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Transient Simulation of Pulsed Gas Metal Arc Welding Processes and Experimental Validation

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Abstract

Gas metal arc welding (GMAW) is one of the most important joining processes in today's industry. Pulsed GMAW is a highly dynamic process with variable welding current, a permanent variation of the temperature and the geometry of the electrodes, the plasma composition (argon and vaporized metal) and the shielding gas flow. Transient simulations are presented, which calculates the complex arc properties by using time-dependent boundary conditions for current and vaporization mass flow and location at the wire. The calculated temperatures and iron distribution inside the arc are in very good agreement with spectroscopic measurements and the transient behavior of current and voltage shows good agreement as well. Finally a purpose-built particle image velocimetry (PIV) system was used to measure the flows of welding arcs and to proof calculated flow characteristic continuously.

Introduction

Gas metal arc welding (GMAW), also known as metal inert gas (MIG) and metal active gas (MAG) welding, is a semi-automatic arc welding process in which a continuously-fed and consumable wire electrode is melted by an electric arc. The arc burns between the wire electrode and the workpiece, Fig. 1. In most cases the wire is the anode (positive polarity) and the workpiece is the cathode (negative polarity). During welding, the process is covered by shielding gas. Widely used are Argon (MIG) or mixtures of Argon and CO_2 (MAG). In most cases, a direct current power source is used. The material transport from the wire to the weld pool can occur in different modes – by short-circuiting, by spray or globular. The pulsed current process, discussed in this paper, uses the globular transfer (short-circuit-free).

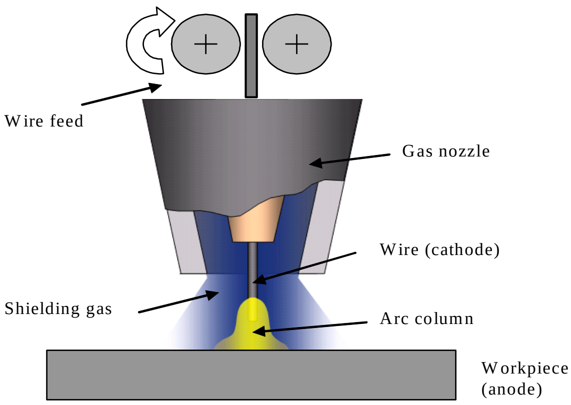

Fig. 1. Gas metal arc welding in principle

The electric arc is a gas discharge. In gas metal arcs temperatures of more than 10 000 K and flow velocities of more than 300 m s^{-1} occur. The pulsed GMAW process is characterised by a basic current which is necessary to preserve the arc and a pulse current which is used to heat the wire, form a droplet and constrict this droplet. Fig. 2 shows the current profile of all experiments and numerical investigations presented in this paper.

