ABSTRACT

The heat transfer control equations of steel pillar girth weld in architectural engineering is obtained according to the analytical method, which is discretized by using Taylor series expansion method, and the one dimensional weld welding thermal cycle characteristics of different node are analyzed. Based on the software ABAQUS, the weld joint thermodynamic properties are obtained by thermal-mechanical coupling numerical simulation, including the field variables and process the output characteristics, of which results shows that the joint change trend of strain and temperature are consistent and the stress yield phenomenon is obvious under the effect of heat flux of continuous welding, while the residual stress is large, temperature falls and strain remains during the free cooling stage.¹

INTRODUCTION

Steel pillar is one of the most important supporting component in architectural engineering. As one of the most important processing technology for steel pillar, welding has obvious advantages, such as simple construction, good versatility and high machining efficiency. But under the influence of high temperature, welding parts are easy to produce larger thermal deformation and thermal stress[1], as a result, there is some ineluctable bad influence on the joint strength, life and reliability, etc. Welding thermodynamics calculation is the key for welding deformation and residual thermal stress evaluation [2]. For the research status, Bachorski [3] calculated welding deformation with volume shrinkage algorithm, Mato [4] analyzed the thermal stress for a specific welding

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defects, Peng Gui[5] studied the relationship between the process parameters and welding deformation, etc. In order to improve the convergence of the calculation, many research scholars use indirect algorithm. However, welding temperature field and stress field belongs to the fully coupling relationship, indirect calculation method has a certain error. In order to improve the calculation accuracy, girth weld of thermodynamics are researched based on the thermal-mechanical coupling numerical simulation method for the transient temperature field and stress field in welding process.

Analytical Method of Welding Temperature Field

HEAT TRANSFER CONTROL EQUATION

In one dimension, the welding heat transfer process can be described by the control Eq. (1) based on the analytical method [6], which is composed of the following four parts: the unsteady term, the convection term, the diffusion term and the source term.

$$\rho \frac{\partial \phi}{\partial \tau} + \rho u \frac{\partial \phi}{\partial x} = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial \phi}{\partial x} \right) + S$$

(1)

Where $\phi$ is a generalized variable, $\rho$ is the density of the material, $\tau$ is time, $u$ is air velocity; $c$ is the specific heat of welding, $S$ is the welding heat source for heat flux, $\Gamma$ is generalized heat transfer coefficient.

In order to represent the equilibrium relationship between the heat supply and the conduction and dissipation energy of the welding heat source, the governing equations of heat transfer in the three-dimensional space Oxyz can be deduced according to the one-dimensional governing equation and the energy conservation principle as follows:

$$\frac{\partial T}{\partial \tau} = \frac{\lambda}{\rho c} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{1}{\rho c} \frac{\partial Q_v}{\partial \tau}$$

(2)

Where $T$ is the temperature, $\lambda$ is the thermal conductivity, $Q_v$ is the energy dissipation of the unit volume. It is necessary to use the analytical method to solve the governing equations of heat transfer, for example, the physical parameters are independent of the temperature, and the initial temperature of the weld is uniform and continuous.

THERMAL CYCLING ANALYSIS

The welding heat source is regarded as a spherical surface with isothermal conditions. Assume that the heat $Q$ at the initial moment began to conduction in the three-dimensional direction, after time of $t$, the distance from the heat source center $R$ ($R^2=x^2+y^2+z^2$) of the node temperature is $T$. At this point, the special solution of heat transfer control equation (2) is as follows:
The temperature gradient in the $x$ direction can be calculated as follows:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\partial}{\partial x} \left( \frac{\partial T}{\partial x} \right) = \frac{\partial}{\partial x} \left( -T \frac{x}{2\Delta t} \right) = -\frac{T}{2\Delta t} \frac{x}{2\Delta t} \left( -T \frac{x}{2\Delta t} \right) = \frac{T}{2\Delta t} \left( \frac{x^2}{2\Delta t} - 1 \right)$$

(4)

Because of the existence of the two order partial derivative, the direct solution of the formula (4) is more difficult, so the equation can be discretized, and the analytical solution of the discrete equation can be obtained by the iterative algorithm. There are four kinds of common methods: Taylor (Taylor) series expansion method, polynomial fitting method, and control volume integral method, balance method, etc.

Through the MATLAB programming, the thermal cycle characteristics can be solved in different $x$ position as shown in Fig.1. According to the TIG welding method, set the heat source line energy is 1600 J/cm, the heat source speed is 2mm/s. It can be seen from Fig.1 that the location of the heat source is close to the heat source, and the temperature of the weld is larger.

