recording of droplet shape, Ar and metal vapour radiation during GMAW process

3. Plasma Properties

As mentioned before it is possible to obtain fundamental composition information about the plasma using a camera/filter technique (figure 5), looking at broad-band radiation from the plasma. However in order to obtain significant data like plasma temperatures a more detailed investigation is necessary.

Plasma diagnostics techniques using spectroscopy has been around for a while and are used to determine densities and temperatures of the various plasma species. The fundamentals of spectroscopic techniques are discussed in detail in [2]. The basic principle is the spectrally resolved measurement of plasma radiation which can be performed using spectrographs, monochromators or narrow band filters, in combinations with adequate recording devices like photo multiplier tubes, cameras, photo diodes etc. From the shape and intensity of the emitted radiation (line width, shapeself absorption etc.), not only the plasma parameters can be determined but also the plasma composition or the local electric field data that can be used to be compared to modelling results [3].

Due to advances in detector technology it is also possible to obtain detailed information about transient (i.e. unstable) processes with the camera based analysis of plasma radiation. With the use of interference filters and a setup of mirrors synchronous imaging of an arc at two different wavelength intervals onto a single camera chip of a high-speed camera is possible with high spatial and temporal resolution. The thus measured side-on radiances result from the local emission coefficients integrated along the line of sight through the arc and can be reconstructed in cylindrical coordinates by the inverse Abel transformation. For each corresponding pixels of the two acquired images local emission ratios can be calculated, enabling high-speed three dimensional determination (in case of axial symmetry) of plasma parameters like temperature and densities of atomic species. The temperature dependency of each calculated emission coefficient for corresponding spectral interval as well as the resulting ratio are described in detail in [4].

However spectroscopic analysis in GMAW plasmas is somewhat difficult as the optical density of the plasma, especially in the case of metal vapour is not known and the necessary assumptions of rotational symmetry and local LTE are not always and everywhere given. One way to verify the spectroscopic measurement might thus be the use of high-speed Thomson Scattering (TS), which is able to provide electron density and temperature as well as – more difficult to do though – ion density and temperature. Usually due to the small scattering cross section this method requires a significant integration time, which in this case of pulsed GMAW would not be able to provide temporal resolution. A solution would be single shot TS or at least limiting the data acquisition to few pulses only at well-defined acquisition times (i.e. fixed current/time values during the pulse especially with respect to the droplet position inside the plasma). Due to advances in camera technology and electronics these challenges can be met. Sufficiently high quantum efficiency of the detection system is needed.

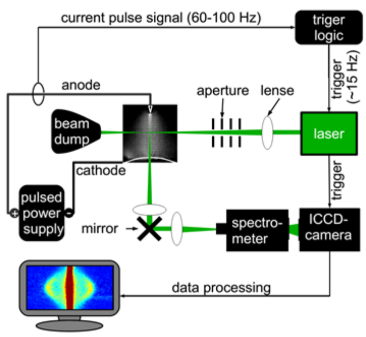

Fig. 6: TS setup for investigation of GMAW process

The setup as shown in figure 6 was used to investigate a pulsed GMAW process with one droplet per pulse detachment. In order to ensure comparable results the signal is integrated during 5 laser pulses in the high current phase and 20 laser pulses in the low current phase. An additional high-speed camera is installed for imaging of the arc. The images were used for the arc shape visualization.

With this kind of setup electron temperature measurements were performed without the assumption of rotational symmetry. Resulting temperature development for a pulsed GMAW process is shown in figure 7 [5].

