High accuracy Numerical simulation on 3D weld-pool shape of large parts

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Abstract. The shape of weld pool and the distribution function of heat source are the premise and foundation of all welding simulations, but many assumptions are given to them which lead to different or even contradictory results. So the model of three-dimensional weld pool should be established without predetermining the shape of weld pool, the shape of free surface and the distribution of heat flux density, moreover it is combined with the thermal model. Through decoupling, the fluid velocity field, the temperature contour and the law of temperature distribution of the weld pool are obtained, the shape of molten pool is also gotten out which is like a revolving body of the pen holder, and the density function of heat flux distribution is fitted out. The internal relationship between simulation results and weld fusion line are presented. Welding experiments of large parts are carried out under the same process conditions. It shows the weld fusion line and the shape of the surface of the weld are in good agreement with the simulation results. This has great practical significance for unifying simulation results, guiding production and improving quality of large welding parts.

1. Preface
Construction machinery mainly includes shovel, transport machinery, lifting, pumping, pile and road machinery, etc. The sales have maintained growth at nearly 100\% every year. But the situation of construction machinery manufacturing industry in our country is severe, especially the skeleton of construction machinery such as manipulator arm, bucket and other large structural parts is lagging behind by backwardness of welding technology, and led to second-class product, poor quality and reliability. So the overall performance of construction machinery is extremely unfavorable. The following is the super long arm of the EX230 excavator, shown in Figure 1.

Fig 1. EX230 super long arm of excavator
The first quality control of large-scale structure welding parts is carried out in the stage of product design. Secondly, the numerical simulation method combining physical test is often used to predict
and control the deformation of large-scale structure welding parts. The simulation need heat source density distribution, but the premise of heat source density distribution is the molten pool shape.

By now, the widely used heat source model is the Gauss model [1] which can be classified into planar heat source and volume heat source according to their different modes of actions [2], it can also be divided into ellipsoid heat source and double ellipsoid heat source according to the heat density distribution. But the result of simulation is not consistent with the actual weld fusion line well [3]. Particularly in the thick plate welding, the simulation shows that temperature is too high in part [4].

In order to make use of the advantages of the both kinds of heat sources, modern welding simulation is mostly using the combined heat sources model. We combine the two kinds of heat sources by adjusting the ratio artificially to fit the actual welding Cross section shape [5]. And it has significance in the application of middle or thick plate welding [6]. But when the welding conditions change, some adjustments should be made to the combined heat sources, otherwise there will lead to large deviations. So it is very necessary to study the pool shape and heat source distribution function. However, the research in this area is few, and mostly focuses on the two-dimensional flow and temperature fields [7]. In order to study the pool shape and heat source in large parts welding, the super-long arm of EX230 excavator is taken as the engineering background. Model of weld pool is established on hydrodynamics, together with the surface control equation and heat convection transfer equation to study the three-dimensional static weld pool shape and heat flux distribution function. Through large calculation, we get laws for production guidance.

2. Model building
We does not specify the shape of molten pool, the shape of free surface, or the heat flux distribution function in advance to avoid the deviation by presuppositions.

Free surface control equation [8].

\[ P_{ac} - \rho g \Phi + C_2 = -\gamma \left( 1 + \Phi_x^2 \right) \Phi_{xy} - 2\Phi_x \Phi_y \Phi_{x} + \left( 1 + \Phi_y^2 \right) \Phi_{yy} \]

\[ \left( 1 + \Phi_x^2 + \Phi_y^2 \right)^{3/2} \]

(1)

\( \Phi \) surface shape function, \( \Phi_x, \Phi_y \) is the first-order partial derivative of the shape function to \( x, y \), \( \Phi_{xx}, \Phi_{yy} \) is the second-order partial derivative of the shape function to \( x, y \), \( \Phi_{xy} \) is the second-order mixed partial derivative of the shape function to \( x, y \), \( C_2 \) undetermined constant, \( \gamma \) surface pressure, \( P_{ac} \) arc pressure. The method of solution refers to literature 9.

Incompressible continuous equation.

\[ \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \]

(2)

When homogeneous fluid is incompressible, \( \rho = \text{const} \).

N-S equation is

\[ \frac{du_x}{dt} = X - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \]

\[ \frac{du_y}{dt} = Y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right) \]

\[ \frac{du_z}{dt} = Z - \frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left( \frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right) \]

(3)
When fluid is incompressible with constant physical properties and no internal heat, convection-conduction equation is

\[
\frac{\partial t}{\partial \tau} + u_x \frac{\partial t}{\partial x} + u_y \frac{\partial t}{\partial y} + u_z \frac{\partial t}{\partial z} = \alpha \nabla^2 t
\]

\[
= \alpha \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right)
\]

(4)

3. Calculation and results

The calculation model is shown in Figure 2, and length, width and height of cube are all 10mm. The calculation initial conditions boundary conditions are as follows: structure steel material is 16Mn, physical property parameters are shown in table 1, the surface arc acts over is a circle area with 2.5mm radius, the temperature on the circle is 6000°C, and pressure is 200pa (gauge pressure), the other surface temperature is 300°C, acting pressure is 0 pa (gauge pressure), just under the pressure of atmosphere. Flow chart of the calculation program is shown in Figure 3.

