Thermal distribution in electrical arc welding of Tungsten inert gas (TIG) process

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For the numerical analysis of tungsten-inert-gas welding TIG process detailed information on both the distribution of energy flow and excess pressure at the weld pool surface is needed. Numerical arc modeling can deliver such information which can be used as input data for weld pool modeling or for the optimization of arc parameters as well as demonstrating physical arc behavior. Through simultaneous solutions of the set of conservation equations for mass, momentum, energy, and current, a mathematical model has been developed to predict the velocity, temperature, and current density distribution in argon welding arcs. The predicted temperature fields in arc regions and distributions of current density and heat flux at the anode are compared with measurements reported in literature. This work could lay the foundation for developing a comprehensive model of the TIG welding process.

Mots clefs:

Thermal analyses; welding; argon arc; plasma; heat transfer.
1. Introduction

In TIG welding process, arc heat, is produced between a non consumable electrode and metal work piece. The weld quality is mainly characterised by welding arc, since the energy for the welding is transferred through arc plasma, and it affects the weld bead formation. The transport phenomena in a tungsten inert gas (TIG) welding arc plays a very important role in producing weldments of high quality. The TIG welding arc exerts heat flux, current density and pressure distributions on the surface of the weld pool [4]. For predicting the weld pool geometry and metallurgical structures, accurate information about the welding arc influencing the weld pool is prerequisite. The behaviour of an arc is governed by a coupled set of physical laws:

- Ohm's Law
- Maxwell's Equations
- Conservation Equations of, mass, momentum, energy, and electrical charge.

In this paper, solutions of the conservation equations are presented for the TIG welding arc. It is a useful intermediate step in the direction of developing a comprehensive representation of the dynamic, two-way interactions, between the transport phenomena in the welding arc and in the weld pool.

2. Formulation

![FIG. 1 – Analysis domain](image)

Fig.1 shows the computational domain used to model the TIG welding arc. The presence of an electric field between the cathode (a tungsten rod) and the anode (metal workpiece) causes the passage of an electric current through the ionised plasma region, which in turn, gives rise to a self-induced magnetic field. The magnetic field interacts with the current transferring momentum to the gas; which is accelerated toward the anode in the form of a characteristic cathode jet. Due to the electrical resistance of the plasma, the energy produced by the current keeps the plasma in the ionised state and provides the heating mechanism for the welding process. For modelling this complex welding arc, some assumptions must be made. The arc model in this paper is based on the following assumptions:

- The arc plasma is in local thermodynamic equilibrium (LTE) which means that that the electron and heavy particle temperatures are equal.
- The arc is steady and radially symmetrical.
- The plasma is optically thin so that radiation may be accounted for using an optically thin radiation loss per unit volume.
- The arc plasma consists of pure argon at atmospheric pressure.
- The arc plasma shows a laminar flow.

2.1 Governing equations [5]

Under the above assumptions, the equations governing the arc region may be written as follows:
Current continuity in terms of electric potential is given by

\[
\frac{\partial}{\partial z} \left( \sigma \frac{\partial V}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \sigma r \frac{\partial V}{\partial r} \right) = 0
\]  

(1)

The current density is given by:

\[
J_r = -\sigma \frac{\partial V}{\partial r} \quad J_z = -\sigma \frac{\partial V}{\partial z}
\]  

(2)

Since the current distribution is axisymmetric, the self-induced magnetic field is given by the following relation from Ampere’s law:

\[
B_\theta = \frac{\mu_0}{r} \int_0^r J_z r dr
\]  

(3)

The Lorenz force components are given as:

\[
F_r = -B_\theta J_z \quad F_z = B_\theta J_r
\]  

(4)

The energy equation is in the following form:

\[
\frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \frac{J_r^2 + J_z^2}{\sigma} + \frac{5}{2} \frac{k_B}{e} \left( J_z \frac{\partial T}{\partial z} + J_r \frac{\partial T}{\partial r} \right) - S_r = 0
\]  

(5)

