Modelling the transient behaviours of a fully penetrated gas–tungsten arc weld pool with surface deformation

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Abstract: Numerical analysis of the dynamic behaviours of a gas–tungsten arc (GTA) weld pool with full penetration is of great significance to designing the process control algorithm. In this paper, a three-dimensional transient numerical model is developed to investigate the dynamic behaviours of a fully penetrated GTA weld pool with surface deformation. A body-fitted coordinate system is used to transform the complex physical boundaries resulted from the surface deformation into regular boundaries. A separated algorithm is employed to solve the strongly coupling problems between the surface deformation, fluid flow, and heat transfer. By using the model, the whole gas–tungsten arc welding (GTAW) process (including arc ignition, weld pool formation and growth, penetration, quasi-steady state, and arc extinguishments) are simulated, and the transient development of a three-dimensional weld pool shape and fluid flow inside the pool are obtained. The predicted weld geometry matches the experimental results. It provides useful basic data for the development of sensing and control systems of GTAW.

Keywords: transient behaviours, weld pool, full penetration, surface deformation, numerical simulation

1 INTRODUCTION

Gas–tungsten arc welding (GTAW) has become indispensable as a tool for many industries because of the high-quality welds produced and the basic role of materials joining in manufacturing industry. This process is typically used for critical and accurate joining where the weld quality must be ensured, such as for the root pass and for the welding of advanced materials, thin and ultra-thin section materials, and pressure vessels, because of its capability in precision control of the welding fusion process [1]. Accurate welding and production of quality welds will involve a complex operation. Typical practice is first to select and design the welding process, welding parameters, fixture, joint geometry, etc., based on materials used and the specified requirements. However, for GTAW, simply following the established procedure is not adequate because normally 100 per cent of full penetration must be ensured without burn-through or over-penetration which damages materials properties. To this end, automated sensing and control of GTAW process must be realized [2]. The design of the control algorithm requires that the underlying process be described using a dynamic model such as a transfer function. However, the welding process is an extremely complex process in which different types of phenomenon occur in a coupled way. Thus, numerical analysis for modelling the dynamic behaviour of the GTAW process is of great significance to designing the process control algorithm.

Although there have been significant advances in the numerical simulation of the GTAW process [3–5], most studies have entailed general simulation
of the process under constant welding parameters and a quasi-steady state, and little attention has been paid to the transient dynamics of the weld pool. Zacharia et al. developed a three-dimensional transient model for the arc welding process [6], but it either was only concerned with partial penetration or did not consider the weld pool surface deformation in the full penetration. Wu and Yan conducted numerical simulation of transient development and decrease in the gas–tungsten arc (GTA) weld pool, but they assumed flat surfaces at both the front and the back sides of the weld pool [7]. In fact, the weld pool surfaces at both the front and the back sides are depressed under the condition of full penetration, and the amplitude of this depression could be considered to reflect the penetration extent. For dynamic control, models are required to reveal how the process variables (weld pool geometry and surface depression) change with the welding parameters (welding current and velocity). In this paper, a numerical model is developed to describe the transient behaviour of a three-dimensional GTA weld pool with full penetration and surface deformation.

2 FORMULATION

2.1 Surface deformation

The weld pool surface is deformed under the action of the arc pressure, surface tension, gravity, and so on. When full penetration is established, pool surfaces at both the top and the bottom are deformed. As shown in Fig. 1, the functions \( Z_{\text{top}} = \varphi(x, y) \) and \( Z_{\text{bottom}} = \psi(x, y) \) are used to describe the configuration of the top and bottom surfaces respectively of the weld pool.

