Numerical study of keyhole behaviors and thermal fluid flow in high current plasma arc welding

by WU Dongsheng**, TASHIRO Shinichi**, HUA Xueming***, and TANAKA manabu**

A fully coupled plasma arc-keyhole-weld pool model was developed to investigate the keyhole behaviors and thermal fluid flow in high current plasma arc welding. The relationship between the forces distribution and fluid flow patterns was revealed. Owing to a constraint effect of the water cooling nozzle, the plasma arc flows downward with high energy and momentum, so a large keyhole forms. Inside the keyhole, the plasma arc mainly flows downward, and very few plasma arc flows upward along the keyhole wall. At the top surface of the keyhole, the plasma arc flows outward. The dominant downward plasma shear stress and negative arc pressure in the z direction cause a dominant anti-clockwise eddy in the weld pool. The outward plasma arc shear stress on the top weld pool surface causes a small clockwise eddy in the weld pool.

Key Words: Plasma Arc Welding, Keyhole Behavior, Thermal Fluid Flow

1. Introduction

Both plasma arc welding and laser welding are characterized as complex interactive effects of the plasma, keyhole and weld pool [1, 2], while the keyhole behaviors that have great influences on the thermal fluid flow are much different in these two welding processes.

In laser welding, the maximum temperature of the weld pool is higher than the boiling temperature of the material [3], so metal vaporization is strong, and the recoil pressure is very high [4]. A small keyhole with a large depth to width ratio generates [5]. The keyhole is very unstable, causing the irregular thermal fluid flow, and weld defects formation [6]. Besides, the laser plasma contains a lot of metal vapor with lower ionization energy and higher net radiative emission coefficient, so the laser plasma temperature decreases. Zhang el.al calculated the electron temperature of the laser keyhole plasma, and found that the value was only about 5720 K [7]. In plasma arc welding, the plasma arc pressure and arc shear stress are dominant forces for the large keyhole formation [8]. The plasma shear stress has a great influence on the fluid flow in the weld pool [9]. The keyhole is relatively stable. Besides, the fluid temperature at the keyhole wall is much lower than the boiling temperature of the material [9], so metal vaporization is very weak, and the plasma temperature is very high [10].

The keyhole behaviors and thermal fluid flow in low current plasma arc welding had been widely investigated [11]. It should be noted that in high current plasma arc welding, the keyhole behaviors and thermal fluid flow may have significant differences.

In high current case, the keyhole becomes large and unstable, and weld defects easily generate. Besides the weld pool temperature increases, and the metal vaporization may become strong.

In this study, a fully coupled plasma arc-keyhole-weld pool model was developed to investigate the keyhole behaviors and thermal fluid flow in high current plasma arc welding. The relationship between the forces distribution and fluid flow patterns was revealed. The energy propagation in the weld pool was analyzed.

2. Numerical model and numerical simulation

The computational domain including a tungsten electrode, a water cooling nozzle, a ceramic nozzle, plasma arc, a keyhole and base metal, is showed in Figure 1. The assumptions for the numerical model, the mass, momentum, energy, current, turbulence kinetic energy conservation equations, ohm’s law, vector potential and magnetic field equations can be seen from our previous study [1].

The energy and momentum boundary conditions are discussed. The additional energy flux including cathode thermionic energy loss, ion heating and radiation energy loss is considered at the cathode surface [12].

\[ H_c = -|j_e|\varphi_e + |j_i|V_i - \varepsilon_0 \alpha T^4 \]  

(1)

The additional energy flux including thermionic heating, and radiation energy loss is considered at the anode surface, [12].

\[ H_a = |j|\varphi_a - \varepsilon_0 \alpha T^4 \]  

(2)

where \(j_e\) is the electron current density, \(j_i\) is the ion current density, \(j\) is the current density at the anode surface, \(\varphi_e\) is the work function of the cathode, \(\varphi_a\) is the work function of the anode, \(V_i\) is the ionization potential of argon, \(\varepsilon_0\) is the surface radiation emissivity, \(\alpha\) is the Stefan-Boltzmann constant.
The principal forces for the fluid flow in the weld pool are arc pressure, Marangoni force, plasma shear stress, Lorentz force, and buoyancy force. The Lorentz force and buoyancy force are volumetric forces. The arc pressure, Marangoni force and plasma shear stress are surface forces which act on the weld pool surface.

