Tube-burst Analysis of SA-213TP437H high Temperature Superheater

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Abstract. A SA-213TP437H high temperature superheater tube burst in a power plant. In this paper, combined with it’s runtime environment, macro examination, metallographic examination, electron microscope observation and micro area composition analysis were used to analyze the failure reason of the sample tube. The results show that: Due to the fine grain size of superheater tube, a large number of brittle phase are precipitated in the metallographic structure in lower temperature. During long-term running, the tube was affected form low cycle fatigue cracking by temperature stress caused by the load change of generator set,start and stop and so on.,which is a long-term over temperature tube burst. Although it is an example of misuse of ultra-fine grain steel pipe, it is recommend that the power plants should conduct spot-check of grain size for other SA-213TP437H high temperature superheater tube, and eliminate similar dangers of superheater tube burst.

1. Introduction
The 5# boiler in a power plant is a 600MW Supercritical front and rear wall opposed combustion boiler, which was put into operation in February 2009. On Seven 29, 2021, It’s high temperature superheater burst when stable operation of thermal power unit above 550MW load. The superheater tube is made of ASME SA-213 TP347H, and the specification is φ 45 × 9mm. The BMCR operating parameters of thermal power unit at that time: Steam pressure at Superheater outlet is 25.5MPa; Feed water temperature is 289℃; Steam temperature at the superheater outlet is 571℃. The burst mouth is located at the sixth ring in the sixth row from east to west, and 2m down from the ceiling. After burst, the tube was bent out of line. Checked the nearby tubes and find no abnormality. In order to find out the cause of burst, four sample tubes were taken nearby the burst mouth , the sample tube as shown in Figure 1, the burst mouth is marked as 1#, The lower two sections of the burst mouth are marked as 2# and 3# respectively, and the upper part of the burst mouth is marked as 4#. Among them, 1#, 2# and 4# are at the burst mouth, and 3# is obtained at 1.5-2 m below the burst mouth.
2. Test Contents and Results

2.1. Macroscopic Appearance and Dimension Inspection
Macro examination shows that the burst mouth of the 1# sample tube is trumpet shaped, and the edge of the mouth is rough and not sharp, there are longitudinal grooves in the inner wall of the burst surface, cracks on the outer wall, the inner wall of opposite the burst is smooth and few longitudinal grooves, as shown in Figure 2. a. The crack on the 2# and 4# sample tubes is the crack propagation section, and there are still longitudinal grooves on the inner wall near the crack, and no cracks on the opposite side. The 3# sample tube is also an extension section of the burst tube, which is about 1.5-2m away from the burst. After sectioning, it can be seen that half of the inner wall has longitudinal groove (presumably the same side of the blast extension line), and the other half is smooth ((presumably the opposite side of the blast extension line), as shown in Figure 2. b. The measurement results of sample tube size are shown in Table 1, and the measurement position is shown in Figure 3. The results show that the outer diameter of all tube sections is thickened and the wall thickness is thinned. The closer to the burst mouth, the thicker the outer diameter and the thinner the wall thickness are. The thickening and thinning at the blast mouth are the largest, and the maximum thickening and thinning amount is 8.8% and 2.59mm respectively.

Figure 1. The picture of sample tubes.

Figure 2. (a) photo of inner and outer walls of burst open; (b) photo of inner wall of 3#.

