A desktop computer model of arc welding for prediction of arc properties, weld pool geometry and workpiece thermal history

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Abstract: A three-dimensional computational model of arc welding has been developed. The importance of including the arc in the computational domain is demonstrated. A user-friendly graphical user interface has recently been added. As well as weld depth and geometry and arc properties, the model predicts thermal histories of the welded metal. This will allow important quantities such as residual stress and distortion to be predicted.

Keywords: arc welding, computational modelling, thermal plasma, GUI, residual stress

1. Introduction

Arc welding is a thermal plasma process that is used very widely in manufacturing and other industries. An arc is struck in a shielding gas between an electrode and the metal parts that are being joined, which are known as the workpiece. The energy transferred by the arc partially melts the workpiece, forming the weld pool.

There are many types of arc welding; the most widely used in manufacturing is MIG/MAG (metal–inert-gas/metal–active-gas) welding, in which the electrode is a metal wire whose tips melt, forming droplets that pass into the weld pool. A shielding gas is used to protect the electrodes; if it is an inert gas such as argon, the term MIG is used; if an ‘active’ gas such as oxygen or carbon dioxide is added to the inert gas, the term MAG is used.

We have developed a sophisticated computational model of MIG welding of aluminium. Unlike most welding models, the arc plasma, the electrode and the workpiece and weld pool are all included in the computational domain self-consistently. The model predicts the depth and geometry of the weld for a wide range of parameters (including arc currents, welding speeds, workpiece and wire alloys, and weld geometries).

After briefly describing the computational model in Sec. 2, we will consider in Sec. 3 the importance of the two-way interactions between the arc, electrode and workpiece in determining the weld depth and shape. We will then discuss, in Secs. 4 and 5, the application of the model in predicting the thermal history of the workpiece metal, which is the input information that is required for predicting important mechanical properties such as residual stress and distortion. The graphical user interface that has been recently developed is introduced in Sec. 6.

2. The model

The computational model of MIG welding of aluminium has been described in previous publications [1-3]. The model solves equations of mass, momentum, energy, metal vapour mass, electrode alloy mass and charge conservation, and Maxwell’s equations, in three dimensions under the assumption of LTE. Special treatments are required at the boundaries between the arc and metal, and to take into account the transfer of mass, momentum and energy by the droplets. The computational domain includes the arc, electrode and workpiece. This allows phenomena such as the influence of the weld pool surface profile on heat transfer from the arc, and the production of metal vapour and its effects on the arc and the weld pool, to be calculated self-consistently. This makes it possible to reliably predict weld pool geometry for a wide range of parameters.

Fig. 1. Schematic diagrams of (a) bead-on-plate and (b) lap-fillet weld geometries.

The model has been applied to both bead-on-plate (butt weld) and lap-fillet weld geometries, which are illustrated schematically in Fig. 1.

3. The importance of arc–surface interactions

Most computational models of arc welding take the arc into account only through boundary conditions at the surface of the workpiece and weld pool. This is a very significant simplification, but decreases the reliability of the model. This is because the heat flux and current density distributions at the interface between the arc and the workpiece depend on the properties of the workpiece as well as the arc. For example, the workpiece surface
profile determines the location of the arc attachment, and the temperature of the weld pool determines the rate of production of metal vapour. The location of arc attachment and metal vapour concentration both in turn affect the heat flux and current density distributions. Hence, there is a strong two-way coupling between the arc and the workpiece. It is therefore not possible to construct heat flux and current density boundary conditions that are accurate over a wide parameter range. Including the arc as part of the computational domain circumvents this difficulty, since the two-way coupling can be taken into account self-consistently.

Fig. 2 shows the temperature distribution in the arc, electrode and workpiece for typical parameters for welding of thin-sheet aluminium. The temperature is highest in the regions close to where the arc attaches to the electrode and workpiece. Metal vapour is produced from the electrode and workpiece in these regions. The flow in the weld pool is also shown; the momentum transferred by the droplets drives flow downwards near the arc attachment point [2].

The presence of metal vapour decreases the temperature of the arc, mainly due to increased radiative cooling. The effect is not as strong for aluminium as for iron [3,4]. The depth of the weld pool is also reduced by the influence of metal vapour. There are two reasons for this: 1) the reduced thermal conduction to the workpiece because of the lower arc temperature, and 2) the lower current density at the workpiece surface, because the metal vapour ionizes at lower temperatures, meaning that the conducting region of the arc extends over a wider area.

Fig. 2. Temperature distribution in arc, electrode and workpiece, and flow vectors in weld pool, for AA4043 wire and AA5754 workpiece. Parameters are: arc current 95 A, wire radius 0.6 mm, welding speed 15 mm s⁻¹, wire feed rate 72 mm s⁻¹, work angle 60°, droplet detachment frequency 93 Hz, workpiece consists of two 3 mm sheets.

