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RESEARCH ARTICLE

2-D FINITE ELEMENT MODELING OF GMA WELDING PROCESS.

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Abstract

Since it has been shown that the velocity and temperature distributions of molten metal affect bead 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. This paper represents a transient Two-Dimensional (2D) axisymmetric model for investigating the heat and fluid flow in weld pools and for determining bead geometry, velocity profile and temperature distribution for the GMA welding 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. 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 bead geometry.

Introduction:-

Generally, mathematical modeling approaches for describing the phenomena happened during the arc welding and investigating how the process parameters affect the weld quality, have become an essential and systematic technique. A number of researchers [1-12] have reported that convection in weld pools can strongly affect the weld bead dimension and the structure of the resultant welds. The early studies regarding weld pool convection have mainly been done through experiments [1-2]. As the experimental research into the heat transfer and fluid flow in weld pools is limited to the measurement of the surface velocity during the actual welding process, mathematical modeling should be developed for the analysis of the whole processes that occur during arc welding. This modeling was pioneered by Andrews and Crane [3] and Atthey [4]. Furthermore, Oreper, et. at. [5] calculated the steady-fluid flow in a weld pool of prescribed shape caused by the combined action of surface tension, electromagnetic and buoyancy forces. The accuracy of the numerical techniques and the solutions were not discussed. Chan, et al. [6] developed a 2D fluid flow model for weld pools for laser welding. They carried out a parametric study for various materials and a variety of operating conditions. Kou and Wang [7] presented the results of a quasi-steady, Three-Dimensional (3D) mathematical model for the flow and heat transfer conditions in weld pools for the GTA welding process.

Generally, the weld pool convection is driven by four distinct driving forces viz. buoyancy, electromagnetic, surface tension and drag forces [8]. However, a number of previous researchers considered only the first three forces, but the drag force was not included as the driving force for mathematical model [6, 8]. Even the situation has altered greatly with the advent of increasing computer efficiency and better understanding of the physics of welding, only two papers were found as showed by a few people [9-10]. Tsao and Wu [9] first presented a mathematical model employing the vorticity stream function and implicit finite difference method, but ignored the flow induced by the droplet surface interactions and arbitrarily fixed the parameters of volumetric heat source. Kim and Na [10] developed 3D convection model for calculating the bead shape, velocity field and temperature distribution by employing a boundary-fitted coordinate system. The heat source corresponding to the metal transfer was not discussed in detail.

The objective of this paper concentrates on the development of the unsteady 2D mathematical model, which incorporates 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 GMA welding process and to study the role of the various forces (buoyancy, electromagnetic, surface tension and drag forces) and the molten metal droplets. Also, measurements of weld pool flow velocity and surface temperature are discussed.

Theoretical model:-

The GMA welding process is a welding process, which yields coalescence of metals by heating with a welding arc between a continuous filler metal (consumable) electrode and the workpiece. The continuous wire electrode which is drawn from a reel by an automatic wire feeder, and then fed through the contact tip inside the welding torch, is melted by the internal resistive power and heat transferred from the welding arc. Heat is concentrated by the welding arc from the end of the melting electrode to molten weld pools and by the molten metal, which is being transferred to weld pools. Molten weld pools and electrode wire are protected from contaminants in the atmosphere by a shielding gas which is obtained from an externally supplied Ar, CO_2, or mixtures Ar with O_2, H_2, He, or CO_2 in various combinations. A controller is used to control wire feed rate, arc current, and welding voltage. In some cases, it is also employed to control the gas flow rate. In modeling the system, the following assumptions were made for 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 the 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 flux and current falling on the free surface are Gaussian characteristics.
(5) The Boussinesq approximation is used.
(6) An undeformable pool surface is assumed for simplifying the problem.

