Study of Fluid Flow and Heat Transfer of a Moving GTA Weld Pool in Longitudinal Magnetic Field

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Abstract
Compared with general Gas Tungsten Arc Welding (GTAW), substantial change happens to liquid metal in external longitudinal magnetic field GTA weld pool. In the paper, mathematical models of fluid flow and heat transfer of external longitudinal magnetic field moving GTAW three-dimensional weld pool are established. Using the multi-coupled analysis function of ANSYS, distributions of current density and magnetic field as well as fluid flow and heat transfer of three-dimensional moving weld pool are systematically studied to understand and reveal the effect of external longitudinal magnetic field on liquid metal in moving GTA weld pool and supply basis for the application of external longitudinal magnetic field welding technique.

Introduction
During GTA welding process, the behavior of weld pool can be changed by an external axisymmetric magnetic field parallel to welding arc centerline. It was found that applying a magnetic field of this type will result in annular flow of liquid metal in weld pool and produce significant influences on fluid flow and heat transfer, as a result, also influence the melting and solidification of weld metal. From 1960s (Reference 1), some researchers began to study this kind of welding technique. They found that applying this kind of magnetic field could control the crystallizing process of weld metal and refine weld metal grain, as well as improve structure property of welding joint. At that time, the main means to study the behaviors of fluid flow and heat transfer of weld pool is experiments (Reference 2,3,4). However, it is very difficult to study fluid flow and heat transfer of moving weld pool and also impossible to essentially reveal external magnetic field distribution rule. From 1997 to 1999 (Reference 5), Luo jian studied the quasi three-dimensional fixed weld pool in external longitudinal magnetic field. Obviously, the simulation of spot weld pool could not reflect the real status of moving welding process, therefore, study on external longitudinal magnetic field moving welding process is very necessary and significant.

Description of Three-dimensional Mathematical Model
According to practical conditions of external longitudinal magnetic field welding process, following assumptions are given

1) Liquid metal in weld pool is incompressible viscous Newtonian fluid. Fluid flow belongs to laminar flow. There is no slipping velocity on liquid-solid interface.

2) Under weak external magnetic field \( B \leq 0.1T \) and low welding current \( I \leq 120A \), heat flux of welding arc on weld pool surface is considered as Gaussian distribution (Reference 5).

3) Under weak external magnetic field \( B \leq 0.1T \) and low welding current \( I \leq 120A \), arc plasma force and surface tension on weld pool surface as well as free surface are ignored.

4) External longitudinal magnetic field has no influence on current density distribution in weld pool.
5) Not dealing with high-energy density, vaporization loss of weld metal and change of chemical constitution are ignored.

6) Under low-speed welding condition, transfer rate of arc energy are ignored.

Figure 1 shows the calculation model of external longitudinal magnetic field welding process. Excitation coil producing magnetic field is fixed at welding torch to ensure the external longitudinal magnetic field coaxial and synchronous with welding arc. The model uses Cartesian coordinate system. Welding heat source moves at constant speed $u_0$ in X-axis direction.

![Figure 1 Calculation Model of External Longitudinal Magnetic Field GTA Welding Process](image)

**Force Equation**

Motion of liquid metal in weld pool under external longitudinal magnetic field is very complex. According to above assumptions, the dominant driving force for weld pool motion in external longitudinal magnetic field GTA welding is electromagnetic forces and rotation drag force of welding arc.

1) Electromagnetic Forces

In external longitudinal magnetic field GTA welding, there are two kinds of electromagnetic forces to drive liquid metal. One is self-electromagnetic force; the other is additional electromagnetic force. Interaction of current density vector in weld pool and its self-induced magnetic field results in self-electromagnetic force. It can be given by

$$\vec{F}_{sm} = \vec{J} \times \vec{B}_{sm}$$  \hspace{1cm} (1)

Where, $\vec{F}_{sm}$ is self-electromagnetic force, $\vec{J}$ current density vector in weld pool and $\vec{B}_{sm}$ self-induced magnetic field.