Figure 3. detection position of thickness and hardness.
Table 1. Measurement result perimeter/outside diame and thickness of sample tube.

| Sample Tube | Perimeter and Outside Diameter/mm | Thickness/mm |
|-------------|-----------------------------------|--------------|
| 1#          | Perimeter of the maximum burst: 151 | 7.16 (A) 6.41 (B) 7.41 (C) 8.09 (D) |
| 2#          | 48.4 49.0                         | 7.25 (A) 7.26 (B) 8.37 (C) 8.22 (D) |
| 3#          | 47.6 47.1                         | 7.77 (A) 7.64 (B) 8.45 (C) 8.55 (D) |
| 4#          | 48.9 48.4                         | 6.85 (A) 7.77 (B) 8.46 (C) 8.17 (D) |

2.2. Mechanical property test
The hardness test of the obvious surface of section thinning (the surface of crater extension line) and the not obvious surface (opposite to the crater extension line) is carried out according to ASTM E10. The detection position is shown in Figure 3, and the results are shown in Table 2. The hardness of the surface and back of the sample tube near the blast mouth or the blast mouth extension line are higher than the requirements of ASME sa-213 for TP347H hardness \( \leq 192\text{hb} \). The hardness of the thinner part of all sample tubes (blast mouth or blast mouth extension line) is higher than that of the thicker part (opposite to blast mouth or blast mouth extension line).

Table 2. Hardness of sample tube (HBW2.5/187.5).

| Sample Tube | Burst Open or The Extension Line | Opposite to The Burst Open or The Extension Line |
|-------------|----------------------------------|-----------------------------------------------|
| 1#          | 260 236 253                      | 233 236 237                                   |
| 2#          | 205 212 211                      | 202 205 198                                   |
| 3#          | 198 207 198                      | 195 194 207                                   |
| 4#          | 222 221 245                      | 223 219 221                                   |

2.3. Metallographic Examination
Metallographic examination was carried out according to GB / T 13298 and ASTM E112, and the results are shown from Figure 4; after slight corrosion by picric acid, hydrochloric acid and alcohol solution, precipitates were found in all four sample tubes, as shown in Figure 4. a. After further corrosion, it is found that the grain size of the sample is finer than grade 9-10, which does not meet the requirements of ASME SA-213 for TP347H grade 7 or coarser, as shown in Figure. 4. b. There are a large number of creep holes near the burst mouth. The closer to the outer wall, the more creep holes and many creep holes have been connected to form cracks, as shown in Figure. 4. c; the micro morphology of inner wall groove is a crack with large opening, the tip is intergranular propagation, and the oxide layer is visible around the crack. The maximum depth measured in the wall thickness direction is about 0.39mm. The closer to the burst mouth, the more creep holes, and the more precipitates at the grain boundary, which are massive. There are more precipitates near the burst mouth than far from the burst mouth. Meanwhile, no creep holes are found3#. 
2.4. SEM/EDS Analysis
After being slightly etched with picric acid, hydrochloric and acid alcohol solution, the massive precipitated phase of 1# metallographic sample was observed and analyzed under scanning electron microscope / energy spectrum. According to the energy spectrum analysis, the main components are Fe and Cr, and the contents of Fe and Cr are colse. Therefore, it can be judged that the precipitated phase is σ phase. Creep holes occur at σ phase, as shown in Figure. 5.

3. Discussion
The grain size of the sample tube is very fine, and the hardness of all sample tubes is higher than the standard requirements. The macroscopic characteristics of the burst mouth are as follows: there are cracks on the outer wall near the burst mouth, and the fracture is rough and blunt. The microscopic characteristics are as follows: a large number of σ phase, creep holes and creep cracks can be seen in the microstructure near the burst mouth. The closer to the outer wall, the more holes and cracks are, and σ Phase also appeared in the remaining sample tubes. The precipitated phase of the burst extension line is significantly more than that opposite side, and in longitudinal direction the farther away from the burst mouth, the less σ phase precipitates and the less carbide precipitated at the grain boundary. The macro and micro morphology are typical characteristics of long-time over-temperature creep burst tube. The hardness of sample tube is higher than the standard requirement, which is due to the increase of matrix hardness caused by the precipitation of more σ phase and carbide.