In the case of partial penetration [Fig. 1(a)], the surface deformation occurs only at the top surface of the workpiece. The top surface of the weld pool is governed by the equation [8]

\[
P_{\text{arc}} - \rho g \varphi + C_1 = -\gamma \left(1 + \varphi_x^2\right) \varphi_{xx} - 2 \varphi_x \varphi_y \varphi_{xy} + (1 + \varphi_y^2) \varphi_{yy},
\]

where \( P_{\text{arc}} \) is the arc pressure, \( \rho \) is the density, \( g \) is the gravitational acceleration, \( \gamma \) is the surface tension, \( C_1 \) is a constant, \( \varphi_x = \partial \varphi / \partial x \), \( \varphi_{xx} = \partial^2 \varphi / \partial x^2 \), \( \varphi_{xy} = \partial^2 \varphi / (\partial x \partial y) \), and so on. At the other area of the top surface, \( \varphi(x, y) = 0 \). Because the total volume of the weld pool is not changed before or after the surface deformation, there is the constraint

\[
\int_{\Omega_1} \varphi(x, y) \, dx \, dy = 0 \tag{2}
\]

where \( \Omega_1 \) is the surface area of weld pool at the top surface. The arc pressure can be expressed as [9, 10]

\[
P_{\text{arc}} = \frac{\mu_0 I^2}{8 \pi \sigma_j} \exp \left( - \frac{r^2}{2 \sigma_j^2} \right) \tag{3}
\]

where \( \mu_0 \) is permeability in free space, \( I \) is the welding current, \( \sigma_j \) is the current distribution parameter, and \( r = \sqrt{(x - u_0 t)^2 + y^2} \), where \( u_0 \) is the welding speed and \( t \) is the time.

For a fully penetrated weld pool [Fig. 1(b)], two equations are required to describe the configuration of the top and bottom surfaces respectively, namely

\[
P_{\text{arc}} - \rho g \varphi + C_2 = -\gamma \left(1 + \varphi_x^2\right) \varphi_{xx} - 2 \varphi_x \varphi_y \varphi_{xy} + (1 + \varphi_y^2) \varphi_{yy} \tag{4a}
\]

\[
\rho g (\psi + L - \varphi) + C_2 = -\gamma \left(1 + \psi_x^2\right) \psi_{xx} - 2 \psi_x \psi_y \psi_{xy} + (1 + \psi_y^2) \psi_{yy} \tag{4b}
\]

where \( L \) is the thickness of the workpiece, \( C_2 \) is a constant, \( \psi_x = \partial \psi / \partial x \), \( \psi_{xx} = \partial^2 \psi / \partial x^2 \), \( \psi_{xy} = \partial^2 \psi / (\partial x \partial y) \), and so on. At the other area out of the weld pool, \( \varphi(x, y) = 0 \) and \( \psi(x, y) = 0 \). The total volume of the weld pool does not vary in full penetration. Therefore

\[
\int_{\Omega_1} \varphi(x, y) \, dx \, dy = \int_{\Omega_2} \psi(x, y) \, dx \, dy \tag{5}
\]

where \( \Omega_1 \) is the surface area of the weld pool at the top surface, while \( \Omega_2 \) is the surface area of the weld pool at the bottom surface.

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![Fig. 1 Schematic diagram of the weld pool surface deformation](image-url)
$C_1$ and $C_2$ are the total sum of other forces that act on the weld pool surface except for arc pressure, gravity, and surface tension. In the calculation, $C_1$ is derived from equations (1) and (2) while $C_2$ is derived from equations (4) and (5) according to

$$C_1 \int \int_{\Omega_1} dx \, dy - \int \int_{\Omega_1} (-P_{\text{arc}}) \, dx \, dy - \int \int_{\Omega_1} \gamma (1 + \psi_y^2)\varphi_{xx} - 2\varphi_x\varphi_y\varphi_{xy} + (1 + \varphi_x^2)\varphi_{yy} \frac{dx \, dy}{(1 + \varphi_x^2 + \varphi_y^2)^{3/2}} = 0$$

