Arc pressure in tandem TIG arc and its relation with plasma jet

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Abstract: A three-dimensional (3D) numerical model of a tandem TIG welding is developed to obtain the arc pressure in arc and demonstrate its relation with plasma jet. It has been found that there are high pressure zones in arc: below the electrodes, above the anode, the interchange of two flow of plasma, which is derived from the plasma jet below the cathode. Besides, the maximum pressure calculated on the surface of anode for the tandem TIG arc is smaller than that for the single arc. It built a basis for the application of tandem TIG arc welding.

Key words: tandem TIG; modelling; pressure; plasma jet


0 Introduction

In recent years, a variety of multi-electrode arc welding processes have been used in manufacturing industry, such as tandem GMAW and tandem TIG welding. The tandem TIG welding was originally proposed by Yamada et. al. This method use a unified arc produced by two separated tungsten electrode to heat the workpiece. It has been demonstrated that this method is good in efficiency and quality for the welding of liquefied natural gas storage tanks.

In welding process, a high current is often used to improve the heat input, thus the welding efficiency. However, if the current is very high, the plasma jet becomes strong, and then an arc crater maybe produces. Hence, it necessary to focus on not only the characteristics of heat source but only its force characteristics. Some studies have been performed to study the heat flux for the tandem TIG arc. Leng Xuefeng et al. measured the heat flux of tandem TIG arc. Ogino et al. and WANG Xinxin et al. modeled the tandem TIG arc and obtained the distribution of temperature and heat flux. However, few researchers have addressed the force characteristics of tandem TIG arc.

The purpose of this study is to investigate the distribution of arc pressure in tandem TIG arc and its relation to the plasma jet. We developed a unified 3D model which includes the two electrodes, the anode and the arc. The magneto hydrodynamics theory was used to describe the transfer of heat, mass and current. The plasma jet was analyzed to illustrate its effect on the pressure in the arc and on the anode.

1 Mathematic and computing models

In this section, a steady 3D model of the tandem TIG arc is presented. The calculation is based on Fluent software. The physical properties for the argon are given by.

(1) Hypothesis

The following assumptions were made in this study:

- Plasma is regarded as a Newtonian and laminar flow.
- Plasma is at local thermodynamic equilibrium (LTE).
- A water-cooled copper is used as the anode, and its surface is not deformable.
- Metal vapor coming from the tungsten electrodes and the copper is negligible.

a. Mass conservation

\[ \nabla \cdot (\rho \vec{v}) = 0 \]  (1)

Where \( \rho \) is the density, \( t \) is the time, and \( \vec{v} \) is the velocity vector.
b. Momentum conservation. 
\[ \nabla \cdot (\rho \mathbf{u} \nabla \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{f} + j \times \mathbf{B} - \rho \mathbf{g} \] 
(2)

Where \( \rho \) is the pressure, \( \mathbf{u} \) is the acceleration of gravity, \( j \) is the current density, and \( \mathbf{B} \) is the magnetic field. The expression of shear stress \( \tau \) is given by
\[ \tau = 2\eta \left[ 0.5 \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) - 0.67 \left( 0.5 \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right) \right] \] 
(3)

\( \eta \) is the viscosity and \( \mathbf{I} \) is the identity matrix.

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c. Energy conservation.
\[ \nabla \cdot (\rho \mathbf{u} \nabla h) + \frac{1}{c_e} \nabla \cdot \mathbf{q} = j \times \mathbf{B} - 3 \frac{k_b}{\mathbf{c}_e} j \times \mathbf{j} - 4 \pi \mathbf{e} \mathbf{n} \] 
(4)

Where \( h \) is enthalpy, \( \lambda \) is the thermal conductivity, \( c_e \) is the specific heat, \( k_b \) is the Boltzmann constant, and \( \mathbf{e} \) is the net emission coefficient.

d. Electrical potential conservation.
\[ \nabla \cdot (\sigma \mathbf{V}) = 0 \] 
(5)

The solution of electrical potential gives \( j = -\sigma \mathbf{V} \)

e. Magnetic potential conservation.
\[ \nabla \cdot (\mathbf{A}) = -\mathbf{B} \] 
(6)

Resolving this equation gives \( \mathbf{B} = \nabla \times \mathbf{A} \)

(3) Energy interface.