2.1 Governing Equations:-

Using the assumptions stated above, the governing equations that describe the transient development of weld pools due to coupled conduction and convection heat transfer are the continuity equation, the momentum equation, and the energy equation.
The continuity equation is represented as

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

The radial momentum equation is presented as

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

The axial momentum equation is described as

$$\rho\frac{\partial u_z}{\partial t}+\rho u_r\frac{\partial u_z}{\partial r}+\rho u_z\frac{\partial u_z}{\partial z}=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}+\frac{\partial^2 u_z}{\partial z^2}\right)+J_r B_\theta+\beta\rho g(T-T_o) \quad (3)$$

The energy equation is expressed as

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

In the GMA welding, a current flow from wire electrode to the workpiece induces a magnetic field, which interacts with arc current to create an electromagnetic or Lorentz force. the electromagnetic force $J \times B$ in weld pools is calculated:

$$(J \times B)_r = - J_r B_\theta \quad (5)$$

$$(J \times B)_z = - J_z B_\theta \quad (6)$$

Surface tension force, which is referred to as the Marangoni effect, describes the flow of liquid at a free surface from a region of low surface tension to a region of higher surface tension. At the surface of weld pools, the surface tension variation with temperature must be balanced by fluid shear stress since the surface must be continuous. Therefore, the shear stress at the surface is equated to the gradient of surface tension. At the free surface, the shear stress due to the Marangoni effect or the surface tension driven flow is included as a boundary condition for the momentum equation:

$$\mu \frac{\partial u_r}{\partial z} = - \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial r} \quad (7)$$

2.2 Boundary Conditions:-

To complete the mathematical description of the problem, all of the boundary conditions are shown in figure 1 and specified as follows:

$$\Gamma_1(AB) \quad u_r = 0, u_z = 0, - k \frac{\partial T}{\partial z} = h_c (T - T_o) + \sigma\varepsilon (T^4 - T_o^4), \frac{\partial \varphi}{\partial z} = 0$$

$$\Gamma_2(BC) \quad u_r = 0, u_z = 0, - k \frac{\partial T}{\partial r} = h_c (T - T_o) + \sigma\varepsilon (T^4 - T_o^4), \varphi = 0$$

$$\Gamma_3(CD) \quad u_r = 0, u_z = 0, - k \frac{\partial T}{\partial z} = q_a = \frac{3Q}{\pi r_q^2} \exp\left(- 3(r / r_q)^2 \right), J_{suf} = - \sigma \frac{\partial \varphi}{\partial z}$$

$$\Gamma_4(DE) \quad u \frac{\partial u_r}{\partial z} = - \left[\left(\frac{\partial \gamma}{\partial T}\right)\left(\frac{\partial T}{\partial r}\right) \right] + \frac{3Vr}{\pi r_a^2} \exp\left(- 3(r / r_a)^2 \right) + \tau_{drag}, u_z = 0,$$

$$- k \frac{\partial T}{\partial z} = \frac{3Q}{\pi r_q^2} \exp\left(- 3(r / r_q)^2 \right) \qquad r < r_s$$

$$T = T_d \qquad r > r_s$$

$$Jsuf = - \sigma \frac{\partial \varphi}{\partial z}$$

$$\Gamma_5(EF) \quad u_r = 0, \frac{\partial u_z}{\partial r} = 0, \frac{\partial T}{\partial r} = 0, \frac{\partial \varphi}{\partial r} = 0$$

$$\Gamma_6(FA) \quad u_r = 0, u_z = 0, \frac{\partial T}{\partial r} = 0, \frac{\partial \varphi}{\partial r} = 0 \quad (8)$$

The drag and the surface tension forces are treated as boundary conditions. The radial distribution of shear stress τ_{drag} was employed by Matsunawa et al. [11]. The liquid-solid phase change and the associated latent heat were modeled using the fixed grid method, which is the definition of the fraction of liquid [12-13]. 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. Consequently, the numerical solution should be carried out on a space grid that remains fixed throughout the calculation.

Numerical procedure:-

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 utilized 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 as shown in figure 2. 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.

