Study on influence of three kinds of stress on crack propagation in butt welds of spiral coil waterwall for ultra supercritical boiler

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Abstract. The spiral coil waterwall is the main pressure parts and the core functional components of Ultra Supercritical Boiler. In the process of operation, the spiral coil waterwall is under the combined action of welding residual stress, installation defects stress and working fluid stress, Cracks and crack propagation are easy to occur in butt welds with defects. In view of the early cracks in the butt welds of more T23 water cooled walls, in this paper, the influence of various stresses on the crack propagation in the butt welds of spiral coil waterwall was studied by numerical simulation. Firstly, the welding process of T23 water cooled wall tube was simulated, and the welding residual stress field was obtained. Then, on the basis, put the working medium load on the spiral coil waterwall, the supercoated stress distribution of the welding residual stress and the stress of the working medium is obtained. Considering the bending moment formed by stagger joint which is the most common installation defects, the stress field distribution of butt welds in T23 water-cooled wall tubes was obtained by applying bending moment on the basis of the stress field of the welding residual stress and the working medium stress. The results show that, the welding residual stress is small, the effect of T23 heat treatment after welding to improve the weld quality is not obvious; The working medium load plays a great role in the hoop stress of the water cooled wall tube, and promotes the cracks in the butt welds; The axial stress on the water cooled wall tube produced by the installation defect stress is obvious, the stagger joint, and other installation defects are the main reason of crack propagation of spiral coil waterwall. It is recommended that the control the bending moment resulting from the stagger joint not exceed 756.5 NM.

1. Introduction
The spiral coil waterwall is the main pressure parts of ultra supercritical boiler. The manufacturing workload is large and the production process is complicated [1]. The spiral coil waterwall is the key functional component of ultra supercritical boiler for variable pressure operation. Therefore, In the manufacture, installation and operation of the spiral coil waterwall, all kinds of stresses occur in the water cooled wall tube, of which the welding residual stress, thermal expansion stress and installation stress are the main factors [2]. The water cooled wall tube will also bear the working fluid stress in the variable pressure operation. This puts forward very high requirements for the performance of T23 material which be used to manufacture the spiral coil waterwall.

Foreign papers [3] reported that T23 joints which the wall thickness is not more than 10 mm, welding not only without preheating, but also cancel the welding heat treatment. Especially, the
simplification of welding process makes T23 an ideal material for producing the spiral coil waterwall for super supercritical boiler. T23 steel is widely used in the spiral coil waterwall of 1000 MW ultra supercritical tower boiler in china.

However, in recent years, it has been reported [4,5] that T23 butt welds of the spiral coil waterwall are prone to crack during operation, leading to leakage accidents and frequent outages of the units. Many scholars have carried out a lot of research on the early failure of T23 butt welds. The failure reasons are classified into three categories: over temperature pipe burst, high temperature corrosion, combined effects of welding stress, thermal stress and working medium stress [6]. The document [7] also pointed out that superimposed effect will produce between the welding residual stress with the working medium stress during the process of operation, start and stop. It is possible that cracks occur in the welded joint and its region nearby under the combined action of welding stress, thermal stress and working medium stress, which eventually results in cracking and leakage of water-cooled wall tubes.

Previous studies on cracks of butt welds in water-cooled wall tubes are rarely involve installation defect stress. In fact, the butt welds of the spiral coil waterwall is divided into the manufacture butt welds and the installation butt welds. The literature [8] pointed out that the cracks in the butt welds of T23 water cooled wall tubes generally appear in the installation butt welds, rarely appeared in the manufacture butt welds which have been made heat treatment after welding. In the process of welding of the spiral coil waterwall on field installation, geometric defects, such as misalignment, discount and angular deformation often occur. These defects cause great stress at the welded joint, which is called installation defect stress, which intensifies the crack propagation in the butt welds of T23 water-cooled wall tubes. Therefore, this paper uses ABAQUS finite element numerical simulation method, to investigate the influence of welding residual stress, installation defects stress and working fluid stress on crack propagation in butt weld of T23 water-cooled wall tubes, so that find out the main factors leading to the failure of butt welds of water-cooled wall tubes.

