Research on Failure Mechanism of Condenser Titanium Tube in Nuclear Power Plant

Dungui Zuo, Zhongwei Zhang*, Yunting Lai, Guodong Zhang
Su Zhou Nuclear Power Institute Co., Ltd, Jiang Su, China
*Corresponding author: zhangzhongwei@cgnpc.com.cn

Abstract. Titanium welded tubes are widely used in condensers and heat exchangers of coastal power plants because of their excellent manufacturing properties and seawater corrosion resistance. In this paper, the leakage analysis of titanium welded tubes of condensers in nuclear power plants that after 4 years of service is carried out, and experimental studies such as morphology analysis, chemical composition analysis, hardness test, metallographic examination, mechanical properties test, and scanning electron microscope analysis are conducted. The results show that the cracks initiated at the maximum vibration amplitude of the titanium welded tube and gradually expanded in a fatigue method. Large vibration of the titanium welded tube is the main cause of the leakage.

1. Introduction
Titanium has been processed into a variety of products and applied in many fields for its excellent corrosion resistance, high specific strength and good processing properties. Titanium tubes are one of the most important varieties in the titanium products and are widely used. As a relatively unique form of titanium product, titanium welded tube is made of cold-rolled titanium strip coil and then welded by tungsten inert gas shielded welding. As titanium welded tube has excellent resistance to seawater corrosion, it also has strong corrosion resistance to marine organisms and deposits. At the same time, it has excellent corrosion resistance to ammonia corrosion in the empty pumping area of the condenser, especially the resistance to high-speed seawater erosion. After being developed, it has replaced stainless steel and copper tubes as the preferred material for various condensers and heat exchangers, and has been widely used in the manufacturing of condensers and heat exchangers taking seawater as the cooling medium available for coastal power stations, seawater desalination, and seawater petrochemicals [1-2]. However, during the operation of condensers in coastal nuclear power plants, titanium welded tubes are under severe working conditions such as mineral salt erosion and seawater impact for a long time, and sometimes the titanium welded tubes break and fail, resulting in tube bundle leakage [3-5]. In this paper, the reasons leading to fracture for the condenser of a power plant was analyzed in this paper, finds out the cause of failure, and provides an effective basis for the subsequent safe and stable operation of the power unit.

2. Experimental Materials
The condenser with titanium tube leakage is a surface condenser with double shell, single process and single back pressure. It is a fully welded structure consisting of upper throat, lower throat, shell, water chamber, hot well, hydrophobic diffuser, bypass diffuser, and low-pressure hydrophobic piping. The condenser throat is rigidly connected with the exhaust port of the low-pressure cylinder, and the bottom of the hot well is rigidly supported by the concrete foundation.
The condenser shell is equipped with four groups of tube bundle modules to condense the exhaust steam turbine of the low-pressure cylinder. An air-cooling area is arranged at the lower part of each group of the tube bundles for extracting non-condensable gas. The top periphery of the tube bundle is made of titanium welded tubes of Φ22.225×0.7/B338 Gr2, and the main condensing area and air-cooling area are made of titanium welded tubes of Φ22.225×0.5/B338 Gr2. The spacing between adjacent titanium tubes is about 6 mm. The end tube plate is titanium composite plate. Both ends of the titanium tube are fixed to the end plate by means of expansion and welding. The end plate assembly and the shell are welded to form an entity, with a support plate in the middle of the tube bundle (titanium tube and the support plate are gap fit, and the gap is about 0.5 mm) to prevent the tube bundle from vibration damage under normal operating conditions. The middle tube plate is welded to the side plate and end plate of the shell through I-beams and ribs.

The cracked titanium tube is located in 4B module of the condenser, as shown in Figure 1. The cracking position of titanium tube is about 6,100 mm away from the inlet end.

