

Numerical analysis for weld pool of pulsed TIG welding *

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Abstract A two-dimensional axisymmetric mathematical model of weld pool of pulsed TIG welding was established. Numerical simulation for weld pool of pulsed TIG welding was done using FLUENT software by selecting the appropriate boundary conditions and strongly coupled control equations. The distributions of temperature field and flow field of weld pool under the periodic change of welding current were obtained. According to the maximum temperature of upper and lower surface of workpiece and depth and width of weld pool, the distributions of temperature field and flow field under different pulsed frequencies and current duty cycles were obtained and periodic variation was analyzed under pulsed current. The analysis results show that with the increase of pulsed frequency, weld pool width increases slightly while depth decreases slightly, and with the increase of current duty cycle, the width and depth of weld pool both increase significantly, and the depth increases greatly.

Key words pulsed TIG welding, weld pool, numerical simulation, FLUENT

0 Introduction

As the welding process refers to heat conduction, convection, evaporation, radiation, physical and chemical processes such as melting and solidification, and the flow of the liquid metal of weld pool also strongly influences the geometry of weld seam and properties of welded joints, through experimental methods to observe the flow of liquid metal is very difficult. Therefore, to analyze the flow and heat transfer of weld pool by numerical simulation method is a feasible approach. As to build numerical modeling for weld pool and analyze it, adopting constant current, the studies on two-dimensional^[1], three-dimensional transient model^[2], influence of active elements to weld pool^[3-4] and mechanism of increasing welding penetration with A-TIG welding were carried out by domestic and foreign researchers^[5].

In recent years, pulsed TIG welding has been increasingly widely used. Compared with the constant current TIG welding, pulsed TIG welding has many advantages such as stable arc, low heat input, easily and precise-

ly to control the energy distribution and helpfully to obtain refined weld seam. The pulsed TIG welding process is non-steady state, and the flow field and thermal field are more complex than constant current TIG welding, so the research on pulsed TIG welding is still not enough. Wu Chuansong et al^[6-8] obtained the flow field and temperature field of weld pool during pulsed TIG welding process through numerical simulation and the variation analysis. To further study pulsed TIG welding, it is necessary to consider the influence of pulsed frequency and current duty cycle to weld pool.

In this paper, on the basis of existed numerical analysis for constant current TIG welding, a mathematical model about flow and heat transfer of non-steady weld pool in pulsed TIG welding process was established using software FLUENT. The distributions of temperature field and flow field were obtained under pulsed current, and the influence of variations of pulsed frequency and current duty cycle were also analyzed.

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1 Mathematical model

1.1 Basic assumptions

Numerical model of weld pool is shown in Fig. 1. In the calculation, assumptions were made for weld pool as follows: free surface of weld pool was a plane, distributions of heat flux density and current density of arc were Gaussian distribution, the liquid metal was laminar flow and incompressible fluid, processing method of buoyancy was Boussinesq assumptions and flow and heat transfer of weld pool were axisymmetric.

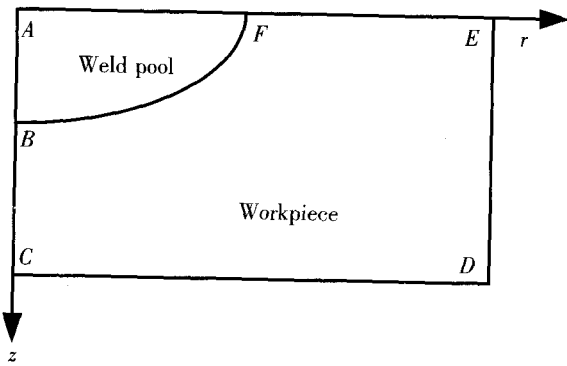


Fig. 1 Numerical model of weld pool

1.2 Governing equations

According to the above assumptions, the following equations can be obtained from the mass, momentum and energy conservation equations with axis coordinate system. Continuity equation;

$$\frac{1}{r} \frac{\partial(ru)}{\partial r} + \frac{\partial v}{\partial z} = 0 \quad (1)$$

Momentum conservation equation in radial direction;

$$\rho \left(u \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial r} + \mu \left(\frac{\partial^2 u}{\partial r^2} + \frac{\partial u}{r \partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2} \right) + S_r \quad (2)$$

Momentum conservation equation in axial direction;

$$\rho \left(u \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial z} \right) = - \frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 v}{\partial r^2} + \frac{\partial v}{r \partial r} + \frac{\partial^2 v}{\partial z^2} \right) + S_z \quad (3)$$

Energy conservation equation;

$$\rho c_p \left(u \frac{\partial T}{\partial r} + v \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial r} \left(\lambda r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + \Delta H \quad (4)$$

In equation (1) - (4), ρ is density, u and v are the speed in r and z direction respectively, S_r and S_z are momentum source terms in r and z direction respectively, λ is thermal conductivity, p is pressure and ΔH is latent heat of fusion.

