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RESEARCH ARTICLE

THERMODYNAMIC ANALYSIS OF TOWER CRANE STANDARD JOINT

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ABSTRACT

Welding is very important in the manufacturing process of tower crane, which can directly affect the safety and reliability of the whole tower crane. This paper takes the standard section of tower crane as the research object, and calculates the thermodynamics by analyzing the welding process between the support rod and the reinforcement rod. The transient temperature field and stress field at different time were obtained by thermo-mechanical coupling method. In addition, metallographic analysis was carried out for different regions of the weld. It is important to deduce the mechanical properties of the weld for improving the performance of the weld.

INTRODUCTION

Tower crane is working at high altitude, which belongs to a special type of work, and the related equipment belongs to a special type of equipment (WANG, 2015). Tower crane needs multiple processes in processing and manufacturing, among which welding process is the most important. The quality of welded joints is one of the key factors to ensure the safety and reliability of the tower crane. The strength and quality of welds directly determine the carrying capacity of the whole tower crane. Most of the welded parts in tower crane are medium carbon steel or low carbon steel, which are easily deformed by heat (JIANG, 2010). In order to ensure the welding strength of the standard section of tower crane, inert gas shielded welding with better welding effect is generally used, which can effectively reduce the defects and thermal deformation after welding. In the welding process, the joints bear a lot of heat, namely temperature load, and the temperature load will lead to thermal deformation and thermal stress of the joints. The relationship between thermal deformation and thermal stress is not independent (LI, 2016), but closely coupled, that is, thermo-mechanical coupling. According to the practical engineering experience, it is very important to predict and calculate the thermal deformation and thermal stress by specific methods for improving the strength and life of each component, reducing the safety accidents and equipment failure rate. Because of the difficulty of test measurement, it is necessary to use advanced CAE method to simulate and calculate the whole welding process to determine welding deformation and residual stress. In addition to the numerical calculation of temperature field and stress field, the microstructure can also be analyzed to verify the quality and characteristics of welded joints.

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The comprehensive application of numerical simulation technology and metallographic analysis technology can effectively ensure the welding quality of the welded parts, thus enhancing the competitiveness of the products, with good economic and social benefits.

Welding Conditions and Thermal Stress Mechanism of Joints

Welding process plan: The standard section of tower crane is the key bearing component of tower crane, which bears huge bending moment load. Therefore, it is necessary to ensure the connection strength between support rod and reinforcement rod. Support rod and reinforcement rod need to be positioned by tooling. The installation diagram is shown in Fig.1. Considering the welding quality and cost, CO_2 gas shielded welding is adopted in the welding scheme. The welded joints have good mechanical properties, including tensile strength, impact toughness and stiffness (WANG, 2015). The welding process includes two parts: the welding between different two support rod, and the welding between the support rod and the reinforcement rod.

- NBC400 series welding machine is selected for the welding between different support rod. The welding medium is high quality welding wire. The type of welding wire is H08MnSiA. The welding current is adjusted and maintained at 300A. The welding voltage is controlled at 30V, the welding speed is controlled at 4mm/s, and the number of welding layers is 3.
- BX300 series welding machine is used for the welding between support rod and reinforcement rod. The welding medium is E4303 type electrode, the welding current is controlled at 120A, the welding voltage is controlled at 20V, and the welding speed is controlled at 1.6mm/s.