On the keyhole wall, the pressure boundary can be shown as:

\[ P = P_{\text{arc}} - \frac{\gamma}{R} \]  

(3)

The momentum boundary of the weld pool surface at the tangential direction can be shown as:

\[ -\mu \frac{\partial n}{\partial n} = r_m + r_p \]  

(4)

The Marangoni force can be obtained as follow [13]:

\[ r_m = \frac{\partial \sigma}{\partial \theta} \]  

(5)

where \( P_{\text{arc}} \) is the arc pressure, \( \gamma \) is the surface tension, \( R \) is the keyhole radius, \( \mu \) is the fluid viscosity, \( v_t \) is the tangential fluid velocity, \( r_p \) is the plasma viscosity, \( v_p \) is the plasma velocity, \( S \) is the tangential vector, \( n \) is the normal vector.

In previous studies, the shear stress caused by the impingement of a jet on a flat surface was adopted to describe the arc shear stress distribution, [14]. In this study, the plasma shear stress can be calculated as follows:

\[ r_p = -\mu_p \frac{\partial v_p}{\partial n} \]  

(6)

where \( r_p \) is the plasma shear stress.

The energy and momentum boundary condition on the keyhole wall can be shown as:

\[ j = \beta e \]  

(2)

where \( j \) is the ion current density, \( \beta \) is the work function, \( e \) is the ion energy.

The energy and momentum boundary condition on the water cooling nozzle can be shown as:

\[ j = \beta e \]  

(2)

where \( j \) is the ion current density, \( \beta \) is the work function, \( e \) is the ion energy.

The energy propagation in the weld pool was analyzed.

3. Experimental method

The welding equipment including a transfer-type plasma arc welding torch (100WH, Nippon Steel Welding & Engineering Co., Ltd.) and a welding power source (NW-300ASR, Nippon Steel Welding & Engineering Co., Ltd.) was used in the welding experiments. The stainless steel SUS304 plates with the dimensions of 300 mm x 100 mm x 4 mm were used as the base metal. The distance between the water cooling nozzle and the base metal was 5.0 mm. A small water cooling nozzle with an orifice diameter of 2.0 mm was used. The electrode setback was 3.0 mm. The welding current was DC155 A, which was much larger than that in our previous study [1]. The welding speed was 3 mm/s. The pure Ar was used as the main plasma gas and shielding gas. For the main plasma gas, the flow rate was 1.7 l/min. For the shielding gas, the flow rate was 7.5 l/min.

4. Result and discussion

Figure 2 shows temperature distributions of the plasma arc and weld pool. It can be seen that owing to a constraint effect of the water cooling nozzle, the maximum plasma arc temperature can reach 29070 K. Inside the keyhole, the plasma arc is confined, and can’t expand freely.
arc mainly flows downward, and very few plasma arc flows upward along the keyhole wall. It can be seen that the plasma arc flows outward on the top surface of the weld pool.

![Image](https://example.com/image1)

**Fig. 3** Velocity distributions of the plasma arc and weld pool.

Figure 4 shows the weld pool convection in the three dimensional view. It can be seen that the molten metal mainly flows downward along the keyhole wall, so a dominant anti-clockwise eddy forms in the weld pool. At the rear part of the weld pool, the molten metal flows rearward, and a small clockwise eddy forms.

![Image](https://example.com/image2)

**Fig. 4** Convective patterns in the weld pool.

The plasma shear stress distributions in the x, y, z directions are showed in Figure 5. In the x direction, the plasma shear stress is negative at the top part of the front keyhole wall, and positive at the bottom part of the front keyhole wall and rear keyhole wall. In the y direction, the plasma shear stress is positive. In the z direction, the plasma shear stress is mainly downward. Only on the top weld pool surface, the plasma shear stress is outward.

![Image](https://example.com/image3)

**Fig. 5** The shear stress distributions at the keyhole wall.

The plasma arc pressure is transformed into volume force. As shown in Figure 6, in the x direction, the plasma arc pressure is negative at the front keyhole wall, and positive at the rear keyhole wall. In the y direction, the plasma arc pressure is positive. In the z direction, the plasma arc pressure is negative at the front keyhole wall and top part of the rear keyhole wall, and positive at the bottom part of the rear keyhole wall.

![Image](https://example.com/image4)

**Fig. 6** The arc pressure volume force distributions at the keyhole wall.
In summary, the dominant downward plasma shear stress and negative arc pressure in the z direction cause the dominant anti-clockwise eddy in the weld pool. The outward plasma arc shear stress on the top weld pool surface causes the small clockwise eddy in the weld pool.

It can be seen from Figure 7 that owing to the large arc pressure and shear stress, a large keyhole forms in the weld pool. The energy is not concentrated at the keyhole wall, and the weld pool temperature is relatively low. The maximum weld pool temperature is only $2140 \text{ K}$.