3. Experiment Results

3.1. Macroscopic Morphology

The results of macroscopic morphology are shown in Figure 2. The cracks of the titanium tubes are located in the middle of the wear marks of two support plates, and the distance between such cracks and the wear marks of support plates is 385 mm. The fracture surface of the titanium tube is relatively flush with no obvious macro plastic deformation in the vicinity, which is brittle cracking. There are many elliptical damages on the outer surface of the titanium tube, and the rubbing direction is circumferential. Under the microscope, the rubbing parts are different in depth and show different colors, and a few parts are blue. There are bright wear marks with a width of 13 mm at the joint between the titanium tube and the support plate, and there is a layer of black deposits on other surfaces.
3.2. Chemical Composition Analysis
The results of the chemical composition analysis of titanium tubes are shown in Table 1. The content of each element sampled by titanium tubes for inspection meets the chemical composition requirements of Grade 2 materials in ASTM B338-2014.

Table 1. Chemical Composition of Titanium Tube (wt.%)

| Sample          | N   | C   | H   | Fe  | O   | Ti   |
|-----------------|-----|-----|-----|-----|-----|------|
| Sampling        | 0.004 | 0.004 | 0.0030 | 0.058 | 0.097 | Allowance |
| ASTM B338 Grade 2 | ≤0.03 | ≤0.08 | ≤0.015 | ≤0.30 | ≤0.25 | Allowance |

3.3. Microstructure examination
The metallographic examination results of titanium tube base material and weld are shown in Figure 3. The metallographic structure of the base material of titanium tube for inspection is fine equiaxed α phase with grain size of grade 8. The inner and outer walls are relatively flat, and there are no defects such as cracks, folds and peeling. The transition between weld and heat affected area is smooth, and the microstructure is serrated α phase and a small amount of needle α phase.

The metallographic examination results of rubbing position of titanium tube are shown in Figure 4 and Table 2. Deformation layers can be seen in the rubbing parts of titanium tube, with different depths and thicknesses of about 61 to 77 μm. From the comparison between the depth of deformation layers and the thickness of titanium tubes, severe rubbing occurs in titanium tubes for inspection. According to the depth of rubbing deformation layer and crack distribution, the deepest deformation layer is located in the uncracked part of the titanium tube.
Figure 3. Metallographic Examination of Titanium Tube (a) base material,(b)welded zone

Figure 4. Metallographic Examination of Rubbing (a) Nine o'clock position(b)Eleven o'clock position

Table 2. Rubbing position of the fracture tube

| Rubbing Position | Wall Thickness of the Rubbing Position (μm) | Thickness of Deformation Layer (μm) |
|------------------|--------------------------------------------|-------------------------------------|
| Point 9          | 460                                        | 61                                  |
| Point 11         | 459                                        | 77                                  |

3.4. Mechanical Property Test at Room Temperature

Tensile test, flattening test and flaring test of the tube at room temperature were carried out on the titanium tube for inspection. The test results are shown in Table 3 and Figure 5 to 7. Mechanical property of the titanium tub is coincided with the requirements of ASTM B338.

Table 3. Tensile properties data at room temperature

| Sample           | Tensile Strength $R_m$/MPa | Yield Strength $R_{P0.2}$/MPa | Post-break Elongation $A/\%$ |
|------------------|-----------------------------|-------------------------------|-----------------------------|
| Sampling         | 458                         | 386                           | 34.6                        |
| ASTM B338 Standard Value | $\geq$345                  | 275$\sim$450                 | $\geq$20                    |
3.5. Hardness Test
The microhardness test results are shown in Table 4. The results indicate that the microhardness of the welded joint is uniformly distributed.

| Test Area            | Hardness Value (HV) | Average Value (HV) |
|----------------------|---------------------|--------------------|
| Base Material        | 152 158 155         | 155                |
| Heat-affected Area   | 170 172 172         | 171                |
| Weld                 | 184 185 182         | 180                |

3.6. Microscopic Analysis of Fracture
The microscopic observation results of fracture are shown in Figure 8. The fracture wear is relatively serious, and fatigue strips can be seen in the undamaged area. The direction of fatigue bands near the weld shows that the crack source is located near the weld.
The morphology of rubbing marks on the external surface of the titanium tube is shown in Figure 9. The appearance of rubbing marks on the external surface is similar, which are clear grooves with clear directivity, and are typical circumferential wear marks.
4. Analysis and Discussions
From the results of the morphology analysis and microscopic analysis, it is inferred that the chemical composition and tensile properties of the titanium tube are coincided with the requirements of ASTM B338. There are no visible cracks after flattening, reverse flattening and flaring tests. The metallographic structure of the base material is fine equiaxed α phase. The transition between the weld and heat-affected area is smooth, and the microstructure is serrated α phase with a small amount of needle α phase. The inner and outer walls of the unworn parts are relatively flat, and there are no defects such as cracks, folds and peeling. In conclusion, manufacturing quality and welding quality of titanium tube can be eliminated.