Weld cross-sections predicted by the model with and without metal vapour are compared with a measured cross-section in Fig. 3. Good agreement is found when metal vapour is considered.

4. Thermal history prediction

As well as predicting the depth and shape of the weld pool, the model also calculates the thermal history (i.e., the time-dependence of temperature) throughout the workpiece as the arc moves along the weld seam. Fig. 4(a) shows a weld cross section, indicating the fusion zone and heat-affected zones, and the thermal history at different positions in the workpiece, for a lap fillet weld produced under the conditions of Fig. 2.

Important properties of the weld, including the residual stress and consequent distortion, and the microstructure of the welded metal, can be calculated using thermal history of the workpiece. Typically, the thermal history is obtained using computational models that only treat the workpiece. In such models, the arc is considered as a heat source, either a two-dimensional source on the surface of the workpiece, or as a three-dimensional source within the workpiece. For example, Muránsky et al. [5] used a three-dimensional ellipsoidal heat source, illustrated in Fig. 5, with power per unit volume \( q \) given by

\[
q = \varepsilon Q \exp \left[ -\left( \frac{x}{r_x} \right)^2 - \left( \frac{y}{r_y} \right)^2 - \left( \frac{z}{r_z} \right)^2 \right],
\]

where \( Q \) is the total arc power, and the efficiency factor \( \varepsilon \) and the radii \( r_x, r_y, r_z \) in the \( x, y \) and \( z \) directions respectively were determined by fitting the predicted temperatures in the workpiece to thermocouple measurements of temperature.
Such an approach is adequate for particular cases, but requires recalibration against a new set of measurements for welding parameters that deviate significantly from those for which the original calibration was performed. Thus, such models cannot be used for predictions over a wide range of welding parameters.

5. Residual stress and distortion

The localized heating and the non-uniform cooling that occur during welding lead to complex residual stress distributions, and to unwanted distortion and deformation of the welded metal. These effects can lead to significant, and potentially severe, reductions in performance and reliability. There is a vast literature on residual stress and distortion; the reader is referred to, for example, the book edited by Feng [6].

Modelling approaches of varying degrees of sophistication and accuracy have been applied, but as noted in Sec. 4, these have relied on cumbersome approaches for calculating the thermal history.

![Fig. 5. The ellipsoidal moving heat source, as used finite element models used to predict residual stress and distortion. Reprinted from [5], with permission from Elsevier.](image)

An important question is that of coupling between the thermal model and the residual stress model. Generally it is reasonable to decouple the models, since the mechanical work is insignificant compared to the thermal heat input [6]. As well as greatly reducing the computational complexity and time, the ability to decouple the thermal model means that thermal histories produced by the arc welding model can be used to replace the heat-source models such as that represented by Eq. (1). This will allow models that predict residual stress and distortion to be developed that can be used over a wide range of welding parameters without calibration against temperature measurements. It is noted that computational models for the calculation of residual stress generally use finite element methods, so some effort will be required to transfer thermal histories calculated using the Cartesian mesh used in the arc welding model to the conformal meshes used for finite element calculations.

Our initial effort at transferring the thermal history and weld reinforcement shape shown in Fig. 4 into a finite element model is shown in Fig. 6.

6. Graphical user interface

A graphical user interface (GUI) has been developed for the arc welding model, and the program runs on most desktop and notebook computers (the only requirements are 64-bit Windows and 6 GB RAM). This means that the model can be used by welding engineers and technicians without any knowledge of computational modelling.

One of the GUI input windows is shown in Fig. 7. The user is able to select welding parameters as shown in the figure, as well as the thickness of the workpiece sheets, the travel and work angles of the electrode, and the alloys from which the electrode and workpiece are made.
After the calculation is complete (which typically takes a few hours on a standard desktop), the user is able to graph weld profiles (as shown in Fig. 4(a)), as well as temperature distributions (as shown in Fig. 2), velocities, current densities, etc.

7. Conclusions
We have developed a sophisticated three-dimensional model of arc welding that predicts distributions of temperature, velocity, current density, metal vapour mass fraction and electrode alloy mass fraction throughout the electrode, arc and workpiece. By taking into account the two-way interactions between the arc, weld cross-sections and thermal histories at all positions in the workpiece can be predicted for a wide range of parameters without the need for calibration against measurements. Weld cross-sections are critical information in the determination of optimum weld parameters, and thermal histories are the input information required in calculation of residual stress and deformation.

A graphical user interface has been developed, allowing the arc welding model to be run on standard desktop and laptop computers by welding engineers and technicians. We plan to increase the power of the model by combining the arc welding model with existing codes for calculation of residual stress and deformation.

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9. References