Numerical simulation of the effect of surface tension and viscosity on the shape of GTA weld bead

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ABSTRACT:
Studies have shown that two heats of steel of the same grade welded in GTA under the same conditions lead to dissimilar welds aspects. This difference is related to the presence of Minor elements in the weld pool. To describe and integrate the forces involved in the weld pool like: the surface tension, Buoyancy force and electromagnetic force, the mathematical tool is necessary. In this paper, the effect of viscosity on the shape of the weld bead is discussed on the basis of numerical simulation

Keywords: GTA welding, Weld shape, Viscosity, Marangoni, Surface tension, Simulation
1. Introduction
The convective movement in the weld pool plays a decisive role in the transfer of heat. The intensity of the velocity and direction of the flow affect the geometric as well as the structure obtained. The convection of liquid metal in the weld pool has been the subject of many studies [1-5]. Athey[6] is the first to take an interest in convective movement in the weld pool considering only the effect generated by electromagnetic Lorentz force. Nevertheless, he emphasizes the importance of the effect of the thermal surface tension gradient in the formation of the weld bead. Oreper[7] emphasized the importance of thermo capillary effect taking into account all the coexisting forces in the weld pool. Several studies have followed, each one treating a particular aspect in TIG welding [8-10]. All results of these investigations show that the effect of surface tension temperature gradient is the most determinant factor.
The purpose of the present work is to study the effect of viscosity on the morphologic weld bead. Special emphasis is placed on the investigation of the influence of viscosity on the flow, in the presence of a heat gradient of positive or negative surface tension, by taking into account other forces in presence in the weld pool.
2. Formulation

In order to develop the mathematical model the term viscous dissipation has been introduced as a source term into the energy equation where the viscosity is considered constant and homogeneous. The physical phenomenon is described by a series of equations. The following assumptions have been adopted for simplification:

1- The welding arc is steady.
2- The liquid metal is Newtonian type.
3- The fluid is incompressible following Buoyancy approximation.
4- The Properties are supposed to be constant in both liquid and solid phase.
5- The flow is laminar.
6- The flow is in 2-D.

2.1. Governing equations [11-12]:

According the above assumptions the equations governing the weld pool may be written as follows:

Mass conservation equation:

\[ \nabla \cdot \vec{V} = 0, \quad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \]

Conservation equation of the amount of movement (Navier-Stokes equations):

\[
\rho \cdot \frac{\partial \vec{v}}{\partial t} = -\left( \frac{\partial p}{\partial \vec{x}_i} \right) + (\rho \cdot g_i) + \left( \frac{\partial \epsilon_{ij}}{\partial \vec{x}_j} \right) + F_i
\]

Amounts of forces related to the pressure, forces, viscous, electromagnetic

This equation becomes:

\[
\rho \left( \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial X} + V \frac{\partial U}{\partial Y} \right) = - \left( \frac{\partial P}{\partial X} \right) + \left( \frac{\partial f}{\partial Y} \right) \cdot \frac{\partial B}{\partial Z} + \mu \left( \frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right)
\]

\[
\rho \left( \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial X} + V \frac{\partial V}{\partial Y} \right) = - \left( \frac{\partial P}{\partial Y} \right) + \rho \cdot g_i (T - T_0) + \left( \frac{\partial f}{\partial Z} \right) \cdot \frac{\partial B}{\partial X} + \mu \left( \frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right)
\]

The Energy Equation:

\[
\rho \cdot c_p \left( \frac{\partial T}{\partial t} + U \frac{\partial T}{\partial X} + V \frac{\partial T}{\partial Y} \right) = \lambda \left[ \frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} \right] + 2 \mu \left[ \frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} \right]^2 + \mu \left( \frac{\partial V}{\partial X} + \frac{\partial U}{\partial Y} \right)^2
\]
Using both the stream formulation and the vorticity formulation, which are adapted for cross linking flow and for 2 D studies, it can be shown that:

The Stream function equation:

\[ U = \frac{\partial \psi}{\partial y}, \quad V = -\frac{\partial \psi}{\partial x} \]

\[ \omega = \frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y} \]

\[ \omega = -\left( \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial x^2} \right) \]

The vorticity equation:

\[ \rho \left[ \frac{\partial \omega}{\partial t} + \frac{\partial \psi}{\partial y} \frac{\partial \omega}{\partial x} + \frac{\partial \omega}{\partial y} \left( -\frac{\partial \psi}{\partial x} \right) \right] - \mu \left[ \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right] = \mathbf{F}_2 - \mathbf{F}_1 \]

\[ \mathbf{F}_2 = -\frac{\partial (j \cdot B_z)}{\partial x} + \rho \cdot g \cdot \beta \cdot \frac{\partial T}{\partial x} \quad ; \quad \mathbf{F}_1 = \frac{\partial (j \cdot B_z)}{\partial y} \]

