SUPPLEMENT TO THE *WELDING JOURNAL,* JANUARY 2014
Sponsored by the American Welding Society and the Welding Research Council

Visualization of Gas Flows in Welding Arcs by the Schlieren Measuring Technique

The influence of typical welding parameters on the gas flow for the GTAW, GMAW, and PAW processes is demonstrated using the high-speed Schlieren technique

BY E. SIEWERT, G. WILHELM, M. HÄSSLER, J. SCHEIN, T. HANSON, M. SCHNICK, AND U. FÜSSEL

ABSTRACT

Gas flows in and around welding arcs have a strong influence on the welding process. Atmospheric gases reach the arc due to turbulences and diffusion mechanisms and this affects the arc and the weld pool. Using optical analysis of the gas flow during welding with and without the arc present reveals possible mixing and thus the causes of contamination can be determined. The Schlieren method offers a simple way to do this. In this paper, the setup of a Schlieren measuring system and the influence of the most relevant setting parameters are described as well as their influence on the Schlieren images.

Introduction

In gas tungsten arc welding (GTAW) the arc and the weld pool are protected against the influence of atmospheric gases by a shielding gas. Contamination of the shielding gas leads, among other things, to arc instability, oxidation, porosity, and spatter. Furthermore, atmospheric gases such as oxygen, carbon dioxide, or nitrogen affect the characteristics of the plasma and influence the arc spots at the cathode and anode. Therefore, one important goal of welding torch development is to generate an optimal gas flow through the welding torch in order to guarantee a stable and protective shielding gas coverage. To achieve this, it is most important to avoid flow separation and turbulence in the shielding gas nozzle.

In order to minimize the experimental effort by performing numerous welding experiments, computational fluid dynamics and gas flow diagnostics can be used.

Dipl.-Ing. E. SIEWERT, Dr.-Ing. G. WILHELM, M. HÄSSLER, Prof. Dr.-Ing. J. SCHEIN, and Dr. T. HANSON are with Center of Excellence AAP (advanced arc processes), a coop of Linde AG Co. and the Lab of Plasma Technology, University of the German Federal Armed Forces, Munich, Germany. Dipl.-Ing. M. SCHNICK and Prof. Dr.-Ing. U. FÜSSEL are with the Department of Joining Engineering and Assembly Technology, University of Technology, Dresden, Germany.

In prior work, attempts were made to follow this route. As described in Refs. 5 and 13, the computational fluid dynamics were used to optimize the welding fume exhaustion. However, in these simulations, the arc was either neglected or significantly simplified by being modeled as a source of thermal energy with a preset momentum. In Refs. 1 and 8, the commercial software ANSYS CFX was used with a contained arc module to calculate the shielding gas flow and the diffusion. However, the models used were based on assumptions and many simplifications. Moreover, the torch geometry was often simplified in order to reduce the numerical mesh size. Thus, verified experimental findings are needed for proofing and calibrating of these models.

To analyze gas flow fields, particle-based methods such as the laser doppler anemometry (LDA) and the particle image velocimetry (PIV) can be used. By Zschetzsche (Ref. 2) the applicability of both methods for the measurement of gas flow in arc welding was tested and the PIV method was adapted to measure different welding processes. The method enabled a nonintrusive and temporally resolved detection of a two-dimensional gas flow field in GTAW and gas metal arc welding (GMAW). However, LDA and PIV measurements are extremely cost-intensive and require a high measuring technique effort. An easier way to visualize gas flows is the Schlieren technique, which has been known since the 17th century (Refs. 3, 7, 14–16). Typical applications where the Schlieren measuring method was previously used are airplane aerodynamics, ballistics, and ventilation technology (Ref. 6).

KEYWORDS

Shielding Gas
Gas Contamination
Gas Flow Dynamics
Gas Tungsten Arc
Gas Metal Arc
Plasma Arc

Schlieren studies of electrical discharges (arcs) were first carried out by Toepler (Ref. 3). In the field of cutting technology, oxygen cutting analyses were carried out by the Schlieren technique in the 1930s (Ref. 9). Gas flow studies of arcs by the Schlieren technique are especially used in plasma cutting processes and thermal spraying (Ref. 6). Gas flow visualization of plasma cutting arcs and the interaction of the arc with the workpiece are known from investigations by Settles (Ref. 10). These investigations can be extended to image the gas flow and turbulences below the workpiece as well. In order to detect instabilities in the plasma-cutting process, Heberlein (Ref. 11) used the Schlieren technique in combination with current and potential measurements as well as acoustic recordings. An explanation of the relationship between nozzle design and cutting quality was derived based on Schlieren images.