1.3 Source term of control equations

The volume force of weld pool in TIG welding consists mainly of buoyancy, surface tension and electromagnetic force. And the source terms as follows:

Buoyancy;

$$G = -\rho g \beta (T - T_0) \quad (5)$$

For the electromagnetic force suffered by weld pool, the formula is;

$$\vec{F} = \vec{J} \times \vec{B} \quad (6)$$

Where radial electromagnetic force is;

$$F_r = - \frac{\mu_m I^2}{4\pi^2 \sigma_j^2} \exp\left(-\frac{r^2}{2\sigma_j^2}\right) \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right] \left(\frac{z}{z_l}\right)^2 \quad (7)$$

Axial electromagnetic force is;

$$F_z = \frac{\mu_m I^2}{4\pi^2 r^2 z_l} \left[1 - \exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right]^2 \left(\frac{z}{z_l}\right) \quad (8)$$

The surface tension of weld pool is provided by surface

tension gradient (Marangoni force) and is parallel to the viscous shear force of surface fluid;

$$\mu \frac{\partial u}{\partial z} = - \frac{\partial \gamma}{\partial T} \times \frac{\partial T}{\partial z} \quad (9)$$

Where the left part is the viscous shear force of surface fluid and the right is Marangoni force.

In equation (5) – (9), β is expansion coefficient, σ_j is current distribution parameter and μ_m is vacuum permeability.

1.4 Boundary conditions

The upper surface AE can be divided into pool surface AF and non-pool surface FE , for pool surface AF :

$$k \left(\frac{\partial T}{\partial z} \right) = q_{\text{arc}} - a_c (T - T_a) - \varepsilon \sigma_b (T^4 - T_a^4) - \omega H_v \quad (10)$$

$$\frac{\partial u}{\partial z} = v = 0 \quad (11)$$

In equation (11), the right part contains thermal generation by arc and heat loss by convection, radiation and evaporation. Where the input heat from arc is:

$$q_{\text{arc}} = \frac{3\eta UI}{\pi \sigma_q^2} \exp\left(-\frac{3r^2}{\sigma_q^2}\right) \quad (12)$$

On the boundary FE :

$$-k \left(\frac{\partial T}{\partial z} \right) = a_c (T - T_0) + \varepsilon \sigma_b (T^4 - T_a^4) \quad (13)$$

$$u = v = 0 \quad (14)$$

On lower surface CD and side face DE , the constraint equations are:

$$-k \left(\frac{\partial T}{\partial n} \right) = a_c (T - T_0) + \varepsilon \sigma_b (T^4 - T_a^4) \quad (15)$$

$$u = v = 0 \quad (16)$$

On the axis line AC , the constraint equations are:

$$\frac{\partial T}{\partial r} = 0 \quad (17)$$

$$u = \frac{\partial v}{\partial r} = 0 \quad (18)$$

In equation (10) – (18), a_c is heat transfer coefficient, ε is radiation coefficient and ω is evaporation coefficient.

2 Numerical simulation

Simulation analysis was carried out with FLUENT software. Mathematical model was built for low carbon steel plate using processing software GAMBIT and mesh generator. In the model, thickness of plate was 4 mm and length was 20 mm. In the solution process, the time step was 0.001 s and the simulated welding time was 8.0 s.

Numerical simulations for weld pool of TIG welding were carried out based on the mathematical model. The thermal parameters were got from the literature [9]. Welding current adopted DC square wave pulse, $I_p = 140$ A, $I_b = 40$ A, and welding voltage $U = 16$ V, and the change of the pulse in 8.0 s was simulated using FLUENT software.

Change of fusion line in 8.0 s is shown in Fig. 2. Fig. 2a shows the change of fusion line when welding current is kept in 90 A and the interval of each two curves is 1 s. Fig. 2b shows the change of fusion line when pulsed frequency is 1 Hz under pulsed current and the interval of each two curves is 0.5 s (Dotted lines indicate that it is at the moment of base current while solid lines indicate it is at the moment of peak current time). As can be obtained from the Fig. 2, width and depth of weld pool increase under the condition of constant current. Under the condition of pulsed current, width of weld pool increases while depth of weld pool decreases to a certain extent.