(6)

$$C_2 \left( \int \int_{\Omega_1} dx \, dy + \int \int_{\Omega_2} dx \, dy \right) - \int \int_{\Omega_1} (-P_{\text{arc}}) \, dx \, dy - \int \int_{\Omega_1} \gamma (1 + \psi_y^2)\varphi_{xx} - 2\varphi_x\varphi_y\varphi_{xy} + (1 + \varphi_x^2)\varphi_{yy} \frac{dx \, dy}{(1 + \varphi_x^2 + \varphi_y^2)^{3/2}}$$

$$- \rho g \int \int_{\Omega_1} (L - \varphi) \, dx \, dy - \int \int_{\Omega_2} \gamma (1 + \psi_y^2)\psi_{xx} - 2\psi_x\psi_y\psi_{xy} + (1 + \psi_x^2)\psi_{yy} \frac{dx \, dy}{(1 + \psi_x^2 + \psi_y^2)^{3/2}} = 0$$

(7)

The iterative method is used to calculate the surface deformation of the weld pool. Firstly, the guessed values of $C_1$ and $C_2$ are employed. Then $\varphi(x, y)$ and $\psi(x, y)$ are obtained through solving equations (1) and (4) and the improved values of $C_1$ and $C_2$ are found by solving equations (6) and (7). Based on the new values of $C_1$ and $C_2$, equations (1) and (4) are solved again to obtain the improved functions $\varphi(x, y)$ and $\psi(x, y)$. The above procedure is repeated until it meets the criterion of convergence and the constraint conditions are satisfied. In addition, the functions $\varphi(x, y)$ and $\psi(x, y)$ are calculated in Cartesian coordinates.

During the transient development of the weld pool, $\partial_1$ and $\partial_2$, i.e. the action areas of the arc pressure and surface tension, change with time. The volume of the weld pool varies with time, and so does the gravity. Thus, the configurations of the weld pool surfaces $\varphi(x, y)$ and $\psi(x, y)$ change with time until the quasi-steady state of the weld pool is achieved.

2.2 Governing equations

A schematic sketch of a typical GTAW process system is shown in Fig. 2. In order to describe the development of the weld pool shape, surface deformation, thermal field, and fluid flow field, a time-dependent model is required. Therefore, it is a transient problem. For a three-dimensional transient problem, the governing equations include the energy, momentum, and continuity equations. Because of the surface deformation, some newly added boundaries appear at both the top and the bottom surfaces, and their positions change with time. Therefore, the calculated domain is no longer a perfect cube for bead-on-plate welding, which causes some boundary conditions that are difficult to deal with. In this study, based on the Cartesian coordinate, the body-fitted coordinate system $(x^*, y^*, z^*)$ is introduced [Fig. 1(b)] to transform the deformed domain to a regular domain according to

$$x^* = x, \quad y^* = y, \quad z^* = \frac{z - \varphi(x, y)}{L + \psi(x, y) - \varphi(x, y)}$$

(8)
Thus, the governing equations in body-fitted coordinate are expressed as

\[ \rho C_p \frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} + W \frac{\partial T}{\partial z} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + S \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + k C_T \]

\[ \rho \left( \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} \right) = - \left( \frac{\partial P}{\partial x} + \frac{\partial P}{\partial z} \right) \frac{\partial z^*}{\partial x} + \mu \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} \right) + C_U + F_x \]

\[ \rho \left( \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} \right) = - \left( \frac{\partial P}{\partial y} + \frac{\partial P}{\partial z} \right) \frac{\partial z^*}{\partial y} + \mu \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \right) + C_V + F_y \]

\[ \rho \left( \frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} \right) = - \left( \frac{\partial P}{\partial z} + \frac{\partial P}{\partial z} \right) \frac{\partial z^*}{\partial z} + \mu \left( \frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2} \right) + C_W + F_z \]

where \( T \) is the temperature, \( U, V, \) and \( W \) are the three components of velocity in the \( x, y, \) and \( z \) directions respectively, \( t \) is the time, \( \rho \) is the density, \( C_p \) is the specific heat, \( k \) is the thermal conductivity, \( P \) is the pressure in the liquid, \( L \) is the thickness of the workpiece, \( F_x, F_y, \) and \( F_z \) are the components of body forces in the \( x, y, \) and \( z \) directions respectively, and \( \mu \) is the dynamic viscosity of liquid metal. Some terms in governing equations are defined as