**Fig. 7** The weld pool temperature distribution.

As discussed in our previous study, energy convection by the fluid flow is the dominant mechanism for energy propagation in the weld pool in keyhole plasma arc welding [8]. The strong anti-clockwise eddy inside the weld pool, and the weak backward flow on the top surface lead to uneven energy distribution between the top and bottom surfaces, which causes the weld defects formation [11]. In high current plasma arc welding, a dominant anti-clockwise eddy also forms in the weld pool. The molten metal flows downward and inward near the rear keyhole wall, which facilitates the weld defects formation.

5. Conclusions

A fully coupled plasma arc-keyhole-weld pool model was developed to investigate the keyhole behaviors and thermal fluid flow in high current plasma arc welding. The additional energy flux including cathode thermionic cooling, ion heating, conduction energy and radiation cooling was considered at the energy boundary conditions. Five principal forces (arc pressure, Marangoni force, plasma shear stress, Lorentz force, and buoyancy force) for the fluid flow in the weld pool were considered at the momentum boundary conditions.

In high current plasma arc welding, inside the keyhole, the dominant downward plasma shear stress and negative arc pressure in the z direction cause a dominant anti-clockwise eddy in the weld pool. The outward plasma arc shear stress on the top weld pool surface causes a small clockwise eddy in the weld pool.

**Acknowledgements**

The authors thank the China Scholarship Council for providing a scholarship.

**Reference**

1) Wu, D., Tashiro, S., Hua, X., & Tanaka, M. (2019). Analysis of the energy propagation in the keyhole plasma arc welding using a novel fully coupled plasma arc-keyhole-weld pool model. International Journal of Heat and Mass Transfer, 141, 604-614.

2) Wu, D., Hua, X., Ye, Y., Huang, L., Li, F., & Huang, Y. (2018). Experimental and numerical study of spatter formation and composition change in fiber laser welding of aluminum alloy. Journal of Physics D: Applied Physics, 51(18), 185604.

3) Wu, D., Hua, X., Li, F., & Huang, L. (2017). Understanding of spatter formation in fiber laser welding of 5083 aluminum alloy. International Journal of Heat and Mass Transfer, 113, 730-740.

4) Qiu, C., Panwisawas, C., Ward, M., Basoalto, H. C., Brooks, J. W., & Attallah, M. M. (2015). On the role of melt flow into the surface structure and porosity development during selective laser melting. Acta Materialia, 96, 72-79.

5) Wu, D., Hua, X., Huang, L., Li, F., & Cai, Y. (2019). Observation of the keyhole behavior, spatter, and keyhole-induced bubble formation in laser welding of a steel/glass sandwich. Welding in the World, 63(3), 815-823.

6) Wu, D., Hua, X., Huang, L., Li, F., & Cai, Y. (2018). Elucidation of keyhole induced bubble formation mechanism in fiber laser welding of low carbon steel. International Journal of Heat and Mass Transfer, 127, 1077-1086.

7) Zhang, M., Chen, G., Zhou, Y., & Li, S. (2013). Direct observation of keyhole characteristics in deep penetration laser welding with a 10 kW fiber laser. Optics express, 21(17), 19997-20004.

8) Wu, D., Van Nguyen, A., Tashiro, S., Hua, X., & Tanaka, M. (2019). Elucidation of the weld pool convection and keyhole formation mechanism in the keyhole plasma arc welding. International Journal of Heat and Mass Transfer, 131, 920-931.

9) Wu, D., Tashiro, S., Hua, X., & Tanaka, M. (2019). A novel electrode-arc-weld pool model for studying the keyhole formation in the keyhole plasma arc welding process. Journal of Physics D: Applied Physics.

10) Jian X, Wu C. influence of Fe vapor on weld pool behavior of plasma arc welding [J]. Acta Metallurgica Sinica, 2016, 52(11):1467-1476.

11) Nguyen, A. V., Wu, D., Tashiro, S., & Tanaka, M. (2019). Undercut Formation Mechanism in Keyhole Plasma Arc Welding. Welding Journal.

12) Tanaka, M., Yamamoto, K., Tashiro, S., Nakata, K., Yamamoto, E., Yamazaki, K., Lowke, J. J. (2010). Time-dependent calculations of molten pool formation and thermal plasma with metal vapour in gas tungsten arc welding. Journal of Physics D: Applied Physics, 43(43), 434009.

13) Tanaka, M., Ushio, M., & Lowke, J. J. (2004). Numerical study of gas tungsten arc plasma with anode melting. Vacuum, 73(3), 381-389.

14) Cheon, J., Kiran, D. V., & Na, S. J. (2016). Thermal metallurgical analysis of GMA welded AH36 steel using CFD–FEM framework. Materials & Design, 91, 230-241.