The Energy Equation becomes:

\[ \rho \cdot c_p \left[ \frac{\partial \psi}{\partial t} + \frac{\partial \psi}{\partial x} \frac{\partial \psi}{\partial y} + \frac{\partial \psi}{\partial y} \left( -\frac{\partial \psi}{\partial x} \right) \right] = \lambda \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + \xi(x, y) \]

\[ \xi(x, y) = \left[ 2 \cdot \mu \cdot \left( \frac{\partial^2 \psi}{\partial x \partial y} \right) - \left( \frac{\partial^2 \psi}{\partial y \partial x} \right) \right] + \mu \left( \frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial x^2} \right) \]

Where \( \rho \) is the density, \( \phi \) is the electric potential, \( \omega \) is the rotation, \( \psi \) is the stream function, \( \eta \) is the performance of the arc, \( \lambda \) is the thermal conductivity, \( h \) is the convective heat transfer coefficient, \( \mu \) is the dynamic viscosity, \( g \) is the acceleration of gravity, \( T_f \) is the melting temperature, \( T_e \) is the arc voltage, \( C_p \) is the calorific capacity, \( \mu_0 \) is the magnetic permeability, \( \sigma_e \) is the electrical conductivity, \( \beta \) is the volume expansion coefficient, \( \frac{\partial Y}{\partial T} \) is surface tension gradient.
2.2. Boundary conditions:

To complete the mathematical description of the problem, the boundary conditions are specified as follows:

Energy Equation:

Fig. 1 shows the calculation domain for energy equation

\[ Q_{imp} = \frac{3 \eta T_e I}{\pi a} e^{-\frac{x}{a}} \]

The Stream function equation:

Fig. 2 shows the calculation domain for equation of stream function

The vorticity equation:

Fig. 3 shows the calculation domain for vorticity equation

\[ \omega = f(T, x) = -\frac{1}{\mu} \left( \frac{\partial y}{\partial T} \right) \left( \frac{\partial T}{\partial x} \right) \]

Equation of potential:

Fig. 4 shows the calculation domain for potential equation

3. Solution Technique

During a welding operation, the area of the work piece exposed to the arc welding is heated until it reaches the melting temperature and the formation of the weld pool starts. To simulate the transition from a solid state to the liquid solid state, a prior calculation was done by pure conduction model, once we get enough points where melting temperature is overtaken; we pass to calculation by the convection model. During a period of time \( \Delta T \), we calculate the speed \((U, V)\) and the thermal field \((T)\), once convergence is satisfied on the current function and on the transfer equation of weld pool as well as on the temperature equation, we will get other points that will have reached the melting temperature which indicate the displacement of melting front. We increment the time until the fixed time which is 1 second is reached.

Fig.5 describes the overall solution algorithm of the equations of flow and energy. For the resolution of equations, the method of finite difference and the ADI (Alternative Direction Implicit) method which presents an unconditional stability have been chosen, therefore the convergence is ensured. The solution is satisfied when the absolute error on the temperature and the current function and the rotational is less than 1%. The half-width is equal to 10 mm and the thickness is 3 mm. The total number of mesh point in the partis \((20 \times 18 = 360\) points). The parameters used in the simulation are shown in table 1.
4. Results and Discussion:
The effect of viscosity on the behavior of the liquid metal in the presence of positive thermal gradient with appositive surface tension $= 10^{-5}$N/m.k is illustrated in Fig. 6 and fig. 7.
The results show that the flow velocity in the weld pool decreases as the viscosity increases. Thus, when the viscosity is $2.10^{-3}$kg/m.s the maximum velocity in the weld pool is 8.2 cm/s. On the other hand, when the viscosity is raised to $9.10^{-3}$kg/m.s, the flow velocity in the weld pool decreases to 5.33 cm/s. This result confirms that the increase in viscosity makes the flow slow and less energetic.

With regard to the evolution of geometrical characteristics of the weld beads, the half width remains constant. On the other hand, the depth of the weld bead increases; it passes from 1.25 mm for a viscosity of $2.10^{-3}$kg/m.s to a depth of 1.58 mm for a viscosity of $9.10^{-3}$kg/m.

The effect of viscosity on the behavior of the liquid metal in presence of a negative thermal gradient of surface tension $= 10^{-5}$N/m.k is illustrated in Fig. 8 and Fig. 9.

It can be seen that the increase in viscosity slows the flow velocity in the weld pool. It is also shown that the half-width of the weld bead decreases in favor of the weld bead depth which increases. Thus, the depth of the weld bead gradually changes from 0.35 mm at a viscosity of $2.10^{-3}$kg/m.s to 0.53 mm for a viscosity of $9.10^{-3}$kg/m.s. On the other hand, the half width of the weld bead which was 6.84 mm at a viscosity of $2.10^{-3}$kg/m.s is reduced to 6.31 mm for a viscosity of $9.10^{-3}$kg/m.s.