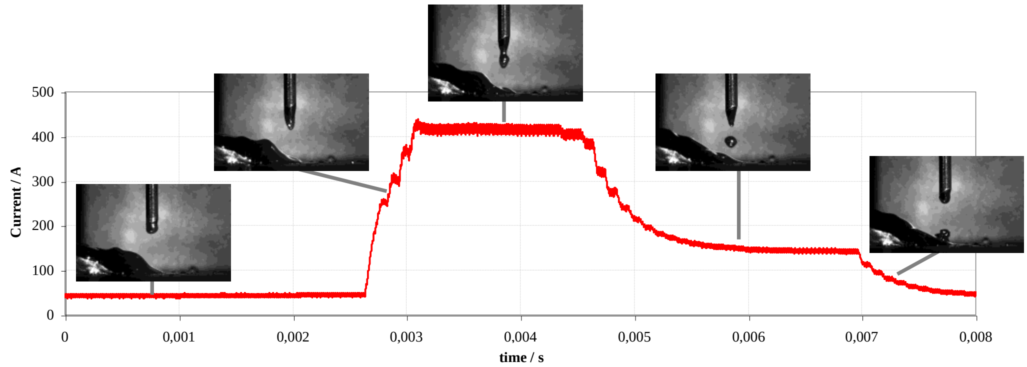

Fig. 2. Droplet formation in a pulsed GMAW process

In the plasma different elements are present; the most import ones are Argon and metal vapour. On different MIG and MAG processes, it has be shown, that the centre of the arc is dominated by metal vapour and that a local minimum in the temperature distribution is in the centre of the arc occurs [1] [2]. Cause and effect of this phenomenon have been investigated numerically by [3]. It was found out, that the high radiation of metal vapour leads to a lost of energy and to reduces temperatures in the centre. Recently spectroscopic measurement where carried out with the very same GMAW pulse process as shown in Fig. 2 [4]. Fig. 3 shows measured metal vapour concentration and measured temperature distribution during the high-current phase of the pulse. The four measured points in time a shown in the very left picture in Fig. 3. The centre temperature is constant about 8 000 K and rises quickly at 1 mm up to a peak temperature of about 13 000 K. The cold centre radius increases during the high-current phase. The evolution of iron percentage in the plasma show that the maximum value is in the centre of the arc up to a radius of about 1 mm. More outside the iron percentage decreases quickly. During the high-current phase the iron percentage in the centre decreases and the metal core gets wider, but there are have quite high uncertainties.

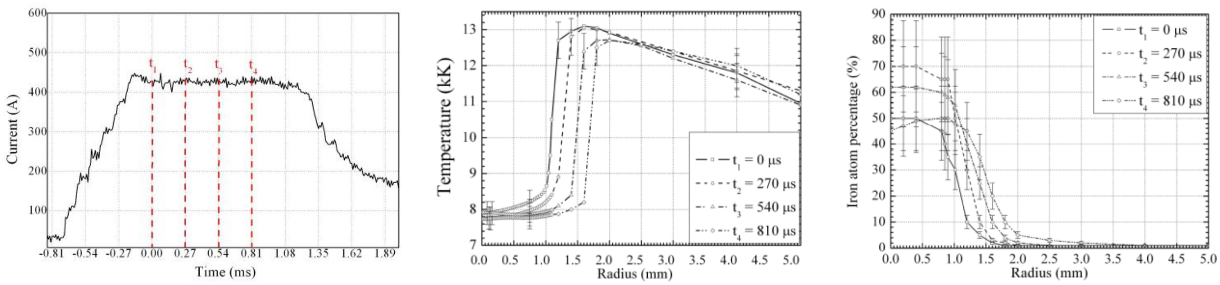

Fig. 3. Spectroscopic measurement of temperature and iron distribution in the arc [4]

1. Transient Simulation of GMAW

The arc behaviour in GMAW is dominated by metal vapour. However, currently there is no model that is able to calculate the complex interaction of arc and temperature of the wire, arc and arc attachment in a fully self-consistent way. Because of this, evaporations with different mass flows and different profiles of the metal vapour source were defined and compared with the experimental results presented in 1. The numerical model uses the commercial software ANSYS CFX for an axisymmetric simulation. The standard equations of computational fluid dynamics for the conservation of mass, momentum and energy are used. The plasma is assumed to be in local thermodynamic equilibrium (LTE), as it is usual for models of welding arcs [5] [6]. Magneto-hydrodynamic and radiative phenomena of thermal plasmas are considered [5] [7] [8]. Joule heating and radiative loss terms are added to the energy equation. The following equations are added to the to the momentum equation:

Magnetic pinch term: $\vec{f} = \vec{j} \times \vec{B}$, $\quad j$ = current density; B = magnetic field; (2.1)

Current continuity: $\nabla \cdot \vec{j} = -\nabla \cdot (\sigma \nabla \varphi) = 0$, $\quad \sigma$ = electrical conductivity; φ = electric potential; (2.2)

Magnetic field: $\vec{B} = \nabla \times \vec{A}$, $\quad A$ = magnetic vector potential; (2.3)

Magnetic vector potential: $\nabla^2 \vec{A} = -\mu_0 \vec{j}$, $\quad \mu_0$ = permittivity of free space. (2.4)

The effects of the sheaths are simplified by using a mesh size of 0.1 mm at the electrodes, as recommended by Lowke and Tanaka [6]. The pressure is equal to atmospheric pressure.

