Introduction

GMA welding is used as a semi-automatic or automatic arc welding process in many applications. In this process the arc is burning between a continuously fed and consumable wire electrode and the workpiece. The shielding gas undertakes a lot of tasks, for example the cooling of the torch, the definition of the arc properties or the protection of the melt from oxidation. In particular, the joining of aluminium, high alloyed steels or titanium requires a cover of shielding gas in order to provide a low PPM concentration of oxygen. Thus, a model is always a compromise of the geometrical complexity of the analysed welding torch design and the necessary inclusion of arc physics or transient behaviour.

In order to obtain a link between the model and the physics observed diagnostic methods to analyse transient phenomena are needed. LDA (Laser Doppler Anemometry) and PIV (Particle Image Velocimetry) are particle based flow measurements [5-7]. Schlieren techniques are widely used to visualize density differences [8, 9]. Most of them have been used already with welding torches, but mostly without an arc in process. That is why the goal of their usage for the gas shield development or investigations in fume extraction of arc welding torches is to enhance these experimental setups for measurements during arc welding.

However, numerical and flow measurement methods can visualize the flow characteristics and their causation and maybe allow to reduce the development effort and to increase gain of knowledge as well. Welding experiments, in step with actual practice, are inevitable to prove the efficiency of developments.

In this paper, the scope and restrictions of numerical and experimental methods for flow characterization at welding arcs will be discussed. Furthermore, it will be shown how they could complement one another.

ABSTRACT

GMA welding is one of the most frequently applied welding techniques in industry. Particularly the joining of aluminium, high alloyed steels or titanium requires a cover of shielding gas in order to provide a low PPM concentration of oxygen. The result of the welding process depends essentially on the chemical and thermo-physical properties of the process gas used. Consequently, it is necessary to be able to describe and to analyse its flow with respect to various influencing variables. However, it is very difficult to realize this during arc welding processes; a poor access is predominant due to the covered areas inside the welding torch and temperatures of up to 20 000 K cause the strong radiation of the arc and electromagnetic fields. This paper deals with experimental and numerical methods for visualization and quantification of process gas flows in arc welding and gives examples for their technical applications. Unlike previous work, the described methods consider the arc as a dynamic element which determines the gas flow. Advanced Particle Image Velocimetry (PIV) and Schlieren measurement were used for characterization of the flow field in the direct vicinity of the arc in GTA and GMA welding. Furthermore, a numerical model including magneto-hydrodynamics and turbulence models was used for a detailed visualization of the flow in the free jet and in the hidden interior of the torch. It is based on a commercial CFD code which allows to model complex 3-D geometries of torch and workpiece design. Mixing effects and turbulence model were validated by oxygen measurements in the gas shield.

IIW-Thesaurus keywords: Arc Physics; Arc Welding; Electric arcs; Flow; GMA welding; GMMA welding; GTA welding; Impurities; MAG welding; Measurement; Measuring instruments; MIG welding; Outdoor environment; Oxides; Oxygen; Photography; Research and development; Shielding gases; Simulating; Torches.
2 Flow measurement
and characterization

2.1 Particle Image Velocimetry in arc welding

The Particle Image Velocimetry (PIV) is a non-intrusive optical method, which enables flow investigations with relatively high spatial and temporal resolution by photographing a two-dimensional flow field twice within a short, well-defined time interval. The flow describing information in the pictures comes from tracer particles, which follow the flow and are two times illuminated by a laser light section. The twin-pictures are taken by one or two cameras, which are synchronized with the laser and positioned orthogonal to the laser light plane. The flow map is calculated by cross correlation between the pixel groups of both pictures and by dividing the two-dimensional displacement of each traceable particle with the time delay between the pictures, (Figure 1). The delay in one picture pair ($\Delta t$) is between 100 and 500 $\mu$s. The reload of the laser and the saving of both pictures take about 0.3 s.