In contrast, Schlieren measurements of welding processes are not so common. For plasma arc welding with alternating current, McClure and Garcia (Ref. 4) de-

WELDING RESEARCH

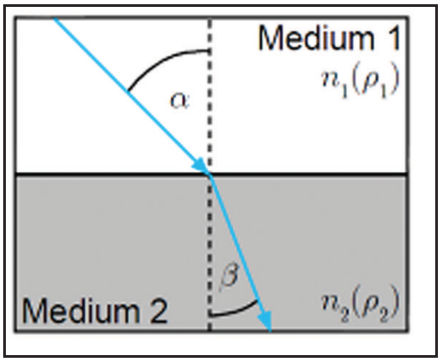

Fig. 1 — The law of refraction as foundation of the Schlieren optic.

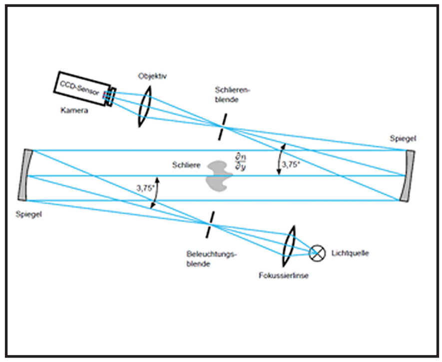

Fig. 2 — Toeplersche Z-Schlieren assembly.

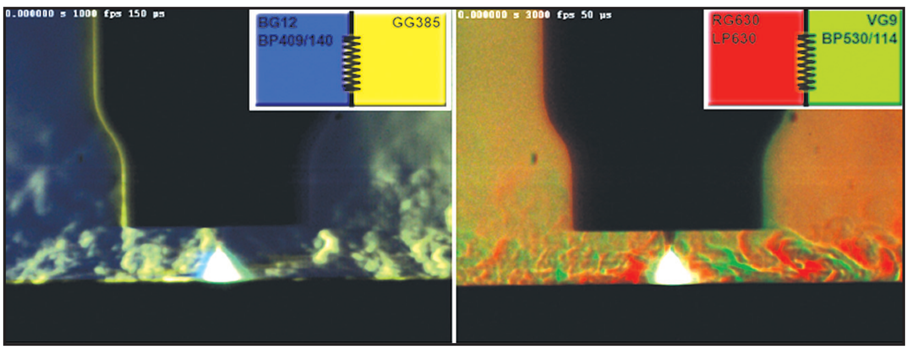

Fig. 3 — Schlieren images, used filter pairs: blue/yellow (left) and red/green (right) with a shielding gas flow of 30 L/min of argon.

scribed the necessity for a gas flow analysis. However, their work contained no corresponding results or Schlieren images. Allemand and Schroeder (Ref. 12) used the Shadowgraph method (Ref. 6) in order to visualize the drop transfer during gas metal arc welding. For illumination, a He-Ne laser was used. The photographs are, however, overexposed due to the presence of the arc and the drop transfer was difficult to observe.

This paper describes an attempt to use the Schlieren technique to visualize the shielding gas flow in different arc welding processes. The principle of operation and the experimental setup of the Schlieren technique are described. The most important settings and their influence on the quality of the Schlieren images of GTA are described so that the range of application and the limit of the Schlieren technique can be specified. The results of the gas flow analysis for GTA, GMA, and plasma arc welding (PAW) are presented, where the influences of typical welding parameters on the gas flow are displayed.

Experimental Procedure

Physical Principle and Measuring System

By the Schlieren technique, differences in density that cause changes in the refraction index n, in the propagation velocity c and in the direction of light propagation direction, can be visualized in transparent media. The angle of refrac-tion relates itself to the incident angle α

$$\frac{\sin\alpha}{\sin\beta} = \frac{c_2}{c_1} = \frac{n_2}{n_1} \qquad (1)$$

Thus each change in density of the medium causes a change in the direction of light propagation — Fig. 1.