The configuration of the model and the definition of the iron vapour mass source are shown in Fig. 4. The arc region is the entire fluid domain. The shielding gas flow rate is 15 l/min Argon. The model implements mixing of argon and metal vapour due to turbulence and diffusion effects. Turbulence was included using the shear stress transport turbulence model. A combined diffusion coefficient model is used to treat diffusion of metal vapour relative to argon [5]. Experiments and numerical simulations were carried out with the identical current run, Fig. 2. The iron mass flow at the wire and can be defined with different percentages relative to the wire feed (4 m/min) and profiles. The profile is defined by the height, where 0 mm is the top of the droplet, see Fig. 4 right. The iron vapour has a defined entering temperature of 3023 K. A more detailed description of the model can be found in [3].

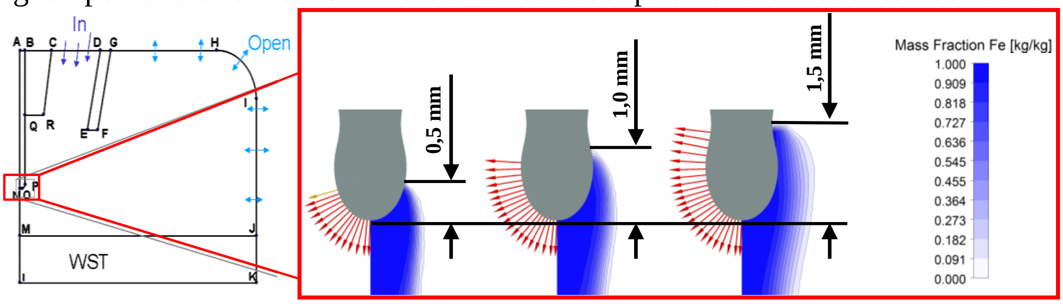

Fig. 4. Numerical model and iron vapour distribution and concentration at the wire tip

The transient simulations show that the arc changes immediately with a different vapour sources. If the percentages of vaporised metal or the profile of the source are modified, the arc will change its temperature and iron distribution immediately. This is reasoned by the very high velocities and the high mixing velocities due to the temperatures. With the peak current of 420 A, the predicted maximal velocity is 500 m s^{-1} and the arc length of 5 mm is passed in 10^{-5} s.

To investigate the behaviour more in detail, at first, different mass flows of iron were investigated, 1 %, 3 % and 5 %. Fig. 5 shows the distributions of temperature and iron mass fraction. It can be seen that higher evaporations and mass fractions of iron lead to reduced temperatures in the arc and move the maximum of the temperature outwards of the centre. The comparison with the experimental results (Fig. 3) show, that evaporation rates of 3 % and 5 % lead to the measured temperature of about 8 000 K in the centre of the arc. It is also good to see that the simulated characteristics in the temperature distribution are not fully adequate yet. There are higher temperatures and fast decreases of the temperatures outwards in the arc than in the experimental results. These differences can be reasoned by the missing radiation model. Such a model calculates the emission of the hot regions in the centre of the arc and the absorption of this radiation in the areas more outside. This should lead to reduced temperatures in the centre and a heating of the regions outside.

