Dynamic analysis of droplet transfer in GMAW: modelling and experiments

M Boselli, V Colombo, E Ghedini and P Sanibondi

Department of mechanical engineering (D.I.E.M.) and Research Centre for Applied Mathematics (C.I.R.A.M), Alma Mater Studiorum - Università di Bologna, Via Saragozza 8, 40123 Bologna, Italy

Abstract: In this work, a pulsed welding process has been investigated to highlight how a time varying profile of current impacts on the metal transfer dynamics. First, the process has been recorded using high-speed camera, allowing to qualitatively evaluate the effectiveness of metal transfer and the synchronization of the droplet detachment with current peaks. Second, a time-dependent axi-symmetric 2-D model has been developed in the FLUENT environment to take into account both the droplet detachment using a volume of fluid (VoF) model and the production and diffusion of metal vapour through a simplified diffusion model (neglecting demixing effects). We report a comparison between experimental and simulative results of a pulsed transfer mode for a steel wire (d = 1 mm) and an Ar shielding gas.

Keywords: thermal plasma, pulsed welding, modelling, metal vapour, high speed imaging

1. Introduction

Gas-metal arc welding (GMAW) [1] is a long-established process used for joining metals, as mild or stainless steel and aluminium. Main process parameters are the arc current time-profile, the total voltage, the wire-feeding rate, the shielding gas flow rate, the welding speed, the wire diameter and material. Depending on the combination of these parameters, the metal transfer to the workpiece can be obtained in different modes: globular, spray, pulsed and short-circuit.

Both modelling and experimental activities play an important role in the optimization of GMAW: the first highlights fundamental processes occurring during metal transfer, which can give insights on the optimal design of the experiments; the second is essential to test several combinations of operating conditions and to check the overall quality of the process, for instance the insurgence of welding sputter. Thermo-fluid-dynamic modelling plays an important role in understanding the relative importance of different operating conditions of GMAW and in highlighting physical phenomena acting during metal transfer (Lorentz forces, surface tension, plasma fluid-dynamics, metal vapour diffusion, etc.).

It has been recently shown [2] that vapours coming from the over-heated wire tip can greatly influence the arc behaviour, with an increased radiation emission that results in an increased cooling of the arc at the centreline. The most advanced models for GMAW include either the time-dependent droplet detachment surface tracking through volume-of-fluid (VoF) approach [3], or the accurate description of the metal vapour diffusion process under steady-state conditions (fixed wire shape), taking into account demixing effects using the combined diffusion approach developed by Murphy [2].

In a previous work by the Authors [4], a time-dependent axi-symmetric 2-D model has been developed in the FLUENT environment to take into account both the droplet detachment using a VoF model as well as the production and diffusion of metal vapour through a simplified diffusion model (neglecting demixing effects). In this work it has been applied to the case of the pulsed welding process. Besides modelling, the same process has been recorded using high-speed camera to validate the overall dynamics of the metal transfer. This integrated approach gives new insights in understanding pulsed GMAW and it can be used as the basis of an efficient tool to optimize the process.

2. Experimental setup

A shadowgraph setup (Fig. 1) composed by a high speed camera (NAC K3) and a DC operated Xenon Short Arc Lamp have been used to study the droplet transfer obtained by means of a welding torch linked to a pulsed welding power source (Cebora SOUND MIG 5040/TD DOUBLE PULSE).

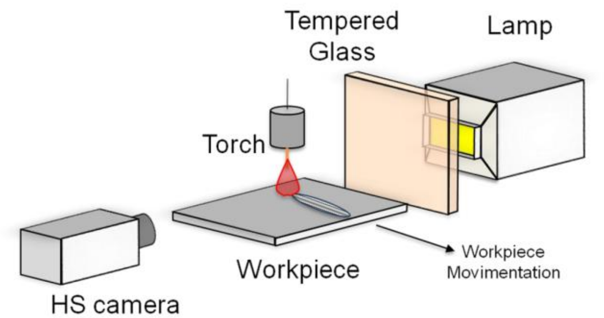

Figure 1. *Schematic of the experimental setup.*

Metal droplets have been continuously transferred on a mild steel workpiece 3 mm in thickness. To avoid piercing or metal accumulation on the workpiece and to reproduce a setup similar to common robot welding, the workpiece has been moved sideways to the high-speed camera at a constant speed of 0.8 m/min. A sheet of tempered glass has been used to protect the lamp from welding spatter with low impact on light dampening.