![Figure 2. calculation model](image)

The basic parameters are shown in follow table [10]

| Table 1. Fluid basic physical parameters |
|-----------------------------------------|
| Item value unit                | Value | Unit |
| Density (solid phase)          | 7600  | kg/m³ |
| Density (liquid phase)         | 7200  | kg/m³ |
| Latent heat of solidification  | 300   | kj/kg |
| Heat capacity (solid phase)    | 680   | J/(kg.ºC) |
| Heat capacity (liquid phase)   | 840   | J/(kg.ºC) |
| The thermal conductivity       | 22    | W/(m.ºC) |
| Melting point (solid phase)    | 1431  | ºC   |
| Melting point (liquid phase)   | 1512  | ºC   |
| Viscosity                     | 0.006 | Pa.s |
Figure 3. Flow chart of calculation program

Through decoupling, simulation result is obtained as following.

Figure 4. X=5mm section velocity vector diagram
Figure 5. X=5mm section velocity cloud picture

Figure 6. X=5mm section temperature cloud picture

Figure 7. X=5mm section pressure cloud picture
4. simulation analysis
The temperature is positively associated to the velocity and flowing direction of fluid. The higher the velocity of flow, the higher the temperature; the slower the velocity of flow, the smaller fluid obtained the energy. Due to the flow of fluid at the bottom is restricted by the high pressure, the downward velocity is little, the upper part of the fluid is open without any restrict, the upward velocity is large. The direction of the edge fluid first flow downwards and then upwards under the high welding pressure,. Therefore, the true shape of the heat source is not an ellipsoid, but a rotating body of a pen holder. While closer to the rotator center, the high temperature layer is thicker and higher; the farther away from the center, the temperature layer is thinner and lower, then thicker the higher again, finally disappears steeply, as shown in Figure 8. With the filling of welding material, the position of weld pool increases taller gradually, and the edge of weld pool will not restrict the pool. When weld pool rises, the top surface of weld pool becomes ellipsoid under gravity operation without supporting solids around the weld pool gradually, as shown in Figure 9. Meanwhile, the simulation shows the shape of weld pool is smaller than the weld section, that is to say, the weld section is not formed by melting-solidification at one time, but melting-solidification repeatedly. So the weld section is formed layer by layer. The shape of the weld section connecting line we usually see is a envelope formed by weld pool overlapping layer by layer, as shown in Figure 10. The welding seam is formed by the superposition of the envelope line of the weld pool in the welding direction, as shown in Figure. 11.

Fig. 8. Heat source section

Figure 9. Heat source section over solid surface.

A Section superposition graph

B Superposition graph with envelope
According to the simulation results, as shown in Figures 12 and 13, the heat flux equation of 16Mn steel welding can be fitted out as following equation:
\[
q(x, y, z) = \frac{10Q}{\pi r_0^2 d} \left( d_0 \right)^2 \left( \frac{25(x^2 + y^2)}{8r_0^2} \left( \frac{z}{z_0} \right)^{10.23} \right) + 3 \exp \left( 100 \cdot \frac{z^2}{z_0^2} - 1 \right)
\]

Here, \( r_0 \) is arc radius, \( z_0 \) the distance between the arc acting surface and the ground, \( x, y, z \) is the coordinates of the points in the model, \( d_0 \) is the arc diameter, and \( d \) is the diameter of the horizontal circle with its point in the model while the center on the central axis.

5. experimental and verification

Referred to the crane girde manufacturing process conditions of large parts, 16Mn steel with thickness 10mm is used as shown in Figure 14. The surface is treated with wire brush for simple rust removal, then welded by manual arc on the seamless board. The welding rod is J422, the current is 110A, and the voltage is 60V. The welding section photographs are compared with the simulation results in Figure 15, showing a high degree of coincidence.

Figure 14. welding steel plate

Figure 15. Comparison of weld photograph and simulation results on seamless board

6. conclusion

(1) Two-dimensional model of molten pool with hypothetical conditions has inherent defects in accuracy. In order to make up for its shortcomings, a three-dimensional static mathematical model of molten pool based on hydrodynamics coupling with heat convection conduction equation is established, which has clear physical meaning and can improve the accuracy of welding analysis.

(2) The weld pool shape obtained by decoupling is a penholder-shaped rotating body, and the size of the weld pool is obviously smaller than that of the actual weld section, which indicates that the actual weld section is formed by multiple melting-solidification of the weld pool.

(3) The heat source density is wavy distribution in the horizontal plane and decreasing distribution in the direction of symmetry line. By analyzing the simulated data, a new heat flux equation of molten pool is fitted out, which provides a reference tool for the analysis of temperature field and stress field of large welding parts.

(4) A welding verification on seamless 16Mn plate under the same welding conditions indicates the experiment is in good agreement with the simulation. The model reflects the basic characteristics of large workpiece welding.

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