Creep failure analysis of heterogeneous steel welded steam pipeline T91-TP347H

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Abstract: Finite element analysis was carried out on the actual service process of dissimilar steel welded pipes of T91-TP347H, and numerical analysis was carried out on the internal and external surface of the joint and the weld interface on both sides from three aspects of maximum principal stress, equivalent stress and stress triaxiality. The results show that the steam side T91-weld area is weakened seriously, the holes are more nucleated, the stress is more concentrated, the holes are easy to expand, it belongs to the high stress triaxial area, the hole density is high, is a dangerous area. Stress relaxation occurs on T91 side with the increase of service time, so the reason for failure is not the increase of stress level in the stress concentration area, but the deterioration of material performance is caused by long service time.

1. Introduction

In super criticality unit, depending on the pipe connection, the parts and all parts of each are not identical, to the requirement of pipe such as high temperature resistance, creep resistance, oxidation resistance, etc., thus in the connection section will there is a lot of dissimilar steel welding joint, such as the T91 steel used for heating furnace tube heat, TP347H is widely used at the low end of the furnace tube of heating surface, therefore, for the super (super) criticality unit, inevitably there is a lot of T91 - TP347H dissimilar steel welding joint.

According to statistics, accidents caused by the failure of the four tubes (superheater tube, re heater tube, water wall tube, and economizer tube) in the furnace accounted for about 2/3 of the total in ultra (super) critical boilers [1]. Furnace tube joints are a more common situation in furnace tube failure accidents. For welded structures, defects caused by pores, slag inclusions, lack of fusion, incomplete penetration, welding cracks and metallurgy, make the service life of steel welded joints usually does not meet the design requirements, usually about 1/5 to 1/2 of the same kind of steel joints. In addition, the difference of various performance parameters at both ends of the joint (such as thermal expansion coefficient, thermal conductivity, etc.) will also lead to unexpected failures of the equipment, and the occurrence of these failures will cause huge economic losses. Therefore, the performance research and life prediction of dissimilar steel welded joints are urgently needed.

At present, many researchers make use of finite element analysis software to analyze and study welded joints. HYUNJESUNG et al. [2] explained the microstructure analysis and creep failure
mechanism of different welding parts of T92 and T22 heat resistant steel, extracted the real stress-strain curve of each area of the joint by using the finite element method, and analyzed that the creep cavity actively formed and combined in the austenite carbon deficient area, leading to the macro brittle fracture. Zhang Bo qi et al. [3] carried out finite element modeling analysis on the welded joints of different types of pearlite/Martensite steel, and the analysis showed that, for the welded joints of different types of steel, the heterogeneity of the structure will bring additional creep damage, so the analysis of the heterogeneous structure needs to be carried out by combining test and simulation. Zhang Jian qiang et al. [4] carried out creep simulation of 12Cr18Ni12Ti/12Cr1MoV welding joints of different kinds of steel, and found that the weld fusion line of 12Cr1MoV side was the weak position of the joints. Combined with the actual working conditions and welding sample size, the service process was simulated, the temperature field and stress field in the calculation results were analyzed, the trend of stress state variation was grasped, and the danger area was obtained. Although the actual conditions cannot be completely restored, the simulation method can be improved to get more accurate results close to the actual conditions, which can play a key role in preventing accidents and taking preventive measures.

In this paper, according to the actual working conditions, creep damage simulation and stress analysis of T91/TP347H dissimilar steel welded joints are carried out.

2.T91/TP347H Creep damage simulation of welded joints of dissimilar steel

2.1 Operating mode analysis
The research object of this paper is the welded joint of super (super) critical unit T91/TP347H. According to the data obtained from the actual operation of the power plant, the welded joint of T91/TP347H is located in the big box, and the amount of smoke outside the pipe is very small, which can be ignored. The overall temperature of the pipe is close to the steam temperature, which is about 580°C.