The differences in density that are observed during the welding process are caused, according to the ideal gas equation, by differences in pressure, temperature, and concentration.

In order to make differences in density in transparent media visible, the interference and the shadowgraph methods can also be used alongside the Schlieren technique.

In the interference method, two light waves are superimposed so that an interference pattern is generated. The interference image allows the reconstruction of the location and the intensity of the light refraction as well as the speed of the gas flow, the density, and the temperature. However, this measurement method requires high precision in the adjustment of the measuring equipment.

By the shadowgraph method, deflection of the light can be made visible by means of the generated intensity of illumination dispersion E, which is proportional to the second derivation of the density along path y (Equation 2).

$$\Delta E \sim \frac{\partial^2 \rho}{\partial^2 y} \qquad (2)$$

This method enables conclusions to be drawn about the density gradient, but not about the direction. Compared to the interference method, a lower resolution and sensitivity can be reached (Ref. 6).

Due to a marginal overhead (the integration of a knife edge), it is possible to separate the deflected from the uninfluenced light, in order to increase the resolution and sensitivity. Furthermore, with the so-called Schlieren technique, it is possible to determine the direction of the measured density gradient. The change in intensity of illumination caused by the light deflection is proportional to the first derivation of density according to the position (Equation 3).

$$\Delta E \sim \frac{\partial \rho}{\partial y} \qquad (3)$$

In contrast to the interference method, the Schlieren technique is a simple and robust measuring system. However, an exact identification of gas flow characteristics is not possible.

The experimental setup is carried out as a Toepler's Z-Schlieren assembly with two concave mirrors — Fig. 2. This assembly is compact and avoids errors due to chromatic aberration caused by the optical lenses.

The concave mirrors are axially parabolic mirrors with a diameter of 150 mm and a focal length of 1200 mm. The diameter lies in the recommended area from D = f/6 to f/12 (Ref. 6). In the region between both mirrors, parallel light is generated. In this optical path, different welding arcs (Schliere) are inserted, influencing the propagation of the parallel light. In the focus of the first mirror, an aperture is placed to produce a point light source enabling the production of parallel light by mirror 1.

The knife edge is placed in the focus of mirror 2. The knife edge is used to improve the contrast by blocking the deflected light. Images of the Schlieren are generated by a high-speed camera with a 200-mm objective with a macrolens.

The exact position in which the Schliere is arranged between the two mirrors has no influence on the measurement outcome. The deflection level of the light a in the Schlieren aperture depends only upon the angle of deflection and the focal length f of the mirror.

$$\Delta a = \varepsilon \cdot f \qquad (4)$$

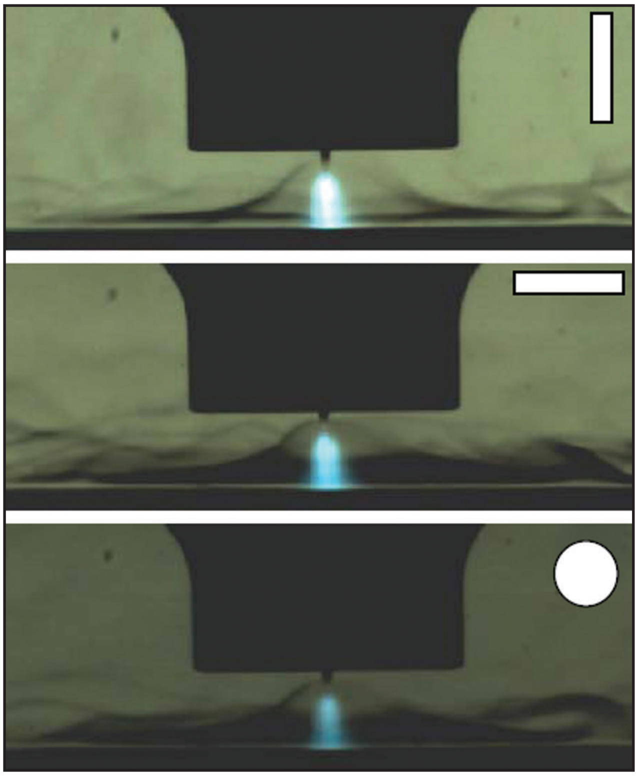

Fig. 4 — Schlieren image of a 100-A gas tungsten arc with vertical (top) and horizontal (middle) apertures, and an iris (bottom).