The above equations are solved simultaneously to give temperature, velocities and electric potential fields subject to given boundary conditions. To numerically solve the governing equations with the associated source terms, a general thermofluidmechanics computer program, PHOENICS code (which was based on the SAMPLE algorithm [14] and developed by CHAM, Ltd [15] to solve coupled sets of partial differential equations governing heat, mass and momentum transfer) was employed. The physical properties used for calculation [5] are given in Table 1. The mathematical model employed a 40×41 non-uniform, fixed rectangular grid system for the calculation of temperature and velocities. Finer grids were utilized near the surface of the workpiece where steep velocity gradients were induced by the surface tension gradient. Far away from the surface, a relatively coarse grid was used. Convergence is completed when the spot values of temperature, pressure, and velocities at the critical location remain unchanged (<0.1%) while the residuals of the governing equations continue to decrease. The residuals must generally decrease by at least 3 orders of magnitude with respect to the first sweep before the run is terminated. The time step used is 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 step, was assumed to be 10^{-9} for radial velocities, axial velocities, temperature pressure.

Table 1 Material properties employed for modeling

Symbol	Value	Symbol	Value
c_p	$753 J/kg - K$	k_s	$31.39 W/m.K$
k_l	$15.48 W/m.K$	T_{liq}	1723 K
T_o	300 K	T_{sol}	1523 K
ρ	7200 kg/m^3	σ_o	$5.67 \times 10^{-8} W/m^2K^4$
¬	$7.14 \times 10^5 \Omega^{-1} m^{-1}$	μ_m	$1.26 \times 10^{-9} (H/mm)$
μ	$6.0 \times 10^{-6} (kg/m.s)$	ε	0.4
$\partial\gamma/\partial T$	$10^{-5} N/m - K$	β	$10^{-4} (K^{-1})$
ΔH	2.47×10^5 J / kg		

Computed results and discussion:-

The detailed information on the fluid flow and heat transfer that occur during the GMA welding process was obtained by numerically solving the mathematical models that represent the essential physical features of the process. The results to be shown have been calculated for the GMA welding process. The arc current and welding voltage are 360 A and 25 V respectively. The effective radius of density distribution and current distribution are 4 mm and 3 mm respectively.

The gradual development of the interface between the liquid and solid regions with time has been shown in figure 3. The occurrence of the finger type of penetration can be easily observed. Contours of temperature and velocity field in weld pool at time of 0.75s due to the combined diving forces(electromagnetic, buoyancy, surface tension and drag forces) are clearly shown in figures 4 and 5. During the GMA welding process, all these forces are simultaneously doing in and on weld pools. The calculated temperature field in weld pools and shape of weld pool are shown in figure 4. As shown in figure 4, the weld pool has 4.26 mm width and 4.09 mm depth of penetration. Figure 5 shows that the velocity field consists 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 2.5m/s. A wider radial flow at surface is mainly induced by the surface tension force at the weld pool surface that 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 center 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 center 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 weld root, the liquid metal by the electromagnetic force flows downward near the center 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 fluid flow has a significant effect on the weld pool temperature distribution and the development of the weld pool shape and size [16].

Figure 6 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 evident from figure 6 that convection mode makes deeper penetration in the workpiece than only conduction model, and weld pool convection which causes a more heat transferred from the heat source to the workpiece, plays an significant role in the formation of the finger penetration. Figure 7 illustrates the comparison of the GMA welding with GTA welding weld pool dimensions, while the input parameters and material properties were not changed. As shown in figure 7, the GMA welding process makes a deeper weld bead penetration into the workpiece than the GTA welding 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. Figure 8 illustrates the comparison of mild steel with titan weld pool profiles at the equal input parameters. These materials have different thermal and physical properties, which would cause different velocity and temperature fields.