2.2 Performance parameters of metal materials
High temperature components are preferred to use high temperature performance of higher heat resistant steel than traditional engineering materials, such as high chromium steel T91, new austenitic heat resistant steel TP347H. Austenitic heat resistant steel TP347H as mature ASME - 213 steel grade, than other TP300 series steel, because of its excellent mechanical strength, creep strength, oxidation resistance is widely used in boiler reheater and superheater tube heating furnace on [5-6], T91 martensite heat-resistant steel [7] has excellent high temperature strength, toughness, weldability, oxidation resistance and thermal fatigue resistance, and easy processing and forming, much lower part is used for heating furnace tube temperature.

2.3 Construction of welding joint model of different kinds of steel
NORTON creep constitutive model is adopted in this paper, and the expression is as follows:

$$\dot{\varepsilon} = A\sigma^n$$  \hspace{1cm} (1)

$\dot{\varepsilon}$ for minimum creep strain rate; $\sigma$ is stress; A and N are the creep coefficient and creep index of materials at A given temperature. The SIZE of the 3D model is 60mm*8mm*250mm, the width of the weld on the inner and outer surfaces is 6mm and 12mm respectively, and the residual height of the weld on the inner and outer surfaces is 1.5 and 2mm. The model is simplified by making a quarter cylinder, and the mesh in the area near the weld is refined in accordance with the gradual refinement from the base metal at both ends to the middle weld. The unit type is thermally coupled unit Solid226, and the sum number is 60976, and the total number of units is 13200.

2.4 The boundary conditions
The simplified quarter cylinder should not be shifted or rotated during the calculation. The x-direction displacement constraint is applied to the left end plane of the model. Meanwhile, the symmetric
displacement constraint is applied to the two axial tube sections generated by the simplified model. The internal pressure acts on the inner surface of the welded joint in the form of surface stress. The size is 26MPa, the temperature is 580℃, and adiabatic boundary conditions are applied to the outer surface. The simulation time is respectively half a year, one year, two years, five years and ten years.

3. Creep analysis of dissimilar steel welded joints T91/TP347H

3.1 Temperature field analysis
According to the internal and external temperature of the steam pipe, the convective heat transfer coefficient and the thermal conductivity of the material, check and compare the results of the calculation time for half a year, one year, two years, five years, and ten years. It can be seen that the model temperature has stabilized in half a year, and it is basically the same as the actual situation of the power plant. In the big box and the tube is wrapped with insulation material, the temperature inside and outside the tube is basically the same as the steam temperature, and the temperature field is evenly distributed after reaching a stable temperature. The overall temperature difference of the furnace tube is less than 1℃.

3.2 Maximum principal stress
The creep failure of welded joints is mainly caused by hole nucleation and expansion at grain boundary interface, and the maximum principal stress is the controlling factor of creep deformation [8]. When the simulated steam pressure is 26MPa, the maximum principal stress along the outer surface and the inner surface is shown in Figure 1-2.

In the time of the figure, the service is 0.5 years, the surface maximum principal stress of extremum is located in the weld center near the TP347H - side seam, 131.96 MPa, with the increase of service time, extreme value point of maximum principal stress to the T91 side of weld offset, serving time for 10 years, the surface maximum principal stress appears near the T91 side of weld, the maximum value of 97.4 MPa. On the whole, the maximum principal stress shows a downward trend with the increase of time. When the service time is 5 and 10 years, the maximum principal stress at the T91-weld seam begins to show a negative value, that is, the phenomenon of extrusion occurs, and the service time is shorter. There is little difference in the stress levels of the welds on both sides. After long-term service, the vicinity of the T91-weld is a dangerous area. Because of the occurrence of stress relaxation, the maximum principal stress peak value will decrease as the service time increases. Inner surface maximum principal stress in the service time of 0.5 years, in the parent metal TP347H near TP347H side of weld and weld are negative, extrusion occur, with the increase of service time, the regional stress increase, from the extrusion to stretching, TP347H - the maximum principal stress of the weld as the service time increases, the maximum stress peak is always appear in the inner surface T91- welds, serving time for 1 year, maximum principal stress of extremum, size of 168 mpa, and T91 - although the maximum principal stress of the weld decreases with the increase of service time,However, the range of variation is smaller than that of other locations, and the stress level is always higher, so the weakening of this area is more serious and the holes are more nucleated.