\[ W_1 = U \frac{\partial z^*}{\partial x} + V \frac{\partial z^*}{\partial y} + W \frac{\partial z^*}{\partial z} - \frac{k}{\rho C_p} \left( \frac{\partial^2 z^*}{\partial x^2} + \frac{\partial^2 z^*}{\partial y^2} + \frac{\partial^2 z^*}{\partial z^2} \right) \]  (12a)

\[ W_1 = U \frac{\partial z^*}{\partial x} + V \frac{\partial z^*}{\partial y} + W \frac{\partial z^*}{\partial z} - \frac{\mu}{\rho} \left( \frac{\partial^2 z^*}{\partial x^2} + \frac{\partial^2 z^*}{\partial y^2} + \frac{\partial^2 z^*}{\partial z^2} \right) \]  (12b)

\[ S = \left( \frac{\partial z^*}{\partial x} \right)^2 + \left( \frac{\partial z^*}{\partial y} \right)^2 + \left( \frac{\partial z^*}{\partial z} \right)^2 \]  (12c)

\[ C_T = 2 \left( \frac{\partial^2 T}{\partial z^* \partial x} + \frac{\partial^2 T}{\partial z^* \partial y} \right) \]  (12d)

\[ C_U = 2 \mu \left( \frac{\partial^2 U}{\partial z^* \partial x} + \frac{\partial^2 U}{\partial z^* \partial y} \right) \]  (12e)

\[ C_V = 2 \mu \left( \frac{\partial^2 V}{\partial z^* \partial x} + \frac{\partial^2 V}{\partial z^* \partial y} \right) \]  (12f)

\[ C_W = 2 \mu \left( \frac{\partial^2 W}{\partial z^* \partial x} + \frac{\partial^2 W}{\partial z^* \partial y} \right) \]  (12g)

\[ C_m = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} + C_m = 0 \]  (11)

where \( \partial z^*/\partial x, \partial z^*/\partial y, \) and \( \partial z^*/\partial z \) can be obtained from equation (8).

Although using the body-fitted coordinates can completely avoid the newly added boundaries resulting from the surface deformation, the governing equations in the body-fitted coordinate system are quite complex, which causes many difficulties in the discretization of governing equations. Some special techniques are employed to overcome these difficulties.

### 2.3 Boundary conditions

Owing to the energy transferred from the arc \( q_{arc} \) to the workpiece, the weld pool forms and grows subsequently. At the same time, some energy is transferred into the solid metal out of the weld pool, and some is lost into the ambient medium by radiation \( q_{rad} \) and convection \( q_{conv} \). Also evaporation \( q_{evap} \) occurs at the surface of the weld pool.

The net heat transfer input at the top surface is

\[ q = q_{arc} - q_{conv} - q_{rad} - q_{evap} \]  (13)

At the symmetric surface, both sides have no net heat surplus. Therefore

\[ \frac{\partial T}{\partial y} = 0 \]  (14)

At all other surfaces, there are only convection, radiation, and evaporation losses. Thus,

\[ q = -q_{conv} - q_{rad} - q_{evap} \]  (15)

For the heat source, an elliptical thermal flux distribution was used in this study, which can be written as follows [11]: when \( x - u_0 t \geq 0 \)

\[ q_{arc}(x, y) = \frac{6\eta EI}{\pi a(b_1 + b_2)} \exp \left[ -\frac{3(x - u_0 t)^2}{b_1^2} \right] \times \exp \left( -\frac{3y^2}{a^2} \right) \]  (16a)
and, when \( x - u_0 t < 0 \)

\[
q_{arc}(x,y) = \frac{6\eta EI}{\pi a(b_1 + b_2)} \exp \left[ - \frac{3(x - u_0 t)^2}{b_2^2} \right] \times \exp \left( - \frac{3y^2}{a^2} \right)
\]