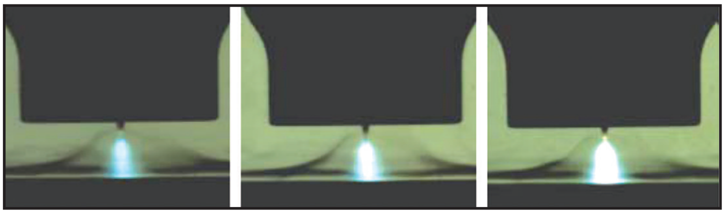

Fig. 5 — Images of Schlieren setups with a 3 × 6 mm focus slit and a Schlieren aperture slit of 2 × 6 mm (left), 3 × 6 mm (middle), and 5 × 6 mm (right).

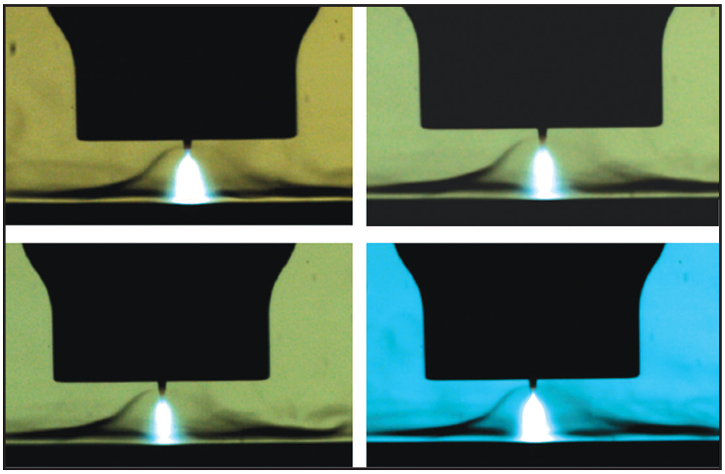

Fig. 6 — Schlieren images made by using 50-W automobile headlight (top, left), 150-W tungsten coiled filament lamp (top, right), 250-W tungsten coiled filament lamp (bottom, left), and 150-W halogen lamp (bottom, right).

Requirements of the Schlieren Method to Analyze Welding Arcs

Alongside the already described basic requirements such as the positioning of the mirrors, the quality of the Schlieren images of arc processes is above all determined by the light source and the slit (knife-edge) or alternatively colored filter pairs, which induce colored shadows and interferences — Fig. 3.

The knife-edge or the filter affects the sensitivity of the Schlieren apparatus, whereas the magnitude of the deflected light can be assigned to different dye by using color filters. The applicability of apertures with horizontal or vertical slits, or an iris as well as two- and four-color filters was investigated. In all experiments, the open area of the slits was equal and the orientation of the illumination and the Schlieren slit was always identical.

The two-color filters (blue/yellow and red/green) as well as a four-color filter, utilizing all four colors, were used. The best results were obtained using the two-color filters, by which the turbulences could be visualized with very strong contrast — Fig. 3. In comparison, using the four-color filter, only marginal color nuances could be recognized. However, the light intensity was reduced when colored filters were used. Thus, the exposure time had to be extended whereby a strong cross-fading due to arc radiation resulted.

Analyses of the influence of the geometry and the orientation of slits clarify that good results can be achieved with slits oriented perpendicular to the workpiece — Fig. 4.

The hot gas above the workpiece was visualized using apertures with a slit, which were oriented parallel to the workpiece. The iris can be used to visualize gas flow in all directions, but the images are characterized by a lower brightness of the image.