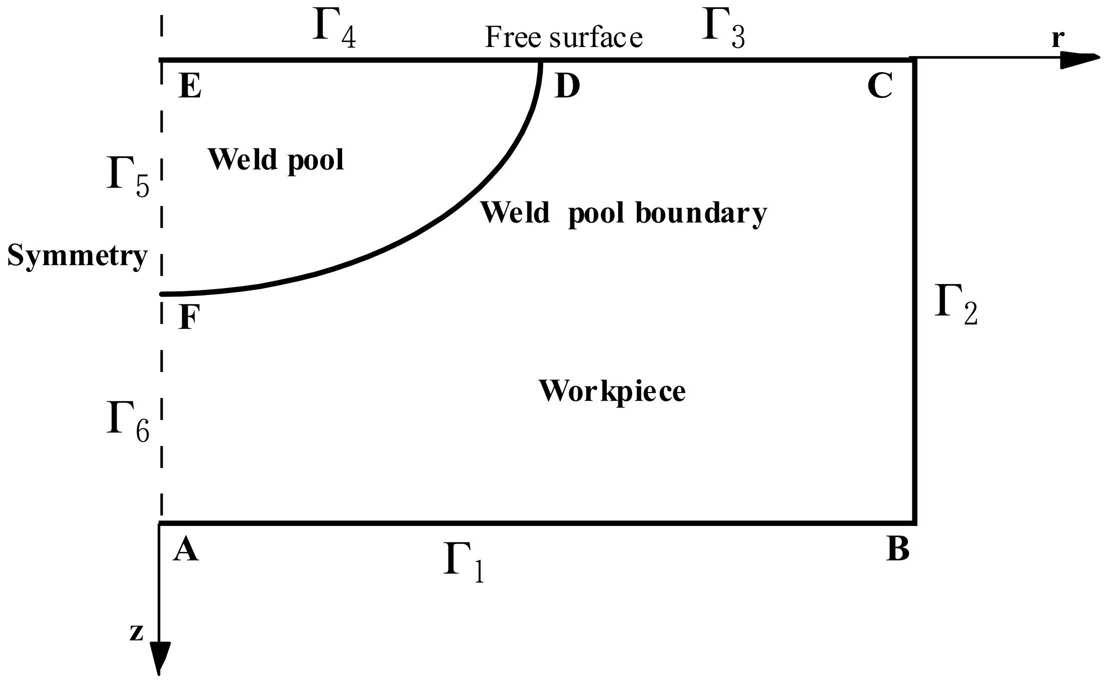

Figure 1 Boundary conditions employed in the mathematical model.

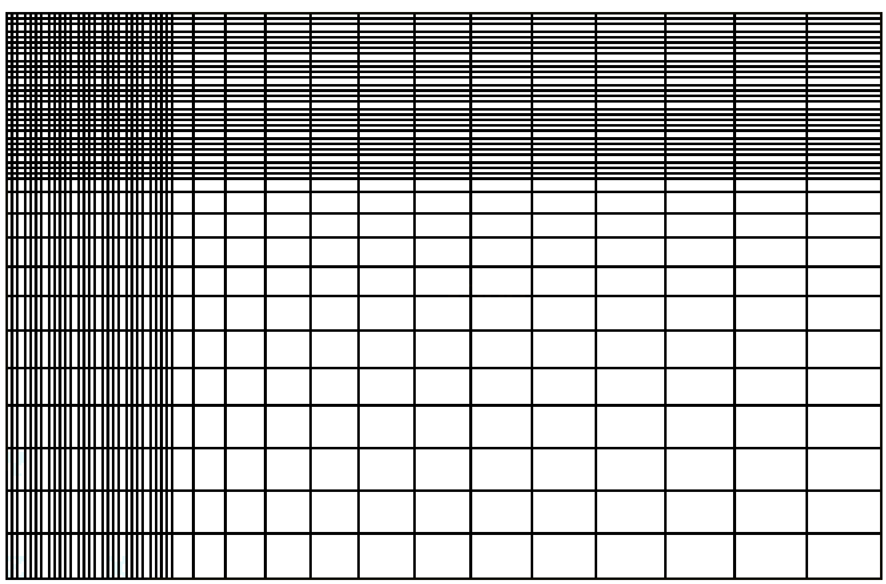

Figure 2 Grid employed for computations.