The fracture of the titanium tube is relatively flat, and no obvious macro plastic deformations can be seen in the vicinity. The fracture wear is relatively serious, and obvious fatigue strips can be seen microscopically at various locations in the undamaged area, which is a typical fatigue fracture. The expansion direction of the fatigue band near the weld indicates that the source of the crack is located near the weld zone. From the relative position of the crack source and the rubbing, the crack initiates at the opposite position of the severe rubbing part of the titanium tube, not at the most serious rubbing part.

The titanium tube is a slender structure with low stiffness and vibrates during operation due to external fluid impact. For the non-end position, the support plate is equivalent to the limit constraint, and the vibration amplitude of the tube in the middle of the two support plates is the largest, which is also the area with the most severe friction between the tubes. Because of the collision and friction between the tubes, the outer wall of the tube is worn and thinned. From the analysis results of rubbing, it can be seen that there is a large amplitude of vibration in the titanium tube for inspection, which makes the collision and friction between the titanium tube. When titanium tube vibrates, it will bear alternating stress, and the magnitude alternating stress is related to the vibration amplitude of titanium tube. While for titanium tube with limit constraint at both ends, the maximum vibration amplitude is located in the middle of the tube section. In a short period of time, the wall thickness reduction caused by fretting friction between titanium tubes is small, so the amplitude of alternating stress at the outer walls of both sides in the main vibration direction of titanium tubes is equivalent. When the amplitude of alternating stress is excessively large, fatigue cracks often initiate in the weak position of the structure, such as the discontinuity of structure or material, and the sudden change of shape, etc. For titanium tube, the longitudinal weld is the weak position on the titanium tube. Although the rubbing in the weld area is not severe, the fatigue cracks still initiate and expand gradually in this area and form annular cracks. The cracked titanium tube is located in the outer layer of the condenser bundle, and the cracks are located in the middle of the two support plates, which should be related to the relatively severe impact vibration of this position.

5. Conclusions
After performing the cause analysis of the tube, the conclusions can be summarized as follows: (1) the chemical composition and mechanical properties of the titanium tube are in accordance with ASTM B338, and the metallographic structure is normal. The inner and outer walls are relatively flat, and there are no defects such as cracks, folding, and peeling. Titanium tube material is qualified. (2) the fatigue crack initiates in the area near the weld., and the vibration of titanium tube with large magnitude leads to the initiation of crack at the maximum vibration amplitude and gradually expands to form annular crack.

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References

[1] C.J.Li. (2013) Analysis on the Development Status of Titanium Welded Tube Industry in China. Titanium Industry Progress., 30:5-7.

[2] Y.S.Deng, Y.He, B.Hao. (2001) Application of Pure Titanium Tubes in Power Stations in China. Corrosion Science and Protection Technology., 13:511-513.

[3] Z.G.YANG,Y.GONG,J.Z.YUAN. (2012) Failure analysis of leakage on titanium tubes within heat exchangers in a nuclear power plant, part: Mechanical degradation. Materials and Corrosion., 63:18-28.

[4] X.H.Yuan, Y.F.Caii. (2014) Fracture Analysis of Failure of Titanium Tube in Condenser. Journal of Wuhan Institute of Technology., 36:53-57.

[5] C.Yao, Z.G.Yang, J.Z.Yuan, J.F.Chen, L.J.Zheng. (2012) Failure Analysis of Abnormal Thinning of Outer Wall of Titanium Tube of Condenser. Journal of Fudan University (Natural Science)., 51:148-155.