By reducing the slit width of the knife edge, less diffracted light, and consequently smaller differences in density, can be visualized (Ref. 6). At the same time the influence of the radiation of the arc decreases. However, less light from the light source passes the knife edge especially if the width of the knife edge is less than the focal diameter. The goal of the slit variation was to be able to visualize the turbulence and the density gradient of the shielding gas flow in the free jet of the process gas in close proximity to the arc individually. It was ascertained that in spite of a small slit width, the density variation produced by the arc dominated — Fig. 5.

When using identical concave mirrors in the geometry described above, it is recommended that the shape of the light sources used be equivalent to that of the slit opening. Therefore, elongated rectangular light sources were used.

Initially, the applicability of simple light bulbs was tested. Only by the use of high-luminosity light sources could the slit opening as well as the exposure time of the camera be reduced, so that:

1) The complete area of the gas flow was illuminated,

2) overexposure of the images due to the arc radiation could be avoided, and

3) minor differences in density could be visualized in the gas-free jet.

Beside the power, the light source must generate a high light intensity on the knife edge. The gas flow in the boundary region of the process gas-free jet can be visualized well using halogen lamps.

However, with the light sources used as described in Fig. 6, the area of the arc cannot be investigated in detail due to its strong brightness. Thus, further analyses employed alternative light sources such as a plasma arc and laser beam.

The radiation energy of a plasma arc is approximately 10 to 20% of the total power. Thus, the radiation emission of a 250-A plasma arc with a voltage of 30 V is about 1000 W. Using this kind of arc is furthermore advantageous since the projection of the light source is rectangular, as the knife edge is. Considering the solid angle of emission, only 1% of the radiation reaches the mirror. Nevertheless, even this amount of light is sufficient to obtain a detailed flow

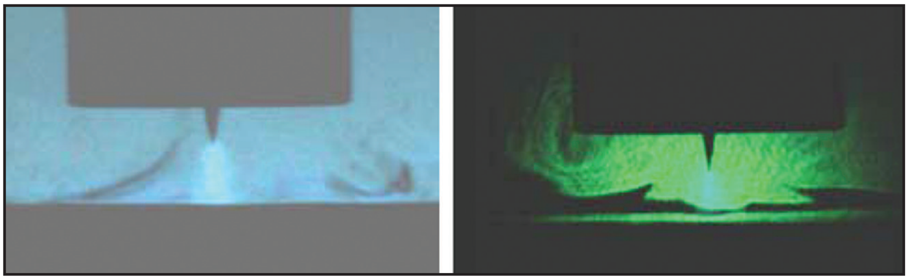

Fig. 7 — Schlieren images made by using 250-A plasma arc (left) and 20-mW continuous wave laser (λ= 532 nm) (right).

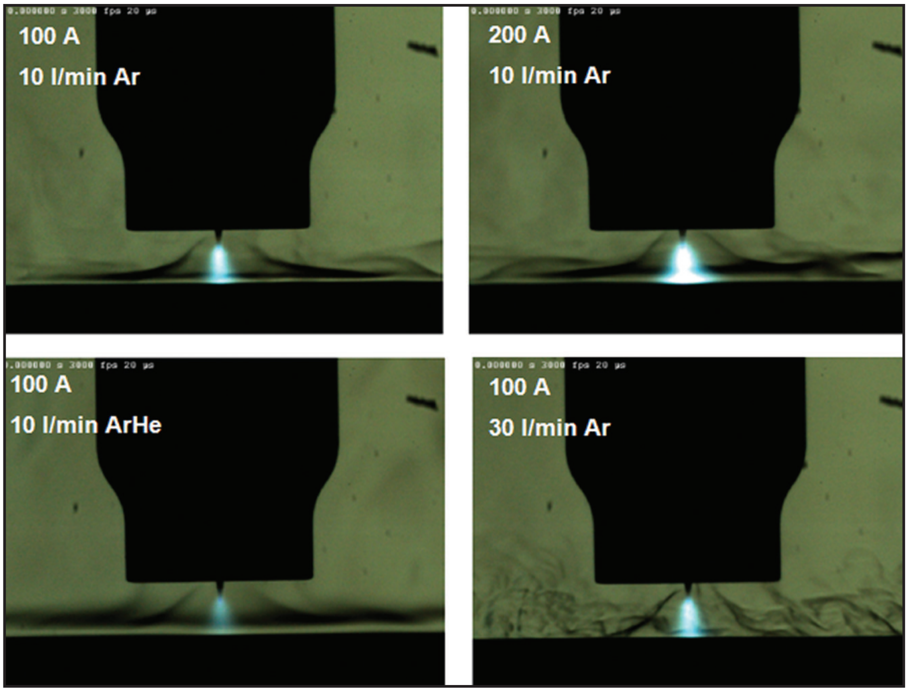

Fig. 8 — Schlieren images of GTAW as a function of current, shielding gas, and flow rate.