(16b)

where \( \eta \) is the efficiency of the arc power, \( E \) is the arc voltage, \( I \) is the welding arc current, and \( b_1, b_2, \) and \( a \) are the parameters related to the welding process. The constraint

\[
a(b_1 + b_2) = 12\sigma_q^2
\]

(17)

exists where \( \sigma_q \) is the characteristic radius of the arc heat flux. In this research, \( a = 1.87\sigma_q, b_1 = 2.51\sigma_q, \) and \( b_2 = 3.91\sigma_q. \)

The heat loss includes convection, radiation, and evaporation losses. They are in the forms [12]

\[
q_{\text{conv}} = h_c(T - T_0)
\]

(18a)

\[
q_{\text{rad}} = \sigma\varepsilon(T^4 - T_0^4)
\]

(18b)

\[
q_{\text{evap}} = W_v H_v
\]

(18c)

where \( h_c \) is the convective heat-transfer coefficient, \( T \) is the temperature of the workpiece, \( T_0 \) is the ambient temperature, \( \sigma \) is the Stefan–Boltzmann constant, \( \varepsilon \) is the radiation emissivity, \( W_v \) is the liquid-metal evaporation rate, and \( H_v \) is the latent heat of evaporation. For the materials SS304, an approximate equation for \( W_v \) in equation (18c) [13, 14] is given by

\[
\log W_v = 2.52 + \left( 6.121 - \frac{18.836}{T} \right) - 0.5 \log T
\]

(19)

The required boundary conditions for the solution of equation (10) are

\[
\frac{\partial U}{\partial z^*} = \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial x}, \quad \text{at } z^* = 0, z^* = 1
\]

(20)

where \( \gamma \) is the surface tension of liquid metal, and

\[
V = 0, \quad \frac{\partial U}{\partial y} = 0, \quad \frac{\partial V}{\partial y} = 0, \quad \text{at } y = 0
\]

(21)

\[
U = 0, \quad V = 0, \quad W = 0, \quad \text{at other boundaries}
\]

(22)

The components of the body forces, \( F_x, F_y, \) and \( F_z \), may be obtained from reference [15].

2.4 Numerical method

An implicit control volume-based finite difference method combined with the SIMPLEC algorithm [16, 17] is used for the solution of equations (9) to (11). A special grid system is utilized for discretization of the welding domain. A uniform grid is used in the \( z \) direction because of the thin plate, while grids of variable spacing are used in the \( x \) direction and \( y \) direction, i.e. finer spacing near the heat source because of the higher temperature and velocity gradients, and coarser away from it. The governing equations with the boundary conditions are transformed into finite difference equations. To deal with the boundary conditions conveniently, the so-called ’inner grid node’ method is employed to discretize the welding domain; i.e. the nodes are located at the centre of the control volumes, and grid lines constitute the faces of the control volumes. The ‘staggered grid’ where the velocity components \( U, V, \) and \( W \) are calculated for the points that lie on the faces of the control volumes for temperature \( T \) and pressure \( P \) is required for numerical stability in fluid flow calculations. The additional source term method [18] is applied to process the boundary conditions.

The calculation of the fluid flow field has to be made first in order to solve the thermal energy equation. The velocity components are governed by the momentum equations. Since the pressure gradient forms a term for a momentum equation, and there is no obvious equation for obtaining pressure, the difficulty in the calculation of the pressure field lies in the unknown pressure field. The pressure field is indirectly specified via the continuity equation. When the correct pressure field is substituted into the momentum equation, the resulting field satisfies the continuity equation. The SIMPLEC algorithm converts the indirect information in the continuity equation into direct information for the calculation of pressure [16, 17]. The alternative direction iteration method [19] is used in the solutions of discretized equations, and so the time step must satisfy the criterion

\[
\frac{k}{\rho C_p} \delta t \left( \frac{1}{\delta x^*} + \frac{1}{\delta y^*} + \frac{1}{\delta z^*} \right) \leq 1.5
\]

(23)

where \( \delta t \) is the time step, and \( \delta x, \delta y, \) and \( \delta z \) are the spacing of grid along the \( x, y, \) and \( z \) directions respectively. In this study, the time step is 0.001 s.

