A COMPUTATIONAL MODEL OF MIG WELDING: EFFECTS OF METAL VAPOUR, AND MIXING OF WIRE AND WORKPIECE ALLOYS

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ABSTRACT

A three-dimensional computational model of metal–inert-gas welding of aluminium has been developed. The model includes the arc and both electrodes self-consistently. Here, the model is used to investigate two phenomena. First, the influence of the metal vapour that is produced from the electrodes on the arc and the weld pool is considered. Second, the mixing of droplets formed from the upper wire electrode with the weld pool is examined. The predicted weld pool shape is compared with measurements.

1. INTRODUCTION

Metal–inert gas (MIG) welding, also known as gas–metal arc welding, is very widely used in manufacturing industry. It is subject to continuing innovation, with the aim of increasing productivity, expanding the range of application, and so on. Computational modelling is becoming an important tool in this development.

In MIG welding, an arc plasma is struck between a wire electrode and the workpiece (usually the cathode). The energy transferred to the workpiece forms a molten weld pool. The wire also partially melts, forming metal droplets that pass through the arc into the weld pool.

The computational model used here [1-3] takes into account many phenomena, including: (1) the motion of the arc relative to the workpiece; (2) the energy, momentum and mass transported by the droplets; (3) flow in the weld pool and deformation of the weld pool surface; (4) the production and transport of metal vapour formed by evaporation of the wire and weld pool; and (5) the mixing of different alloys used for the wire and the workpiece.

The main approximation made in the model is that the formation of droplets, and their influence on the arc and weld pool, is included in a time-averaged manner [2]. In this paper, I will focus on the influence of metal vapour on the arc and weld pool, and the mixing of the wire and workpiece alloys.

2. INFLUENCE OF METAL VAPOUR

Spectroscopic measurements have demonstrated that the large production of metal vapour in MIG welding, mainly from the wire, has a strong influence on the arc properties. This includes a large decrease in arc temperature and the formation of a local minimum in temperature on the arc axis. For example, Zielinska et al. [4] measured a temperature of around 8000 K on the arc axis, increasing to a maximum of about 12 000 K of axis, for an argon MIG arc with steel electrodes and an arc current of 326 A. In contrast, typical maximum temperatures in TIG arcs, in which metal vapour is present in much lower concentrations, are about 20 000 K, and occur on the arc axis.

Two mechanisms have been proposed for the strong cooling of the arc and the presence of a local minimum on the arc axis. The first is the increase in radiative emission due to the presence of metal vapour. The second is the influx of a large amount of relatively cold metal vapour into the plasma from the wire. Schnick et al. [5] found that the former mechanism was dominant, while Haidar [6] neglected the influence of increased radiative emission but still found significant cooling due to the second mechanism.

In neither calculation was the vapour production rate calculated self-consistently. As well as not taking into account the influence of metal vapour on the radiative emission, Haidar did not include diffusion of the metal vapour. Schnick et al. used an estimated vaporisation rate of the wire.

The production of metal vapour from both the wire electrode and the weld pool, and its transport in the plasma, were included in the MIG welding model presented here in a self-consistent manner [3]. The mass fraction $\overline{Y_M}$ of the metal vapour was determined by solving the conservation equation:

$$\nabla \cdot \left(\rho \boldsymbol{v} \overline{Y_M}\right) = -\nabla \cdot \overline{\boldsymbol{J}_M} + S_M ,$$

where ρ is mass density and $\boldsymbol{v}$ is the flow velocity of the plasma, $\overline{\boldsymbol{J}_M}$ is the average diffusion mass flux of the metal vapour species, and S_M is the net production of metal vapour (the net mass flux of the vapour multiplied by a geometric factor).

Fig. 1 compares the temperature distribution with and without the inclusion of the effects of metal vapour. The presence of aluminium vapour strongly decreases the arc temperature; the maximum temperature in the presence of vapour is 11 200 K and without vapour 14 200 K. Fig. 2 shows the metal vapour mass fraction distribution in the arc. Most of the aluminium vapour is produced at the wire anode. The vaporisation rate is 0.017 g s^{-1}, or 7.9% of the wire mass (the remainder of the wire is converted into droplets). The vaporization rate of the weld pool is more than an order of magnitude lower.