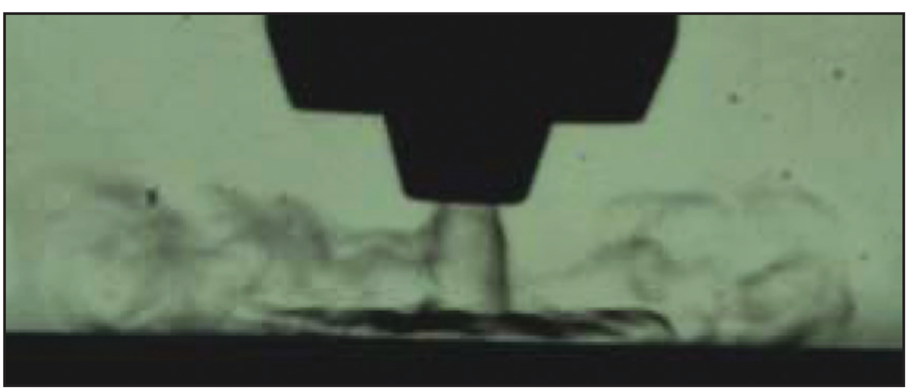

Fig. 9 — Schlieren image of a pilot arc (3 L/min plasma gas flow) where the hot plasma jet is clearly observable. The impinging hot gas on the workpiece and the effluent hot gas on the surface of the workpiece are visible by a dark plateau. Stalls in the periphery are detected by means of eddies.

image in an area that was not recognizable before — Fig. 7.

Using a 20-mW continuous wave laser of wavelength 532 nm in combination with a neutral gray filter with a transmittance of 1%, the radiation of the arc could be completely faded out — Fig. 7. However, by using a laser (point light source), a "digital" Schlieren image without intensity gradations results.

Results and Discussion

In order to analyze the gas flow even at the boundary region of the process gas-free jet, despite the intensive arc radiation, a GTAW arc is used as a light source. The orientation of the light source, as well as that of the Schlieren slit, is vertically aligned to the surface of the workpiece.

The Schlieren technique was used to make high-speed images of the GTAW, PAW, and GMAW processes.

GTAW

GTAW with differing shielding gases, flow rates, and currents was analyzed — Fig. 8.

The transition of the process gas-free jet to the atmosphere is especially good to visualize using argon with an appreciable helium percentage (50%) as shielding gas. However, it has to be assumed that helium has an essential influence on the arc geometry and, above all, on the gas flow.

The arc current influences the temperature of the arc and the temperature of the effluent gas. From the Schlieren images, it can be clearly seen that the arc moves up farther on the tungsten cathode, that the core of the arc is brighter, and that there is a stronger flux of hot gas above the workpiece. Despite the brightness, the edges of the arc can be clearly detected.

The Schlieren measurement method can be used to detect the turnover from a laminar to a turbulent gas flow of the process gas-free jet in GTAW. Turbulences surrounding the arc and turbulences in the effluent hot gas can be clearly distinguished at shielding gas flow rates of 30 L/min and more.

PAW

Investigating plasma arc keyhole welding was carried out by bead-on-plate welds (6-mm-thick, mild-steel plates). To ignite the main arc between the tungsten cathode and the workpiece, a pilot arc between the cathode and the copper nozzle (anode) must be initialized. The pilot arc serves as preionization of the arc gap between the electrode and the workpiece — Fig. 9. The Schlieren method is excellently suited to image the gas flow of the pilot arc. An advantage is the low radiation emission of this plasma jet.

The Schlieren images of real keyhole welding trials were correlated with the respective welding results — Fig. 10.