The results show that as the viscosity increases, the depth of the weld bead increases to the detriment of the weld bead width in the case of negative surface tension of the thermal gradient. On the other hand, the weld bead width remains constant in the case of positive thermal gradient of surface tension. It indicates that the increase in viscosity could foster a centripetal flow. This result can be explained with the help of calculation of the Peclet and Reynolds numbers. The Peclet number represents the ratio of heat transfer by convection to conduction transfer.

\[
Pe = \frac{U \cdot D}{\alpha}
\]

\[
Re = \frac{U \cdot D}{\mu}
\]

Where $U$ is the characteristic speed, $D$ is the characteristic distance, $\alpha$ is the thermal diffusivity, $\mu$ is the dynamic viscosity.

The evolutions of Reynolds and Peclet number as function of the viscosity in the case of negative and positive temperature gradient of surface tension are shown in Fig. 10 and 11.

The results reveal in both cases that the Reynolds number decreases when the viscosity increases, what at tests that the flow of the metal liquid in the weld pool slows down by the viscosity, which is due to the forces of viscous friction.
Concerning the evolution of the Peclet number, it says that this number decreases when the viscosity increases, which means that the increase in viscosity causes a decrease in transfer by convection in favor of transfer by conduction. Knowing that the thermal variations caused by conduction transfer are less significant than those caused by convection transfer [11]; therefore, all the forces which are dependent to thermal gradients in the weld pool are dwindling. Thus, the role of Buoyancy force as well as the thermal gradient of surface tension will be altered and reduced. On the other hand, the centripetal effect of the electromagnetic force is not affected. This explains the increasing depth of the weld in both cases, when the viscosity increases.

5. Conclusion:
In the case of positive thermal gradient of surface tension, the flow rate of liquid metal gradually decreases as the viscosity increases. For different values of viscosity simulated, the half width remains constant. On the other hand, the depth of the weld bead increases.

In the case of negative temperature gradient of surface tension, when the viscosity increases, the depth gradually decreases to the detriment of the width.

The increase in viscosity reduces the effect of the Buoyancy force as well as the temperature gradient of surface tension. This is due to the effect of viscous forces that slow the rate of flow and temperature differentials, the source of Buoyancy and Marangoni convection, will be diminished by the transfer by thermal conduction. On the other hand, the effect of electromagnetic forces remains unaffected.
References


Table 1
Parameters used in the simulation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Nomenclature</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>The performance of the arc</td>
<td>0.8</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Thermal conductivity</td>
<td>20W/k.m</td>
</tr>
<tr>
<td>$h$</td>
<td>The convective heat transfer coefficient</td>
<td>0.4(W/k.m²)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
<td>$6 \times 10^{-3}$ (kg/m.s)</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity</td>
<td>9.8 (m/s²)</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Melting temperature</td>
<td>1800 k</td>
</tr>
<tr>
<td>$T_e$</td>
<td>Arc voltage</td>
<td>13.2 (volts).</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Calorific capacity</td>
<td>753 (j/kg.k).</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Magnetic permeability</td>
<td>$126 \times 10^{-6}$ (H/m)</td>
</tr>
<tr>
<td>$\sigma_e$</td>
<td>Electrical conductivity</td>
<td>$7.14 \times 10^{-6}$ (Ohm⁻¹.m¹)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Volume expansion coefficient</td>
<td>$7.14 \times 10^{-6}$ (Ohm⁻¹.m¹)</td>
</tr>
<tr>
<td>$\left[ \frac{\partial y}{\partial T} \right]$</td>
<td>Surface tension gradient</td>
<td>$10^5$ (N/m.k).</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>7200 (kg/m³)</td>
</tr>
</tbody>
</table>

Figures

Figure 1: Calculation domain for energy equation
Figure 2: Calculation domain for equation of stream-function

Figure 3: Calculation domain for vorticity equation

Figure 4: Calculation domain for potential equation
Figure 5: Diagram shows the sequential solving equations

Figure 6: Evolution of speed in the weld pool in the case of $\frac{\partial y}{\partial T} = 10^{-5}$ N/m.k
Figure 7: Evolution of penetration in the weld pool in the case of $\frac{\alpha_y}{\alpha_T} = 10^{-5}$ N/m.k

Figure 8: Evolution of speed in the weld pool in the case of $\frac{\alpha_y}{\alpha_T} = -10^{-5}$ N/m.k

Figure 9: Evolution of depth and half-width of the weld bead in the case of $\frac{\alpha_y}{\alpha_T} = -10^{-5}$ N/m.k
Figure 10: Evolution of Reynolds and Peclet numbers in the case of $\frac{\partial T}{\partial t} = -10^5$ N/m.k

Figure 11: Evolution of Reynolds and Peclet numbers in the case of $\frac{\partial T}{\partial t} = 10^5$ N/m.k