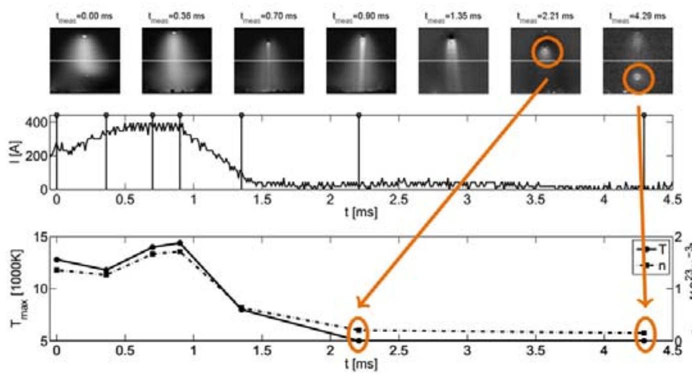

Fig. 7: Results of TS measurements for Al wire/Ar gas combination (electron temperature and density (bottom)) during a pulsed GMAW process. The line in the images (top) gives the position of the laser, the vertical lines in the current display (centre) the time of data acquisition during the current pulse, the circles mark the droplet position in the high-speed images and in the measurement results.

4. Energy into the workpiece

In order to be able to understand the melting and the energy input into the workpiece the shape of the current density of the arc attachment is essential. One way this problem was solved in the past for TIG welding was the use of a so-called split anode method [6] however this approach does not work for GMAW as the insulator that is located between the different parts of the split anode would be bridged by the metal droplets coming from the electrode.

Another ansatz is used to determine the current density in the footprint of the plasma by measuring the magnetic field around the workpiece.

Once the arc travels across the workpiece in *y*-direction the current is flowing from the footprint of the arc to the attachment point of the return cable of the current circuit acting as a current sink as seen in figure 8. If the footprint of the arc current has a distinctive shape the current density inside the workpiece is influenced. This can be seen using the following example: A current of 100 A is flowing through the workpiece. This current is flowing in either the *y*-direction (direct path to current sink) or in *x*-direction (figure 8).

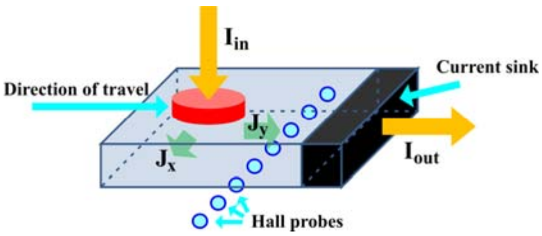

Fig. 8: Principle of *B*-field evaluation underneath workpiece (dotted line). Current input (magenta circle)

It can be seen from an electrostatic model that J_x changes if the current distribution transferred through the cylinder (red in figure 8) changes even though the total current through the footprint remains constant. This change is recordable using small sensitive hall-probes. The data proves the applicability of this method. An inverse modelling approach should be taken to quantitatively determine the current density in the footprint.

An actual measurement of the magnetic flux is given in figure 9, where the result of a hall probe signal (*x*-direction) underneath a workpiece in the case of gas metal arc welding is shown, while the arc is moved across the workpiece in *y*-direction. The higher magnetic flux in the left part of the signal is due to the arc being on the left (figure 9) of the hall probe, thus all the current flows across the area where the hall probe is placed underneath. With increasing travel the current drops as more as more current will be able to flow to the current sink without having to cross the hall-probe sensitive area.

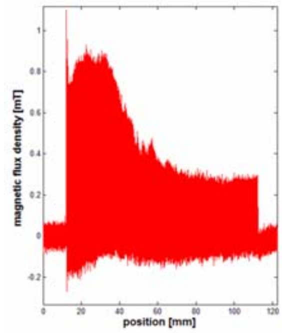

Fig. 9: Measured *B*-field in *x*-direction for traveling arc footprint as sketched in figure 8.

5. Conclusion

Using two-colour pyrometry, Thomson Scattering (TS) and *B*-field measurements the pulsed GMAW process is investigated. Using a high-speed camera system it is possible to determine droplet temperatures with high temporal resolution. A plug-and-play system has been developed and can be used further on for detailed analysis of similar processes. It has been shown that TS can be used in the challenging GMAW environment. More work is needed to enhance the system to provide higher temporal resolution and ion feature analysis using high definition single shot TS. *B*-field measurements to determine current density are still in the need of further research but promise to provide important information using a non-intrusive setup. The GMAW process is a thankful candidate for further diagnostic research.

6. References

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