Additional magnetic force, which results in the annular flow of liquid metal in weld pool, is produced by the interaction of longitudinal magnetic field and weld current in weld pool. It can be given by

$$\vec{F}_{am} = \vec{J} \times \vec{B}_{am}$$  \hspace{1cm} (2)

Where, $\vec{F}_{am}$ is additional magnetic force, $\vec{B}_{am}$ is external longitudinal magnetic field.

It can be easily found that the two forces, in nature, are all produced by the interaction of magnetic field and current density vector. According to Ref.6, wherever there exists current, ANSYS will automatically calculate the electromagnetic force applied in the region. If no external longitudinal magnetic field, ANSYS will calculate self-electromagnetic force, otherwise, additional magnetic force. Therefore, before solving the forces, current density vector must be obtained firstly. In cylinder coordinate system $(r, z, \varphi)$, the current density is calculated from (Reference 7)
\[
\begin{align*}
    j_r &= -\frac{1}{\mu_0} \frac{1}{r} \frac{\partial \psi_e}{\partial z} \\
    j_z &= \frac{1}{\mu_0} \frac{1}{r} \frac{\partial \psi_e}{\partial r}
\end{align*}
\]

Where, \(\mu_0\) is the permeability of air and \(\psi_e\) is defined as (Reference 8)

\[
\psi_e = \frac{\mu_0 j_0 L}{k_c \sqrt{\pi / 2}} \int_0^r \left[ \exp[-2\left( \frac{r - r_c}{k_c} \right)^2] + \exp[-2\left( \frac{r + r_c}{k_c} \right)^2] \right] r dr \cdot (1 - \frac{z}{L})
\]

Where, \(L\) is workpiece thickness, \(j_0\) current density constant of weld pool surface, \(k_c\) centralized coefficient of current density on weld pool surface, \(I\) welding current and \(r_c\) radial distance of current density peak value.

According to finite difference method, Equation (3) can be expanded as

\[
\begin{align*}
    j_r &= -\frac{1}{\mu_0} \frac{1}{r} \frac{\psi_{e,r,z} - \psi_{e,r,z-1}}{\Delta z} \\
    j_z &= \frac{1}{\mu_0} \frac{1}{r} \frac{\psi_{e,r,z} - \psi_{e,r-1,z}}{\Delta r}
\end{align*}
\]

Where \(\Delta z\) and \(\Delta r\) are difference step size in \(z\) and \(r\) directions respectively. \(\psi_{e,r,z}, \psi_{e,r,z-1}\) and \(\psi_{e,r-1,z}\) are respectively the value of \(\psi_e\) at coordinates \((r, z, \phi)\), \((r, z-1, \phi)\) and \((r-1, z, \phi)\).

Based on Finite Difference Method and ANSYS’ Parameter Design Language (APDL), a program designed to calculate current density distribution of weld pool is embedded in electromagnetic field calculation program as boundary condition to complete electromagnetic force calculation.

In the paper, a hollow cylinder coil excited by a constant-current source produces external longitudinal magnetic field. During the magnetic field analysis, the helicity of coil turn and the non-uniformity of the whole coil current are ignored to greatly reduce computation time. Practice shows the method only produces minimal error between calculation value and practical measurement value (Reference 9).

Figure 2 shows the calculation model of external longitudinal magnetic field. Involved media have welding workpiece, excitation coil and air.

