WELD POOL DEVELOPMENT DURING GAS METAL ARC WELDING PROCESSES

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ABSTRACT

A transient two-dimensional (2D) model was developed for investigating the heat and fluid flow in weld pools and for determining velocity profile and temperature distribution for the Gas Metal Arc Welding (GMAW) process. The mathematical formulation considers four driving forces for weld pool convection: electromagnetic; buoyancy; surface tension; and drag forces. The formulation also deals with energy exchange between the molten filler metal droplet and weld pools. A general thermofluid-mechanics computer program, PHOENICS, was employed to numerically solve the governing equation with the associated source terms. The results of computation have shown that the electromagnetic and surface tension forces as well as the molten filler metal droplet have major influence in shaping the weld pool geometry.

INTRODUCTION

Since it has been shown that the velocity and temperature distributions of molten metal affect weld pool geometry, the microstructure and mechanical properties of the weld produced, there has been a significant interest in the quantitative representation of heat transfer and fluid flow phenomena in weld pools. Experimental studies of the flow conditions in weld pools are limited to the measurement of the surface velocities only. Furthermore, accurate observation of the surface velocities is extremely difficult during the actual welding process because of the presence of the arc over the weld surface. Therefore mathematical modelling approaches for describing the phenomena happened during the arc welding and investigating how the welding process parameters affect the weld quality, have become an essential and systematic technique.

In recent years, considerable progress has been accomplished in modelling heat transfer and fluid flow conditions in weld pools during the Gas Tungsten Arc Welding (GTAW), GMAW and laser welding process (Tsao and Wu 1988, Kim and Na 1994). However, a completely general mathematical model of the GMAW process incorporating the moving heat source and the details of the weld pool circulations is not currently available.

This paper concentrates on the development of the unsteady 2D mathematical model which includes all important physical phenomena that control the heat transfer and convective flow condition in weld pools. The model developed was employed to investigate the heat transfer and the fluid flow in the GMAW process and to study the role of the various forces (buoyancy, electromagnetic, surface tension and plasma drag forces) and the molten metal droplets. Also, measurements of weld pool flow velocity and weld pool surface temperature are discussed.

MODEL FORMULATION

A spatially distributed heat and current fluxes fall on the free surface at $z = 0$, which is the surface on the workpiece. The weld bead penetration occurring in the GMAW process will be caused by the heat of the welding arc coming on the weld pool surface and the transfer of heat by the incoming droplets inside the workpiece. As a result, convection flow, free and forced, is induced in both radial and axial directions in molten weld pools.

In modelling the system, the following assumptions were made for the present analysis:

1. The flow is Newtonian and incompressible, in view of the relatively small size of weld pools expected.
2. The flow is laminar and axisymmetric, with no circumferential variations in terms of the size of weld pools.
3. All the physical properties of the liquid and solid metals are constant, independent of temperature except surface tension and thermal conductivity.
4. A spatially distributed heat and current fluxes falling on the free surface are Gaussian characteristics.
5. The Boussinesq approximation is employed.

6. An undeformable pool surface is assumed for simplifying the problem.

Governing Equations

The continuity equation is represented as

$$\frac{1}{r}\frac{\partial}{\partial_r}(\rho r\, u_r) + \frac{\partial}{\partial_z}(\rho\, u_z) = 0 \qquad (1)$$

The radial momentum equation is presented as

$$\rho\frac{\partial u_r}{\partial t} + \rho u_r\frac{\partial u_r}{\partial r} + \rho u_z\frac{\partial u_r}{\partial z} = -\frac{\partial p_m}{\partial r}$$
$$+\mu\left[\frac{\partial^2 u_r}{\partial r^2} + \frac{1}{r}\frac{\partial u_r}{\partial r} - \frac{u_r}{r^2} + \frac{\partial^2 u_r}{\partial z^2}\right] - J_z B_\theta \qquad (2)$$

The axial momentum equation is described as

$$\rho\frac{\partial u_z}{\partial t} + \rho u_r\frac{\partial u_z}{\partial r} + \rho u_z\frac{\partial u_z}{\partial z} = -\frac{\partial p_m}{\partial z}$$
$$+\mu\left[\frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r} + \frac{\partial^2 u_z}{\partial z^2}\right] + J_r B_\theta + \beta\rho g(T - T_r) \qquad (3)$$

The energy equation is expressed as

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u_r\frac{\partial T}{\partial r} + \rho C_p u_z\frac{\partial T}{\partial z} = k\frac{\partial^2 T}{\partial r^2} + k\frac{\partial^2 T}{\partial z^2}$$
$$+\frac{\Delta H \partial f_L}{\partial t} \qquad (4)$$

Boundary Conditions

The plasma drag and the surface tension forces are treated as boundary conditions. The radial distribution of shear stress was employed by (Matsunawa et al. 1988). The liquid-solid phase change and the associated latent heat were modelled using the enthalpy method, which is the definition of the fraction of liquid (Brent et al. 1988). The essential feature of this method is that the evolution of latent heat is taken account of the governing energy equation by defining a heat source terms.