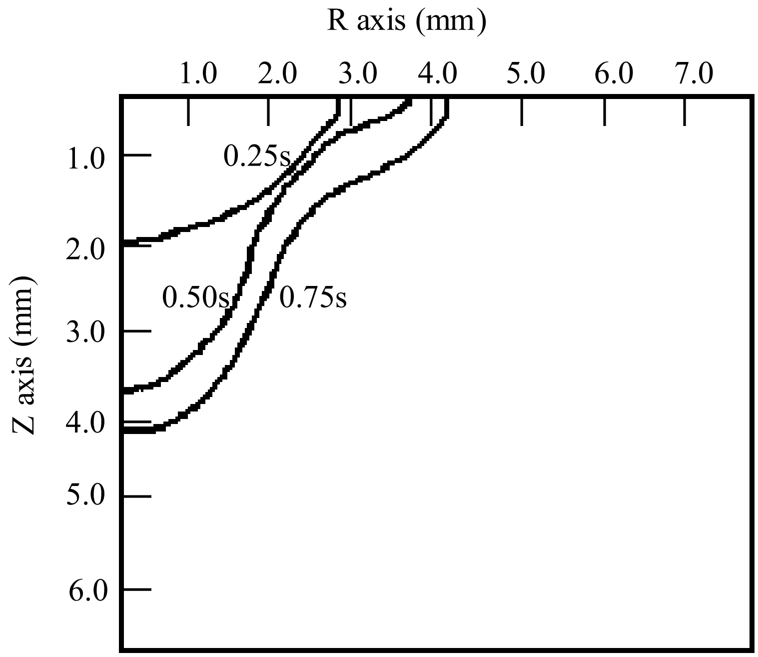

Figure 3 Liquid-solid interface of the GMA WELDING process at different times.

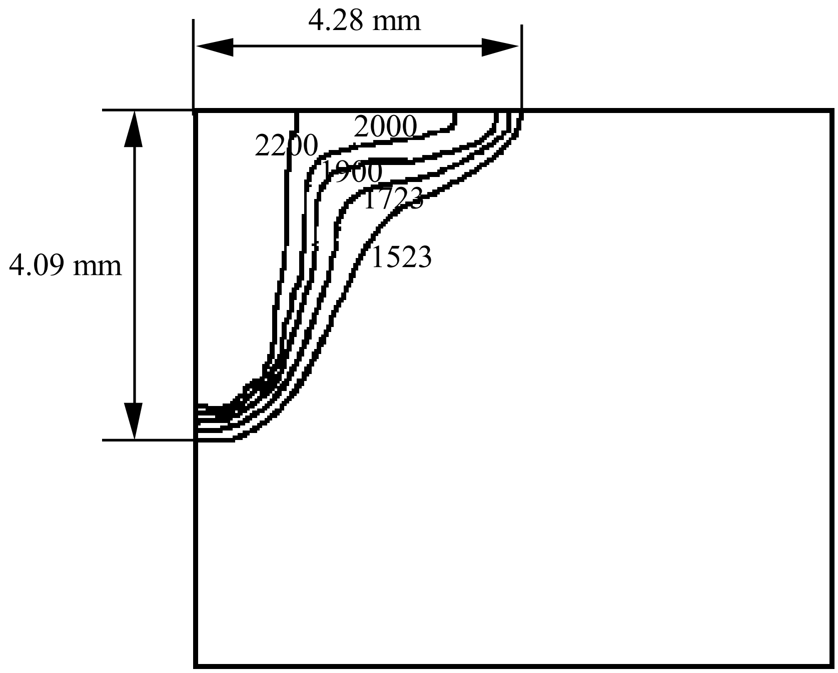

Figure 4 Temperature field in weld pools due to the combined driving forces.