According to the comparative analysis of different positions and service years, it can be concluded that the steam side T91-weld is a weak area.
Figure 1. Distributions of maximum principal stresses on the outer surface

Figure 2. Distributions of maximum principal stresses on the inner surface

3.3 Stress triaxiality
Research results in recent years show that the fracture mode of materials is determined by the stress state of materials. For steel used for pressure vessels such as steam pipelines, the fracture mode can be divided into dimple type and shear type. The dimple type fracture appears as a flat fracture on the macro level, while the shear type fracture appears as a inclined fracture on the macro level [9-11]. The stress triaxial degree is used to measure the stress state of the material [12], which is the key to control the fracture mode of the material [13]. The specific judgment criterion is whether the stress triaxial degree reaches the critical value; the critical value of the stress triaxial degree is the material constant; if it reaches the critical value, it is dimple type; if it does not reach the critical value, it is shear type.
Stress triaxiality factor $R^\sigma$ expression is as follows:

$$R^\sigma = \frac{\sigma_m}{\sigma_{eq}}$$

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

$$\sigma_{eq} = \frac{1}{\sqrt{2}} \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/3}}$$

Which $\sigma_m$ as the mean stress, $\sigma_{eq}$ for equivalent stress, $\sigma_1$, $\sigma_2$, $\sigma_3$ are the first, second and third principal stresses respectively.

When the simulated steam pressure is 26MPa, the stress triaxial factor distribution along the outer surface and the inner surface is shown in Figure 3-4.

It can be seen from the figure that when the service time is 0.5 years, the extreme triaxial value of external surface stress is located at 12.55mm from the TP347H side to the weld center, and its size is 0.658. With the increase of service time, the maximum triaxial value of external surface stress began to shift to the T91 side. When the service time was 10 years, the maximum value was distributed at the distance of 35.75mm from the weld center on the T91 side, with a size of 0.414. The outer surface T91-weld and TP347H-weld decreases with the growth of time. After two years of service, both of them become negative, namely, extrusion occurs simultaneously. The surface T91-weld is more severely squeezed than TP347H-weld. When the service time is less than 5 years, the stress triaxiality at the inner surface TP347H-weld is negative and in the squeezed state, which increases with the increase of time. After 5 years of service, the stress becomes positive and in the tensile state. The maximum internal surface stress triaxial value shifted to the TP347H side with the increase of time. In 10 years, the maximum internal surface stress triaxial value appeared in the area near the weld center TP347H-weld, and the area near the TP347H-weld stress reversed, resulting in more serious fatigue damage.

The triaxial distribution law of stress at T91-weld and TP347H-weld is basically the same. With the increase of service time, the triaxial distribution law of stress at the inner surface side increases, while that at the outer surface side gradually decreases to negative value, resulting in extrusion phenomenon. Compared with TP347H, the inner surface of T91-weld is always in a state of higher stress triaxiality and in a stable state, without negative value. The stress is relatively concentrated, the holes are easy to expand, and the area of higher stress triaxiality and the hole density are relatively high [14]. Therefore, T91-weld interface is weaker under high temperature conditions.
4. Conclusions
According to the finite element analysis results of T91-TP347H dissimilar steel welded pipe in actual service process, a conclusion can be drawn:

(1) Inner surface maximum stress peak value is always appear in the T91 -welds, serving time for 1 year, maximum principal stress of extremum, and T91 - although the maximum principal stress of the weld decreases with the increase of service time, but the change in the other position is small, always in
a high stress level, thus weakening the region is more serious, more transfigure nuclear holes.

(2) Compared with TP347H, the welding seam of inner surface T91-weld is always in a state of higher stress triaxial degree and in a stable state, without negative value. The stress is relatively concentrated, the hole is easy to expand, the area of higher stress triaxial degree and the hole density is relatively high.

(3) According to the analysis, TP347-weld interface has stronger creep resistance than T91-weld interface, and the inner surface of T91-weld is always in a higher stress triaxial state and in a stable state than TP347H-weld. Comprehensive consideration shows that the stress triaxial representation effect is better, and the steam side of T91-weld is a weak area.

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