Because tungsten electrode has the same permeability as air, air property is assigned to tungsten electrode region to simplify calculation model complexity. The calculation of external longitudinal magnetic field in the paper deals with an open infinite domain. Because Magnetic Vector Potential (MVP) at the boundary of welding workpiece and excitation coil cannot be obtained by experiment, and all the air surrounding the model also cannot be included into the model, this paper define a layer of far-field elements simulate the
open infinite domain (Reference 6). Assuming all the media are isotropic, according to electromagnetic field theory, Maxwell equation set, which external longitudinal magnetic field follows, is given by

\[
\begin{align*}
\nabla \times \vec{E} &= 0 \\
\nabla \cdot \vec{D} &= \rho_e \\
\nabla \times \vec{H} &= \vec{J} \\
\nabla \cdot \vec{J} &= 0 \\
\n\nabla \cdot \vec{B} &= 0
\end{align*}
\]  

(6)

Where, \( \vec{E} \) (v/m) is electric field intensity, \( \vec{B} \) (T) magnetic induction intensity, \( \vec{D} \) (c/m\(^2\)) electric displacement vector, \( \vec{H} \) (A/m) magnetic intensity, \( \vec{J} \) (A/m\(^2\)) current density, \( \rho_e \) (C/m\(^3\)) charge density.

The following equations are given to describe the macro-electromagnetic character of media in external longitudinal magnetic field.

\[
\begin{align*}
\vec{J} &= \sigma \vec{E} \\
\vec{B} &= \mu \vec{H} \\
\vec{D} &= \varepsilon \vec{E}
\end{align*}
\]  

(7)

Where, \( \mu \) is permeability and \( \sigma \) electric conductivity.

(2) Arc Rotation Drag Force to Weld Pool Surface

In external longitudinal magnetic field, welding arc rotates at high speed and at the same time drags weld pool surface to rotate (Reference 5). The force is from the interaction of external longitudinal magnetic field and welding current density vector in arc region. It can be given approximately by (Reference 8)

\[
\vec{F}_{sm} = k_b \vec{J}_r
\]  

(8)

Where, \( \vec{F}_{sm} \) is arc rotation drag force, which has the same direction with external longitudinal magnetic field and approximately equal to magnetic induction intensity of weld pool surface. \( \vec{J}_r \) is the \( r \) direction component of weld pool surface current density.

**Continuity Equation**

Liquid metal in weld pool is incompressible fluid, that is to say, metal density is invariable during welding process. Therefore, the continuity equation is given by

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

(9)

Where, \( (u, v, w) \) are fluid velocity component in \((x, y, z)\) direction respectively.

**Momentum Equation**

In view of the incompressibility and Newtonianism of weld pool liquid metal, the momentum equation is given by

\[
\rho[(u - u_0) \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}] = \mu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}) + F_x
\]
\[
\begin{align*}
\rho[u - u_0] \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + F_y \\
\rho[u - u_0] \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &= \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + F_z
\end{align*}
\] 

where, \( \rho \) is liquid density, \( \mu \) viscous coefficient, and \( (F_x, F_y, F_z) \) components of body force in weld pool fluid in \((x, y, z)\) directions respectively.

**Energy Equation**

Energy equation is given by

\[
\rho C_p [(u - u_0) \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z}] = \frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z})
\]

Where, \( t \) is time, \( C_p \) constant pressure specific heat, \( T \) temperature, and \( k \) coefficient of heat transfer.

**Analysis**

External longitudinal magnetic field welding process deals with heat transfer, phase transition and the interaction of electromagnetic field and flow field, moreover, fluid flow and heat transfer are interacting, therefore, it is very difficult to solve the problem with analytic solution. Based on commercial finite element software ANSYS, the problem is automatically loaded and solved by program designed by APDL. If no special statement, in experiments and numerical simulation of this paper, excitation current is 20 A, gap between coil and upper surface of workpiece is 10 mm, welding current 100 A, arc length 2 mm, tungsten diameter 3.2 mm, tungsten cone angle 60 degree, argon flow quality 8 L/min, welding velocity 3 mm/s. Direct current and normal polarity are adopted.

**Initial and Boundary Conditions**

Before solving the coupled field of flow field and thermal field, boundary conditions should be specified. Furthermore, because welding is a transient process, initial condition also should be given in advance.