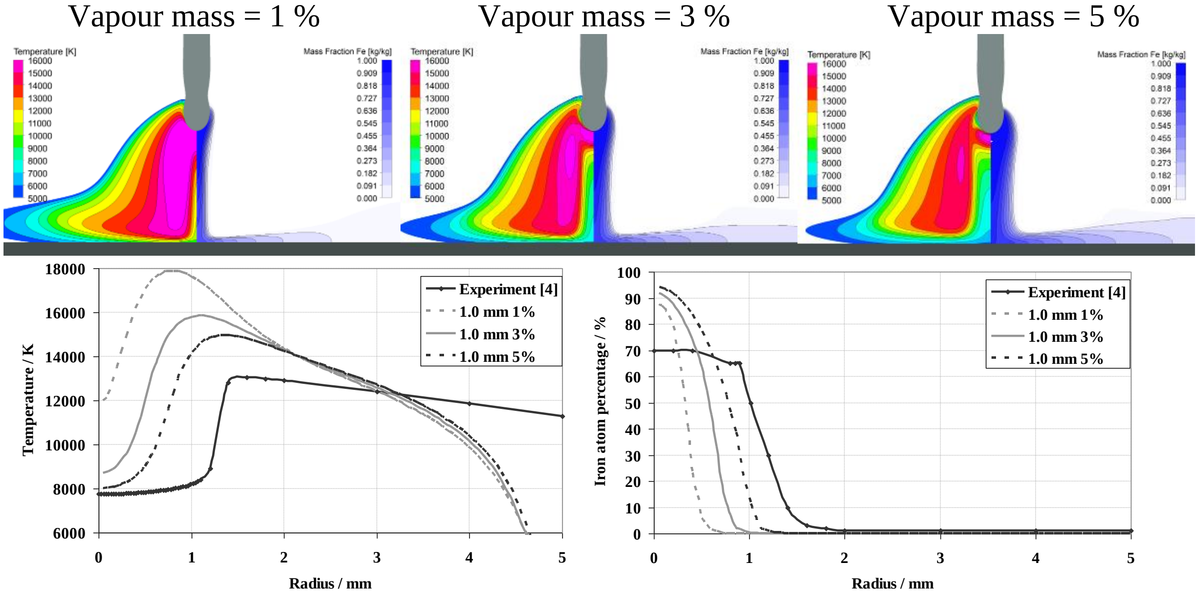

Fig. 5. Temperature and iron distribution for different evaporations (vapour source at 1 mm)

Secondly it can be seen, that the numerically calculated percentages of iron in the centre of the arc higher than the experimentally measured ones. The simulation calculates about 90 % iron the centre, nearly independent of the amount of evaporated iron (1 %, 3 % or 5 %). Of particular interest is the fact that the gradient of distribution is nearly the same for all amounts of iron. Only the iron core in the centre gets wider with rising evaporation.
An evaporation rate of 5 % shows the best agreement of experimental and numerical results. An evaporation rate of 5 % seems to be quite high, because the measured amounts of metal in the emissions are much lower. But this difference can be reasoned by condensation processes at the cold workpiece next to the weld seem. Due to these results, the influence of the location of the vapour source was investigated, as shown in Fig. 4. The results show that the defined location does not have a significant influence on the iron percentage or the temperatures on the centre. With a smaller vapour source (0.5 mm) the centre gets little colder and the iron percentage rises. But the differences are within the measurement uncertainties.

It can be summarized that the arc transports the metal vapour to its centre. As shown, the peak temperatures and the iron distributions are mainly influences by the mass of evaporated iron. The location of this evaporation on the other hand does have a significant influence. Consequently the experimentally observed transient changes of the plasma have to be caused by the mass source. These changes are caused by different wire temperatures and the arc attachments.

Using these results, transient simulations were carried out. Fig. 6 shows the comparison of experimental and numerical results. The illustration via phase room diagrams allows the visualization of transient processes such as pulsed GMAW. Especially the illustration of voltage over current is widely used for welding processes. It is good to see, that the characteristic runs and even discontinuity (dotted circles in Fig. 6) are in very good agreement. The necessary voltage during the up-slope (rising edge of the pulse current) is higher than the necessary voltage during the down-slope. The voltage runs from the maximal current of 420 A to the basic current of 40 A are in both cases nearly linear. The difference between the numerical and measured voltage is with about 11 V nearly constant. This difference can be reasoned by the missing sheath model. The summarized voltage drop in the cathode and anode sheath can be assumed to be that high. It can be concluded that the numerical model calculates the arc column and the influence of metal vapour correctly over a wide current range. The characteristic run in voltage over current has the best agreement of numerical and experimental results with a defined evaporation rate of 1 %.

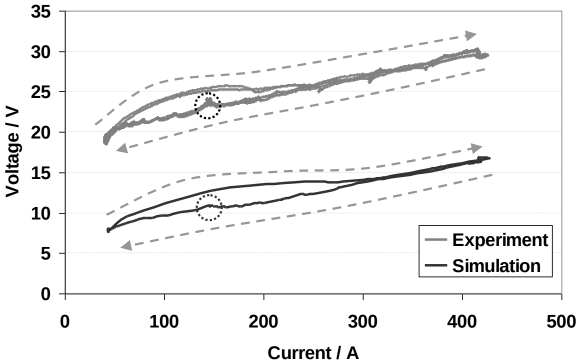

Fig. 6. Phase space diagram of U-I for numerical and experimental data

2. Flow Diagnostics - Particle Image Velocimetry

Due to the high dynamics in pulsed GMAW the flow behaviour in the gas shield is affected. Because of the changes of the electric current, temperatures and flow velocities in the arc change high dynamically as well and optimizations of the process are difficult since most flow measurements does work in the arc ambient. This limitation is caused high radiation and high temperatures. A special purpose-built particle image velocimetry (PIV) system enables the measurement of the gas shield flow and the proof of numerical results [9]. The measurement configuration is built up with a high speed camera (resolution of 40 000 frames per second with 348 x 512 Pixel) and a triggered pulse laser.