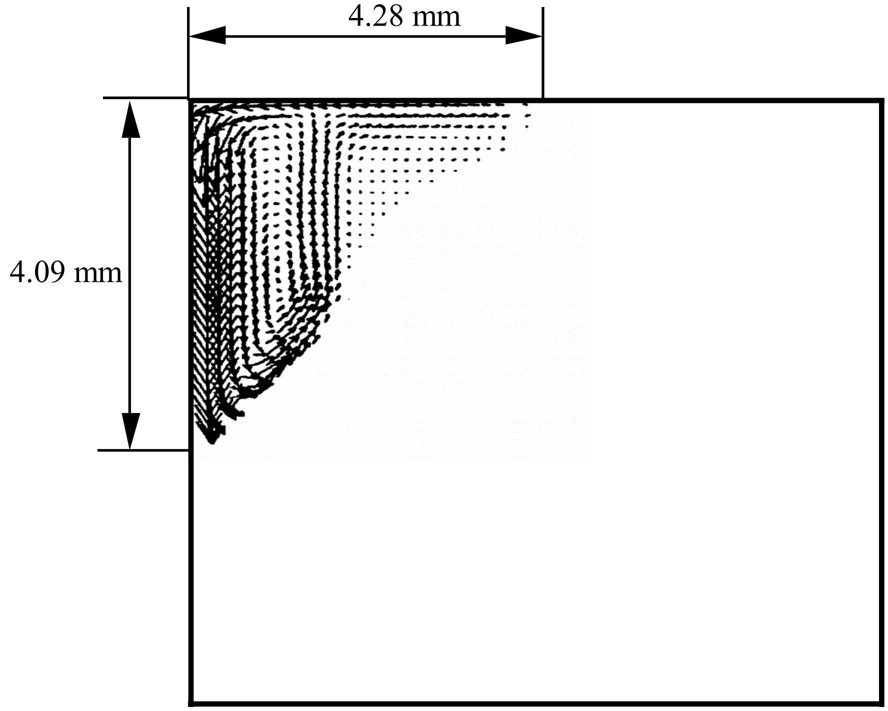

Figure 5 Velocity field in weld pools due to the combined driving forces.

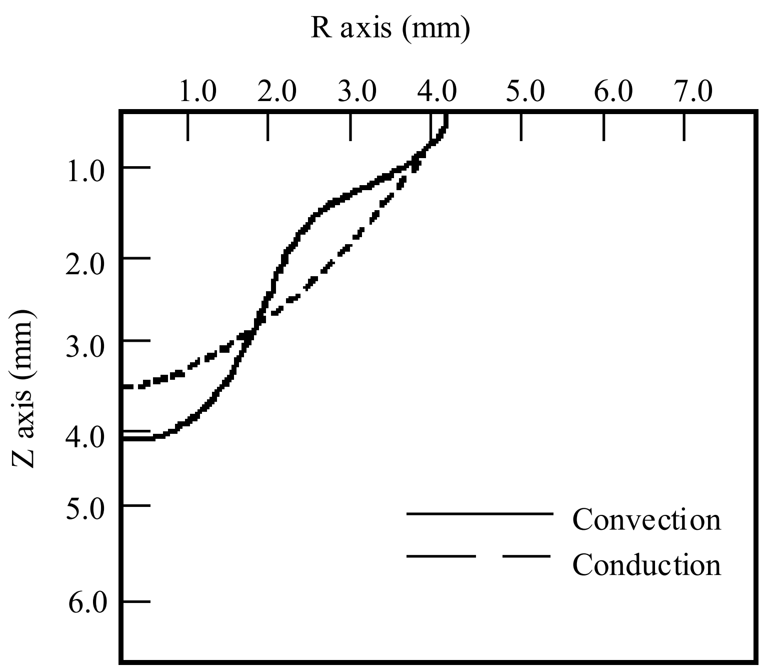

Figure 6 Comparison of weld pool boundaries with the same heat input.