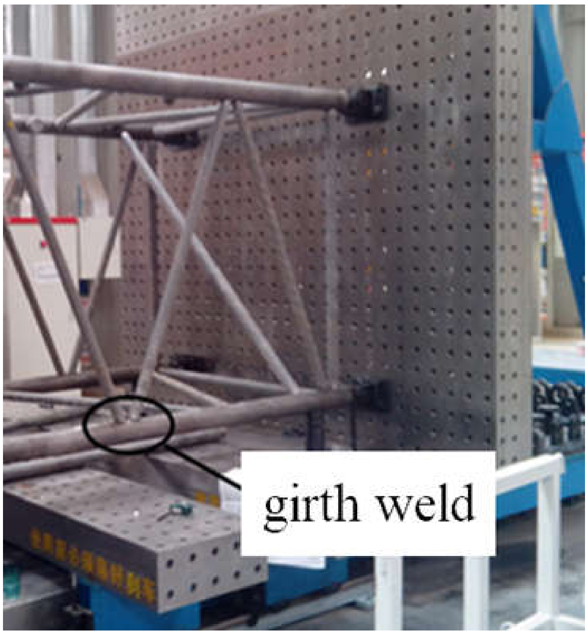


Fig. 1. Installation location of welded parts

Construction of Injection Model

Welding heat concentration, especially multi-pass welding, will produce significant thermal stress phenomenon when the weldment is cooled. In the process of heat generation and heat dissipation, the thermal fatigue of the welded joint will eventually result. In the welding process, the mechanical properties of qualified welds are better than those of base metal. The welding thermal stress is mainly caused by the change of internal microstructures, which makes the structure near the joint have different mechanical properties. The plastic deformation during expansion and contraction is one of the main factors to reduce the welding quality. For the standard section, there is a certain mechanical equilibrium relationship between the joints of each member. Taking the internal force as the object of analysis, the whole internal force and the internal force of the welded piece have zero moment to any point. The magnitude of thermal stress is affected by the restraint conditions. The greater the restraint force, the greater the internal thermal stress after welding. In some cases, larger thermal stress will lead to hot cracks in the joint (FU, 2007). Hot crack is a difficult problem in welding technology, and it is also one of the key problems leading to weld failure. According to the characteristics of metallographic structure, welded joints can be divided into three parts: base metal zone, heat affected zone and weld zone. Among them, the superheated zone in HAZ is the worst part of mechanical properties and the most vulnerable location of thermal cracks, which can extend to the depth of the surface. In actual production, in order to reduce thermal stress, heat treatment before and after welding is generally adopted.

Thermo-mechanical Coupling Analysis of Welded Joints

Governing equation of heat transfer: Welding process is essentially a physical phenomenon of heat generation, heat transfer and heat dissipation. According to heat transfer theory, the welding process can be expressed by unsteady heat transfer control equation, which can express the unsteady part, convection heat transfer part and heat generation part of the whole physical phenomenon. In three-dimensional space, the unsteady heat transfer governing equation can be expressed as

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

Where T is temperature, Q_v is energy dissipation per unit volume. ρ is the density of the material, C is the specific heat capacity of the welded parts.

According to the heat transfer process expressed in Eq.1, there is a certain balance between the external heat flow supplied by the welding heat source and the internal heat conduction, heat diffusion and heat convection during the whole welding process. By solving the equation, the transient temperature distribution of the welded parts can be obtained.

Establishment of finite element model

In order to obtain the temperature and stress field characteristics of welded joints, based on the thermo-mechanical coupling theory, the finite element method is used to simulate the whole process. Taking the welding between the support rod and the reinforcement rod as the research object, a three-dimensional software PRO/E is used to establish the model, and the model is imported into the finite element analysis software ABAQUS in the form of intermediate data format. When building the three-dimensional model, considering the calculation accuracy and efficiency, some structural parameters which have little influence on the analysis results are ignored. Finally, the model is shown in Fig.2. Because the model is symmetrical, the semi-model is used in the actual analysis.

