Computer Intelligent Numerical Simulation of TIG Welding Using Platy Tungsten Electrode

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Abstract. In order to reveal the law of arc plasma flow and heat transfer in the process of flat tungsten electrode TIG welding as auxiliary heat source for hardfacing of cast iron surface. According to the free burning TIG arc using platy tungsten electrode, A three dimensional (3D) model for tungsten inert gas welding using platy tungsten electrode has been developed. The whole region of platy tungsten TIG arc, namely, platy tungsten cathode, arc plasma and anode surface is treated in a unified numerical model. By using fluent software to do the second development of equations source and solve these equations, the distribution of temperature, velocity and current density are obtained. The simulation results show that the current of flat tungsten electrode is more dispersed, and the heat generation of arc is more dispersed, which leads to the decrease of arc temperature; The current density on the cathode is much higher than that on the anode.

Keywords: TIG arc, Surface surfacing of cast iron, three dimensional model, numerical analysis

1. Introduction

TIG welding arc is a kind of heat source widely used in welding. The improvement of TIG welding arc is often accompanied by the application of new welding methods. Among them, in order to meet some specific welding requirements, scholars at home and abroad have carried out special processing on the shape of tungsten electrode. For example, Doi et al [1]. Processed a through hole in the center of columnar tungsten electrode so that the laser could enter the molten pool through the center of tungsten electrode to form the welding process of coaxial hybrid welding of hollow cathode TIG and YAG laser. Yong Huang et al [2]. Made the cylindrical tungsten electrode tip into four sharp corners to reduce arc pressure to reduce welding defects such as undercut, and Liang Zhu et al [3]. Made the tungsten electrode flat to allow TIG welding to be used in narrow gap welding.

Due to the complexity of the welding process and the plasma state of the arc, there are still unsolved theoretical problems at the micro level. All these bring great difficulties to the experimental research. With the discovery and popularization of computer simulation technology and the gradual improvement of numerical calculation theory, numerical simulation has become a scientific research means, and there have been more research results in numerical simulation [5]-[10].
In this paper, for flat tungsten electrode TIG welding process, Using CFD software Fluent 6.3, a three-dimensional mathematical model of flat tungsten TIG welding arc was established by adding the electromagnetic field equation with a custom scalar (User Defined Functions, UDS) and adding the source term and boundary condition with a custom function (User Defined Functions, UDF). The temperature field, flow field and current density distribution of flat tungsten TIG welding arc were calculated. It provides a reference for further and more comprehensive study of the complex physical phenomena of flat tungsten TIG welding and further revealing that flat tungsten TIG welding is used as an auxiliary heat source for hard surfacing welding of cast iron.

2. Mathematical model

2.1. The basic assumptions
In order to facilitate the establishment of the mathematical model, the following basic assumptions are made:

(1) The arc plasma is a continuous, laminar Newtonian fluid. The arc plasma is in a steady state and satisfies the local thermal equilibrium hypothesis (Local Thermodynamic Equilibrium, LTE);
(2) Arc plasma satisfies the optically thin property that the reabsorption of the plasma radiation is negligible compared to the radiation of the whole wavelength;
(3) The complex physical state of the cathode region and the anode region is not considered;
(4) Arc is an argon arc under atmospheric pressure;
(5) The heat loss caused by the viscosity effect and the influence of gravity are ignored.

2.2. The governing equation
According to the above basic assumptions, the governing equations under three dimensional coordinates are established.

Mass conservation equation

\[
\frac{\partial(\rho)}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

Momentum conservation equation

\[
\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla P + \nabla \cdot \mathbf{\tau} + j \times \mathbf{B} + \rho \mathbf{g}
\]

Where, \( \rho \) is density; \( \mathbf{v} \) is the velocity vector; \(\mathbf{\tau} \) is the viscous stress tensor, the specific expression refer to literature [6]; \( j \) is the current density; \( \mathbf{B} \) is the magnetic flux density; \( \mathbf{g} \) is the acceleration of gravity.

Energy conservation equation

\[
\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p \mathbf{v} T) = \nabla \cdot (k \nabla T) + \frac{j^2}{\sigma} + \frac{5k_e}{2e} j \cdot \nabla T - S_R
\]

Where, \( \sigma \) is electrical conductivity; \( k_B \) is Boltzmann constant; \( k \) is the thermal conductivity; \( e \) is the electronic charge. On the right side of the equation, the conduction heat, Joule heat, electron transport enthalpy and arc radiant heat loss \( S_R \)

Continuity equation of current

\[
\nabla \cdot (\sigma \nabla \Phi) = 0
\]
Ohm's law

\[ j = -\sigma(\nabla \Phi) = \sigma E \]  

(5)

Poisson's equation for magnetic loss

\[ \nabla^2 \cdot A = -\mu_0 j \]  

(6)

Magnetic flux density

\[ \nabla \times A = B \]  

(7)

Where, \( \sigma \) is the conductivity, \( \Phi \) is the potential, \( A \) is the magnetic loss, \( E \) is the electric field intensity, and \( \mu_0 \) is the vacuum permeability. Thermophysical parameters of arc plasma are functions of temperature, selected from literature [11].