The latent heat term is added to the energy equation via $-\frac{\Delta H \partial f_L}{\partial t}$ where

$$f_L = \begin{cases} 1 & T > T_{liq} \\ (T - T_{sol})/(T_{liq} - T_{sol}) & T_{sol} \le T \le T_{liq} \\ 0 & T < T_{sol} \end{cases} \qquad (5)$$

In GMAW process, the shape of weld pools appears to be determined primarily by the momentum and special distribution of the stream of droplets from the melting electrode. To develop the numerical model in this study, it was assumed that not only the heat input distributions are described as uniform droplet temperature over a central circular area, equivalent to droplet radius and a Gaussian - distributed arc heat source, over a circular area equivalent to the arc, but also molten electrode is transferred from the melting electrode to the weld pool surface with the Gaussian - distributed velocities. The distributed velocities were added to the converged velocities of fluid components at the weld pool surface in the iterative calculation procedure. Tichellar et al. (1977) determined the average temperature of droplets as 2400 ^{o}C for steel. The droplet radius has been taken from previously published experimental work (Lancaster 1984) as 0.46 mm. Since there is a close relationship between gas flow rate and arc current in GMAW, arc current 360 A is calculated by wire feed rate of 0.207 m/s for 1.2 mm wire diameter from previously published experimental work (Lancaster 1984). The volumetric feed rate of electrode was calculated from these date and effective radius of the velocity distribution was assumed 2 mm. This method easily adapts to the general algorithms of the PHOENICS code as it is designed to solve non-linear equations through iterative techniques. The latent heat content is directly coupled to the nodal temperature, which produces fairly accurate results, especially for non-isothermal solidification of metals.

SOLUTION OF METHOD

In order to enhance the accuracy of calculation in the weld pool area and to reduce the cost of analysis, grids of variable spacing were employed. Finer grids were utilised near the heat source, while further away from it, a relatively coarse grid was employed. The mathematical model was employed a 40×41 non-uniform fixed rectangular grid system for calculation of temperature and velocity fields. Magnitude of weld pool zone was estimated as approximate 4 mm. The minimum radial grid was 0.15 mm, while the minimum axial grid was 0.14 mm.

To numerically solve the governing equations with the associated source terms, a general thermofluid-mechanics computer program, PHOENICS code (Spalding 1993) which was based on the SIMPLE algorithm (Patankar 1980) and developed by CHAM, Ltd to solve coupled sets of partial differential equations governing heat, mass and momentum transfer, was used. Initial convergence difficulties were overcome by using a simultaneous solver for the pressure-correction equation and false-time step relaxation on temperature and velocities. Convergence was accomplished when the spot values of the relevant dependent variables at the critical grid location remain fixed (<0.001), but the residuals of all governing equations keep decreasing. Generally, the residual must decrease by at least 3 orders of magnitude with respect to the first sweep before the run is terminated. The time step employed was 10^{-3}s. The number of sweeps needed to achieve a converged solution depends on a number of parameters such as initial guess, material properties, fine-turning of the relaxation parameters. The reference residual employed as a stopping criterion to determine when the calculations should advance to the next time step, was assumed to be 10^{-9} for radial velocities, axial velocities, temperature and pressure.

RESULTS AND DISCUSSION

The detailed information on the fluid flow and heat transfer that occur during the GMAW process was obtained by numerically solving the mathematical models that represent the essential physical features of the process. The computational model was employed to simulate the welding process in order to quantitatively understand the effects of different forces on the fluid flow and heat transfer. The arc current and welding voltage are 360 A and 25 V respectively. The effective radius of density distribution and effective radius of current distribution are 4 mm and 3 mm.