Clearly visible at low shielding gas flow rates is that the fluid flow above the hot weld joint (left of the torch) is dominated by thermal buoyancy. In contrast, above the cold steel sheet (right of the torch) an equal and laminar outflow can be seen. With higher shielding gas flow rates, the differences between the gas flows over the hot and the cold steel sheet are less pronounced. It is assumed that the high shielding gas flow counteracts the thermal buoyancy as well as causing the outflowing

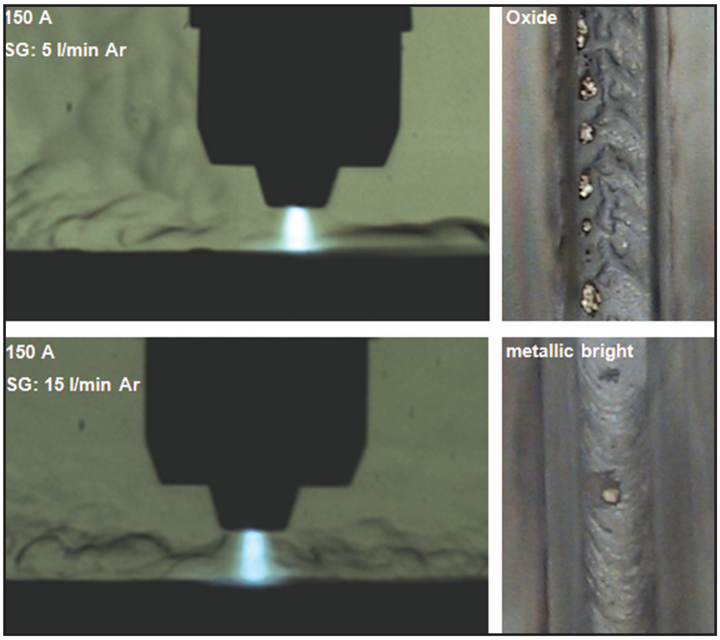

Fig. 10 — Schlieren images of plasma arc welding (S235, 6 mm; welding speed, 20 cm/min; PG-flow, 3 L/min; plasma gas three-hole-nozzle, 3 mm; torch distance, 5 mm; shielding gas flow 5 L/min (top); 15 L/min (bottom).

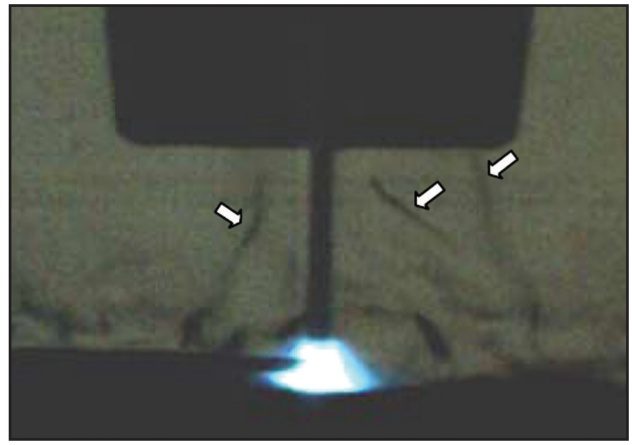

Fig. 11 — Schlieren adaptor of a short arc (3 m/min wire feed).

gas to deviate from laminar flow. Using low shielding gas flows, a considerable formation of oxides can be determined, which is due to contamination of the protective cover. It must be concluded that the formation of a turbulent gas flow (15 L/min shielding gas) does not always lead to bad gas protection cover of the weld pool. A sufficient gas flow is necessary in order to counteract the thermal buoyancy above the hot workpiece.

GMAW

Gas metal arc welding is characterized by a high radiation emission of the metal vapor plasma. Schlieren images of gas metal arc welding processes are therefore especially difficult to create at high currents. As part of the investigations, Schlieren images were taken of a short arc — Fig. 11. In the images, gas flow separations at the shielding gas nozzle and the contact tip are, in contrast to GTAW, clearly visible. A reason for that is the high, very hot contact tip located inside the shielding gas nozzle caused heating of the shielding gas.

For the analysis of a pulsed arc or a spray arc, it is necessary to use powerful light sources or to mitigate wavelengths with special intensive radiation emission of the arc by filters.