2.3. The boundary conditions

The solution domain is shown in Figure 1, and the boundary conditions are shown in Table 1.

![Figure 1. The model of TIG welding with plasty tungsten electrode](image)

**Table 1. Boundary conditions**

| Boundary                      | \( v \)/m·s\(^{-1} \) | \( T \)/K | \( \Phi \)/V | \( A/Wb\cdot m^{-1} \) |
|-------------------------------|------------------------|---------|-------------|---------------------|
| ABCD face                     | —                      | 3000    | \( -\sigma \frac{\partial \Phi}{\partial z} = \frac{I_1}{L} \) | \( \frac{\partial A}{\partial n} = 0 \) |
| DFEC face                     | \( V_z = V_{giv} \)    | 2500    | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| GKJF face \( \frac{\partial (\rho w)}{\partial n} = 0 \) | 1000                     | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| GKJF face \( \frac{\partial (\rho w)}{\partial n} = 0 \) | 1000                     | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| EFJI face \( \frac{\partial (\rho w)}{\partial n} = 0 \) | 1000                     | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| Tungsten electrode surface    | 0                      | coupling | coupling    | coupling            |
| IJKH face \( \frac{\partial v}{\partial n} = 0 \) | 0                     | 5000     | 0           | \( \frac{\partial A}{\partial n} = 0 \) |
| AEIH face \( \frac{\partial v}{\partial n} = 0 \) | \( \frac{\partial T}{\partial n} = 0 \) | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
| AGKH face \( \frac{\partial v}{\partial n} = 0 \) | \( \frac{\partial T}{\partial n} = 0 \) | \( \frac{\partial \Phi}{\partial n} = 0 \) | \( \frac{\partial A}{\partial n} = 0 \) |
In the calculation area, DFEC face is the argon inlet, ABCD face is the tungsten section, GKJF face and EFJI face are argon gas outlets, IJKH face is the anode surface, AEIH face and AGKH face are planes of symmetry. \( n \) is the boundary unit direction quantity, \( v_{giv} \) is the given axial velocity, \( l \) and \( d \) are the length and width of the tungsten pole boss.

In this paper, the complex physical state of the cathode sheath area is ignored, and the coupling boundary conditions used by Bini et al.[5], and the cathode area treatment method used by Fan Ding et al.[6], are adopted for the interface between the arc and tungsten electrode.

### 2.4. Numerical processing

Use GAMBIT software for geometric modelling. Since the flat tungsten TIG welding arc is symmetrical about the X axis and Y axis, the calculation domain is one quarter and the size is 5mm*15mm*12.4mm. Y axis is the width direction of the flat tungsten electrode, X axis is the thickness direction of the flat tungsten electrode, and Z axis is the height direction of the flat tungsten electrode. The tungsten section size is 8mm*1.34mm, the tungsten tip cone Angle is 50°, the tungsten tip cone Angle is 26°, and the tungsten tip is equipped with a 7mm*0.12mm boss. The calculated height of tungsten electrode is 7.4mm, and the calculated height of arc area is 5mm. Due to parts of the geometric irregularity, using the classification method of the grid points, the local refinement in the region of the large deformation gradient, combining structured and unstructured mesh grid, generate hexahedral grid, a total of about 320000 divided into a grid computing domain, the whole calculation area and mesh of tungsten electrode area is shown in figure 2.

![Figure 2. Mesh generation at computational domain(a) and platy tungsten electrode(b)](image)

### 3. Calculation results and discussion

#### 3.1. Analysis of calculation results

The welding parameters used in the numerical simulation are: tungsten electrode current 150A, arc length 5mm, gas flow rate 15L/min.

Figure 3 shows the arc temperature field on surface xoz. The arc temperature field shows a bell jar shape, which is similar to the temperature field in the section of columnar tungsten TIG welding [6], [10]. The reasons for the temperature distribution of flat tungsten electrode along the thickness direction, i.e., plane xoz, are discussed. If any tungsten electrode along the front end of the flat tungsten electrode is considered as a single cubic tungsten electrode, the discharge behavior of this tungsten electrode along the thickness of the tungsten electrode is similar to that of the columnar tungsten electrode. In the study of Savas et al [9], columnar tungsten electrode was simplified to cubic tungsten electrode for simulation study, and the research results showed that the arc morphology also presented a bell-shaped shape, which was similar to the temperature field distribution in surface YOZ in this paper.
As shown in Fig. 3, the highest temperature of flat tungsten TIG welding is about 14500K, which is different from the simulated maximum temperature 17000K [10] of columnar tungsten TIG welding under the same welding parameters. The difference is mainly due to the different shape of the tungsten electrode, which leads to the different cross-section area of the tungsten electrode. At 150A welding current, the current density of the flat tungsten electrode TIG welding cross-section is $1.39 \times 10^7 \text{A/m}^2$, while that of the columnar tungsten electrode TIG welding cross-section is $1.86 \times 10^7 \text{A/m}^2$, which is only 74.7% of the latter. The difference of current density directly leads to the change of arc heat generation term (The arc heat generation mainly comes from Joule heat, and the Joule heat is a function directly related to current density, as shown in Formula 3), which is ultimately reflected in the difference of arc maximum temperature. In addition, due to the tip discharge effect, the main discharge site of the arc is the tungsten front boss. The total length of the flat tungsten boss is 14.268mm, while that of the cylindrical tungsten boss with a straight 0.5mm boss is 1.6mm. As a result, the current in the flat tungsten electrode is more diffuse, and the arc heat is more diffuse, resulting in a temperature drop.