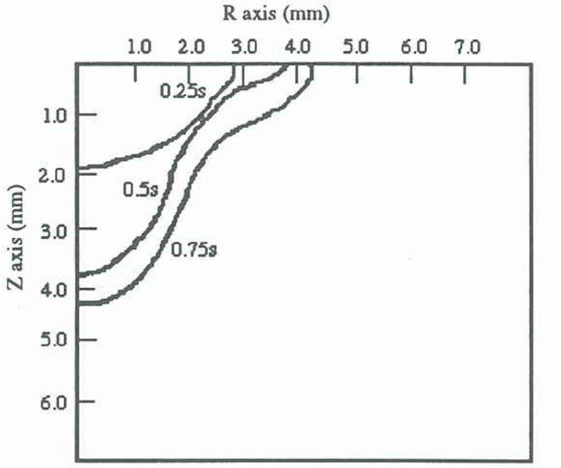

Fig. 1 Liquid-solid interface of the GMAW process at different times.

The gradual development of the interface between the liquid and solid regions with time has been shown in Fig. 1. The occurrence of the finger type of penetration can be easily observed. Contours of temperature and velocity field in weld pools at time of 0.75s due to the combined driving forces (electromagnetic, buoyancy, surface tension and plasma drag forces) are clearly shown in Figs. 2 to 3. During the GMAW process, all these forces are simultaneously applied in and on weld pools. The calculated temperature field in weld pools and shape of weld pools are shown in Fig. 2. The weld pool has a width of 4.26 mm and a depth of penetration of 4.09 mm. Fig. 3 shows the velocity field which is composed of a double loop circulation pattern - a wider radial flow at surface and a central penetrating flow loop.

The computed results indicate that there is the difference in the velocity scale between the first and second loop circulation patterns. The maximum surface velocity observed is of the order of 2.5 m/s. A wider radial flow at surface is mainly induced by the surface tension force at the weld pool surface which is caused by temperature gradients at the weld pool surface and possibly by surface active agents in weld pools. Surface tension of the liquid metal at the weld pool surface is lower near the centre and higher near the boundary because surface tension of the liquid metal tends to decrease with increasing temperature. As a result, the calculated flow pattern by surface tension force was from centre to weld pool boundary.

A central penetrating flow loop is dominated by the electromagnetic force caused by the interaction between the divergent current path in weld pools and the magnetic field it generates. Since the divergence of the electric current fields in weld pools develops a downward electromagnetic force near the central part of weld pools and pushes the liquid metal in the region downward to the weld root, the liquid metal by the electromagnetic force flows downward near the centre of weld pools and upward near the boundary. Since the flow pattern induced by the electromagnetic force promotes heat transfer from the heat source to the weld root, the transport of hot liquid metal down the axis of the weld pool will result in deep weld penetration. The results also indicate that the fluid flow has a significant effect on the weld pool temperature distribution and the development of the weld pool shape and size.

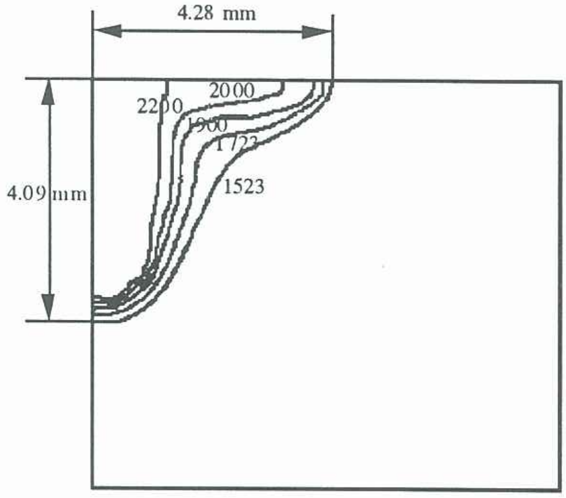

Fig. 2 Temperature field in weld pools due to the combined action of forces.

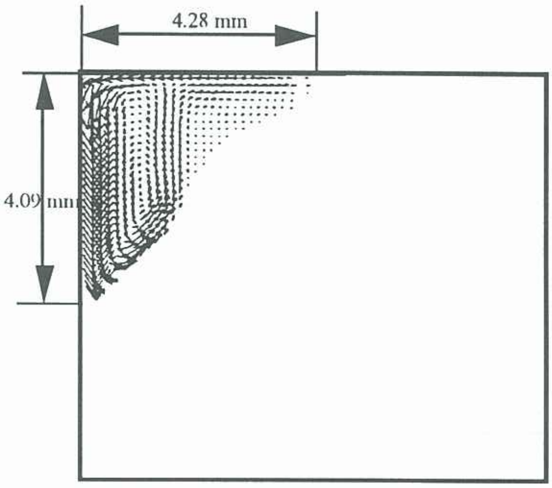

Fig. 3 Velocity field in weld pools due to the combined action of forces.