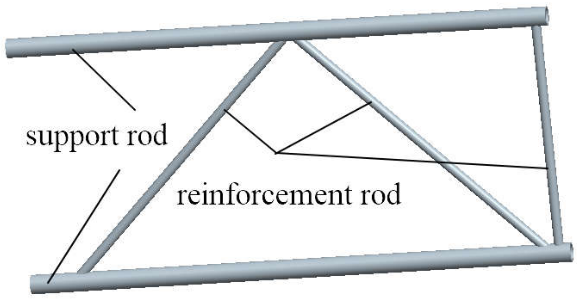


Fig. 2. Connection between support rod and reinforcement rod

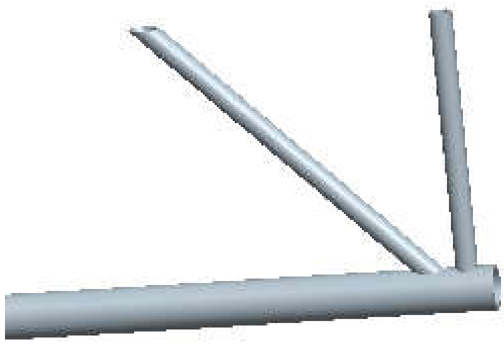


Fig. 3. Semi model

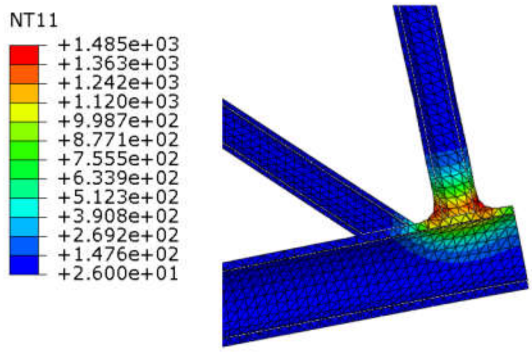
The finite element analysis software ABAQUS has a thermo-mechanical coupling solver, which can directly solve the temperature field and stress field of the model. The main contents of the pre-processing of the finite element model are: (1) the definition of material properties. The material to be welded should be defined in terms of the relationship between temperature and the material to be welded. (2) The C3D8T element with temperature-displacement coupling characteristics is selected as the element type. The element is an eight-node hexahedron element, which can realize the solution of three-dimensional linear displacement and temperature. (3) For the solver, the implicit algorithm (ZHU, 2005), is chosen. (4) For heat dissipation boundary conditions, both radiation heat transfer and convection heat transfer are expressed in terms of heat transfer coefficient, and the environmental reference temperature is set to 26 C. (FU, 2007) Heat flow load is applied in the form of heat flow density. In order to study the effect of temperature change on stress and deformation, the type of analysis step is temperature-displacement coupling (LIU, 2014), and the factors of material nonlinearity, expansion and creep are considered. The total time of transient analysis is defined as 300 seconds and the welding heat flow load is 100 seconds. The convective heat transfer and thermal radiation are expressed by the heat transfer coefficient of the film. According to the flow rate and temperature of the protective gas and referring to the empirical value, the convective heat transfer and thermal radiation are defined as 50 W/(m^2·K) and the environmental reference temperature is 26. Define that the degrees of freedom at both ends are 0, that is, fixed constraints.

Analysis of field variable result

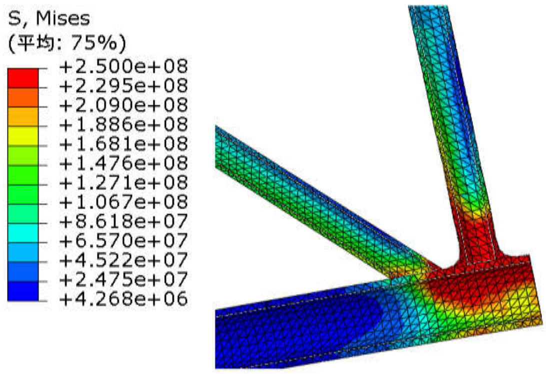
After continuous iteration calculation, the cloud image of numerical simulation is finally obtained. In order to facilitate the observation and analysis of the internal structure, the model is semi-sectioned, and the analysis results at 100s and 300s are shown in Fig.3 and Fig.4, respectively. In Fig.3, it can be seen that the peak temperature is located near the weld due to the energy concentration of heat flow load, and the thermal diffusion phenomenon is obvious. Under displacement constraint and thermal load, the stress concentration phenomenon is obvious. As can be seen in Fig. 4, with the continuation of the heat dissipation process, the whole temperature field becomes more uniform, and the peak temperature gradually deviates from the center of the weld. After 200 seconds of heat flow dissipation and transmission, the residual stress is still remarkable. The stress extremes in the model are more than ten times different, but the stress concentration phenomenon has been improved.