Fig. 7 shows the PIV-pictures and numerical results. It is good to see, that the flow behavior and the eddies caused by the current changes are visualized very well. Thus it can be said that the PIV-system is able to measure the flow behavior in welding arc, especially the shielding gas protection, and to control the numerical simulation. The combination of methods allows a better understanding of the complex interactions and the improvement of GMAW processes.

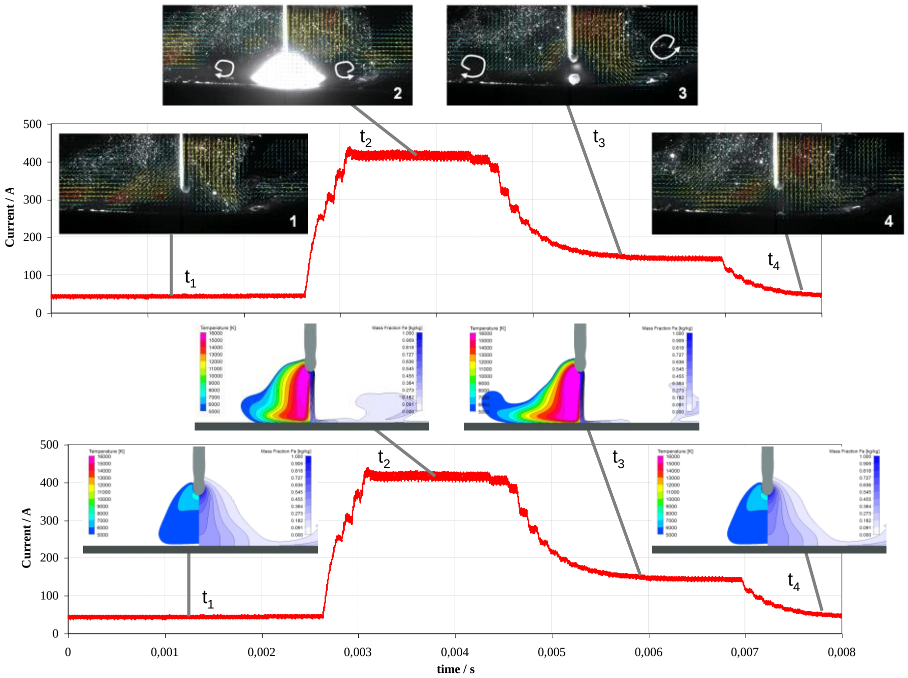

Fig. 7. Pulsed current GMAW –experimental (PIV) and numerical results

Summary

Gas metal arc welding (GMA) welding is a semi-automatic arc welding process in which a continuously-fed and consumable wire electrode is melted. Pulsed current GMAW is a highly dynamic process with changing temperatures and metal vapour concentrations in the arc. Metal vapour dominates the GMAW process. The paper presents the model used to simulate these transient arc processes considering the influence of metal vapour. The amount of vaporised iron (proportional to the wire feed of 4 m/min) and the location of the vapour source were changed. For an identical pulsed GMAW process, numerical and experimental results are compared. The results show that only high vaporisation rates of 5 % can cause the temperature minimum of 8000 K in the arc. The differences of the temperature distribution and the higher peak temperatures could be leaded back to not treated radiation transport in the model. The numerical results show additionally that the location of the metal vapour source has little influence on the arc because the arc leads the metal vapour into its centre nearly independent of the distribution at the wire. The characteristic phase space run of voltage over current shows very good agreement between experimental and numerical results.

Finally a custom-built flow diagnostic for transient arc processes is presented. Particle Image Velocimetry is able to visualizes and measure the dynamic flow behaviour of the arc and the shielding gas with very high resolutions. It is a non-intrusive measurement system and can be used to validate numerically calculated processes and to improve the understanding of the complex interactions in GMAW processes.

Acknowledgement

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