Fig. 3 shows the typical flow field under the conditions of constant current and pulsed current respectively. Change of flow field of weld pool in 7 s is illustrated in Fig. 3a when welding current is kept in 90 A and change of flow field in a pulsed period is shown in Fig. 3b when

pulsed frequency is 1 Hz. The flow field consists of two parts, as shown in Fig. 3. Temperature gradient of surface tension resulted in clockwise flow of the molten metal in the upper pool, and electromagnetic force resulted in counterclockwise flow of the molten metal in lower pool. The counterclockwise flow was not obvious when adopting pulsed current.

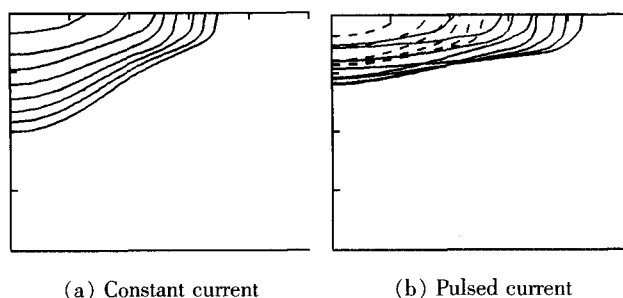


Fig. 2 Change of fusion line

3 Simulation results and analysis

3.1 Influences of different pulsed frequencies

The maximum temperature curves of upper and lower surface of workpiece are shown in Fig. 4 when pulsed frequency is 0.5 Hz, 1 Hz, and 5 Hz respectively and duty

cycle is 50%. From the Fig. 4, it can be obtained that the temperature of workpiece changes periodically with the periodic change of pulsed current. Judging from the overall trend, the temperature gradually increases but the rising trend is slow. At the beginning, the temperature increase of upper surface was relatively fast. However, with the continuation of welding, the temperature increase of lower surface was faster. The maximum temperature of upper surface of workpiece increased greatly during the peak current time while it decreased quickly during the base current time. The temperature sensitivity of upper surface of pulsed current was stronger than that of the lower surface. Considering the influence of latent heat of fusion and evaporative heat in the numerical calculation, the maximum temperature was obtained about 2 400 K finally. From Fig. 4, the maximum temperature of lower surface rises and falls periodically when pulsed frequency is 0.5 Hz under the action of pulsed current. When the pulsed frequency is 1 Hz or 5 Hz, the maximum temperature of lower surface has no decline in one cycle but increases slowly during base current time. With the increase of pulsed frequency, the decline trend is increasingly obvious.