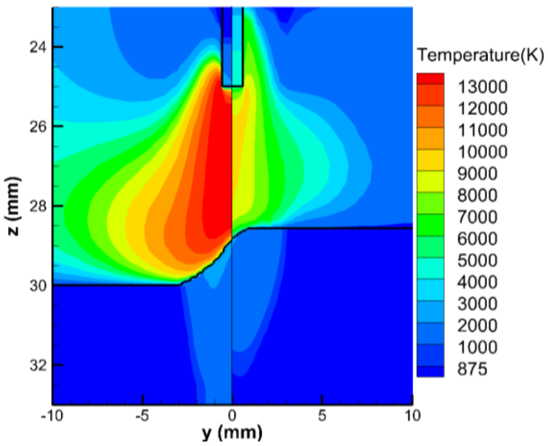

Fig. 1 Distribution of temperature in the x = 0 plane including (right) and neglecting (left) the influence aluminium metal vapour Results are for arc current 95 A, wire radius 0.6 mm, welding speed 15 mm s^{-1} in the -y direction, wire feed rate 72 mm s^{-1}, droplet detachment frequency 93 Hz, bead-on-plate welding with 3 mm thick workpiece, wire and workpiece alloy AA5745. From [3].

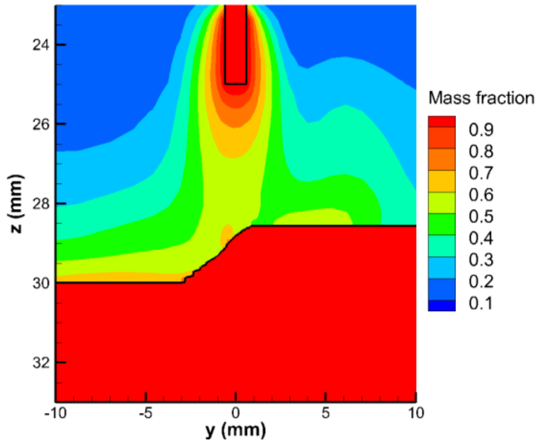

Fig. 2 Distribution of aluminium vapour mass fraction in the x = 0 plane for the same conditions of Fig. 1. From [3].

The metal vapour is reasonably strongly concentrated near the arc axis, due to the strong downwards convective flow. The flow speed has a maximum value of 155 m s^{-1}, and is driven partly by the magnetic pinch force and partly by the evaporation of vapour from the wire tip.

A local minimum in temperature near the arc axis is apparent in Fig. 1, for axial positions within about 1 mm of the wire tip, when metal vapour is considered. To investigate this effect, as well as the reasons for the overall decrease in arc temperature, calculations were performed including and neglecting the influence of metal vapour on the radiative emission coefficient, and including and neglecting the influence of the strong flux of vapour from the wire anode. The results [3] indicated that the increased radiative emission due to the presence of metal vapour is important in the overall decrease in the arc temperature, but that the local minimum in arc temperature near the arc axis is a consequence of the strong flux of relatively-cool vapour from the wire anode into the arc plasma.

It is important to note that this conclusion only applies for the relatively low arc currents considered here. The influence of the increased radiative emission due to metal vapour becomes more significant for larger currents, since the arc temperature is then increased, which in turn increases radiative emission. Further, since iron vapour radiates more strongly than aluminium vapour, radiative cooling will have a stronger influence in the case of iron or steel electrodes. These factors were analysed in detail in Ref. [3].

3. MIXING OF WIRE AND WORKPIECE ALLOYS

Different alloys are often used for the wire and the workpiece. The droplets formed from the wire pass into the weld pool, so the two alloys become mixed. To taken into account droplets of different composition to the workpiece metal, it is necessary to solve an additional conservation equation, for conservation of the mass fraction Y_d of the droplet metal:

$$\frac{\partial \rho Y_d}{\partial t} + \nabla \cdot (\rho \mathbf{v} Y_d) = -\nabla \cdot \left(\rho D_d^l \nabla Y_d \right) + S_d \,,$$

where D_d^l is the self-diffusion coefficient of the liquid metal and S_d is input of droplet alloy mass per unit volume and time.

