Numerical analysis of fully penetrated weld pools in gas tungsten arc welding

Y M Zhang, PhD, MemASME, MAWS, SMSME, **Z N Cao**, PhD and **R Kovacevic**, PhD, MemASME, MAWS, SMSME
Center for Robotics and Manufacturing Systems, University of Kentucky, Lexington, Kentucky, USA

Full penetration welding is widely used in metal joining, but it has been ignored in previous convective numerical models. In addition to the free surface on top of the pool, an additional free surface appears on the bottom of the workpiece. It can be shown that the top surface, temperature distribution and fluid flow field in the weld pool are all coupled with the pool's bottom surface. This complicates the numerical process and therefore no convective models have previously been developed for fully penetrated weld pools. In order to improve the numerical solution for the fully penetrated weld pool, a three-dimensional model is proposed. Free top and bottom pool surfaces have been included. The electromagnetic force, buoyancy force and surface tension gradient (Marangoni) are the three driving forces for weld pool convection. Welding parameters are changed in order to analyse their effects on weld pool geometry. It is found that the depression of the top surface contains abundant information about the full penetration state as specified by the back-side bead width.

Key words: GTA weld pool, full penetration, numerical modelling, heat transfer, fluid flow

NOTATION

$\boldsymbol{B}$	magnetic induction vector
C_p	specific heat
$\boldsymbol{F}$	body force vector
F_x, F_y, F_z	components of body force
$\boldsymbol{g}$	gravitational acceleration vector
h	convection coefficient
I	welding current
$\boldsymbol{J}$	current density vector
K	thermal conductivity
L	thickness of specimen
$\boldsymbol{n}_t$	normal unit vector to top surface
$\boldsymbol{n}_b$	normal unit vector to bottom surface
p	pressure
P_a	arc pressure
q_{conv}	heat loss from convection
q_{evap}	heat loss from evaporation
q_{radi}	heat loss by radiation
r	radial distance
$\boldsymbol{t}_{bx}$	tangential unit vector of bottom surface parallel to the xz plane
$\boldsymbol{t}_{by}$	tangential unit vector of bottom surface parallel to the yz plane
$\boldsymbol{t}_{tx}$	tangential unit vector of top surface parallel to xz plane
$\boldsymbol{t}_{ty}$	tangential unit vector of top surface parallel to the yz plane
T	temperature
T_∞	ambient temperature
T_m	melting temperature
u_m	arc voltage
u_0	welding speed
u	x direction velocity
v	y direction velocity
$\boldsymbol{V}_b$	velocity vector of bottom surface
$\boldsymbol{V}_t$	velocity vector of top surface
w	z direction velocity
W	evaporation mass flux
x, y, z	coordinates
β	coefficient of volume expansion
γ	surface tension
$\partial\gamma/\partial T$	surface tension temperature coefficient
ε	surface emittance
η	arc efficiency
μ	viscosity
μ_0	magnetic permeability
ρ	density
σ	Stefan–Boltzmann constant
σ_j	arc current flux distribution parameter
σ_q	arc heat flux distribution parameter
ϕ	shape function of top pool surface
φ	shape function of bottom pool surface

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1 INTRODUCTION

Numerical analysis plays an important role in understanding the welding process. Due to the complexity of the welding process, different assumptions have been used to simplify the analysis. It is apparent that the calculations depend on the assumptions used, but in order to achieve accurate results, the assumptions must be realistic. It has been shown that convection in the weld pool is one of the major factors that dominates the welding process (**1–6**). Also, the deformation of pool surface is an inherent characteristic of the arc welding process. The arc energy distribution (**7, 8**), weld defects (**8**) and weld penetration (**7, 9**) are correlated with the deformation of the pool surface.

The deformed weld pool surface and convection have been used by Szekely and co-workers (**10, 11**) to analyse the welding process, but the deformation of the weld pool was acquired from experimental data and not from calculations. In the study by Tsai and Kou (**12**), the pool free surface was calculated using an orthogonal boundary-fitted coordinate system, but a stationary arc was used. Zacharia *et al.* (**13**) developed a three-dimensional computer model for analysing the transient heat and flow fields. The free pool surface was calculated by the marked element technique based on an approximate pool surface deformation equation. In