**Velocity Boundary**

Velocity boundary includes the liquid-solid interface of molten domain and non-molten domain, and also free surface of weld pool. During welding process, the liquid-solid interface, where latent heat of phase change takes place, is moving. During the solution of fluid flow and heat transfer, the most difficult problem faced with is the moving of the liquid-solid interface. General measure is to assume there is a minute time lag between transferring of heat energy into the interface and its result, moving of the contact surface. That is to say, during a minute time step, liquid-solid interface is supposed to be stationary. Under the assumption, flow field and thermal field are solved. Then according to the calculated thermal energy transferred into liquid-solid interface, latent heat of phase change and other heat balance conditions, the displacement of every node on the interface is calculated to obtain new position of the moving interface. Based on the new position, flow field and thermal field of next time step can be calculated. According to the method, the flow field and thermal field of the whole welding process can be calculated. Obviously, the algorithm of this measure is fairly complicated to realize. Moreover, the calculation accuracy is dependant on time step size. The smaller time step is, the higher calculation accuracy is. However, minute time step is at the cost of lots of CPU calculation time.
In order to overcome the deficiency of this measure, this paper adopts Liquid Solid Identity Method. In the method, solid phase is also regarded as liquid phase. That is to say, in the region, where temperature is less than or equal to solidus temperature $T_s$, very great viscosity (about $10^9$ order) is assigned to ensure flow velocity in the region is zero. However, in the rest region, where temperature is greater than or equal to liquidus temperature $T_l$, real viscosity is used, therefore, when electromagnetic forces are applied, the region with little viscosity will move. With this method, program will automatically handle the moving liquid-solid interface and update physical properties of material according to calculated temperature field without artificial intervention.

The other velocity boundary is free surface of weld pool. At present, ANSYS cannot handle three-dimensional free surface, therefore, normal velocity of liquid metal of weld pool surface is prescribed to be zero. Under low welding current ($I \leq 120A$), the upper surface of general GTA weld pool can be regards as plat surface (Reference 10). Furthermore, according to Reference 5, during external longitudinal magnetic field GTA welding process, the displacement of the upper surface of fixed weld pool is very small and can be ignored. As a result, this processing method will is reasonable.

FLOTRAN analysis module of ANSYS requests that fluid region must be defined before FLOTRAN analysis. In this paper, solid phase is regarded as liquid phase; therefore, fluid region should be the whole welding workpiece. Therefore, the normal velocities of other five outer surfaces other than free surface also should be assigned a zero value to determine the unique fluid region.

**Thermal Boundary**

Heat flux of external longitudinal magnetic field moving GTA welding arc presents Gaussian distribution (Reference 5). It is given by

$$Q_{arc} = \frac{\eta_a U I}{3\pi \sigma_q^2} \exp\left(-\frac{r^2}{3\sigma_q^2}\right), \quad r \leq \sigma_q$$

(12)

Where, $\sigma_q$ is heat flux distribution parameter of welding arc. It is defined as radial distance from arc center to the position where heat flux decays to 5% of heat flux maximum. $U$ is arc voltage, $\eta_a$ coefficient of efficiency of welding heat source, $Q_{arc}$ heat flux distribution of welding arc.

Because of the temperature difference between welding workpiece and ambient medium (gas), heat exchange will take place. Convection and radiation are dominating forms. Experiments show, during welding process, radiation is leading thermal loss and convection loss is relatively very small, moreover, the higher temperature is, the more thermal loss is (Reference 11).

For certain stationary surface infinitesimal adjacent with certain flowing medium (gas or fluid), its convective loss can be given by (Reference 12)

$$q_c = h_c (T - T_0)$$

(13)

Where, $q_c$ is convection loss, $T$ surface temperature of solid, $T_0$ temperature of flowing medium. $h_c$ is coefficient of convection heat transfer, which depends on surface flow condition, surface property, and flow medium property as well as temperature difference $T - T_0$. Speaking strictly, it is also associated with workpiece position. However, it is difficult to measure coefficient of convection heat transfer of different position, so a constant is assigned in the paper.