References [1] pointed out that the σ phase is hard, brittle and magnetic, which leads to great changes in the properties of tubes: reducing metal plasticity, toughness and even high-temperature creep strength. Since the low cycle fatigue resistance of materials depends on the plasticity of material, the low cycle fatigue strength of tubes decreases due to the reduction of plasticity. The cyclic change of tube wall temperature (unit startup and shutdown, etc.) causes material expansion or shrinkage deformation. The groove in the inner wall is distributed along the longitudinal direction of the tube.
The circumferential stress is the thermal stress in operation, which causes the expansion and contraction of the tube, leads to low cycle fatigue cracking.
To sum up, due to a large number of $\sigma$ harmful phase precipitated in the tube wall, the high temperature creep property of the tubes is greatly reduced, and the long-term creep burst occurs. At the same time, in the long-term operation process, due to the influence of temperature difference stress caused by unit load change, start and stop, longitudinal low cycle fatigue cracking occurred inside the tubes wall.

For pressure parts of boiler heating surface, the maximum design working temperature of TP347H material is 650 $^\circ$C. The metallographic examination of the sample tube shows that a large amount of $\sigma$ phase precipitates. $\sigma$ phase is a kind of intermetallic compound with square structure, which is a brittle hard phase. It is mainly precipitated in the form of FeCr in 18-8 austenitic stainless steel, which is one of the main reasons for the decrease of plasticity and increase of hardness of the sample tube, it is a harmful phase. In general, $\sigma$ phase precipitates in a wide temperature range for a long-term service. In the book "metallogic problems of stainless steel" edited by academician Jimei Xiao [2], it is considered that the temperature range of $\sigma$ phase present is usually above 520 $^\circ$C and below 820 $^\circ$C. The higher the Cr content of stainless steel, the more $\sigma$ phase formed. It is also pointed out in reference [2] that the most easily precipitated temperature range of $\sigma$ phase is 750 $^\circ$C ~ 870 $^\circ$C. $\sigma$ phase usually precipitates on the grain boundary, especially at the trigeminal grain boundary, which will also precipitate in the grain after a long service time. Wang[3] found that, the rod shape $\sigma$ phase begin to precipitate along the TP347H grain boundary, after 3650 hours aged at 700 $^\circ$C. In addition, the higher the temperature, the easier the precipitation of $\sigma$ phase. This component has been operated for about 8 years, less than the general design life. A large number of harmful phases have been precipitated, and the tube burst presents the characteristics of long-time over-temperature creep. Is there any over-temperature phenomenon during operation? In addition, it is pointed out in reference [4] that the finer the grains are, the easier it is to form $\sigma$ phase. Ze T's paper [5] also mentioned that the grain size of local over-temperature part is fine. Is the creep burst of sample tube related to too fine grain size? It also needs further studied.

4. Conclusion
4.1 The burst mouth of the sample tube presents the characteristics of typical long-term over temperature operation. The cause of leakage is that a large amount of $\sigma$ brittle phase precipitates during unit operation, leading to the reduction of creep performance of the tubes. Under the action of stress, the tube thickens, and A large number of creep microcracks are derived from the crack at austenite intergranular $\sigma$ phase, which form cracks on the outer surface near the burst mouth, and gradually aggregate and expand into macro axial cracks. At the same time, the crack propagates from the outer wall along the wall thickness direction under the affect of stress, and finally forms a burst mouth. The grooved crack inside the inner wall surface is the low cycle fatigue crack caused by the temperature difference stress (the change of load, unit start and stop, etc) during long-term operation. It's also related to the reduction of fatigue properties caused by the precipitation of a large number of $\sigma$ brittle phases.

4.2 This case belongs to the misuse of sa-213tp347h steel tube with ultra-fine grain, resulting in a large amount of precipitation of $\sigma$ brittle phases at a lower temperature, further leading to the low cycle fatigue cracking formed. It’s belongs to a case. However, it is recommend that the power plants should conduct spot-check of grain size for other SA-213TP437H high temperature superheater tube, and eliminate similar dangers of superheater tube burst, to ensure the safe and stable operation of the power plants.
References
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