Metallographic Analysis of Welded Joints

The weld between support rod and reinforcement rod is taken as the object of metallographic analysis. The metallographic samples were prepared by cutting, inlaying, grinding, polishing and corrosion. Through metallographic microscope, 400 times magnification observation of microstructures, and then realize the judgment of welding quality and mechanical properties. The microstructures in the base metal area are shown in Fig. 5. It can be seen that the microstructures show remarkable band morphologies, in which the black structure or grain is pearlite, and the white structure or grain is ferrite. Because the base metal has been annealed before welding, the grain size shows some fine characteristics, and the distribution is more uniform, symmetrical, and the mechanical properties are good. With the transfer of welding heat, the structure near the weld zone is affected by high temperature, which makes the base metal structure produce some qualitative and deformation, that is, the heat affected zone of the weld. According to the typical morphology, the heat effect can be divided into partial phase transition zone and normalizing zone, as shown in Fig. 6 and Fig.7, respectively.

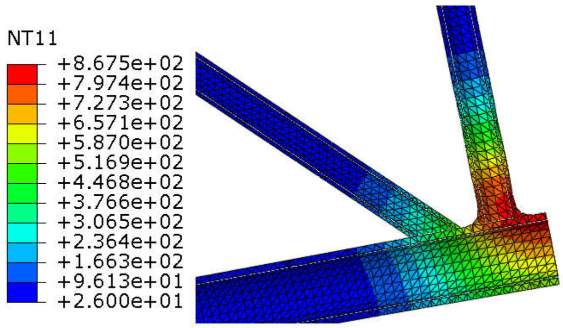


(a) Transient temperature field nephogram

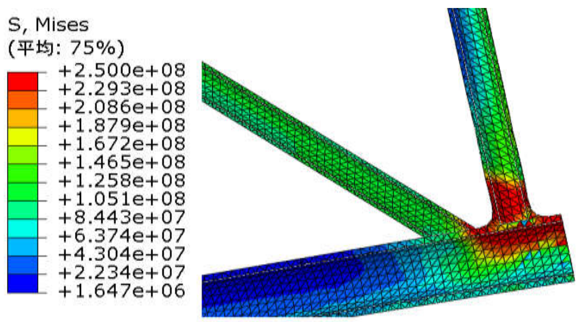


(b) Transient stress field nephogram

Fig. 3. Analysis results at 100s



(a) Transient temperature field nephogram



(b) Transient stress field nephogram

Fig.4 Analysis results at 300s

In Fig. 6, it can be seen that part of the phase transformation zone retains the banded morphology of the base metal zone, but the grain size is smaller. After transformation, the ferrite and pearlite grains with smaller size increase, the spacing decreases and the distribution is dense. It can be inferred that the plasticity of ferrite and pearlite is better than that of base metal. In Fig.7, it can be seen that the banded structure in the base metal area has completely disappeared, and has been replaced by a large number of ferrite and pearlite in phase distribution. The size difference of each grain is small, so the normalizing zone is also the best structure for the mechanical properties of the whole weld zone.

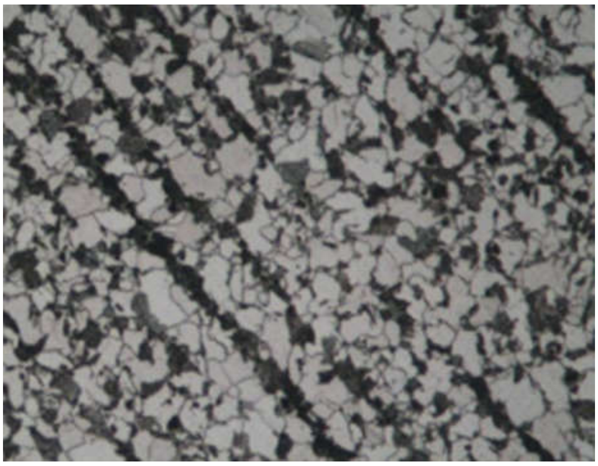


Fig. 5. Base metal area (400 times)

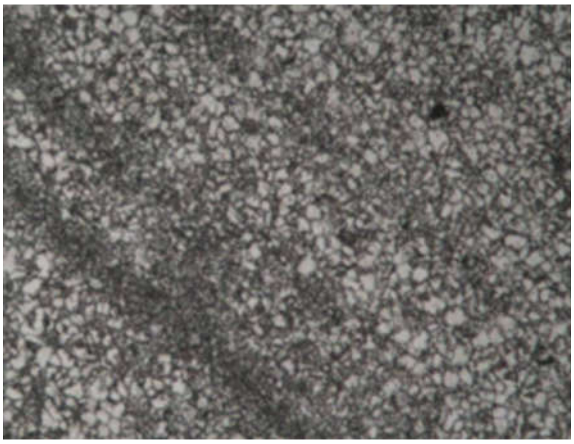


Fig. 6 Partial phase change zone (400 times)