Conclusions

The Schlieren method was used to visualize gas flows in welding processes. The main conclusions are as follows:

1) The Topler Z-Schlieren configuration enables cost-efficient and time-resolved gas flow analysis.

2) It was ascertained that a powerful tungsten filament lamp and arcs were especially appropriate as light sources. In contrast, inferior images were obtained with widened laser beams.

3) It is possible to detect the transition from a laminar to a turbulent gas flow in a process gas-free jet in GTAW by increasing the shielding gas flow from 10 to 30 L/min.

4) Through the Schlieren method, the gas flow of a nontransfer pilot arc can be excellently visualized. During studies on a plasma arc keyhole welding process, it was shown that high shielding flow rates, despite intensive turbulences, provide a better protection of the process and counteract diffusions effects.

5) First investigation on GMAW processes showed that high torch temperature principally abets the Schlieren analysis of the process gas-free jets. Due to the high radiation emission of the arc, powerful illuminants in combination with optical filters are necessary, especially in the analysis of spray and pulsed arcs.

References

1. Schnick, M., Füssel, U., and Zschetzsche, J. 2006. Simulation and measurement of plasma and gas flows in plasma arc welding and cutting. *8th International Seminar — Numerical Analysis of Weldability*, Graz, Austria.

2. Zschetzsche, J. 2007. Diagnostics of gas shielded arc welding processes. *Dresdner Fugetechnische Berichte*. Band 14.

3. Toepler, A. 1906. Observations according to a new optical method. *Ostwalds Klassiker der Exakten Wissenschaften Nr*. 158. Leipzig, Germany.

4. Garcia, G., McClure, J. C., Hou, H. and Nunes, A. C. Gas flow observation during VPPA welding using a shadowgraph technique. NASA-CR-204347.

5. Cooper, P., Godbole, A., and Norrish, J. 2007. Modelling and simulation of gas flows in arc welding. Implications for shielding efficiency and fume extraction. *Proc. on the 60th Annual Assembly of the International Institute of Welding,* Dubrovnik, Croatia.

6. Settles, G. S. 2001. *Schlieren and Shadowgraph Techniques*. Springer; Berlin, Germany, ISBN 3-540-66155-7.

7. Schardin, H. 1934. Toepler's Schlieren method: Basic principles for its use and quantitative evaluation. *Forschungsheft 367 — Beilage zu Forschung auf dem Gebiet des Ingenieurwesens Ausgabe B Band*. July/August.

8. Speiseder, M., and Lang, A. 2006. Optimization of the MIG-welding process by the use of numerical simulation and PIV measurement. The electric arc — A technology with a non-exhausted potential. *Dresdner Fugetechnisches Kolloquium*, TU Dresden, Germany.

9. Zobel, T. W. 1936. Increase of the cutting speed while flame cutting by the use of a new nozzle geometry. *VDI-Verlag GmbH*, Berlin, Germany

10. Settles, G. S. 1998. Visualization of liquid metal, arc, and jet interactions in plasma cutting of steel sheet. *8th International Symposium on Flow Visualization.*

11. Kim, S. J. 2009. Fluid dynamic instabilities in plasma arc cutting. PhD dissertation. Minnesota, Faculty of the graduate school, University of Minnesota.

12. Allemand, C. D., Schoeder, R., Ries, D. E., and Eagar, T. W. 1985. A method of filming metal transfer in welding arcs. *Welding Journal* 64(1): 45–47

13. Ebert, L. 2007. Optimization of fume extraction of torch integrated fume extraction devices. *TU Chemnitz. Abschlussbericht AiF-Vorhaben* 14:436 BR.

14. Foucault, J. B. 1859. *Annales de l'Observatoire Impérial de Paris.*

15. Mach, E. 1889. Further ballistic-photographic experiments. *Sitzungsband Akad. Wiss. Wien*. 98: 1303–1309.

16. Rheinberg, J. H. 1896. On an addition to the methods of microscopical research, by a new way of optically producing coulour-contrast between an object and its background, or between definite parts of the object itself. *J. Roy. Microsc. Soc*., Ser. 2, 16(8):373–388.