2. Physical model and numerical simulation

2.1 Establishment of Physical Model

Take a the T23 butt weld crack of spiral coil waterwall for 1000MW ultra supercritical boiler in a power plant as an example, as shown in Figure 1. When ultra supercritical boiler is the rated load of the working medium pressure P in water-cooled wall tubes is 27.9MPa, tube wall temperature is about 400 °C~550°C, the tube specification is 38.1 mm ×6.8 mm, take length 100mm which include the butt weld as the test sample. The physical parameters of T23 steel at various temperatures are shown in Table 1. Relationship between wall temperature and allowable stress of T23 steel tube are shown in Table 2. In the meshing of finite element mesh, the simulation of the welding temperature field uses the unit type DC3D8, the simulation of the stress field uses the unit type C3D8R. The mesh is divided into a cube with 1mm sides, it can not only guarantee the accuracy of calculation, but also greatly reduce the time required for calculation and improve the computational efficiency.
TABLE 1. The physical parameters of T23 steel at various temperatures

| Temperature/℃ | 20  | 50  | 100 | 200 | 300 | 400 | 500 | 600 | 650 |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Elastic modulus /GPa | 208 | 206 | 203 | 196 | 189 | 181 | 171 | 160 | 154 |
| Thermal conductivity /W/m.K | 34.4 | 34.8 | 35.6 | 36.6 | 35.8 | 34.4 | 33.3 | 32.2 |
| Expansion coefficient /10⁻⁶/K | - | 11.3 | 11.6 | 12.6 | 13.1 | 13.1 | 13 | 14 |
| Specific heat /J/(kg.K) | 440 | 460 | 480 | 510 | 550 | 630 | 660 | 770 | 860 |

TABLE 2. Relationship between wall temperature and allowable stress of T23 steel tube

| T23 wall temperature /℃ | 450 | 500 | 525 | 550 |
|--------------------------|-----|-----|-----|-----|
| allowable stress /MPa    | 117 | 111 | 105 | 87  |

2.2 Numerical Simulation of Welding Process

The welding process is sequentially coupled, that is, the simulation of the welding temperature field is first carried out, and then the calculated temperature field is introduced into the stress calculation model to calculate the stress field. Combined with birth and death element method, the Finite Element Method (FEM) is applied to simulation of welding temperature field. The welding process of finite element simulation will need to remove the weld part (kill), and then the welding step by step to add (reborn).

The environmental temperature during welding has some influence on the welding stress. In this paper, the predefined temperature field is defined as the ambient temperature of 20 ℃. When the welding is defined in Interaction, the convection coefficient between the inner and outer walls of the T23 tube and ambient air is 20w/m².℃. According to the actual welding process of T23 water-cooled wall tubes, T23 water-cooled wall tubes after welding is cooled to room temperature by the air. During the simulation of welding temperature field, the heat source is imposed to body in the form of the thermal flow. Firstly, needs to define the collection “set” which can impose load to body, then each “set” is subjected to a load of body heat flow. The magnitude of the load can be calculated from the welding process. According to the actual welding process parameters: I=100A, U=10V, welding speed 20mm/min, it is calculated that appropriate heat flux density is 6.25×10⁻⁶w/m², select the heat transfer efficiency is 40%, then each load unit set is 2.5 × 10⁻⁶.

3. Numerical simulation analysis

3.1 Influence of Welding Residual Stress
The residual stress field is obtained by finite element numerical simulation. It is found that the maximum residual stress 89.6MPa, which is located in the outer wall of the heat affected zone. According to the ASME standard, the relation between allowable stress and wall temperature of T23 material is shown in Table 2. In the ultra supercritical boiler, the working temperature of T23 water-cooled wall tubes is about 450℃~550℃, apparently, the residual stress of single layer welding is very high, and it is close to or higher than the allowable temperature under the highest equivalent temperature. The local stress distribution in the weld is shown in Figure 2. The residual stress in the heat affected zone is the largest. It shows that the heat affected zone is easy to cause cracks in the fluctuating load of the ultra supercritical boiler under variable pressure operation. Many documents have mentioned that cracks occur in the heat affected zone, probably due to welding residual stresses.