3. Numerical Solution

To solve energy equation we have used finite volumes method. The computational domain is shown in Fig.1 and the corresponding boundary conditions are given in Table1 [1][2]. The boundary conditions are presented in the table bellow [1][2]:

<table>
<thead>
<tr>
<th></th>
<th>AB</th>
<th>BC</th>
<th>CE</th>
<th>EF</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>( \frac{\partial V}{\partial r} = 0 )</td>
<td>V=Cte</td>
<td>( \frac{\partial V}{\partial r} = 0 )</td>
<td>( \frac{\partial V}{\partial r} = 0 )</td>
<td>Eq.(6)</td>
</tr>
</tbody>
</table>
As the calculation domain for $u$, $v$ and $T$, the area $ABCEF$ is chosen; but the domain for $V$ is chosen as the smaller area $ABCD$, since the exact boundary condition for $V$ along the line $FA$ is unknown. Due to symmetry, only half of the flow domain was considered for the calculation. Along the centreline $AB$, symmetry conditions are used, zero velocities are specified along the solid boundaries $BC$ and $FA$. Along the far field boundary $CE$, zero radial gradients for all variables are specified. A constant electrical potential is specified along the anode surface $BC$ because the anode is assumed to be a perfect conductor relative to the plasma.

Along the boundary $EF$, the temperature is taken as $1000K$ and the radial velocity components is neglected. At the cathode surface $FA$, the temperature is assumed to be $3000K$.

The current density distribution along the line $DA$ is assumed to be Gaussian [6]:

$$J_c = J_0 \exp\left(-3\left(\frac{s}{s_p}\right)^2\right)$$

Where $s$ is the coordinate along the electrode surface, and $s_p$ is the distribution parameter defined as the distance at which the intensity of current density is 5% of the maximum intensity $J_0$ at the electrode tip center. Then the welding current $I$ can be derived by integrating the current density distribution over the electrode surface as the following equation:

$$I = 2\pi \int_0^{R_e} J_0 \exp\left(-3\left(\frac{s}{s_p}\right)^2\right) r ds$$

the equation below can be rewritten by converting $r(s)$ as follows:

$$I = 2\pi J_0 \int_0^{R_e} \exp\left(-3\left(\frac{s}{s_p}\right)^2\right) s \sin(\theta / 2) ds$$

where the $\theta$ is the electrode vertex angle.

Then $s_p$, the distribution parameter for a given electrode can be determined as the equation of:

$$s_p = \frac{3I}{\sqrt{J_0 \pi \sin(\theta / 2)}}$$
From the equation below it is known that the current density distribution over the electrode surface is affected by the electrode shape, mainly, the electrode vertex angle.

\[ J_0 = 100 \text{A/m} \]

4. Results and discussion

In order to understand the behaviour of electrical arc versus the different parameters, temperature variation was calculated considering:

- Arc length.
- Welding current intensity.

FIG. 3 – temperature distribution between Anode and cathode for I=100A, (a) L=10mm, (b) L=15mm, (c) L=20mm
Fig. 3 shows temperatures variation versus arc length. The temperatures increase as we approach the electrode tip, and as the arc length increase the temperature decrease.

![Graph showing temperatures variation versus arc length.](image)

**Fig. 4** – temperature distribution between Anode and cathode for $L=10\text{mm}$, (a) $I=200\text{A}$, (b) $I=250\text{A}$, (c) $I=300\text{A}$

Fig. 4 shows temperature variation versus welding current intensity, as we have expected the temperature increase with increasing welding current intensity.

5. Conclusion

The model we developed to study heat flux, lay the foundation for developing a comprehensive model of the TIG welding process. This model contributes to carry out temperature distribution within the electrical arc. We have noted thermal field variation versus several parameters:

- Arc length.
- Welding arc current.
- Welding voltage.

We hope to develop a model considering a real gas flow in order to be able to calculate radial and axial velocity. We suggest also to use calculated temperature, at the anode surface as boundary conditions instead the constant value.
References