Fig. 4 shows the arc temperature field distribution along the width of the flat tungsten electrode on the yoz face. Compared with the columnar tungsten electrode with the same thickness in X direction and Y direction, the width of flat tungsten electrode is much larger than the thickness, so the arc temperature of flat tungsten TIG welding expands in Y direction.

Fig. 5 shows the arc velocity distribution on face xoz and face yoz. It can be seen from the figure that the arc velocity near the cathode is higher than that near the anode. This is because the arc plasma is affected by the electromagnetic force. In the place near the cathode area, the current density is larger, the electromagnetic force is larger, and the arc plasma has a faster flow rate.
Fig. 6 shows the current density distribution on face Yoz and face Xoz. It can be seen from the figure that the current density at the side of the tungsten electrode and the sharp corner of the tungsten electrode boss is the largest, which is in line with the phenomenon of tip discharge. The current flows through the anode surface into the arc region and then through the cathode interface into the cathode region. Because the radial distribution radius of the current flowing through the anode surface is much larger than the cathode surface, the current density on the cathode surface is much larger than the anode current density.

4. Conclusion
On the basis of reasonable basic assumptions, a three-dimensional mathematical model of flat tungsten TIG welding arc is established. The temperature field and flow behavior of non-two-dimensional axisymmetric arc can be numerically analyzed by the model of DC flat tungsten TIG welding arc. The simulation results of temperature field, velocity field and current density distribution of flat tungsten TIG welding arc are obtained. The results show that the temperature field of flat tungsten electrode is similar to that of columnar tungsten electrode in the direction of thickness, but there is a great difference in the direction of width. The different shape of tungsten electrode leads to the great difference of the maximum arc temperature under the same welding current. The simulation results also fully demonstrate that FLUENT can reliably simulate the non-axisymmetric arc.

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References

[1] Dio M. Coaxial hybrid process of hollow cathode TIG and YAG laser welding[J]. Welding International, 2010, 24(3): 188-196.

[2] Huang Yong, Hao Yanzhao, Qu Huaiyu, et al. Measurement and analysis of arc pressure in coupled arc tungsten electrode TIG welding [J]. Transactions of the China welding institution, 2013, 34(12): 33-36.

[3] Li Yuanbo, Zhu Liang. Transactions of the China welding institution, 2014, 35(7): 55-58.

[4] Liu Yi, Liang Rundong, Jiang Yue, et al. Numerical analysis of radial force of double volute centrifugal pump based on fluent [J]. Journal of gansu science, 2014, 26(3): 69-72.

[5] Bini R, Monno M, Boulos M I. Numerical and experiment study of transferred arcs in argon. J. Phys. D: Appl. Phys., 2006, 39(15): 3253-3266.

[6] Fan Ding, Huang Zicheng, Huang Jiankang, Wang Xinxin, Huang Yong. Three-dimensional Numerical Analysis of Arc And Pool Interaction in Tungsten Inert Gas Welding Considering Metal Vapor [J]. Acta physica sinica, 2015, 64(10): 304-314.

[7] Yuan Feng, Wang Pingyang, Ouyang Hua, Liu Xiao, Du Chaohui. Numerical Simulation of Thermal State of Steel Rod Bottom Electrode in DC Electric Arc Furnace [J]. Journal of Iron and Steel Research, 2007(06): 21-25.

[8] Guo Hongzhi, Zhang Shuchen, Kan Wanxi, Cheng Xiaohu. Numerical Calculation of Arc Velocity field and Temperature Field in DC Arc Furnace [J]. Journal of Iron and Steel Research, 2003(01): 6-10+26.

[9] Savas A, Ceyhun V. Finite element analysis of GTAW arc under different shielding gases [J]. Comput. Mater. Sci., 2011, 51: 53–71.

[10] Tanaka M, Yamamoto K, Tashiro S, et al. Metal vapour behaviour in gas tungsten arc thermal plasma during welding [J]. Welding in the World, 2008, 52(11): 82-88.

[11] Choo R T C, Szekely J. On the calculation of the free surface temperature of gas tungsten arc weld pools from first principles part [J]. Metall. Mater. Trans. B, 1992, 23B(6): 357-369.