When relative small matter (its temperature is $T$) is welded in relative broad ambient (its temperature is $T_0$), radiation loss is given by (Reference 11)
\[ q_r = \varepsilon C_0 (T^4 - T_0^4) \]  

(14)

Where, \( C_0 \) is Stefan-Boltzmann constant, \( \varepsilon \) radiation emissivity.

**Initial Conditions**

External longitudinal magnetic field moving GTA welding is a transient process, so initial temperature and velocity must be given. In the paper, initial temperature of the whole welding workpiece is ambient temperature and its initial velocity is zero.

**Treatment of Latent Heat**

Thermal analysis module of ANSYS provides thermal enthalpy method to treat latent heat of phase change. But the method cannot be applied to thermofluid coupling analysis. In the paper, Equivalent Specific Heat Method is used. It is given by (Reference 13)

\[ C_E = C - L_h \frac{\partial f_s}{\partial T} \]  

(15)

Where, \( C_E \) is equivalent specific heat, \( C \) the real specific heat, \( T \) workpiece temperature, \( L_h \) latent heat of phase change, and \( f_s \) solid phase ratio. Solid phase ratio is a non-dimensional number and its increase and decrease are proportional to release and absorption of latent heat. When \( f_s \) is equal to zero, metal is in liquid condition. When \( f_s \) is equal to one, metal is in solid condition. When \( f_s \) is greater than zero and less than one, metal is in mushy phase change zone. Solid phase ratio of different matters can be given by

\[ f_s = \frac{T - T_s}{T_l - T_s} \]  

(16)

Where, \( T_l \) and \( T_s \) are solidus temperature and liquidus temperature respectively.

**Thermophysical Properties and Related Parameters**

Welding material in the paper is stainless steel AISI 321. The volume of welding workpiece is 100mm \( \times \) 50mm \( \times \) 5mm. Thermophysical parameters and welding technological parameters is listed in Table 1.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (AISI 321)</td>
<td>( \rho )</td>
<td>Kgm(^{-3})</td>
<td>7200</td>
</tr>
<tr>
<td>Solidus Temperature</td>
<td>( T_s )</td>
<td>K</td>
<td>1523.0</td>
</tr>
<tr>
<td>Liquidus Temperature</td>
<td>( T_l )</td>
<td>K</td>
<td>1713.0</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>( T_0 )</td>
<td>K</td>
<td>298</td>
</tr>
<tr>
<td>Viscosity</td>
<td>( \mu )</td>
<td>Kgm(^{-1})s(^{-1})</td>
<td>Equation (17)</td>
</tr>
<tr>
<td>Permeability(AISI 321)</td>
<td>( \mu_m )</td>
<td>Hm(^{-1})</td>
<td>( 1.26 \times 10^{-6} )</td>
</tr>
<tr>
<td>Latent Heat</td>
<td>( L_h )</td>
<td>JKg(^{-1})</td>
<td>( 2.47 \times 10^3 )</td>
</tr>
<tr>
<td>Property</td>
<td>Symbol</td>
<td>Unit</td>
<td>Value/Formula</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------</td>
<td>----------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>$C_p$</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
<td>Equation (18)</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$k$</td>
<td>W m$^{-1}$ K$^{-1}$</td>
<td>Equation (19)</td>
</tr>
<tr>
<td>Convective Heat Transfer Coefficient</td>
<td>$h_c$</td>
<td>W m$^{-1}$ K$^{-1}$</td>
<td>20.0</td>
</tr>
<tr>
<td>Emissivity</td>
<td>$e$</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Stefan-Boltzmann Constant</td>
<td>$S$</td>
<td>W m$^{-2}$ K$^{-4}$</td>
<td>$5.669 \times 10^{-8}$</td>
</tr>
<tr>
<td>Welding Arc Heat Efficiency</td>
<td>$\eta_a$</td>
<td></td>
<td>0.85</td>
</tr>
<tr>
<td>Effective Radius of Heat Source</td>
<td>$\sigma_q$</td>
<td>mm</td>
<td>3.5-4.5</td>
</tr>
</tbody>
</table>