Typical results are shown in Fig. 3, for a wire composed of aluminium alloys AA4043 and an AA5754 workpiece. In the weld pool, the droplet impact drives flow downwards. The droplet alloy follows the flow vectors into the weld pool. Eventually, the complex flow patterns, and diffusive mixing, lead to the droplet and workpiece alloys becoming fully mixed, as shown in Fig. 3(d), which shows the composition of the weld after solidification. Similar results are obtained for AA5554 wire.

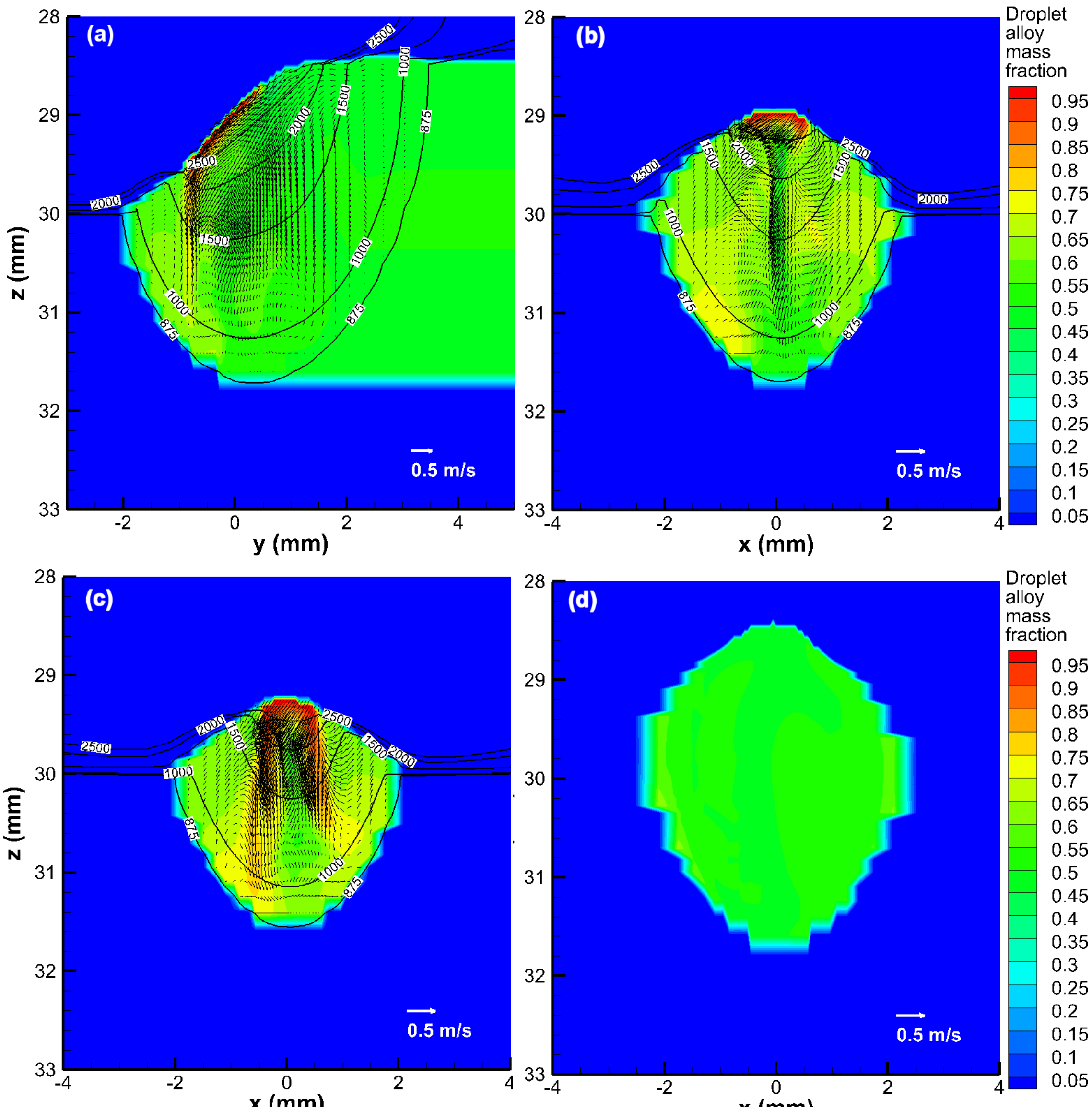

Fig. 3 Fraction of the droplet alloy in a cross-section of the weld pool, for the a) x = 0 plane, (b) y = 0 plane, (c) y = -0.5 mm plane, (d) y = 6 mm plane. The wire is AA4043 and the workpiece alloy is AA5754; other conditions are as for Fig. 1. Velocity vectors and temperature contours for 875, 1000, 1500, 2000 and 2500 K are also shown.