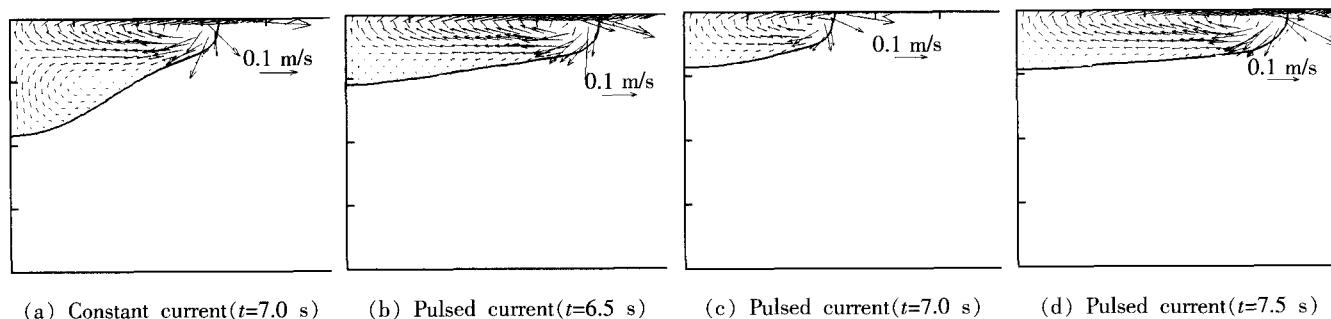


Fig. 3 Change of flow field of weld pool

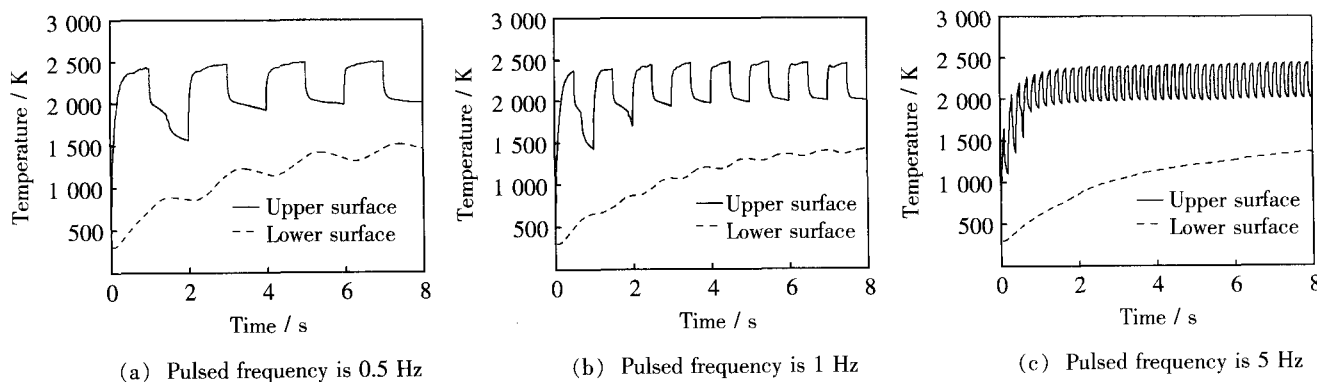


Fig. 4 Maximum temperature curves of workpiece surface at different pulse frequencies

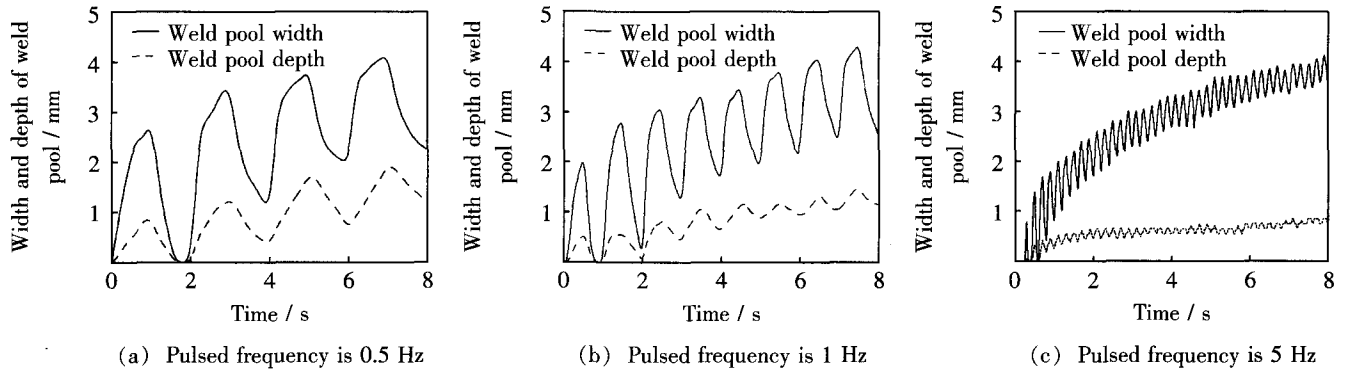


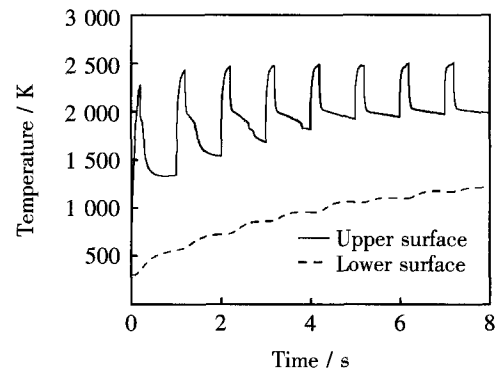
Fig.5 Curves of depth and width of weld pool at different pulse frequencies

The curves of width and depth of weld pool at different pulsed frequencies are shown in Fig. 5. From Fig. 5, it can be obtained that the width and depth of weld pool both increase gradually at peak current time. At base current time, the width and depth of weld pool decreased gradually and the change of weld pool was relatively large. Overall, at the beginning of welding, width and depth of weld pool were gradually increasing and the increase rate of weld pool width was larger. With the continuation of welding, the increase rate decreased and the change of width and depth of weld pool also decreased in each pulsed cycle. In Fig. 5, as the increase of pulsed frequency, the melting and solidification frequency of workpiece surface are growing, so that the change range of weld pool width in one cycle decreases gradually and the average length of the weld pool width increases while the average length of depth decreases. Due to the electromagnetic force affected by the welding current, when pulsed frequency was low, the time of peak current was relatively long in one cycle. Therefore heat accumulation of weld pool was large and action time of electromagnetic force was long in this period time so that the increase of weld pool depth was large. On the contrary, the decrease of weld pool depth was also large at base current time. As the increase of pulsed frequency, the change of weld pool depth was small. Therefore, the size of weld pool can be controlled effectively by changing pulsed frequency.