The energy balance at the interfaces of arc-cathode and arc-cathode must be taken account. At the anode surface the heat flux \( q_a \) is given by
\[ q_a = \left[ \frac{1}{2} \right] \mathbf{c}_e \left( \mathbf{V} - \mathbf{c}_e \phi \right) \] 
(7)

And the heat flux \( q_t \) at the cathode surface is given by
\[ q_t = \left[ \frac{1}{2} \right] \mathbf{c}_e \left( \mathbf{V} - \mathbf{c}_e \phi \right) \] 
(8)

where \( \mathbf{c}_e \) is the conduction heat, \( \mathbf{c}_e \) is the unit vector of cathode surface, \( \mathbf{V} \) is the fall voltage of cathode and \( \phi \) is the cathode work function. The radiation cooling losses on the electrodes is negligible.

(4) Calculation domain and boundary conditions.

Figure 1 shows the geometry of the model. To reduce computational load, an axisymmetric model is used. The two tungsten electrodes are the same in shape and size, whose diameter \( R \) is 2.4 mm. The sharp corner and platform diameter are, respectively, 38° and 0.6 mm. The angle between the electrodes and \( z \) axis are both 23°. The space between two electrode tips is 6 mm, and the electrode tips are at 6 mm above the copper anode. The size of the water-cooled copper is 40 mm× 4 mm× 4 mm.

A unified arc is generated by two separated welding power (WSM–400) with a current of 120 A through each electrode. The shielding gas is pure argon with a flow of 10 L/min. The boundary conditions used in the model is given in table 1. Besides, to compare with traditional TIG welding, an axisymmetric model of single TIG arc is also constructed. A tungsten electrode 2.4 mm in diameter is located 6 mm above the anode in \( z \) axis. The current through the singe electrode is 240 A, which is equal to the total current used in tandem arc welding.

<table>
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<th>Zone</th>
<th>( \text{speed/m} \cdot s^{-1} )</th>
<th>( T/K )</th>
<th>( V/V )</th>
<th>( A(T_e) )</th>
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<td>( \Phi /\mu \text{A} = 0 )</td>
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</table>

2 Results and discussions

(1) The plasma jet in the arcs

The velocity distribution in the tandem TIG arc is shown in Figure 2. It can be seen that a maximum speed of about 223 m/s occurs at 1.5 mm below each electrode. The plasma is projected from the electrodes, which is called as 'plasma jet' \( \Phi \). To illustrate the cause of this phenomenon, we distract a stream of plasma across the arc. A force analysis for a local plasma in the stream is analyzed. The expression of these forces can be seen from the momentum conservation equation (2). The electromagnetic force \( \mathbf{F}_e = j \times \mathbf{B} \) caused by the current is the leading force. The gravity is negligible. The pressure \( \mathbf{P}_q \) is produced to balance a part of the electromagnetic force. The shear force caused by the viscosity does not change the flow direction. Therefore, a resultant force forms to shrink the arc and to move the plasma from the electrode to the anode.

Figure 3 shows the velocity distribution in the single TIG arc. There is a maximum speed of about 454 m/s occurs at 3.0 mm below the electrode. It is obvious that the ‘plasma jet’ in the single TIG arc is stronger than that in the tandem TIG arc. To explain the difference of
velocity in two arcs, we estimate the magnetic force in a current-carrying cylinder with a radius of $R_c$. The magnetic field $B$, at the position of $r$ can be deduced by Biot-Savart law:

$$B = \frac{\mu_0 I}{2\pi R_c}$$

(9)

Then, the magnetic force $F$, caused by the self-magnetic field is expressed as

$$F = \frac{\mu_0 I}{2\pi R_c} \frac{I}{R_c} = \frac{\mu_0 I^2}{2\pi R_c^2}$$

(10)

From equation (10), we know that the magnetic force caused by self-magnetic field is proportional to the square of the current. Although the current flux and the density in arc are not uniform, the above relation can qualitatively explain the phenomenon of ‘plasma jet’. In tandem TIG, the current through each electrode is 120 A, which is half of that in single TIG. Based on above analysis, we can know the magnetic force in tandem TIG arc will be weaker than that in single TIG arc.