In the welding process of support rod and reinforcement rod, the temperature far from the weld has not exceeded the austenite transformation temperature, so the grain in this area (part of phase transformation zone) has not undergone qualitative change. In the normalized zone, the heat transfer temperature of welding is higher than that of austenite transformation, and the holding time of the temperature range is long enough in the process of heat transfer, so many pearlite and ferrite grains with uniform distribution and small interval are formed. In the process of sample interception, it is required that the metallographic samples in the weld zone should be sampled just in the center line of the weld, which is helpful to analyze the formation mechanism of the weld structure. The morphology of the weld zone is shown in Fig. 8. It can be seen that there are a lot of martensite structure in the weld zone, which is due to the transformation from liquid to solid. During the transformation process, because of the rapid cooling rate of the liquid metal, coarse grains occur again. There are also a lot of cylindrical ferrite in the weld zone, which is due to the multi-pass welding. When the welding is completed, the subsequent welding heat has heat treatment effect on the previous weld. According to the structure and morphology of the weld zone, it can be inferred that the weld zone has high strength and stiffness.

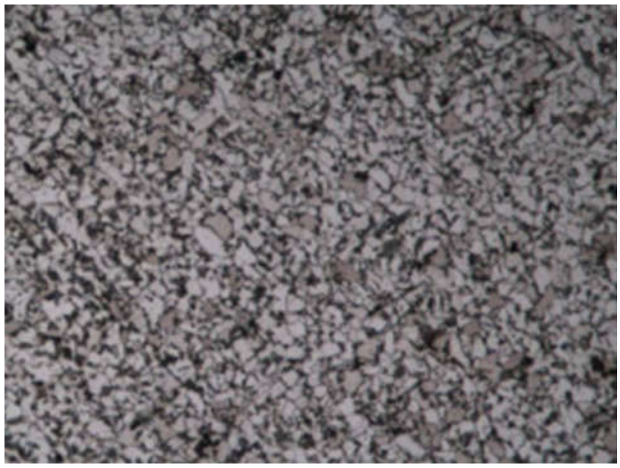


Fig. 7. Normalized zone (400 times)

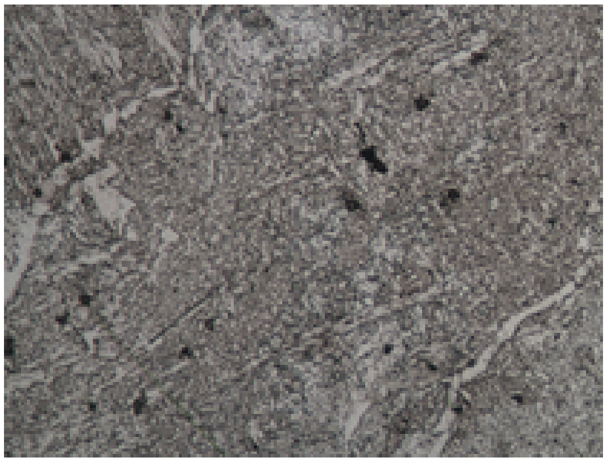


Figure 8. Weld zone (400 times)

Conclusions

In this paper, the welding joint of standard section of tower crane is taken as the research object. The CAE simulation technology based on finite element method and the experimental method based on metallographic analysis are synthetically used to study all aspects of weld performance. In order to improve the calculation accuracy of temperature field and stress field, considering the interaction and influence between them, the temperature-displacement coupling is set as the analysis type. The results show that the changes of stress field and temperature field show a certain matching. The changes of temperature are the result of the combined action of heat conduction, heat convection and heat radiation. Under the influence of welding temperature, the grains in some transformation zone and normalizing zone are finer, and the strength and plasticity are improved to some extent. The weld zone consists of multi-pass welds, and the final microstructures are composed of martensite, ferrite and sorbite, which have high strength and stiffness.

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