In order to implement the calculations mentioned above, the computer program is designed and debugged. As mentioned above, since the surface deformation of the weld pool and the introduction of the body-fitted coordinate system, the calculation of heat and fluid flow fields in transient state are much more complex than in
steady and quasi-steady conditions. A separated
algorithm is employed to solve the surface deforma-
tion, fluid flow, and heat transfer in transient
conditions; i.e. these three problems are calculated
separately and improved in turn. In this way the
strongly coupling problems between the surface
deformation, fluid flow, and heat transfer are
solved successfully. The code is written as a modu-
lar structure. The whole calculation procedure con-
ists of the following main steps:

(a) performing domain discretization and grid
system formation;
(b) calculating the temperature distribution based on
the initial conditions;
(c) determining the three-dimensional weld pool
geometry based on the temperature profiles;
(d) calculating the surface deformation of the weld
pool;
(e) conducting the coordinate system transfor-
mation;
(f) calculating the fluid velocity field inside the weld
pool under the body-fitted coordinate system and
obtaining convergent results;
(g) calculating the temperature field over the
whole domain and obtaining the convergent
results;
(h) repeating steps (c) to (g) and improving the
calculation accuracy until the convergent
criterion for the weld pool surface deformation,
fluid flow field, and temperature distribution are
all met;
(i) going to the next time step, and repeating steps
(c) to (h).

3 RESULTS AND DISCUSSION

Numerical simulations are performed for GTAW
on type 304 stainless steel and low-carbon steel
Q235. A half-workpiece with a welding domain of
200 mm × 50 mm × 3 or 2 mm is divided into a mesh
of 352 × 60 × 10 grid points. A finer grid spacing is
utilized in the molten region. The specific heat \( C_p \),
dynamic viscosity \( \mu \), and thermal conductivity \( k \) are
temperature dependent, and can be expressed as
follows [15, 20]. For type 304 stainless steel

\[
\mu (\times 10^{-3} \text{ kg/m s}) = \begin{cases} 
37.203 - 0.0176T, & 1713 K \leq T \leq 1743 K \\
20.354 - 0.0087T, & 1743 K \leq T \leq 1763 K \\
34.849 - 0.0162T, & 1763 K \leq T \leq 1853 K \\
13.129 - 0.0045T, & 1853 K \leq T \leq 1873 K \\
\end{cases}
\]

(25)

\[
C_p (\text{J/kg}) = \begin{cases} 
438.95 + 0.198T, & T \leq 773 K \\
137.93 + 0.597T, & 773 K \leq T \leq 873 K \\
871.25 - 0.25T, & 873 K \leq T \leq 973 K \\
555.2 + 0.0775T, & 973 K \leq T \\
\end{cases}
\]

(26)

For Q235 steel

\[
k (\text{W/m K}) = \begin{cases} 
60.719 - 0.027857T, & T \leq 851 K \\
78.542 - 0.0488T, & 851 K \leq T \leq 1082 K \\
15.192 + 0.00977T, & 1082 K \leq T \leq 1768 K \\
349.99 - 0.1797T, & 1768 K \leq T \leq 1798 K \\
\end{cases}
\]

(27)

\[
\mu (\times 10^{-3} \text{ kg/m s}) = \begin{cases} 
119.00 - 0.061T, & 1823 K \leq T \leq 1853 K \\
10.603 - 0.025T, & 1853 K \leq T \leq 1873 K \\
36.263 - 0.0162T, & 1873 K \leq T \leq 1973 K \\
\end{cases}
\]

(28)

\[
C_p (\text{J/kg}) = \begin{cases} 
513.76 - 0.335T + 6.89 \times 10^{-4}T^2, & T \leq 973 K \\
-10.539 + 11.77T, & 973 K \leq T \leq 1023 K \\
11.873 - 10.2T, & 1023 K \leq T \leq 1100 K \\
644, & 1100 K \leq T \leq 1379 K \\
354.34 + 0.21T, & 1379 K \leq T \\
\end{cases}
\]

(29)

Other thermophysical properties and parameters
used in the calculation are summarized in Table 1.