As shown in Figure 2, the stress variations along the fusion line to the weld root from the outer heat affected zone. The stress from the outer heat affected zone of the tube to the weld root is reduced first and then increased, and the minimum stress is 72MPa, appearing at about 2.3mm from the outer wall. The maximum stress is in the heat affected zone of the outer wall, the stress at the welding root is 84.2MPa, and the stress values are relatively high.

3.2 Influence of Working Fluid Stress
The rated working pressure of ultra supercritical tower boiler is 27.9MPa, so the maximum internal pressure of T23 water wall tube is 27.9MPa, and the external operating temperature is about 500℃. According to the internal pressure 27.9MPa, the calculated axial tensile stress of the tube is 16.8MPa. The welding residual stress field is loaded into the model as the initial stress field, and set the ambient temperature is 500 ℃. The stress distribution of the T23 water-cooled wall tubes after superposition of the working load and the welding residual stress is shown in Figure 3. As can be seen from Figure 3, the maximum stress of the T23 water-cooled wall tube is distributed on the inner wall of the tube, where the stress at the welding root is concentrated, and the maximum stress is 113MPa. According to the established column coordinates, the radial, circumferential and axial stress field distributions of the work load and the welding residual stress are superimposed, can calculate radial forces, circumferential forces, and axial forces, respectively. The largest of the three is the circumferential stress, and where the welding root it reaches 65MPa.
In the installation of T23 water-cooled wall tubes, it is used brute force to butt joint when the stagger, the discount and the angle shift occur frequently. The welding process of T23 water-cooled wall tubes in the installation:

- When welding parts correspond, the inner wall should be flush, and the wrong boundary value of the tube shall not exceed 0.5mm. When meet the wrong boundary value of the tube, can only be opened on both sides of fin by cutting, and then force counterparts, after the butt weld be done, the fin on the both sides will again weld between the T23 water-cooled wall tubes. The length of the fin being cut is not able to the same, and the force required to correct the T23 tube is different, and the bending moment is different for the weld.

The effect of bending moment remains when the T23 water-cooled wall tube is welded well. The influence of bending moment on stress distribution in T23 tubes by using ABAQUS. The stress field superimposed on the welding residual stress and the work load is taken as the initial stress field into the model, and then the bending moment load is applied at one end. The change of the three principal stresses of the T23 tube and the bending moment is obtained, as shown in Figure 4. With the increase of bending moment, radial stress, hoop stress and axial stress increase, but radial stress and hoop stress increase less, axial stress increases obviously.

According to table 2, it is found that the allowable stress is between 117-87MPa at the working temperature (450℃~550℃) of the T23 water-cooled wall tubes. In order to ensure the safety of use, choose 87MPa as the reference of the allowable stress. In order to avoid the axial stress beyond the allowable stress of the material, the maximum bending moment under the allowable stress is calculated by the finite element software. When the axial stress maximum allowable stress 87MPa, the maximum bending moment allowed is 756.5NM, the stress distribution is shown in Figure 5. The maximum stress value 238MPa is located in the outer heat affected zone of the pipe inside the bend. At this time, the radial stress is very small between the three, only 12.2Mpa. the hoop stress is larger than 74Mpa, and it is located in the inner part of the bend.
4. Conclusions

The welding residual stress, especially the main stress in the three directions, is small, which the tensile stress is not enough to cause the damage of the material. Therefore, the effect of post welding heat treatment on reducing welding residual stress is not obvious. The working load has great effect on the hoop stress of T23 water-cooled wall tubes. The stress of T23 water-cooled wall tubes is mainly determined by the working load without considering the tension of the fin. The bending moment caused by the stagger mouth has obvious effect on the axial stress of the T23 water-cooled wall tubes. In order to ensure the safe and reliable operation of the T23 water-cooled wall tubes, it is recommended that the bending moment not exceeding 756.5NM be used.

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