Fig. 4 depicts weld pool boundaries in comparison with those of calculation in only conduction mode while the input parameters and material properties were fixed. It is noted from Fig. 4 that convection mode makes deeper penetration in the workpiece than only conduction model, and weld pool convection which causes greater heat transfer from the heat source to the workpiece, plays a significant role in the formation of the finger penetration.

Fig. 5 illustrates the comparison of the GMAW with GTAW weld pool dimensions, while the input parameters and material properties were not changed. As shown in Fig. 5, the GMAW process makes a deeper weld bead penetration into the workpiece than the GTAW process, while a smaller weld pool because some of the input energy is employed to melt the filler metal and raise its temperature to that of the liquid metal.

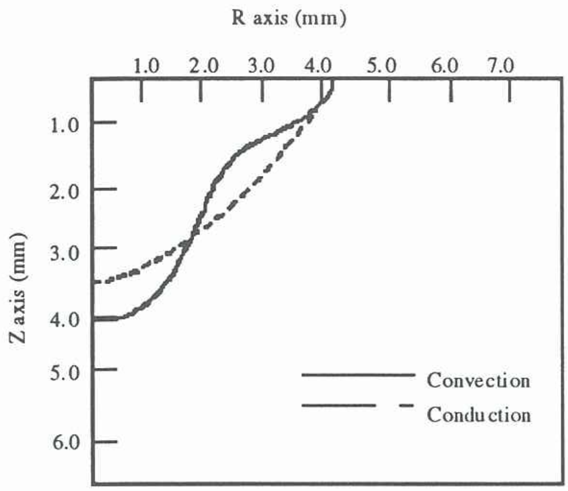

Fig. 4 Comparison of weld pool boundaries with the same heat input.

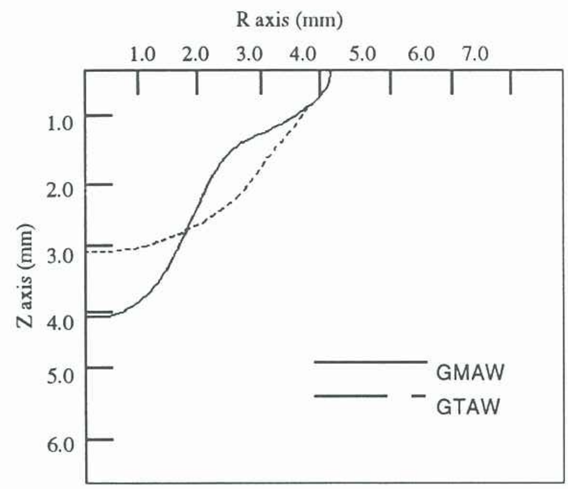

Fig. 5 Comparison of the GMAW with GTAW weld pool dimensions.

CONCLUSIONS

1. Fluid flow and heat transfer in weld pools for the GMAW were theoretically investigated through a transient axisymmetrical solution of Navier-Stokes equation and the equation of conservation of energy.
2. The computer model incorporates the four distinct forces (electromagnetic, buoyancy, surface tension and plasma drag forces) and the molten metal droplets.
3. A double loop circulation pattern can coexist with weld pools: one in a central penetrating flow loop by the electromagnetic force and the other in a wider radial flow at surface by surface tension.
4. The computed results clearly indicate that the electromagnetic and surface tension forces as well as the molten metal droplets are the dominant factors that control the weld pool convection, while the buoyancy and plasma drag forces seem to have little significance.
5. With reference to Fig. 4, it is obvious that there is a significant difference between the results from models with and without convective heat transfer. Weld bead penetration is strongly affected by fluid flow in weld pools.

NOMENCLATURE

B_θ	azimuthal magnetic field
c_p	heat capacity
f_L	fraction of liquid
g	gravitational acceleration
J_r	radial current density
J_z	axial current density
k	thermal conductivity (liquid steel)
P_m	pressure
r	radial direction
T	temperature
T_o	initial temperature
T_{liq}	liquid temperature
T_{sol}	solid temperature
t	time
u_r	radial velocity
u_z	axial velocity
z	axial direction
ΔH	latent heat of fusion of steel
μ	dynamic viscosity
β	volume coefficient of thermal expansion
ρ	density of workpiece

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