The development of the weld pool includes the
following stages: the weld pool forming after the arc
ignition, the pool expanding, and the pool reaching
the quasi-steady state. Figure 3 shows the transient
development of the weld pool geometry and fluid
The weld pool moves backwards relative to the electrode centre-line \( (x = 0) \). The penetration depth changes slowly at first and then more rapidly than the pool width and length. Figure 6 shows the transient variation in the fluid flow field after the arc has been extinguished. Because of the disappearance of the arc pressure and electromagnetic forces, the fluid flow is driven only by the surface tension gradient and buoyancy; therefore it lasts a very short time, and the amplitude of flow velocity is much lower than in the quasi-steady state.

Experimental measurements are made to validate the model. The common commercial charge-coupled device camera combined with a special narrow-band filter is used to capture the images of the weld pool during the GTAW process. Once the image of the weld pool captured by the camera is digitized through a frame grabber, it is stored in a computer as a matrix in which one element represents a dot of image. A special image-processing algorithm has been developed to extract the weld pool edges so that the weld pool geometry, surface deformation, and predicted weld pool surface geometry generally agrees with the measured geometry except for the trailing part. Because the latent heat is not considered in the model, the calculated weld pool trail is not elongated. Figure 8 shows a comparison of the calculated cross-section configurations of the weld pool in cross-section. The experimental and the predicted results. It can be seen that the predicted weld pool surface geometry generally agrees with the measured geometry except for the trailing part. Because the latent heat is not considered in the model, the calculated weld pool trail is not elongated. Figure 8 shows a comparison of the calculated and experimentally observed geometries of the weld pool in cross-section. The experimental and the predicted cross-section configurations of the weld are consistent with each other although the weld width has a slight difference. Further studies are continuing to improve the accuracy of simulation.

### 4 CONCLUSIONS

1. A three-dimensional transient numerical model is developed to investigate the dynamic behaviours of the weld pool geometry, surface deformation,
Fig. 3 Transient variation in the three-dimensional weld pool shape and fluid flow field (workpiece, Q235; thickness, 2 mm; arc voltage, 16 V; welding current, 110 A; welding speed, 160 mm/min).

(a) Top View

(b) Side View

(c) Front View
heat transfer, and fluid flow in a fully penetrated GTA weld pool. The simulation results lay the foundation for process control of the GTAW process.

2. For GTAW on a low-carbon steel Q235 plate of 2 mm thickness with an arc voltage of 16 V, a welding current of 110 A, and a welding speed of 160 mm/min, the weld pool emerges at $t = 1.62$ s, the workpiece is penetrated at $t = 2.88$ s, and the quasi-steady state is reached at $t = 4.20$ s. The maximum fluid velocity is in the region near the electrode centre-line ($x = 0$), and the value is 0.007 m/s at $t = 2.0$ s and 0.040 m/s at $t = 4.12$ s.

3. For the welding conditions used (type 304 stainless steel plate with a thickness of 3 mm, a welding...
current of 100 A, an arc voltage of 14 V, and a welding speed of 120 mm/s), the quasi-steady state is achieved at $t = 4.0$ s; then the arc is intentionally extinguished and both the welding current and the welding speed become zero. The transient behaviours of the weld pool when the arc is extinguished are also calculated. It is found that the weld pool disappears totally at $t = 4.6$ s.
4. GTAW experiments are carried out to obtain the cross-section of weld. The predicted and measured data are in agreement.

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**REFERENCES**


19 Tao, W. Q. *Numerical Heat Transfer*, 1987 (Xi’an Jiaotong University, Xi’an, People’s Republic of China).