Thermophysical properties used in finite element are cited from authoritative documents (Reference 14) and technological parameters are from experiments. In Table 1, heat conductivity, specific heat and viscosity are all the function of temperature. Therefore, during welding process, physical properties of every point will be updated with the change of temperature field. These properties can be given by

$$k = \begin{cases} 10.717 + 0.014955T & T \leq 780k \\ 12.076 + 0.013213T & 780k \leq T \leq 1672k \\ 217.12 - 0.1094T & 1672k \leq T \leq 1727k \\ 8.278 + 0.0115T & 1727k \leq T \end{cases}$$

$$C_p = \begin{cases} 0.43895 + 1.98 \times 10^{-4}T \times 10^3 & T \leq 773k \\ 0.13793 + 5.9 \times 10^{-4}T \times 10^3 & 773k \leq T \leq 873k \\ 0.87125 - 2.5 \times 10^{-4}T \times 10^3 & 873k \leq T \leq 973k \\ 0.5552 + 7.75 \times 10^{-5}T \times 10^3 & 973k \leq T \leq 1727k \end{cases}$$

$$\mu = \begin{cases} 6.0 \times 10^9 & T < 1713K \\ (37.203 - 0.0176T) \times 10^{-3} & 1713k \leq T \leq 1743k \\ (20.354 - 0.0087T) \times 10^{-3} & 1743k \leq T \leq 1763k \\ (34.849 - 0.0162T) \times 10^{-3} & 1763k \leq T \leq 1853k \\ (13.129 - 0.0045T) \times 10^{-3} & 1853k \leq T \leq 1873k \end{cases}$$

**Coupling Strategy of Electromagnetic Field, Flow Field and Thermal Field**

During external longitudinal magnetic field moving GTA welding process, excitation coil is supplied by constant-current source and the constant-current source is switched on in advance. Therefore, electromagnetic force will be applied on welding workpiece as soon as welding process starts. But only when weld pool appears, will electromagnetic force work.

Because excitation coil is supplied by constant-current source, the external magnetic field is stationary field. In the paper, the effects of fluid flow on magnetic field and current density vector are ignored; therefore, during welding process, with the moving of welding torch, current density distribution in weld pool is invariable with respect to moving welding torch. As a result, during welding process, electromagnetic force produced by the interaction of invariable magnetic field and invariable current density is also invariable with the moving welding torch.

In view of above analysis, in the paper, current density distribution, external longitudinal magnetic field distribution and induced magnetic field of current density in weld pool are firstly calculated. Then,
electromagnetic coupling calculation is performed to calculate electromagnetic force of every node. Finally, based on the electromagnetic coupling calculation results, coupling calculation of fluid field and thermal field is performed to ultimately complete the coupling calculation of electric field, magnetic field and thermal field as well as flow field.

**Coupling Computation of Electromagnetic Field, Flow Field and Thermal Field**

According to coupling strategy, calculation of this paper includes two steps. The first step is electromagnetic field coupling calculation. In this step, element coordinate system adopts cylinder coordinate system. Element type of excitation coil, welding workpiece and gas are SOLID97 and the element type of infinite boundary layer is INFIN111. The second step is thermofluid-coupling analysis. This step only involves welding workpiece. Element coordinate system adopts Cartesian coordinate system. Element type of welding workpiece is FLUID142. In general, great temperature and velocity gradient exist in welding seam, so relative fine element is assigned to the region. Finally, there are altogether 21,810 elements and 23,349 nodes in the finite element model.

**Analysis Results & Discussion**

Figure 3 and figure 4 are the sectional view of calculation results of current density and external longitudinal magnetic field in weld pool respectively. It can be found that external longitudinal magnetic field produced by single hollow cylinder coil is parallel to arc centerline and can be approximately regarded as longitudinal magnetic field. Current density vector maximum in weld pool appears at certain annular region deviating weld pool center. Moreover, the closer to weld pool center, the smaller the included angle between current density vector and magnetic induction density is. Especially, at weld pool center, current density vector is almost parallel to magnetic induction density.