4. COMPARISON WITH EXPERIMENT

Measurements of the weld cross-section were performed by welding a flat aluminium plate along a straight line. The measured weld cross-section is compared in Fig. 4 to that predicted by the computational model. Measurements and calculations were performed for an AA4043 wire and an AA5754 workpiece. When metal vapour is neglected, the computational model predicts that the weld pool penetrates the workpiece completely. When metal vapour is taken into account, the weld pool is shallower, in good agreement with the measured depth. There are two main reasons that the weld pool is shallower in the presence of metal vapour. The first is that the arc temperature is lower, decreasing the conductive heat flux to the workpiece. The second is that the current density at the top surface of the workpiece is lower, owing to the increased electrical conductivity of the arc plasma at lower temperatures.

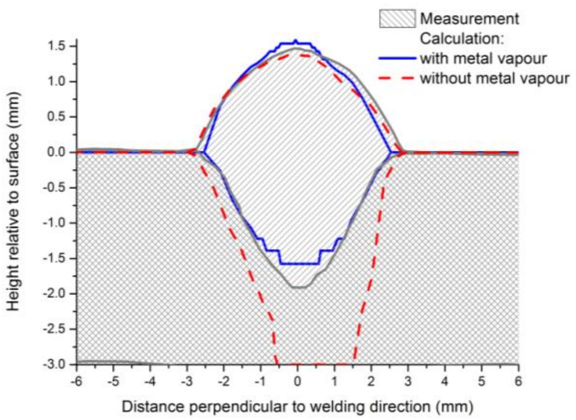

Fig. 4 Comparison of measured and predicted weld cross-sections for AA4043 wire and AA5754 workpiece alloys; other conditions are as for Fig. 1. Predictions including and excluding the influence of metal vapour are shown.

5. CONCLUSIONS

A three-dimensional computational model of MIG welding, in which the wire, workpiece and arc plasma are treated self-consistently, has been developed. The formation of metal vapour from the electrodes and droplets is also included self-consistently. The mixing of droplets in the weld pool is calculated, allowing different wire and workpiece alloys to be treated.

It is found that the arc plasma is cooled by the increased radiation associated with the presence of metal vapour, and that the influx of metal vapour from the wire electrode leads to a local minimum in temperature below the wire. This is due to the flow of relatively-cool vapour into the arc at this position. Further, the presence of metal vapour decreases the weld pool depth.

It is found that the droplet alloy is thoroughly mixed with the workpiece alloy. When the effects of metal vapour are taken into account, the weld cross-section predicted by the model agrees well with the measured cross-section.

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REFERENCES

[1] A. B. Murphy, “A self-consistent three-dimensional model of the arc, electrode and weld pool in gas–metal arc welding”, J. Phys. D: Appl. Phys., **44**, 194009, 2011.

[2] A. B. Murphy, “Influence of droplets in gas–metal arc welding – a new modelling approach, and application to welding of aluminium”, Sci. Technol. Weld. Join., **18**, 32-7, 2013.

[3] A. B. Murphy, “Influence of metal vapour on arc temperatures in gas–metal arc welding: convection versus radiation”, J. Phys. D: Appl. Phys., **46**, 224004, 2013.

[4] S. Zielinska et al., “Investigations of GMAW plasma by optical emission spectroscopy”, Plasma Sources Sci. Technol., **16**, 832-8, 2007.

[5] M. Schnick et al., “Modelling of gas-metal arc welding taking into account metal vapour” J. Phys. D: Appl. Phys., **43**, 434008, 2010.

[6] J. Haidar, “The dynamic effects of metal vapour in gas metal arc welding”, J. Phys. D: Appl. Phys., **43**, 165204, 2010.