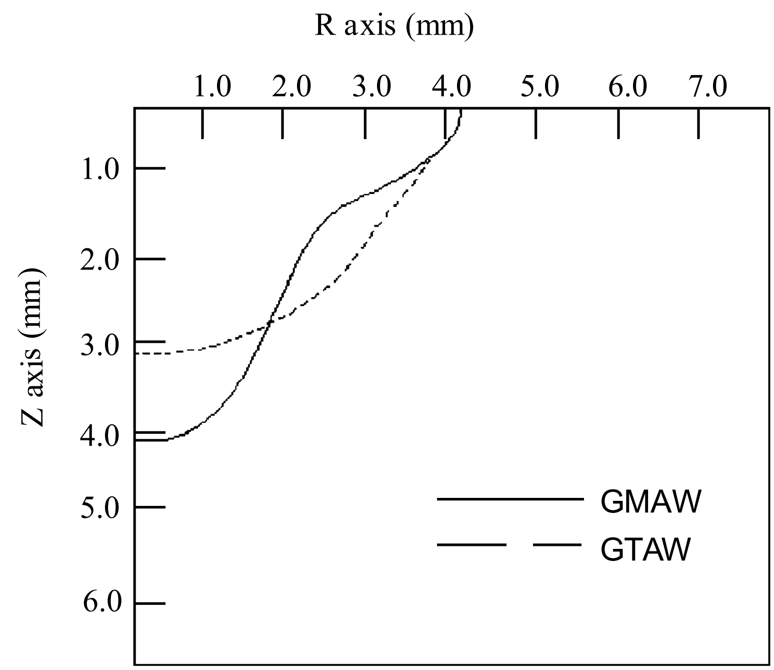

Figure 7 Comparison of the GMA welding with GTA welding weld pool dimensions.

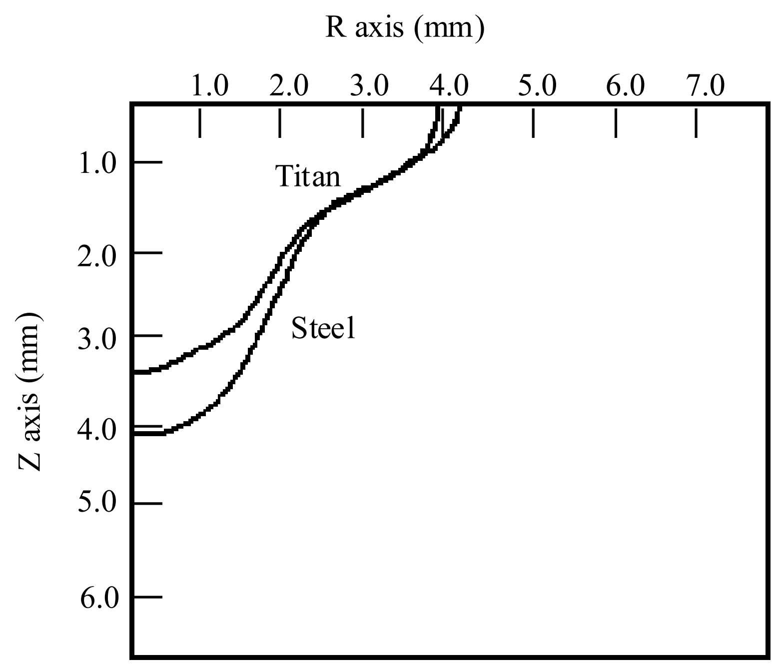

Figure 8 Comparison of mild steel with titan weld pool boundaries at the same conditions.

Concluding remarks:-

A theoretical evaluation of the development of weld pools during the GMA welding process has been studied and the following conclusion reached:

1. Fluid flow and heat transfer in weld pools for the GMA welding were theoretically investigated through a transient axisymmetrical solution of Navier-Stokes equation and 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 forces 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 figure 8, 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
g	gravitational acceleration
J_r	radial current density
J_z	axial current density
H	heat transferred into weld pools
ΔH	latent heat of fusion of steel
k_l	thermal conductivity (liquid steel)
k_s	thermal conductivity (solid steel)
Q	heat flux
P	pressure
r	radial direction
r_j	effective radius of the current
r_q	effective radius of the density
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
$\partial\gamma/\partial T$	surface tension
μ	dynamic viscosity
¬	electrical conductivity
τ_{drag}	drag force
⁊	heat input efficiency
φ	electric potential
β	volume coefficient of thermal expansion
μ_m	magnetic permeability
⅃	density of workpiece
σ_o	Stefn-Boltzmann constant
ε	emissivity

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