![Figure 3 Magnetic Induction Intensity Distribution in Thickness Direction](image)
Figure 5 shows the relationship of fluid velocity maximum and time during external longitudinal magnetic field moving GTAW welding process. It is found that during initial 0.23 second, maximal velocity of “fluid” is very low and keeps at $10^{-11}$ order. That is because there is no metal reaching melting point, as a result, there is no liquid metal in weld pool. From 0.24 second to 0.28 second, examining calculation results of temperature field, it is found that there is a small quantity of metal reaching melting point, however, velocity maximum still keeps at $10^{-11}$ order. The reason is that weld pool volume is very small and weld pool width is also very small at the time. But at weld pool center, current density vector is basically parallel to magnetic induction intensity, so suffered electromagnetic force is too little to drive liquid metal to move.

After 0.29 second, fluid velocity maximum rises to $10^{-3}$ order in 0.01 second, and rises to $10^{-1}$ order in very short time. Subsequently the velocity maximum basically keeps at 0.23m/s. Obviously, with the growing up of weld pool volume, weld pool width increases to the annular region where electromagnetic force exists, which results in the accelerated motion of weld pool fluid. But with further moving of welding arc, the metal behind weld pool will solidify and the metal in the front of weld pool will melt, which eventually results in fluid motion to reach certain quasi-steady flow state.

Figure 6 shows the calculation results of velocity field of external longitudinal magnetic field moving GTA weld pool surface. It can be found, in external longitudinal magnetic field moving GTA welding process, fluid in weld pool makes nonaxisymmetrical annular rotation motion. According to Reference 5, external longitudinal magnetic field spot GTA weld pool makes axisymmetrical rotation motion about arc centerline.
As a result, the nonaxisymmetrical annular rotation motion results from the moving of welding arc. It is also found that velocity field maximum appear at certain annular region deviating weld pool center. That is because the maximum of electromagnetic force applied on weld pool also appears at annular region deviating weld pool center.

![Image](image1.png)

**Figure 6: Velocity Field of External Longitudinal Magnetic Field Moving GTA Welding Pool Surface**

Figure 7 shows temperature field calculation results of external longitudinal magnetic field GTA welding process at 0.33 second. In the figure, only the region, where temperature is above melting point, is drawn up. It can be seen that weld pool presents a wide and shallow shape under externally applied longitudinal magnetic field. The author thinks there are two reasons. Firstly, under external longitudinal magnetic field, welding arc expands (Reference 15,16) to result in energy fall on unit area. Secondly, because of the high-speed rotation of weld pool fluid, centrifugal force is produced to drive liquid metal to move towards the weld pool brim, at the same time, part of the thermal energy also is brought to the brim of weld pool. The two reasons eventually result in the special weld pool shape.

![Image](image2.png)

**Figure 7: The Shape of External Longitudinal Magnetic Field Moving GTA Welding Pool**

**Conclusion**

In the paper, according to multi-coupled analysis function of ANSYS, during external longitudinal magnetic field moving GTA welding process, current density distribution, external longitudinal magnetic
field distribution as well as fluid flow and heat transfer in three-dimensional moving weld pool are systematically studied.

The study on the distribution of external longitudinal magnetic field shows that the magnetic field hollow coil produces can be regarded approximately as longitudinal magnetic field.

The study on current density distribution indicates that current density appears at certain annular region deviating weld pool center. The closer to arc center and upper surface of welding workpiece, the smaller the angle between current density vector and longitudinal magnetic field is.

The studies on fluid flow and heat transfer behaviors reveal that weld pool presents a wide and shallow shape under externally applied longitudinal magnetic field. The establishment of velocity field has a time lag after welding starts. Liquid metal in weld pool will rotate because of the effects of magnetic force and rotating force of welding arc. Maximum of the rotating velocity appears at certain annular region deviating weld pool center.

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