The classical PIV setup is not suited for flow measurements in light intensive arc or plasma processes because of overexposure of the pictures. To circumvent this problem, an extremely short exposure time of 67 ns was used and, additionally, all wavelengths beside the wavelength of the illuminating laser $\lambda = 532$ nm were filtered with a band gap filter of 3 nm half-intensity width.

The tracer particles, which are necessary for PIV measurements, are subjected to a variety of requirements such as providing an intensive scattered or reflected light for the pictures, following the gas flow immediately and showing appropriate stability in the flow. For the measurements in arcs or plasma, only solid particles with high melting temperatures can be used, which have a much higher density than the carrier gas. To provide a sufficient capacity of following the flow, the particles should be as small as possible. Furthermore, they should not interact with the welding process by chemical reactions, volume expansion or deflection by Lorentz forces. Magnesium oxide particles with 1 $\mu$m maximum diameter, melting temperature of 2 640 °C, density of 3.65 g/cm$^3$ and an extended chemical stability at high temperatures were used. Only a small fraction of particles is melted in the arc and deposited as slag onto the welding bath. The majority of the particles pass the flow field unmolten by the welding process. The correct dosage of particles into the shield gas flow requires a special apparatus to prevent the powder from bridging. A funnel formed storage vessel with the shield gas inlet at the small diameter, which is mounted on a vibration plate, was used as dosage unit. The shield gas flows upwards through the funnel and carries the particles over, while the vibrations prevent powder bridging. The magnesium oxide powder was dried before at 350 °C for one hour.

The calculated flow maps of a pulsed GMAW process are shown in Figure 2. The results demonstrate that the flow of the shielding gas is strongly influenced by the arc. The flow map at the beginning of the pulse is totally different from that of the down slope at the end of the pulse or during the background current.

There are essential differences between the flow maps of single measurement and the average value of 50 single measurements that are triggered to the very same pulse phase time of every 30th pulse. A transient behaviour of the gas shield and large eddies were found in single measurements. Studies demonstrate that not only the design of welding torch and gas nozzle but also the gas flow, the average and peak current, the torch position and welding...
speed, as well as the wire and the workpiece materials, influence the gas shield during arc welding.

The used PIV measurement system enables flow characterization in the direct vicinity of the arc. There are no particles visible inside the arc. The flow should only have a low vector component orthogonal to the visualization plane. Otherwise, the particles are only visible in one of the two pictures and correlation fails. Beside the flow map it is possible to gather eddies from the rotation of pixel groups. Statements concerning diffusion and the oxygen concentration are not feasible.

2.2 Schlieren techniques

The Schlieren technique is also a non-intrusive measuring method. It is based on the differences in the density of a transparent media that cause changes of the refractive index and a deflection of the light beams. The generated interference-scheme is easy to picture at a white board or with a (high-speed) camera. The differences in density can come from:

- mixture of different gases, e.g. air, argon, helium or carbon dioxide,
- pressure gradients cause by eddies and turbulences and
- temperatures of the torch and the arc.

The Toepler Z Schlieren technique is suitable because of the compact measurement setup, Figure 3. The light source, the mirrors and the aperture determine the results notably. The usage of coloured filters increase the sensitivity but also the blurring.

The Schlieren technique is conventionally used without an arc; exceptions are TIG welding and very short short-arcs [10]. In general the self-radiation of the arc superposes the Schlieren lightning. Especially by high welding current
and GMAW with metal vapour radiation cross fades the Schlieren.

Figure 4 shows pictures of a TIG process (100 A) with different amounts of shielding gas (Ar50/He50). The increase of the shielding gas flow causes the change to a turbulent flow characteristic. The left picture with 10 l/min shows a laminar flow of the gas shield, only the Schlieren at the arc edge are visible. Additionally, strong Schlieren structures beside the arc are visible in the middle and right picture, which can be addressed to turbulences at the edge of the shielding gas jet and above the workpiece. The transition point from laminar to turbulent flow behaviour can be identified very easily.