The experiment was performed with a wire feed rate of 5 m/min and a mild steel SG2 wire of 1 mm diameter. The distance between the surface of the workpiece and the contact tip of the torch was nearly 15 mm, with granted an average arc length of 4 mm and a stick out length of 11 mm. As shielding gas we used argon with a constant flow rate of 10 l/min. The pulsed current waveform [5] used for experiment had a period of 9 ms, with peaks of current of nearly 360 A and a background current of 30 A. The high-speed camera video was shot with a frequency of 10000 fps and with the aid of some neutral density filter.

3. Modelling approach

The model implies the solution of the following equations:

Mass continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = 0$$

Momentum conservation

$$\frac{\partial \rho \bar{v}}{\partial t} + \nabla \cdot (\rho \bar{v}\bar{v}) = -\nabla P + \nabla \bar{\bar{\tau}} + \rho \bar{g} + \\ + \bar{J} \times \bar{B} + \bar{F_S} - K\bar{v}$$

Energy conservation

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\bar{v}(\rho e + P) = \nabla k_{th} \nabla T + \bar{J} \cdot \bar{E} + S$$

Volume of fluid conservation

$$\frac{\partial F}{\partial t} + \bar{v} \cdot \nabla F = 0$$

where ρ is the plasma density, t is the time, v is the velocity vector, P is the pressure, τ is the viscous stress tensor, J is the current density, B is the magnetic induction, g is the gravitational force, e is the specific energy, k_{th} is the thermal conductivity, T is the temperature and F is the volume of fluid fraction.

The presence of both plasma and metal is taken into account by adding different source terms for momentum and energy equations. F_s represents the forces acting on the surface of the liquid, which are the surface tension force and the Marangoni force [6]. K is function of metal temperature that represents the drag term during melting phase [3].

The energy source term for the surface of the metal includes electron heating due to the work function of metal and radiative cooling using Stefan Boltzmann law [7] and an emission coefficient of 0.25. The latent heat of fusion is considered through variations of liquid fraction ratio. The source term for the plasma includes radiation losses and Thomson effect.

Diffusion of metal vapour from the molten metal has been taken in account using a simplified diffusion model, allowing the use of plasma properties weighted on the mass fraction of shielding gas and metal vapour. The production of metal vapour has been self-consistently calculated on the surface of the wire using Hertz-Knudsen-Langmuir equation, allowing to add the heat of vaporization cooling effect into the energy conservation equation; to grant a stable cathode arc attachment we impose on the workpiece a Gaussian temperature profile that allows us to add an imposed vapour mass flow. Turbulent effects on flow have been neglected; the electromagnetic field equations have been solved in their vector potential form using the extended field approach. The workpiece works as cathode with imposed current density on the wire inlet section.