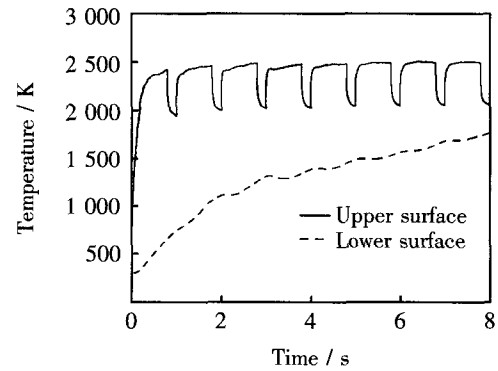
3.2 Influences of different current duty cycles

The maximum temperature curves of upper and lower surface of the workpiece are shown in Fig. 6 when pulsed frequency is 1 Hz and current duty cycle is 20% and 80%

respectively. It can be obtained from Fig. 6 that the temperature of the workpiece surface changes periodically with the variation of the pulsed current. Considering the influence of latent heat of fusion and evaporative heat, the maximum temperature of the upper surface reaches a relatively fixed range of 2 400 K. It can be obtained from



(a) Duty cycle is 20%



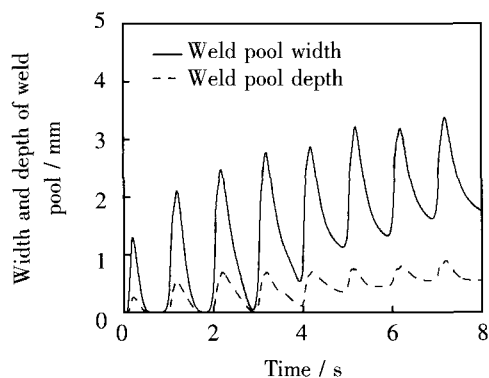
(b) Duty cycle is 80%

Fig.6 Maximum temperature curves of workpiece surface under different duty cycles

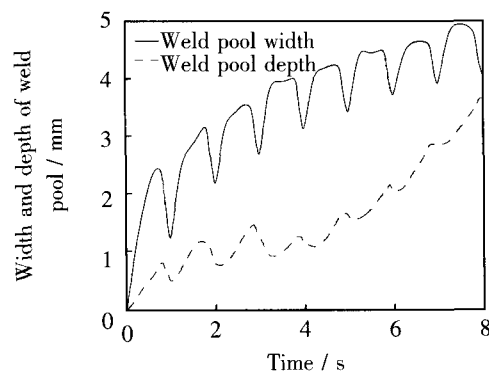
Fig. 6 and Fig. 4b that the change of current duty cycle results in the variation of heat input directly. With the in-

crease of current duty cycle, the accumulation of heat in workpiece increases gradually, which leads to the maximum temperature of lower surface of the workpiece greatly increase finally.

The curves of width and depth of weld pool are shown in Fig. 7 when welding frequency is 1 Hz and duty cycle is 20% and 80% respectively. As the current duty cycle increased, the heat input of the workpiece surface became larger, which led to a larger weld pool width, as shown in Fig. 7 and Fig. 5b. With the increase of duty cycle, the heat accumulation in weld pool became increasing, and the action time of electromagnetic force became longer, which eventually led to a significant increase of weld pool depth. The increase rate of weld pool depth was larger than that of weld pool width. Therefore, the variation of width and depth of weld pool can be effectively controlled by changing the duty cycle.



(a) Duty cycle is 20%



(b) Duty cycle is 80%

Fig. 7 Curves of width and depth of weld pool under different duty cycles

4 Conclusions

(1) A two-dimensional numerical model of weld pool

of pulsed TIG welding was established and numerical analysis was carried out for weld pool at different pulsed frequencies and different current duty cycles.

(2) With the periodic change of pulsed current, temperature filed and flow field change periodically, and these lead to the temperature of workpiece. Weld pool width and depth also change periodically at different pulsed frequencies and different current duty cycles.

(3) Overall, with the increase of pulsed frequency, the weld pool width increases while depth decreases and the change range is not large. With the increase of current duty cycle, width and depth of weld pool both increase greatly and the change of weld pool is relatively larger.

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