The advantages of the Schlieren techniques are the low costs and the easy handling of the measurement setup. The practicability of Schlieren for arc welding is limited by the emitted arc radiation. Furthermore, the density gradients are very small inside a laminar gas shield, thus these flows are hard to analyse by the Schlieren technique.

2.3 Measurement of the oxygen concentration in the arc

In the literature, the measurement of the oxygen concentration is documented, above all, for shielding and forming gases, but without an arc. However, these measurements have only limited value because of the intensive flow of the arc and the rise in the diffusion coefficient of the gases along with the temperature.

The experimental determination of the oxygen content in the arc is based on the arc pressure measurement setup of [11]. A small pump is in place of the pressure sensor and it extracts a small partial flow through a borehole in the water-cooled copper anode which is analysed by a broadband lambda probe. The measurement is insensitive to magnetic fields and, because of the temperature regulation system integrated in the probe, to temperature fluctuations as well. The measuring setup is shown on Figure 5.
The measuring method is easy to apply for arc welding with non-consumable electrodes. Predictions were done for the gas shield of GMAW torches by using a tungsten electrode. However, the removed gas volume influences the flow and the local oxygen concentration. This effect manipulates the results especially in regions of low flow velocity and high concentration gradients in the outer areas. Furthermore, low concentrations of nitrogen monoxide and hydrocarbons can fail the results because of the physical principle of a lambda probe.

Simulation of shielding gas flow

The commercial software ANSYS CFX can be used for the process simulation of arc welding. The software offers high solver stability, good parallelization and advanced physical models for turbulence, radiation and particle tracking as well. For arc simulation the software was enhanced by models of:

– MHD effects to implement electromagnetism [12]
– Sheath layers near to the electrodes [12-13] and
– Diffusion to include mixing and demixing [13-15].

ANSYS ICEM CFD was used for meshing the complex torch design by using a high quality hexahedral mesh, which is recommended for arc calculations with ANSYS CFX.

As shown above, the arc determines the flow of shielding gas. Therefore, a simulation of the gas shield quality is insufficient without the influence and dynamic of the arc. In addition to the momentum, mass, energy and turbulence conservation equations the electric current and the magnetic field have to be calculated, Equations (1-3).

\[ j = -\sigma \nabla \Phi \]  
\[ \Delta \vec{A} = -\mu_0 j \]  
\[ \vec{B} = \text{rot} \vec{A} \]  

where

\( j \) is the electric current density,
\( \sigma \) is the electric conductivity,
\( \Phi \) is the electric potential,
\( \vec{A} \) is the magnetic vector potential,
\( \mu_0 \) is the magnetic permeability and
\( \vec{B} \) is the magnetic force.

The calculation of the magnetic field is done by solving for the magnetic vector potential. The model can be used for non-axially symmetric arcs as they happen caused by the setting angle of the torch or the environment in welding. Electromagnetism affects the flow by resistive heating \( Q_{\text{heat}} \) Equation (4) and by Lorentz force \( \vec{F}_L \) Equation (5).

\[ Q_{\text{heat}} = \frac{j^2}{\sigma} \]  
\[ \vec{F}_L = j \times \vec{B} \]  

The arc attachment at the wire and the workpiece can be simplified by using a grid solution of 0.1-0.4 mm. However, the simplification of the arc attachment and the neglect of metal vapor influence may cause limitations of the model.

Contaminations of the gas shield by atmosphere gases results from turbulence and diffusive mixing. A number of different turbulence models, e.g. two equation models (k-epsilon, k-omega, SST), Reynolds stress models (BSL, SSG) and large eddy simulation (DES, SAS, LES), are available in ANSYS CFX. The shear stress transport (SST) model is an easy to apply two-equation-model that combines the advantages of the k-epsilon and the k-omega turbulence models [16]. Numerical studies of different turbulence models and comparisons to measured oxygen concentration distribution at the workpiece demonstrate similar results for SST and Reynolds models but a much lower numerical expense of SST model (Figure 6). The results of the 6°-model predict lower values of oxygen as measured in the outer areas. The contamination of the shielding gas by the atmosphere due to turbulences is not represented correctly. Thus it is proven that the geometrical complexity of the torch is too much simplified in most published numerical investigations.