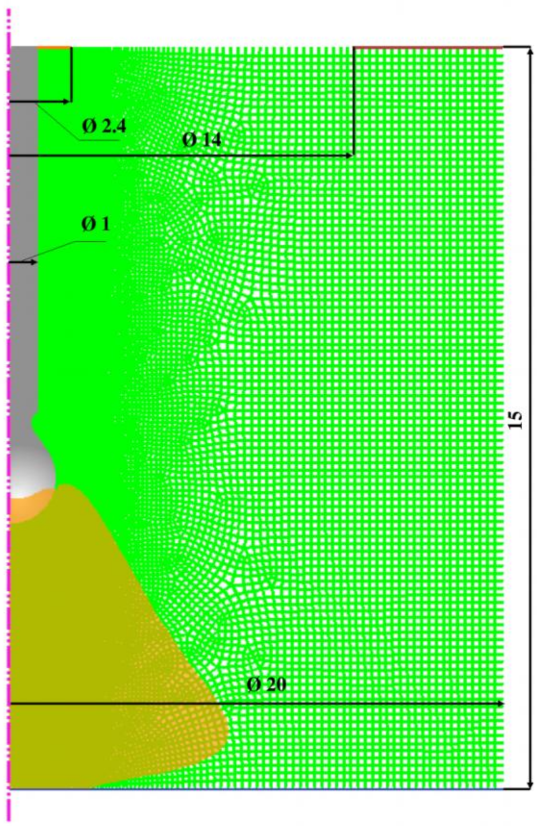

Figure 2. *Schematic of computational domain (dimensions in mm).*

4. Results

Numerical simulation have been executed in the FLUENT environment on the same operating conditions of the experimental setup: a steel wire with a 1 mm diameter fed at a 5 m/min rate, with a 10 l/min flow rate of argon and the same experimental current profile (Fig. 3). In Fig. 2 a schematic of the computational domain is displayed. We report results for the temperature and iron mass fraction fields at different time steps (Fig. 4-6). Time step (a), which is shown in Fig. 4, is characterized by a current of 30 A with overall low iron vapour concentration. In this phase, a temperature peak on the axis has been obtained because of the low values of iron mass fraction. In Fig. 5 it is shown that with 360 A of current there is a massive increase in iron vapour concentration along the axis of the discharge, due to both a temperature on the surface of the wire close to boiling point (≈3100 K) which increases vapour production and to an increase of plasma axial velocity due to magnetic pumping [2]. The off-axis displacement of the maximum in temperature could be explained by the increase of radiative dissipation due to iron vapour [1]. Fig. 6 shows that even with 180 A of current of frame (d) the droplet has been stretched enough to obtain the detachment, as it can be seen in frame (e). Even with lower currents the production of metal vapour is kept high by the increase in the surface of the liquid metal, both before and after the detachment. A comparison with the experimental images in the top right of each frame shows that the overall dynamic behaviour of the droplet detachment is well represented.

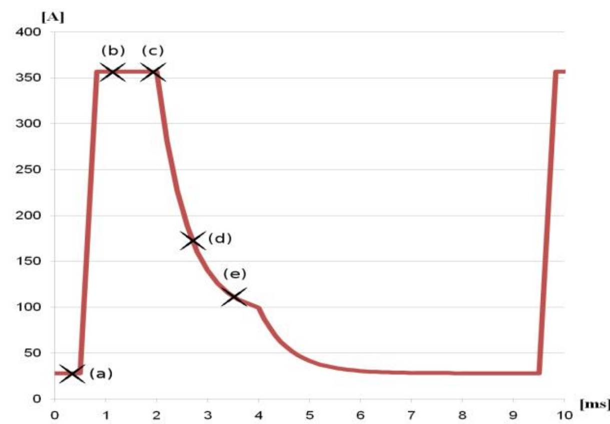

Figure 3. *Electric current waveform imposed on both experiment and numerical simulation.*

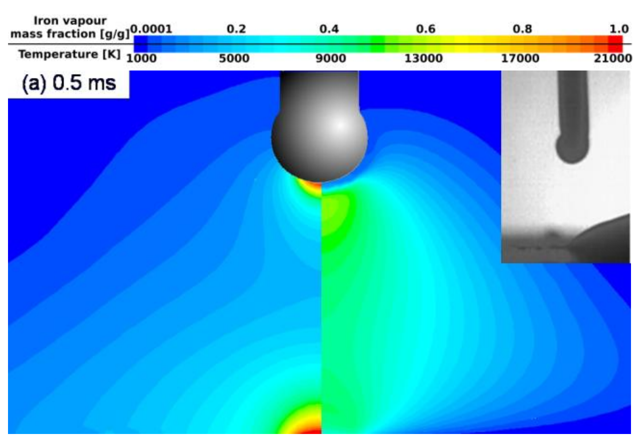

Figure 4. *Iron vapour mass fraction (left) and plasma temperature (right) at different time steps. On the top-right, experimental high-speed images.*

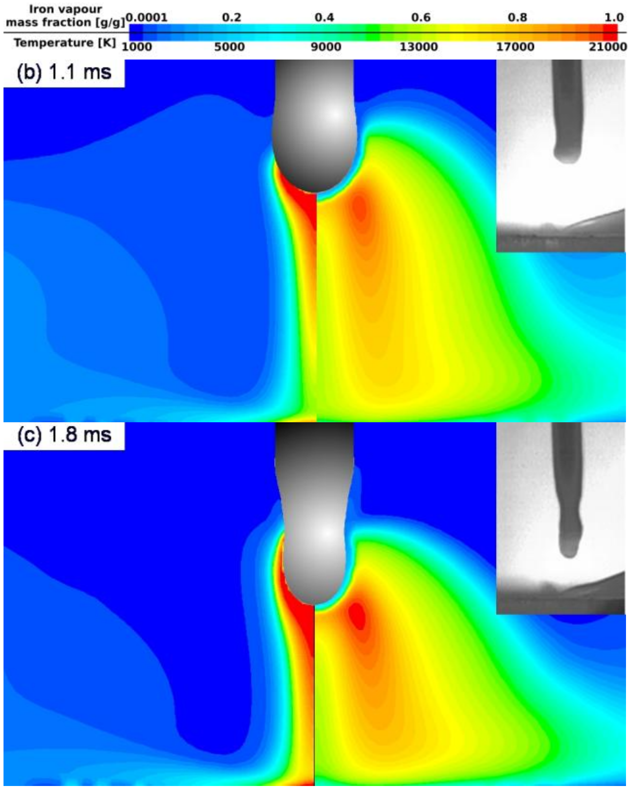

Figure 5. *Iron vapour mass fraction (left) and plasma temperature (right) at different time steps. On the top-right, experimental high-speed images.*