![Figure 1. Thermal cycling at different nodes.](image)

According to the relationship between the stress components and the physical components of the welded joints under thermal cycling, the equilibrium differential equation of the stress field can be derived. In solving the stress field, deformation due to thermal components as the basic unknown functions, according to the boundary conditions and loads to determine the stress function, and then through the derivation of stress function results of requirements to verify the compatibility equation. The compatibility equation can be expressed in two-dimensional planar $Oxy$ as follows:

$$\left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \left( \sigma_x + \sigma_y \right) = 0$$

(5)
Where $\sigma_x$ and $\sigma_y$ are respectively principal stress in x and y direction.

**Numerical Simulation of Thermo Mechanical Coupling**

**MODEL ESTABLISHMENT AND PRETREATMENT**

Welding belongs to complex thermal-structure coupling process, which is difficult to express the complete thermodynamic characteristics with the analytical method. Numerical simulation is an effective method for the study of the phenomenon of welding. Through the establishment of the model and the boundary conditions, the numerical simulation based on software ABAQUS can be used to predict the welding deformation, which has great significance for the optimization of welding process. The structure of the steel pillar joint schematic is shown in Fig.2 (a), it can be seen that in the end of the outer pillar through hoops in the shoulder, the welding position is on the left end of the steel hoop. The three-dimensional model of joint is established in ABAQUS, using the C3D8T unit hexahedron mesh for temperature and displacement coupling, as shown in Fig.2 (b), which can achieve to solve field variable output.

![Figure 2. The diagram of the pillar model.](image)

Before the primary processing model, the pretreatment is needed to set as follows: Set analysis type as transient temperature-displacement coupling analysis, with the total length of time is 180 s and the load step is 0.005 s, considering the nonlinear factors such as swelling and creep; Set the contact type for the butt joint surface as "hard contact", considering the effect of heat radiation in the welding process; Set the definition of initial conditions and model materials property, etc.

The joint material is 30CrMoSi, which has normalizing and tempering heat treatment before the welding. In order to improve the accuracy of calculation, according to the metal material Handbook, the material characteristics of different temperature conditions are introduced into the model.
RESULT ANALYSIS

The characteristics of transient field variables can be obtained by continuous iteration. In this paper, the transient temperature field, the stress field and the displacement (deformation) of the 104 s moment are extracted, as shown in Fig.3. From Fig.3, it can be seen that due to the 100s time to stop the heat input, the temperature field presents uniform distribution trend. The maximum stress contact position located in the outer end surface of the pillar and steel hoop in the shoulder, it because that the outer end surface of the pillar is free for expansion of steel in the shoulder limit. The stress concentration occurs the maximum deformation position, near the weld zone, due to the position of continuous high temperature and long time. In order to improve hoop rigidity and reduce the amount of deformation, the method of displacement constraint can be carried out.

In software ABAQUS, it can be obtained through the process output results that the thermodynamic parameters of any node change with time. Any node of the outside and inside the shaft shoulder end surface of the pillar through contact as the analysis object. The node temperature (T) - strain (ε) – time (t) curve is shown in Fig.4 (a), and the stress (s) – displacement (L) - time (t) curve is shows in Fig.4 (b). As we can know from Fig.4, before the heat input is stop, the strain, displacement and temperature were increased linearly with time. The stress value increases rapidly in the initial stage with the increase of temperature, but when it increases to a certain value, it is unchanged in a certain period of time, which shows obvious yield phenomenon. During the overall
time, the temperature and the stress is decreasing, until eventually remained
stable, while the strain and displacement is always maintained at a stable value,
of which energy transfer has significant linear features.

CONCLUSIONS

In this paper, the thermodynamic properties of the welded joint of the steel
pillar in architectural engineering are studied, which provides an important
basis for the evaluation of the welding effect and the post welding treatment.
The conclusions are obtained as follows:

(1) The welding heat source is regarded as a spherical surface with
isothermal conditions. Through the calculation based on MATLAB, the thermal
cycle characteristics can be solved in different x position, which shows that the
location of the heat source is close to the heat source, and the temperature of the
weld is larger.

(2) According to the simulation results of ABAQUS, it can be known that
the stress of joints increases sharply with the increase of temperature, but when
it increases to the yield limit, the plastic deformation will occur, and the residual
stress will be larger.

REFERENCES