Murphy [17] calculated ordinary diffusion coefficients of argon-air mixtures. His results demonstrate that the diffusion coefficient at 10 000 K is approximately 500 times higher than the known coefficient at 300 K. Therefore, the diffusion coefficients \( D_{x_{\text{Ar}, \text{Air}}} \) were implemented as functions of the gas temperature.

The model can provide different transient boundary conditions. This could be pulsed current and gas flow or a defined change of the torch geometry by mesh motion.

![Content of oxygen](image)

**Figure 6** – Oxygen concentration at the workpiece without an arc – Comparison between different turbulence models and oxygen measurements
This option in ANSYS CFX can be used for an optimization of the nozzle design or for a realization of an oscillating motion of the welding torch.

The simulation of the gas flow inside the torch can be done without an arc model. The gas distributor can cause a transient flow with a lot of eddies and turbulences (Figure 7). Especially by small boreholes and a high gas flow the transient flow and turbulences influence the gas shield below the gas nozzle and in the range of the arc.

Figure 8 demonstrates the influence of the arc on the shielding gas flow. The shielding gas is drawn into the arc and causes a smaller recirculation zone below the contact tube and the gas shield. This effect is more significant at high welding current and long stick-out length. Additionally high welding current causes a high radial velocity above the workpiece that scatters welding fume. Figure 9 visualizes the effects of too small a shielding gas volume. The increased oxygen concentration is caused by the high diffusion coefficient at high temperatures inside the arc.

Figure 10 demonstrates the transient behaviour of an AC TIG process. The calculations show that especially at the end of the pulse or during reversion of polarity the flow velocity inside the arc decreases and the diffusion effects cause increased values of oxygen inside the arc, see Pictures 4 and 6. The predicted oxygen concentrations demonstrate that in case of a small nozzle diameter and a high nozzle-to-workpiece distance the diffusion causes a strong contamination in the arc process. Furthermore the numerical investigations predict a decrease of oxygen concentration in the arc and at the workpiece when the arc is in high-arc current phase. This statement was proven by oxygen measurements.

**4. Conclusion**

An effective gas shield is indispensable to guarantee the process stability of welding and to decrease the costs of subsequent works. The development of modern welding torches realizing a better gas shield by the same or reduced gas consumption necessitates modern methods of flow and mixing visualization during the arc welding process and in the hidden regions inside a welding torch. However, these methods would also be very useful for the development and optimization of fume extracting welding torches.

The PIV and Schlieren techniques can be used for the visualization of gas flow during arc welding. The advantage of PIV is the high resolution especially by observing pulsed current arc welding and the applicability on GMAW. The Schlieren technique causes much lower costs but is difficult to use at high welding current or in GMAW. Oxygen measurement can be done at a water-cooled copper anode using a pump for the separation of a small gas portion towards a broadband lambda probe. This method is unfortunately usable only for TIG or PTA welding. The classification of the gas shield of GMAW torches makes it necessary to substitute the wire by a tungsten electrode (EP).

The CFD simulation of the shielding gas flow enables the visualization of the gas flow and gas concentration at the arc region and inside the torch. Based on the available models the influence and the dynamics of the arc can be
considered. The numerical simulation allows a high resolution and detailed predictions. Furthermore, design changes during development process can be directly taken over in grid generation and numerical studies. This allows a decrease of development time and costs. The discussed flow visualization methods and oxygen measurement can be used for the validation of the model. The model is used for modelling the gas shield of TIG and GMAW processes neglecting the weld pool depression and the transient effects of wire feed and melting. Analyses of their influence could be content of future works.

However, welding experiments are still necessary to prove the efficiency of developments.

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References


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