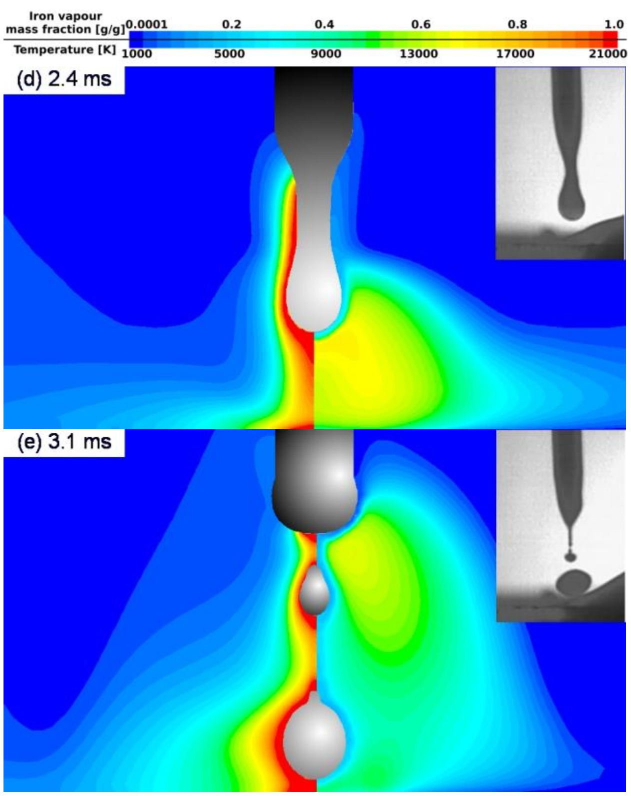

Figure 6. *Iron vapour mass fraction (left) and plasma temperature (right) at different time steps. On the top-right, experimental high-speed images.*

5. Conclusions

A pulsed welding process has been investigated using 2D time-dependent modelling and high-speed camera imaging. It has been shown that metal vapour from the overheated wire tip induces an off-axis temperature peak during the high current phase of the cycle, whereas during the base phase the temperature peak is on the axis.

Acknowledgement

Funding from D.I.E.M./Cebora S.p.A. research contracts on project MIUR-D.M.28562 (Art.12EMec) is acknowledged.

References

[1] A.B. Murphy, "The effects of metal vapour in arc welding", J. Phys. D: Appl. Phys. 43, 434001 (2010)

[2] M. Schnick, U. Fuessel, M. Hertel, M. Haessler, A. Spille-Kohoff and A. B. Murphy, “Modelling of gas–metal arc welding taking into account metal vapour”, J. Phys. D: Appl. Phys. 43, 434008 (2010)

[3] H. G. Fan and R. Kovacevic, “A unified model of transport phenomena in gas metal arc welding including electrode, arc plasma and molten pool”, J. Phys. D: Appl. Phys. 37, 2531–2544 (2004)

[4] M. Boselli, V. Colombo, E. Ghedini and P. Sanibondi, “Time dependent modeling of droplet detachment in GMAW including metal vapor diffusion”, to be published on IEEE Trans. Plasma Sci., 6th Triennial Special Issue on Images in Plasma Science, 2011

[5] C. S. Wu, M. A. Chen, and Y. F. Lu, “Effect of Current Waveforms on Metal Transfer in Pulsed Gas Metal Arc Welding”, Meas. Sci. Technol.,**16 (**12), 2459–2465 (2005)

[6] V. A. Nemchinsky, “Heat transfer in a liquid droplet hanging at the tip of an electrode during arc welding”, J. Phys. D: Appl. Phys., **30** 1120–1124 (1997)

[7] H. Guo, J. Hu, H. L. Tsai, “Three-Dimensional Modeling of Gas Metal Arc Welding of Aluminum Alloys”, J. Manuf. Sci. Eng., 132, 021011 (2010)