(2) The pressure in the arcs

Figure 4 presents the pressure distribution in the tandem TIG arc on xz face. In this study, the pressure is expressed as the value in excess of atmospheric pressure. It can be observed that high pressure occurs below the cathode electrode (599 Pa) and above the anode (380 Pa) and at the center of the arc (348 Pa). Figure 5 shows the pressure distribution in the single arc. High pressure appears below the cathode (1560 Pa) and above the anode (1420 Pa).

In order to illustrate the cause of the pressure in the arc, we analyze the pressures at four positions in a stream for the tandem TIG arc: A (the entrance of gas), B (below the cathode), C (the center of the arc) and D (above the anode). This stream comes across the high pressure zones. The pressure is analyzed by Bernoulli’s principle:

$$p_1 + \frac{1}{2} \rho v_1^2 = p_2 + \frac{1}{2} \rho v_2^2 + \rho h$$

(11)

Where $p_1$ and $p_2$ is the pressures at two positions in the downstream and upstream of a stream, $v_1$ and $v_2$ is the velocities at the two positions, $\rho_1$ and $\rho_2$ is the densities at the two positions, $h_1$ is the power per unit mass produced by the electromagnetism, and $h_v$ is the viscous power loss per unit mass.

In the motion of the plasma, the electromagnetic force do positive work, and its value is biggest at position B, thus a high value of $h_1$ is produced. Compared with the electromagnetic force, the viscous power loss $h_v$ is negligible. Since the electromagnetic force is dominant at position B, a high pressure is produced. At position C, two stream of plasma crash, and the velocity is reduced (See figure 2). Hence, the pressure increases at the center of the arc. At position D, the plasma is obstructed by the anode, and a high pressure occurs above the anode.

(3) The pressure on the anode

Figure 4 presents the pressure on the anode for the tandem arc and the single arc. It can be seen that maximum pressure occurs in the position x=0 for both arcs. The maximum pressure calculated for the tandem arc (380 Pa) is smaller than that for the single arc (1420 Pa), due to a weak plasma jet in tandem arc. To validate the modelling results, the experiment measurement performed by Yamauchi and Taka is introduced. In their study, an argon arc in 200 A with an arc length of 3 mm was measured. A maximum pressure of 802 Pa is measured.
located at the center of the arc. This value is less than the calculated pressure of 1420 Pa in single arc, which is partly because the current used in their study (200 A) is less than that in the modelling of single arc (240 A). The small difference between the modelling results and experimental results is acceptable. As a consequence, the model gives an accurate solution of arc pressure.

3 Conclusion

(1) A steady 3D model of the tandem TIG arc is developed to obtain the distribution of pressure and to demonstrate its relations with plasma jet.

(2) By modelling, the plasma jet was observed near the tungsten electrodes, which is caused by a large current density at there. The self-magnetic force shrinks the arc and moving it from the cathode to the anode.

(3) The plasma jet cause high pressure in these zones: below the electrodes, above the anode, the center of the arc. The plasma jet provides kinetic energy for the production of these high pressure zones.

(4) The pressure on the anode for the tandem TIG arc is much less than that for the single arc. When a current of 240 A is used, the maximum value is 1420 Pa for tandem arc and only 380 Pa for single arc. This founding provides some theatrical basis for the application of tandem TIG arc welding.

Acknowledgement

This work was supposed by Nation Natural Science Foundation of China (No. 51175374, No. 51475325 and No. 51675375 ) and the 863 state science and technology support program (No. 2014BAF12B05).

References: